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TECHNICAL NOTE

Identifying Leachate Plume Accumulation Zones at Lapite Dumpsite in Nigeria Employing Very Low Frequency Electromagnetic (VLF-EM) Method

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Abstract: A geophysical investigation involving the use of the very low frequency-electromagnetic (VLF-EM) method was carried out at the Lapite dumpsite, which has been operational since 1998. The aim was to map conductive lineament features and the extent of contaminant plume in the subsurface for potential groundwater pollution. The VLF-EM survey was deployed at 10 m intervals with the aid of ABEM WADI VLF-EM meter. Nine VLF-EM profiles with lengths stretching between 120 and 250 m were arranged inside the dumpsite. A control profile of VLF-EM data was placed approximately 500 m from the dumpsite. The VLF-EM measurements were construed using Fraser and Karous-Hjelt filtering processes. Fraser graphs and current density pseudo-sections show the existence of west-orientated conductive structures/leachate accumulation zones at various depths, cutting across the dumpsite. The 2D current density sections indicate that leachate accretion/fluid-filled structures have high conductivity values (low resistivity), aligning with the outcomes acquired from the preceding electrical resistivity survey. The contaminant leachate may infiltrate the shallow groundwater system situated on the west side of the dumpsite.

Keywords: Leachate plume, VLF-EM, Current density pseudo-section, Dumpsite, Shallow groundwater.

1. Introduction

Wastes generated from daily anthropogenic activities are of different forms and sizes. Households, organizations, and factories generate solid wastes that must be disposed of properly in an approved landfill or open dumpsite [1]. In many African countries, limited land availability for waste disposal has led to unrestrained dumping of wastes on the outskirts of the cities and main road channels, posing serious environmental and public health hazards [2-3]. There has been a significant rise in the generation of municipal solid wastes in Nigeria over the past decades [3-4]. Among the explanations for the increase in municipal solid waste generation are population growth, rural-urban migration, and inadequate provision of suitable disposal systems by relevant environmental agencies [5-6]. Indiscriminate disposal of solid waste affects air quality, soil, and nearby shallow aquifer units [1, 5, 7]. The composition of municipal solid waste (MSW) deposited in a particular landfill/dumpsite depends on social status, consumption pattern, urban setting, and nearness to industries [8-10]. MSW consists of unused plastics, animal remains, household materials, factory solid wastes, papers, fertilizers, toxic materials, and many biodegradable materials. Besides polluting dumpsite soil, MSW causes different appealing and public health problems [11-13]. The solid waste deposited in open dumpsite experiences gentle, anaerobic disintegration over the years

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and produces considerable expanse of leachate plumes in addition to other disintegrating formations like dumpsite gas, metalloids, and perilous contaminants that may trickle out of the dumpsite into nearby shallow groundwater units, consequently contaminating greatly required groundwater bodies [13-14]. Leachate, a liquid formed from putrefied waste, has been reported to have a higher conductivity (lower electrical resistivity) value [13, 15]. Therefore, the existence of leachate in lithologies and the soil matrix can enhance their electrical conductivity from weak/modest to exceptionally high [16-17]. Pollutants such as leachate plumes hardly ever remain at the point of release but are rather distributed via the soil matrix by four principal transport methods: advection, diffusion, dispersion, and sorption [4, 18-19]. Besides, leachate settles near the surface or beneath the dumpsite, with the resultant piezometric head stimulating both the downward and outward movement of the leachate plume out of the dumpsite to the nearby shallow aquifer units [13, 15]. Pollution of shallow groundwater sources by leachate plumes from nearby dumpsites occurs typically as a result of the percolation of contaminants through the permeable soil/ parent materials into shallow groundwater [20-21].

Many authors have investigated the geophysical and geochemical impacts of leachate on soil and nearby groundwater resources [15, 22-25]. Researchers have also assessed the environmental impacts of contaminant leachate from the Lapite dumpsite on air quality [5] as well as soil and groundwater [1, 5]. Specifically, Popoola and Fakunle [1] used the geophysical method to depict leachate plume regions and the extent of leachate migration, respectively.

The VLF-EM is an electromagnetic technique that utilizes radio waves from global network transmitter stations in the frequency range of 15 - 30 KHz [26]. This method relies on transmitted currents prompting secondary responses in conductive subsurface structures [17, 27]. The VLF-EM survey is particularly used to locate subsurface conductors that may act favorably as conduits for the leachate movement [28-30]. Oladejo *et al.* [31] investigated the groundwater potential of a granitic area using VLF-EM, while Monteiro Santos *et al.* [29], Moradzadeh *et al.* [32], and Abdullahi *et al.* [30] applied this method to detect leachate accumulation zones and extent of their migration.

In this present study, the VLF-EM technique was utilized to examine the accumulation and spreading of leachate plumes within the dumpsite. The core aims of this study were: (a) delineation of conductive features within the dumpsite, which is underlain by basement complex formation, and (b) delimitation of the extent and depth of the contaminant leachate plume.

2. Depiction of the Survey Area

Lapite dumpsite (Fig. 1) is situated in Ibadan city and delimited by longitudes 3.91160°E and 3.91464°E and latitudes 7.5825°N and 7.57032°N [4]. The inspected dumpsite was opened in 1998 and is still in use to this day. It spans approximately 20 ha along Old Oyo Road [1, 15]. According to records from the Oyo State Waste Management Authority (OSWMA, 2016), the Lapite dumpsite receives approximately 31% of the generated solid wastes [5]. The site experiences a humid climate typical of southwestern Nigeria, with an average annual rainfall of about 1270 mm, an average annual potential evapotranspiration of 1467 mm, and a mean annual maximum temperature of 33°C [33].

A detailed description of the geological setting and other physical features of the study area has been previously reported [4].

3. Methodology

The very low frequency electromagnetic (VLF-EM) survey was carried out on the dumpsite to detect potential linear conductive features such as faults, fracture zones, and leachate plumes. A previous study by Ganiyu *et al.* [4] investigated part of the study area using the electrical resistivity imaging method.

The present study offers several advantages, as the survey profiles were oriented approximately in a north-south direction with uniform inter-profile spacing. This acquisition methodology is expected to enhance the accuracy of delineating and mapping contaminant leachate pathways.

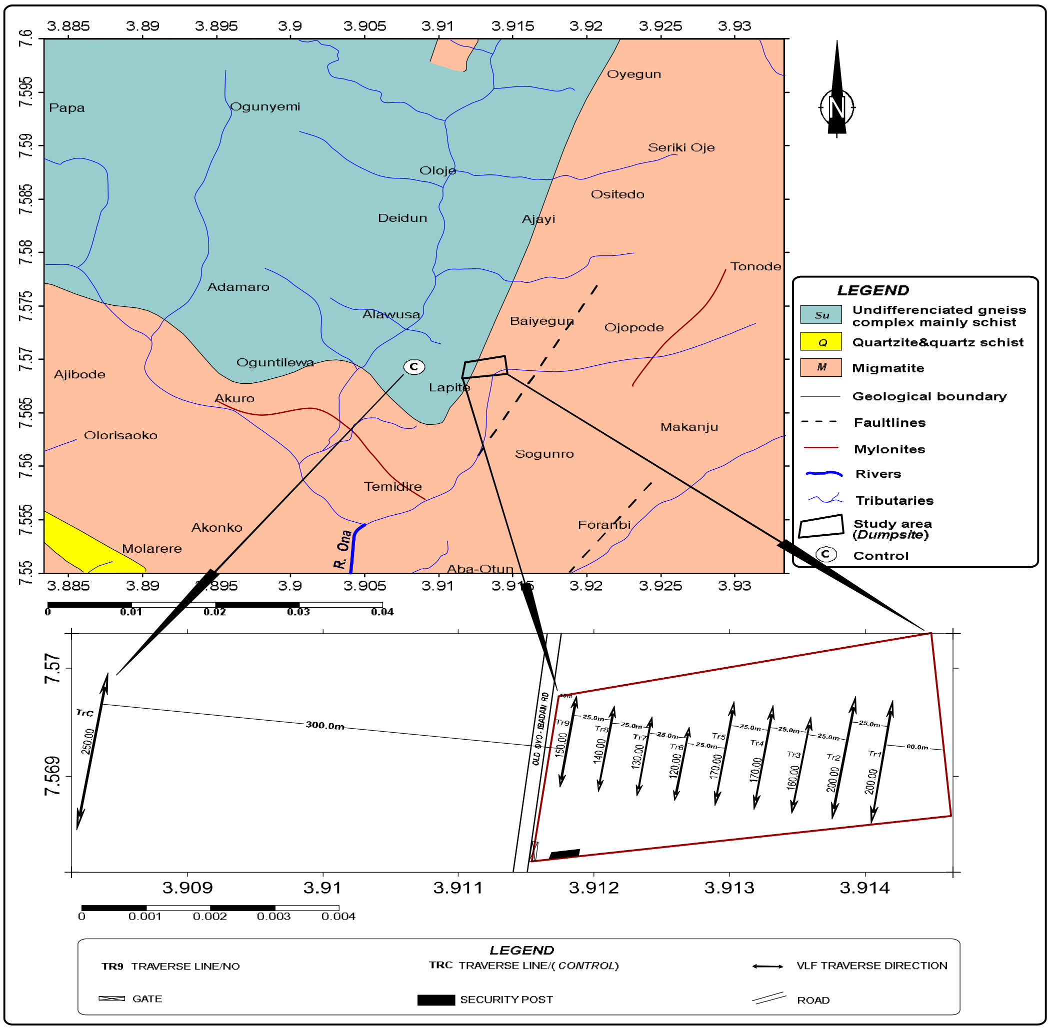


FIG. 1. Geological map of the study area showing the field layout for the VLF-EM survey.

Nine (9) parallel VLF-EM traverses with inter traverse separation of 25 m and length varying between 120 and 250 m were planned inside the dumpsite. Additionally, a control profile was laid along the road, approximately 500 m away from the dumpsite. VLF-EM data were acquired along each profile utilizing the ABEM WADI VLF meter at a measurement interval of 10 m. A frequency of 18.2 KHz was used for the measurements. All VLF-EM profiles were oriented in a north-south direction across the dumpsite. The data acquisition layout for the VLF-EM survey is depicted in Fig. 1.

The WADI VLF meter recorded both the perpendicular (H_z) and parallel (H_x) components of the secondary electromagnetic field along the laid profiles at 10 m intervals. The ratio H_z / H_x gives a scalar B, tipper that has real and imaginary parts [17, 29, 34]. The real constituent of B is utilized in this study. The acquired real VLF-EM data were processed using Fraser and Karous-Hjelt filtering methods [35-36] to generate response graphs against station positions. Fraser filtering transforms every genuine crossover or inflection point in the real anomaly into a positive peak, whereas reverse crossovers become negative peaks. The Fraser filter Q [35] was computed using a filter operator given by:

$$Q = f_{2,3} = (M_4 + M_3) - (M_2 + M_1) \qquad (1)$$

where Q = $f_{2,3}$ refers to the EM data, and the subscripts are station positions (i.e., M_1, M_2, M_3, and M_4 are the readings of the measured real at stations 1, 2, 3, and 4, respectively). The values are plotted between M_2 and M_3 points. The resulting plots of both raw and filtered real values against station positions for each profile are presented as Fraser plots.

The KHFILT inversion software was used to obtain relative current density pseudosections based on the real component [37].

4. Results and Discussions

4.1. Interpretation of VLF-EM Profiles

The VLF-EM profiles were interpreted using the response signal of the Fraser graph for the identification of conductive features and/or leachate accumulation zones, while Karous-Hjelt current density pseudosections were employed to detect leachate plumes and map their spatial distribution. These are shown in Figs. 2 to 6.

Profile 1 shows diagnostic points indicative of conductive features and/or leachate accumulation zones between horizontal distances of 52–80 m on the Fraser graph. Correspondingly, the Karous-Hjelt pseudosection shows high positive current density values at 48 m (near the base) and 75 m (toward the top) of the profile, suggesting the presence of a conductive structure that may facilitate the migration of leachate plumes, as seen in Fig. 2(a).

Profile 2, depicted in Fig. 2(b), reveals multiple locations with relatively high current density values, signifying significant occurrences of conductive materials and leachate plume accumulation zones with varying depth extensions.

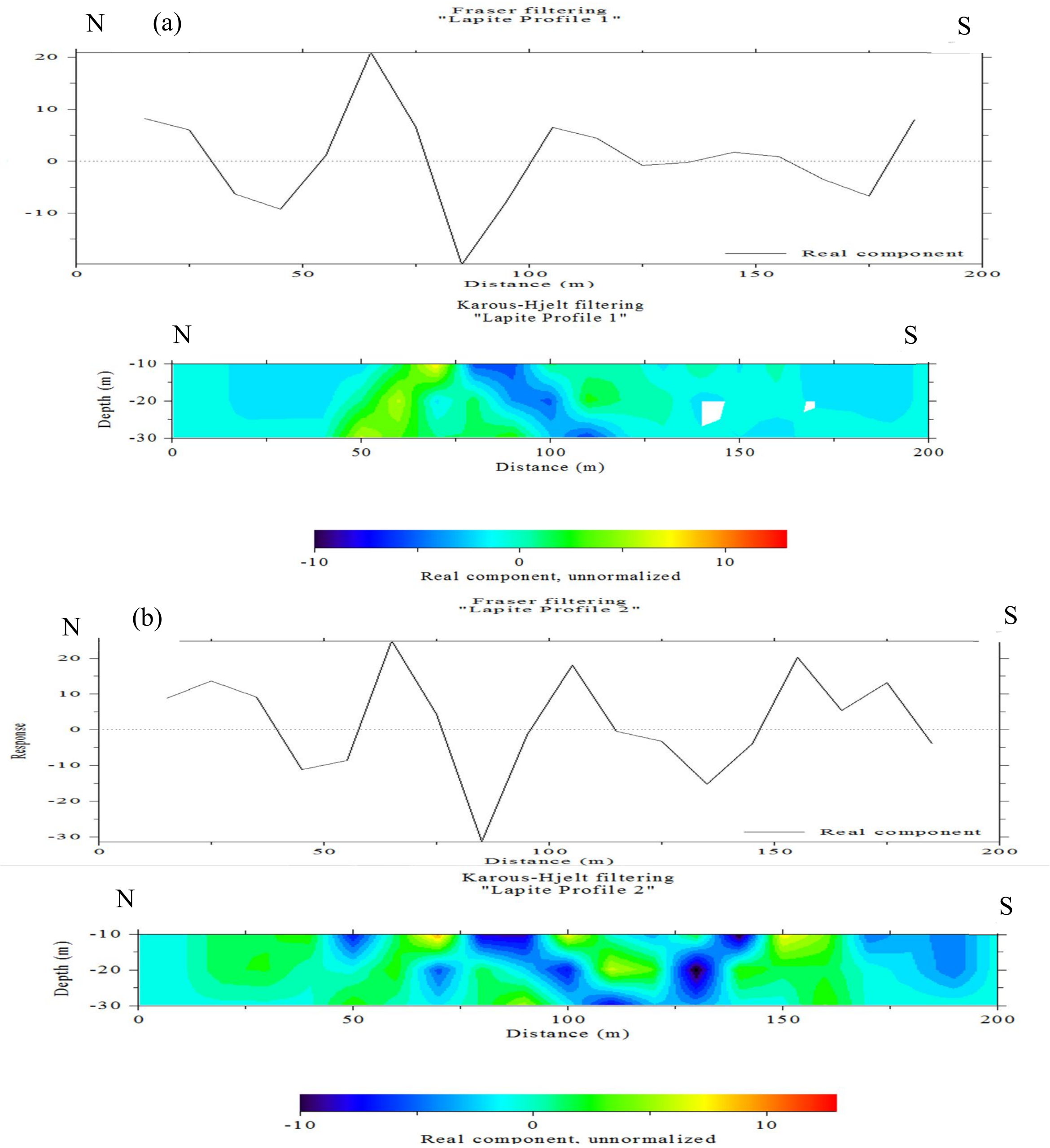
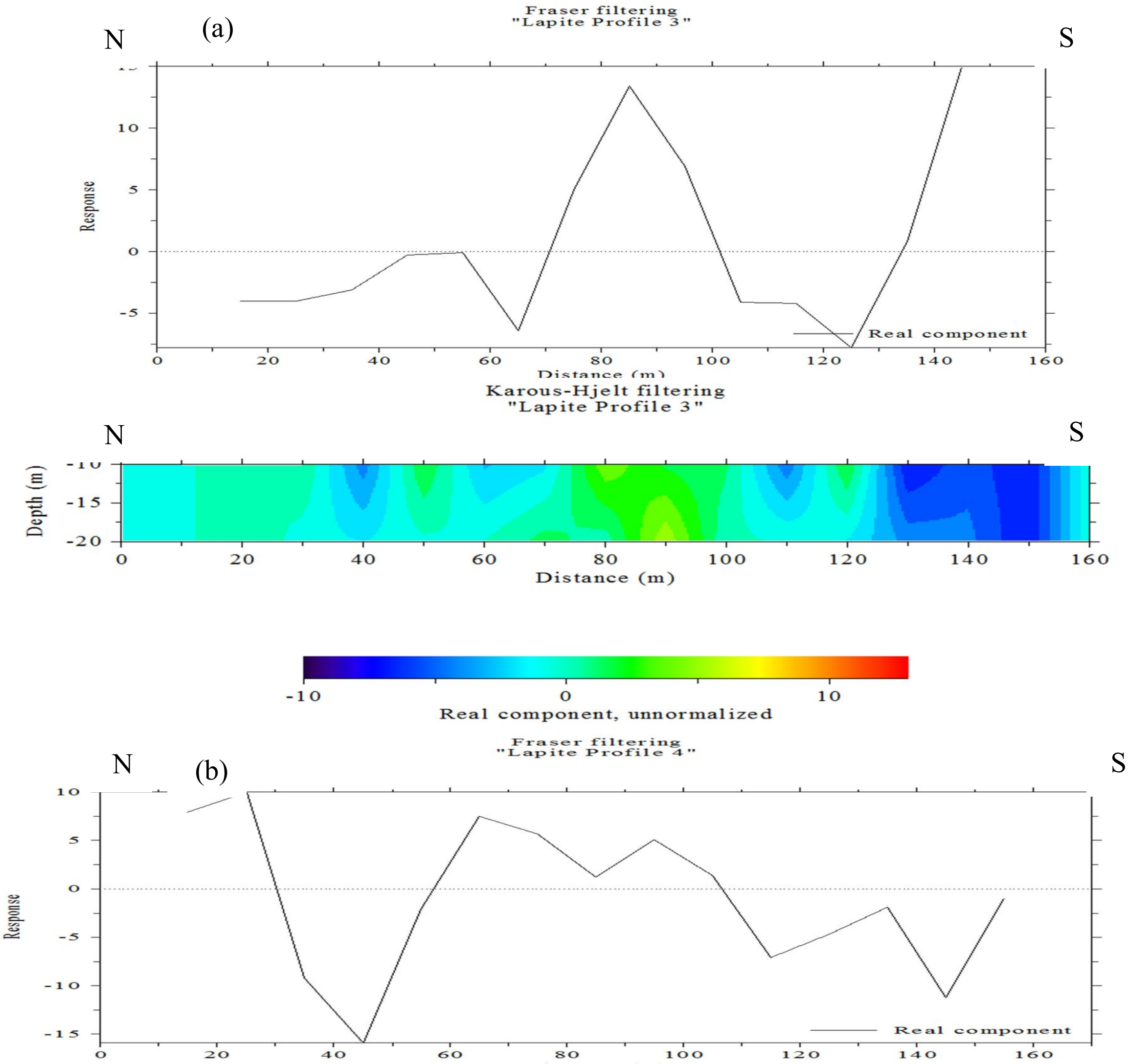


FIG. 2. Frazer graphs and 2D sections for profiles 1 and 2.

The Fraser filtering graph of the VLF-EM profile 3, located on the southern side of the landfill, reveales points diagnostic of a conductive zone, suggesting the presence of a contaminant plume at horizontal distances of 70-105 m and 135-145 m along the traverse, as illustrated in Fig. 3(a). The Karous-Hjelt pseudosection for profile 3 exhibites a slightly elevated positive conductivity anomaly, indicating leachate accumulation or a conductive structure. This centrally located conductive region extends from 78 m at the top to 98 m at the bottom of the profile, as depicted in Fig. 3(a).

A slightly high conductivity response, likely corresponding to a leachate plume or conductive lineament features, was observed at horizontal distances of 18–25 m and 55–105 m along profile 4, as seen in Fig. 3(b). The Karous-Hjelt pseudo-section for profile 4 reveals weakly conductive zones at a horizontal distance of 18–30 m and an approximate depth of 25 m. Additionally, another linear conductive body was detected at 65 m at the top, extending to 88 m at the base of the profile, as illustrated in Fig. 3(b).



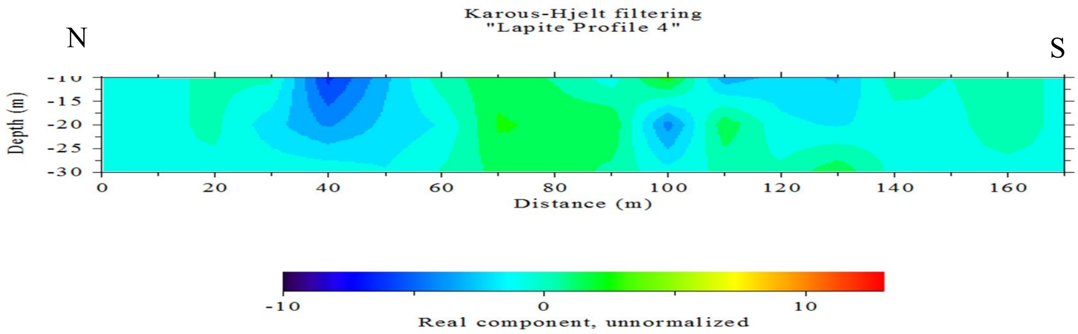
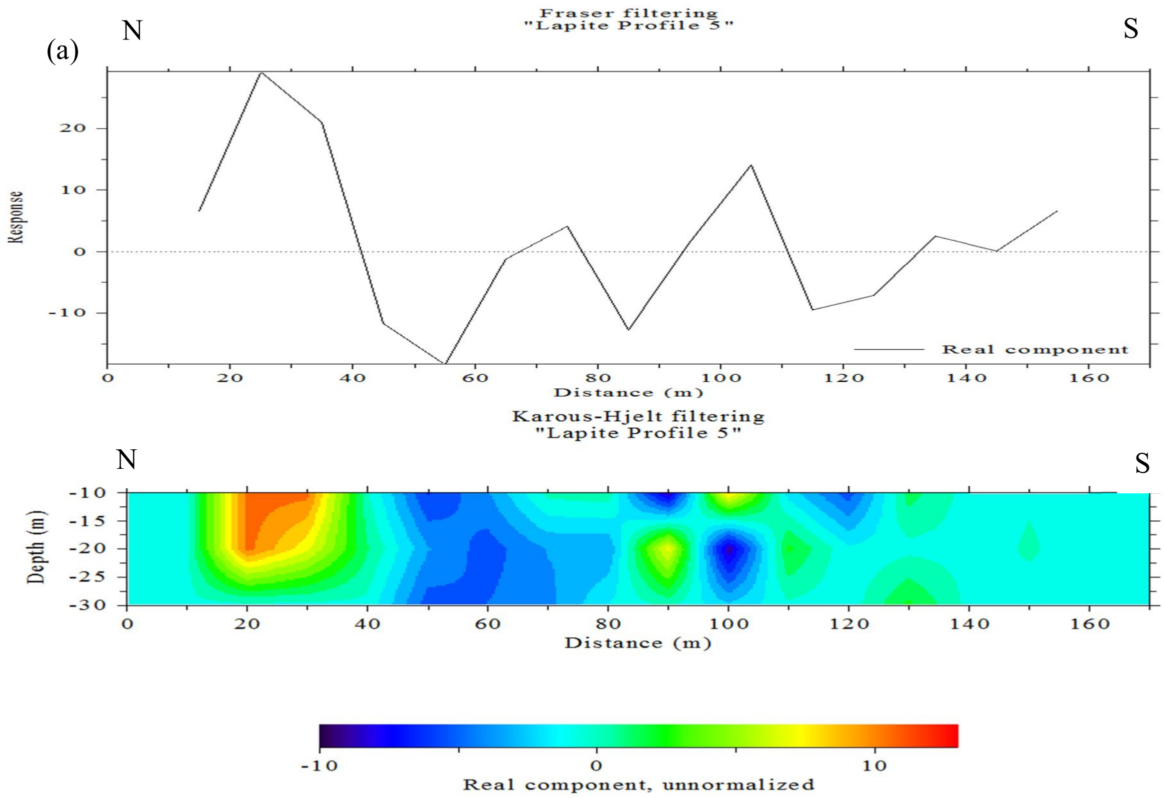


FIG. 3. Frazer graphs and 2D sections for profiles 3 and 4.

The Fraser graph of profile 5 indicates a high conductivity response at a horizontal distance of 12–42 m. The Karous-Hjelt filtering section further reveals a contaminant leachate plume or conductive subsurface structure, characterized by a higher positive current density at a horizontal distance of 12–38 m, at an approximate depth of 27 m below the surface, as shown in Fig. 4(a). Additionally, a narrow conductive region extends between station points 98–104 m, along with several other closures of conductive bodies on the profile, as depicted in Fig. 4(a).

The Fraser filtering graph of profile 6 indicates that the presence of conductive material extends from a horizontal distance of 88 m to 105 m along the profile, as seen in Fig. 4(b). The Karous-Hjelt pseudo-section of profile 6 further reveals a conductive subsurface structure or leachate accumulation, which is visible between coordinates 89 and 115 m towards the end of the profile, as shown in Fig. 4(b).



(b)

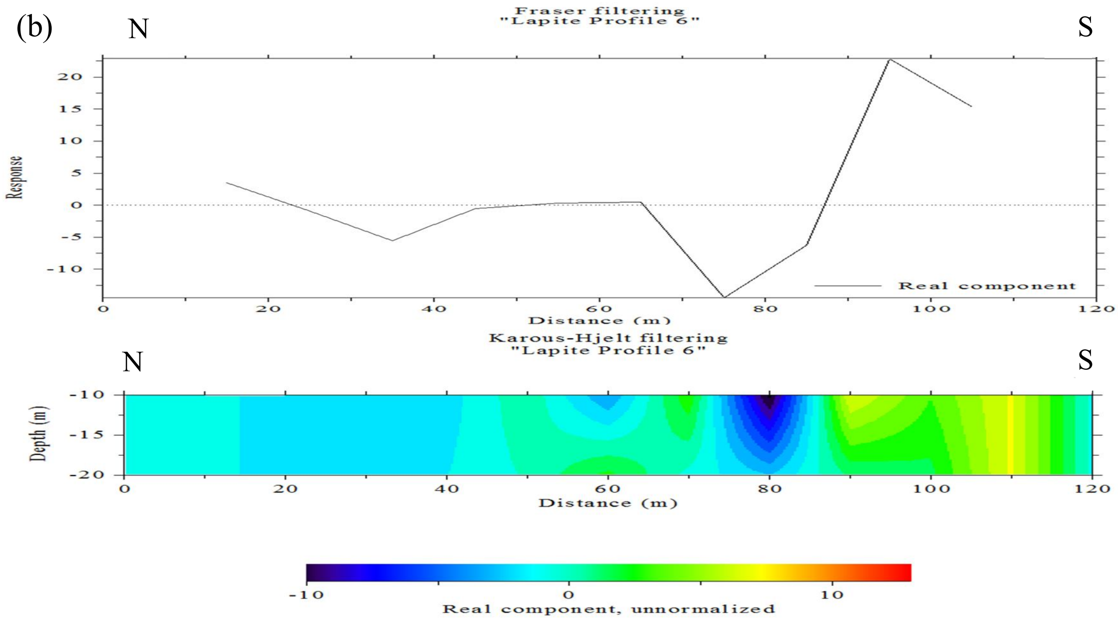
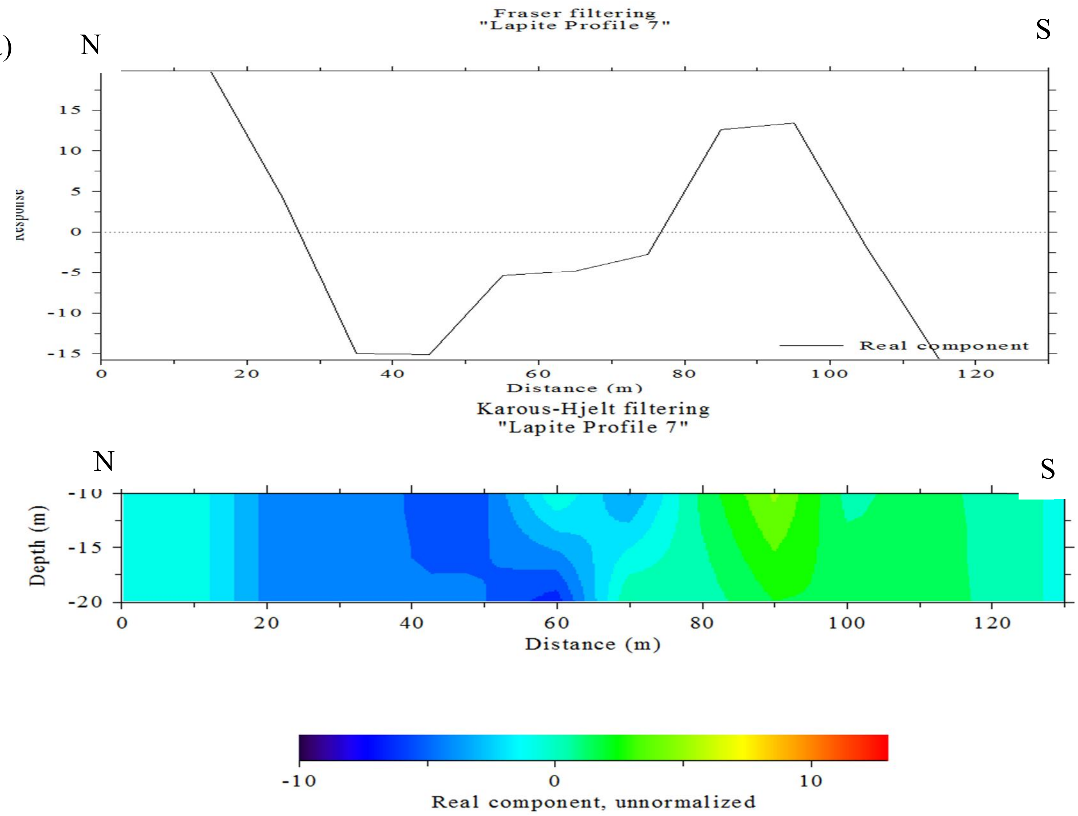


FIG. 4. Frazer graphs and 2D sections for profiles 5 and 6.

The Fraser filtering graph of profile 7, depicted in Fig. 5(a), shows the response of a slightly conductive body with a wide base at a horizontal distance of 78-105 m along the profile. The current density anomaly value on the Karous-Hjelt section of profile 7 is relatively high positive at a horizontal distance of 82-96 m, at a depth of 20 m below the surface, revealing the presence of leachate accumulation or a conductive structure.

The Fraser graph of profile 8 shows diagnostic points of a conductive zone at horizontal distances of 30-48 m and 70-92 m along the profile, as seen in Fig. 5(b). The Karous-Hjelt pseudosection of profile 8 further reveals thinly conductive bodies extending to varying depths between station distances of 38-42 m and 70-82 m across the profile.

(a)



(b)

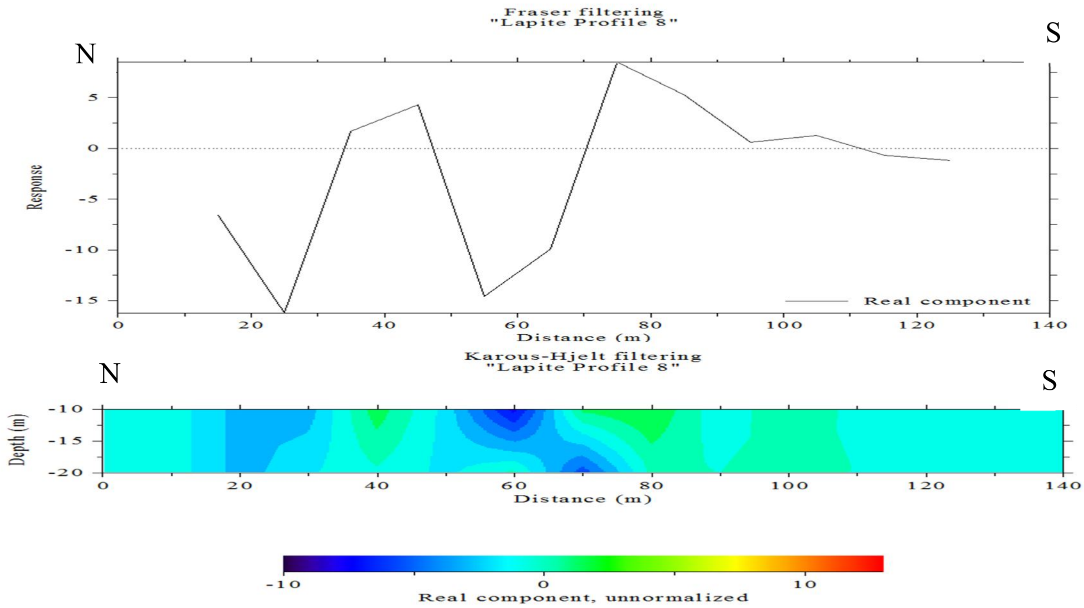
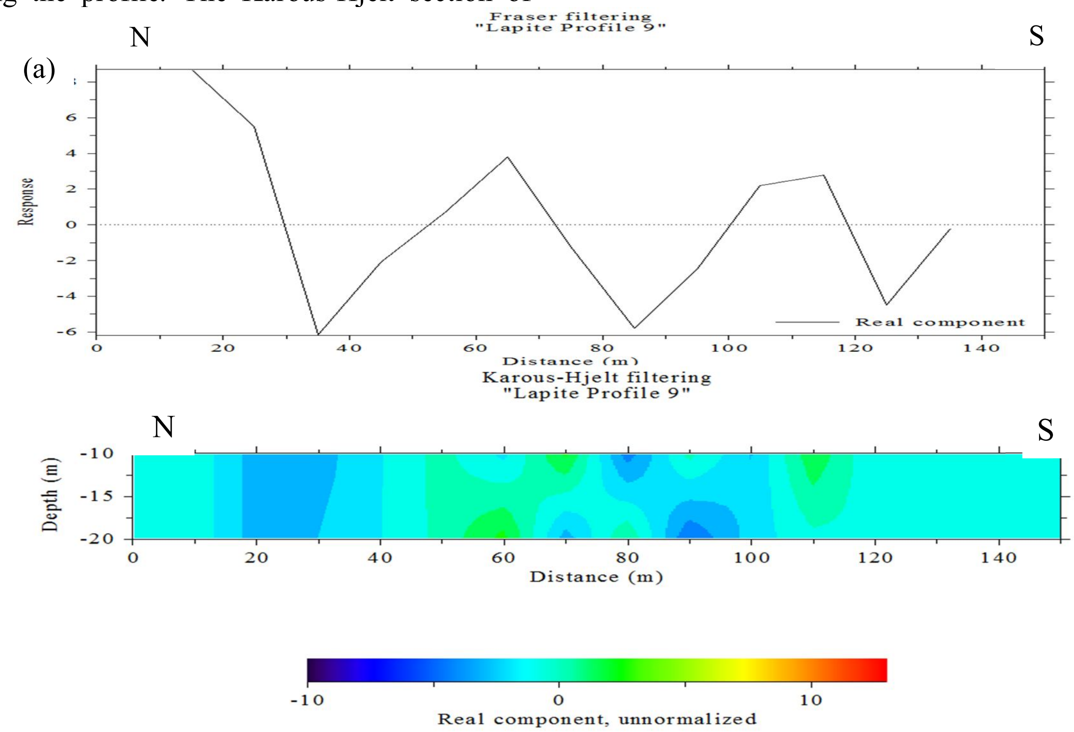


FIG. 5. Frazer graphs, VLF-EM plots of real parts, and 2D sections for profiles 7 and 8.

A low positive conductivity response on the Fraser graph of traverse 9 occurs at horizontal distances of 50-72 m and 100-120 m along the profile, as depicted in Fig. 6(a). The Karous-Hjelt pseudosection of profile 9 indicates weakly conductive bodies at 48-72 m and 106-117 m along the profile.

The Fraser graph of the control traverse, depicted in Fig. 6(b), located 300 m away from the dumpsite, exhibits a high conductivity response at a horizontal distance of 80–105 m along the profile. The Karous-Hjelt section of the control traverse reveals a high conductivity value in the apparent current density section at a profile distance of 97–103 m. This could be attributed to clay formation beneath the ground surface rather than the presence of a leachate plume. Conductivity anomalies diminish to natural values at a horizontal distance of 152 m along the profile, indicating the absence of leachate on the control profile. However, a lower current density (highly resistive thick overburden) is observed at station positions 120–150 m along the profile.

(a)



(b)

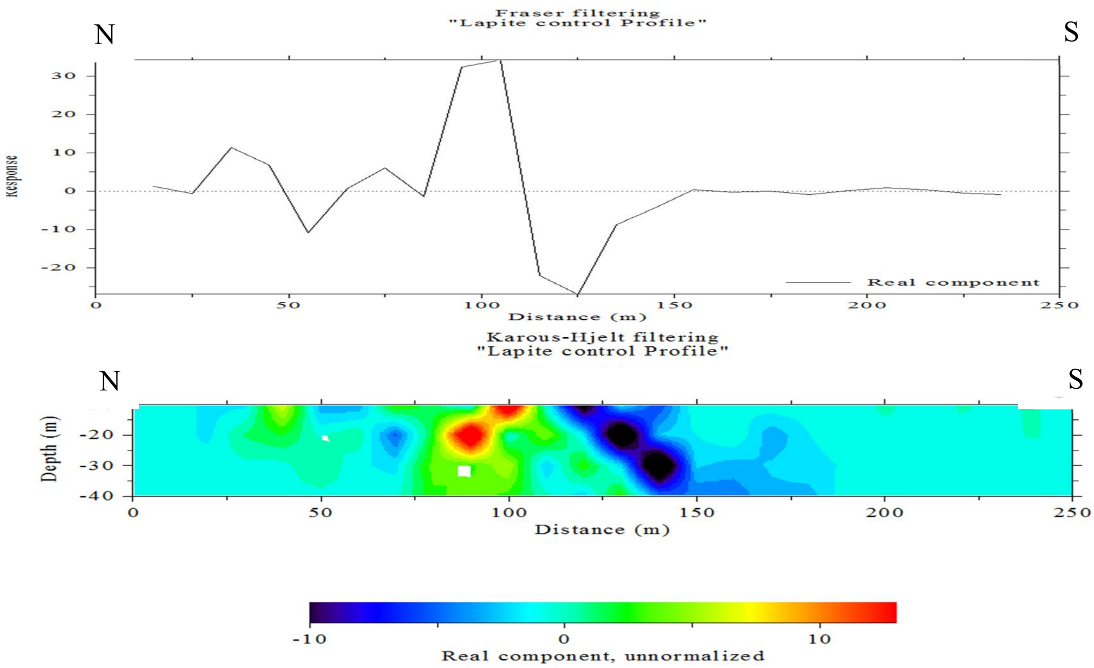


FIG. 6. Frazer graphs, VLF-EM responses, and 2D sections for profiles 9 and the control.

The VLF-EM data models depict the contaminant leachate plumes as high-conductivity values in the apparent current density pseudosections. Generally, the results from the Karous-Hjelt sections for the surveyed profiles reveal a strong presence of subsurface conductive structures and/or leachate accumulation in the western part of the dumpsite. A similar observation was reported in the interpretations of the 2D ERT inverted sections from a previous study [4].

Furthermore, Popoola and Fakunle [1] reported that the lowest resistivity value (an indication of dumpsite leachate) and the maximum horizontal distance (X_{MHD}) traveled by the leachate were observed on the western side of the dumpsite. The westward flow of the leachate plume is further supported by findings from [38], which indicate that the northwest part of the site has a relatively lower elevation compared to other areas of the dumpsite.

Conclusions

The study shows the practicability of investigating solid waste dumpsites with the VLF-EM technique. The VLF-EM method serves as a suitable technique for the detection of conductive subsurface structures/leachate accumulation zones with low resistivity values and high conductivity responses. The current density pseudo-sections indicate conductive features/ leachate plumes at different depths. A close agreement exists between the Fraser-filtered responses of the VLF-EM data and 2D current density pseudo-sections. The interpretation of the 2D current density sections suggests that the leachate plume extends deepest towards the western end of the dumpsite. Consequently, the contaminant leachate may infiltrate the shallow groundwater system located on the west side of the dumpsite.

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