

ASSESSMENT OF POTENTIAL LEACHATE MIGRATION AND WATER QUALITY AROUND THE KABAMA MUNICIPAL SOLID-WASTE DUMPSITE, ZARIA, NIGERIA, USING VLF-EM EL AND PHYSICOCHEMICAL ANALYSIS

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ABSTRACT

Groundwater and surface-water contamination by municipal solid waste (MSW) leachate is an important environmental concern, particularly in rapidly urbanizing areas where inadequate waste management can promote contaminant infiltration. This study assessed potential leachate migration and water quality around the Kabama municipal solid waste dumpsite, Zaria, northwestern Nigeria, using Very Low Frequency Electromagnetic (VLF-EM) surveying and physicochemical analysis of water samples. Six VLF-EM traverses were conducted across the dumpsite, with measurements acquired at 5 m station intervals and processed using Fraser and Kous-Hjelt filtering techniques to delineate subsurface conductive anomalies. In addition, two hand-dug well-water samples and one stream-water sample were collected and analysed for pH, electrical conductivity (EC), total dissolved solids (TDS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), chloride, and selected heavy metals. The VLF-EM results revealed several pronounced conductive anomalies from near surface to an apparent depth of about 25 m across the investigated profiles, particularly within and around the dumpsite, indicating zones of enhanced subsurface conductivity potentially associated with leachate-affected materials, clay-rich units, or buried metallic waste. The physicochemical results showed pH values of 6.57, 6.71 and 6.51 for the well, stream and control well samples, respectively, while EC values were 850, 984 and 800 $\mu\text{S}/\text{cm}$ and TDS values were 620, 671 and 350 mg/L. Elevated organic pollution indicators were observed, with BOD values of 415, 523 and 50 mg/L and COD values of 745, 751 and 35 mg/L. Chloride concentrations were 314, 479 and 100 mg/L, while Pb, Fe, and Mn concentrations ranged from 0.051, 0.060 and 0.011; 0.310, 0.403 and 0.290; then 0.163, 0.191 and 0.050 mg/L, respectively. These elevated concentrations indicate deteriorating water quality near the dumpsite. Increases in the physicochemical parameters measured in water samples from the existing well and stream suggest that solid waste leachate deposition has contaminated the groundwater, supporting the geophysical data.

Keywords: Leachate; Dumpsite; Contaminants; VLF-EM; Subsurface.

INTRODUCTION

Municipal solid waste (MSW) disposal is an increasing environmental challenge in rapidly urbanizing communities, particularly where inadequate waste-management practices result in uncontrolled or poorly managed dumpsites. As waste

decomposes, it generates leachate containing dissolved organic and inorganic contaminants that can infiltrate soil and migrate through the subsurface into nearby groundwater and surface-water systems. This problem is especially concerning in communities where shallow hand-dug wells are a major source of domestic water (Alao et al., 2024; Rosado-Fuentes et al., 2021). Subsurface lithology, permeability, weathering, fractures, and groundwater conditions strongly influence leachate migration and distribution. Consequently, reliably characterizing potentially contaminated zones requires methods that can detect subsurface variations without extensive excavation or drilling (Marchetti et al., 2013). Very Low Frequency Electromagnetic (VLF-EM) surveying provides a rapid, non-invasive approach to identifying subsurface conductive anomalies that may be associated with leachate-affected materials, saturated zones, clay-rich formations, fractures, or other conductive features. When complemented by physicochemical analysis of groundwater and surface-water samples, VLF-EM can provide supporting evidence for assessing potential leachate influence and associated changes in water quality. Recently, several geophysical techniques have been used to locate buried contaminants, including dumpsites, illegally buried waste, and underground utilities such as steel storage tanks, pipes, and buried cables (Marchetti et al., 2013; Marchetti et al., 2002; Al-Tarazi et al., 2008). However, these buried materials sometimes show different conductive and non-conductive characteristics than the surrounding soils (Alao et al., 2024), which VLF-EM can identify. VLF is a non-intrusive and non-destructive geophysical method of surveying subsurface objects that allows investigation of the earth's subsurface without coming into contact with the ground (Gürer, 2009; Zhang, 2015; Telford et al., 1990).

Many of today's societal challenges are subsurface-related, from groundwater and minerals to complex subsurface infrastructure that drives the energy sector and the environment (Alao et al., 2024). Thus, building a better future requires understanding subsurface systems. For example, a noteworthy study found that limited knowledge of VLF-EM applications has prevented its widespread use in groundwater exploration, particularly in sedimentary basins (Ohwoghere-Asuma et al., 2020). This inconsistency has limited the use of the VLF-EM technique. However, ground VLF-EM geophysical prospecting for conductive and non-conductive targets has received remarkable momentum due to recent advancements in lightweight receivers, which have reduced the significant geologic noise component resulting from the high transmission frequency (Ohwoghere-Asuma et al., 2020). Ground-penetrating radar (GPR) and electrical resistivity

tomography (ERT) are promising geophysical techniques for locating buried targets (Giao & C. Vichalai, 2006; Poluha et al., 2017; Chantasen et al., 2018). However, investigating the impact of VLF-EM in identifying buried waste can offer an alternative geophysical technique to evaluate buried materials where either ERT or GPR is not available.

Municipal solid wastes are included in the category of unwanted manufactured items and/or edible crops and foods that have been used for specific purposes (Wei et al., 2017; Islami et al., 2020). The increase in municipal solid waste (MSW) generation in most developing nations is due to several factors, including population growth, rural-urban migration, land scarcity for safe waste disposal, and a lack of adequate disposal systems that support waste-to-wealth initiatives (Igelle et al., 2024). Waste materials on dumpsites not only contaminate dumpsite soil but also cause numerous public health issues (Ojo et al., 2022; Badmus et al., 2022). Different types of MSWs scattered on open landfills constantly decompose and produce an appreciable amount of leachate, in addition to various decaying products like dumpsite gas and potentially hazardous elements that could migrate away from the dumpsite and infiltrate nearby shallow aquifer units, negatively altering both the environment's and the dumpsite's inherent quality (Abdel-Shafy et al., 2024). Leachate pollution of the groundwater system occurs when pollutants infiltrate shallow groundwater sources, affecting the quality of residents' main drinking water source. Therefore, the subsurface water resources are at great risk when a municipal solid waste dumpsite is located in a high-density residential area with shallow hand-dug wells (Igelle et al., 2024).

This work aims to apply the very low frequency electromagnetic method to assess potential leachate migration and water quality around the Kabama municipal solid waste dumpsite, Zaria, North-West, Nigeria. To the best of our knowledge, no previous study has integrated these approaches to investigate potential leachate-related contamination at the study site.

MATERIALS AND METHOD

Geology of the Study Area and Site Description

Geologically, the study area is located within the Basement Complex terrain of northern Nigeria. Crystalline basement rocks, predominantly granites, gneisses, migmatites, amphibolites, and quartzites, underlie the area. These rocks are generally mechanically competent and tend to respond to tectonic stresses through brittle deformation and fracturing. Surface water infiltrates through these fractures, thereby enhancing chemical weathering processes within the subsurface. Among the basement rock units, gneisses and migmatites are generally more susceptible to weathering compared to granitic rocks (Abdullahi et al., 2010). The study area has a typical tropical Savannah climate with distinct wet and dry seasons. The dry season generally extends from October to April, while the rainy season occurs between May and September. The region receives about 1270 mm of rain on average each year, with August often receiving the highest precipitation. Seasonal temperature varies from below 15°C during the Harmattan period in December and January to roughly 32°C during the warmer months of March and April. In terms of hydrogeology, previous geophysical investigations and borehole drilling records have revealed two principal aquifer systems in the area. These include the overburden weathered aquifer, composed mainly of clayey sand and sandy materials, and the fractured crystalline basement aquifer (Dan-Hassan & Olorunfemi, 1999). The overburden aquifer is generally rich in groundwater and is widely

exploited through hand-dug wells for domestic water supply. In certain locations, the weathered and fractured aquifers are hydraulically interconnected, forming a continuous groundwater table and a unified hydrogeological system. The study area is the Kabama municipal solid waste disposal site behind the shooting range, Sabon Gari, Zaria metropolis, Kaduna State, North West Nigeria (Fig. 1). The site is geographically located between latitude 11° 08' 38"N to 11° 08' 45"N and longitude 007° 45' 48"E to 007° 45' 56"E. Fig. 1 below presents the geological map of the study area.

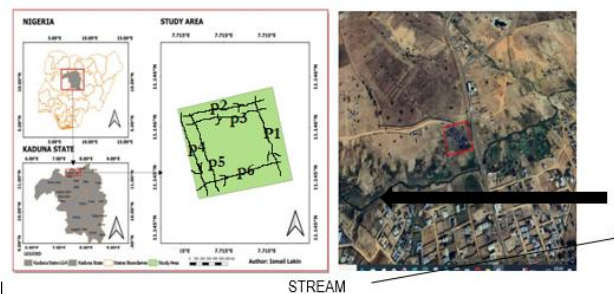


Figure1 Map of the Study Area

Data Acquisition

The VLF-EM technique was used at the dumpsite to detect potential linear conductive subsurface features such as faults, fracture zones and leachate accumulation zones. VLF-EM is a passive electromagnetic technique that uses signals from military global network transmitters in the 15–30 kHz frequency range (Adagunodo et al., 2023; Adeniji et al., 2024). For this study, we measured VLF-EM data using a T-VLF instrument (Fig. 2) in tilt ellipticity mode laterally on each traverse, at 5 m intervals and a signal strength of 16.4 kHz, at Gildeska, Sweden. Within the open dumpsite, we created 6 matching VLF-EM traverses, spaced 10 m apart between parallel profiles. The orientation of the VLF-EM traverses was such that 3 of the 6 traverses trended from north to South, while the remaining 3 traverses trended from east to west across the dumpsite. The acquired VLF-EM response data were processed and interpreted via Fraser and Karous Hjelt filtering techniques (Fraser, 1969; Karous & Hjelt, 1983). These filtering techniques extract unwanted fluctuations and compute pseudosections of the relative current density that form the true (i.e., in-phase and quadrature) data using KHFFILT software (Fraser, 1969; Adagunodo et al., 2023). Additionally, the KHFFILT program was used to convert observed VLF anomalies from raw data to current density distribution plots; Fraser filtered data instances where backward crossovers changed to negative readings, and genuine crossovers were modified to positive peak values (Alao et al., 2024; Adagunodo et al., 2023).

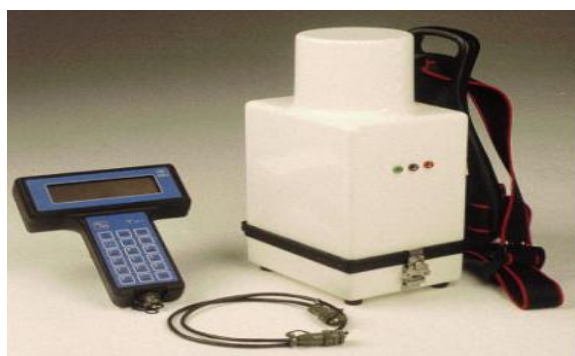


Figure 2 T-VLF Receiver

Collection of Water Sample for Physicochemical Analysis

Water quality analysis was performed on water samples from a hand-dug well (named well water WW) with a depth of 6.8 m, located 45 m away from the dumpsite, and a stream 100 m away from the dumpsite (named stream water SW), in order to determine the degree of groundwater contamination by the solid waste leachate. The stream flows along the eastern margin of the dumpsite. Another sample of water from a hand-dug well (control well water, CWW) located 300 m east of the dumpsite was collected. For physical/chemical examinations, the water samples were kept in clean, well-drained 1000 mL sterile plastic vessels that had previously been rinsed with the same WW and SW samples. Before the chemical characterization, the water samples collected for chemical analysis were acidified with dilute nitric acid and stored in a refrigerator. Heavy metal concentrations in water samples were measured using an Atomic Absorption Spectrophotometer (AAS) at the National Steel Raw Materials Exploration Agency (NSRMEA), Malali, Kaduna. Analysis of all the physical characteristics (pH, Conductivity, Chemical oxygen demand (COD), Biochemical oxygen demand (BOD), Total dissolved solids (TDS), and Chloride (Cl⁻) was done via the numerous standard techniques for water analysis at the Water Resources Department, Ahmadu Bello University, Zaria.

RESULTS AND DISCUSSION

Figures 3, 4, 5, 6, 7, and 8 demonstrate typical current density sections, which show the nature of the VLF-EM anomalies from the study area. The colour pane indicates conductive, nonconductive and intermediate zones. The resistive medium is depicted in a bluish-to-green colour; the conductive medium is presented in a yellowish-to-red colour range, while the black colour indicates that most of the waste is dumped there. Fraser filtering improved the location of non-conductive and conductive anomalies by removing false impressions from false cross-over points that normally challenge VLF data interpretation (Amini, 2005; Alao *et al.*, 2024). The current density distribution plot of profile 1 (Fig. 3) showed several high conductive values at station points 18-40, 62-82, 90-107, and 122-138 m at the top of the plot, as well as 60-98 m at the base part of the profile, suggesting the existence of conductive features or lineaments. A significant resistive component manifested at the station offset point to 3 m at the top of the profile, spreading downward to 40 m at the base of the profile, as well as at the bottom far right of the profile. The black colour on the profile indicates where most of the waste is dumped (Abdullahi *et al.*, 2010).

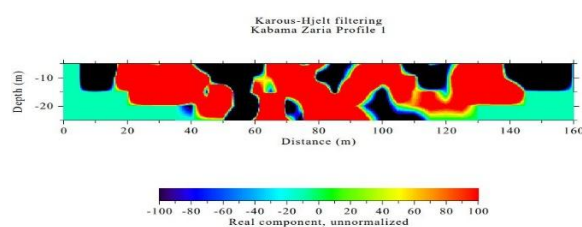


Figure 3 Current Density Plot of Profile 1

The current density distribution plot of VLF-EM traverse 2 (Fig. 4) shows several positions with relatively high current density readings, indicating permeable subsurface structures and/or leachate-associated regions with varying depths of extension (Ganiyu *et al.*, 2025). Resistive zones can be seen at the beginning of the traverse and at 90-110 m, then towards the end of the traverse. The VLF-EM profile 3 current density plot, which is parallel to profile 2 and orthogonal to profile 1, showed several locations with relatively high current density readings, suggesting the presence of conductive subsurface structures (Fig. 5). However, unlike profiles 1 and 2, the current density plot of profile 3 revealed a highly conductive part (with current density values ranging between 80 and 100) was visible between distances 130 and 160 m.

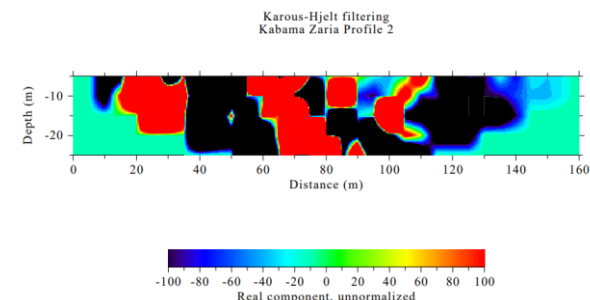


Figure 4 Current Density Plot of Profile 2

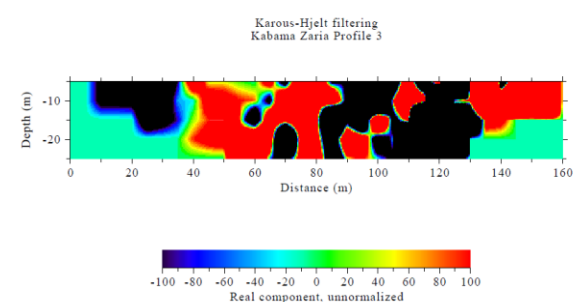


Figure 5 Current Density Plot of Profile 3

The current density plot (Fig. 6) revealed that conductive subsurface structures or leachate-associated zones have higher current density values greater than 80 at lateral positions 32-43, 100, and 120-140 m. However, the plot showed a slightly conductive section (current density values ranging from 0-70) between distances 10, 30, 42 and 73 m. The current density plot of profile 5 depicts a slightly conductive zone at lateral distances 20-26 and 75-86 m. These low-conductive formations also appeared at 93 m and 115-130 m at the base of the profile, which may

indicate leachate accumulation (Fig. 7).

The current density plot of the VLF profile (Figure 8) delineated two distinct regions in relation to the current density distribution. The first is a highly conductive body with a current density greater than 10, located between traverse distances of 31-50, 62-95, and 130 m. These could be clay units, saturated weathered regions, or possibly buried metallic objects beneath the ground surface. The second is the highly resistive region with a current density value < 0. This was observed at lateral distances 0-20 m and 117-160 m at the base part of the profile, indicating the absence of leachate in these regions. Overall, the current-distribution plots for the VLF-EM profiles showed strong conductive anomalies and leachate-accumulation sections at the Kabama dumpsite.

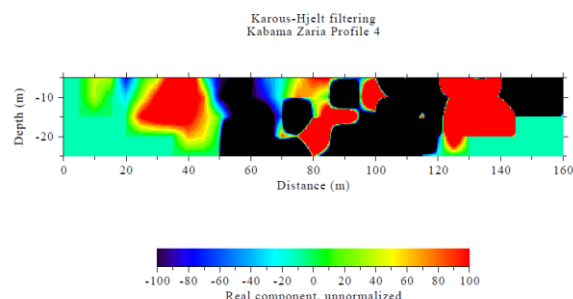


Figure 6 Current Density Plot of Profile 4

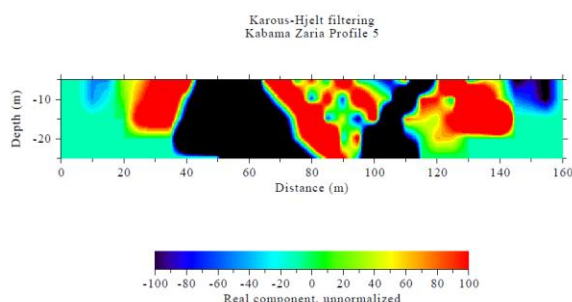


Figure 7 Current Density Plot of Profile 5

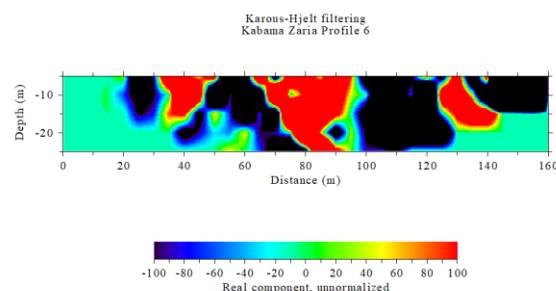


Figure 8 Current Density Plot of Profile 6

Physicochemical Analysis for the Water Samples

The physicochemical analysis shows that the stream water is more contaminated than the well water, as evidenced by its continuously higher electrical conductivity, BOD, COD, TDS, heavy metal concentrations, and chloride content. This indicates that the stream is receiving more direct leachate discharge, while the overlying soil and weathered rocks have partially attenuated the groundwater. Comparing the control well with the dumpsite-affected well and stream water is particularly important for distinguishing natural geochemical variation from possible anthropogenic contamination. Parameters showing elevated concentrations in the dumpsite well and stream relative to the control well may indicate an influence from waste-derived contaminants and possible leachate infiltration. Conversely, parameters with comparable concentrations across the three sampling locations may reflect natural background conditions or regional hydrogeochemical characteristics. The control well therefore strengthens the interpretation of the hydrochemical results and provides additional support for evaluating the dumpsite's potential influence on surrounding water resources. The extremely high levels of COD, BOD, chloride, iron, manganese, and lead provide evidence of significant leachate contamination originating from the municipal solid waste dumpsite. These results closely agree with the geophysical investigation. The VLF-EM survey mapped conductive lineaments that likely serve as contaminant pathways. The agreement between the geophysical and hydrochemical datasets provides supporting evidence consistent with possible leachate migration through the weathered/fractured basement into the nearby groundwater and surface water systems. As a result, water sources near the dumpsite are unfit for domestic use without proper treatment, underscoring the need for ongoing environmental monitoring, groundwater protection, and improved municipal solid waste management. Table 1 presents the physicochemical analysis results. latitude 11° 08' 38"N to 11° 08' 45"N and longitude 007° 45' 48"E to 007° 45' 56"E.

Table 1. Physicochemical Analysis of Well and Stream Water

Parameter	Unit	Well Water (WW) 11° 08' 38"N, 007° 42' 51"E	Stream Water (SW) 11° 08' 41"N, 007° 42' 55"E	Control Well water (CWW) 11° 08' 37"N, 007° 42' 50"E	WHO
pH		6.57	6.71	6.51	6.5-9.5
Conductivity	µs	850	984	800	-
COD	mg/l	745	751	35	-
BOD	mg/l	415	523	50	-
TDS	mg/l	620	671	350	-
Lead	mg/l	0.051	0.060	0.011	0.010 (WHO, 2022)
Zinc	mg/l	2.800	2.920	2.112	3 (WHO, 2024)
Iron	mg/l	0.310	0.403	0.290	0.300 (Abdullahi <i>et al.</i> , 2010)
Manganese	mg/l	0.163	0.191	0.050	0.080 (WHO, 2024)
Chloride	mg/l	314	479	100	250 (Abdullahi <i>et al.</i> , 2010)

The integrated interpretation of the VLF-EM and physicochemical results indicates a spatial and hydrochemical relationship consistent with potential leachate influence around the Kabama dumpsite. VLF-EM delineated several high-current-density conductive anomalies, including zones exceeding 80 units along Profile 4 and zones exceeding 10 units along Profile 6, which may represent leachate-affected materials, saturated weathered zones, clay-rich units, fractures, or buried metallic waste. The physicochemical results support this interpretation, with the dumpsite-associated well and stream showing higher contaminant indicators than the control well. COD increased from 35 to 745–751 mg/L, BOD from 50 to 415–523 mg/L, chloride from 100 to 314–479 mg/L, and Pb from 0.011 to 0.051–0.060 mg/L. TDS also increased from 350 mg/L in the control well to 620–671 mg/L in the affected waters. The correspondence between the VLF-EM conductive anomalies and elevated physicochemical parameters provides supporting evidence consistent with possible leachate-affected subsurface zones and associated water-quality deterioration. However, the VLF-EM anomalies are not uniquely diagnostic of leachate and may also reflect clay, saturation, fractures, or buried metallic materials. Thus, the integrated results strengthen the interpretation of potential leachate migration, rather than conclusively proving it.

Conclusion

This study integrated VLF-EM and physicochemical analysis of water samples to investigate leachate plume accumulation and migration and the extent of contamination at the Kabama, Zaria dumpsite, Northwest Nigeria. The integrated VLF-EM and physicochemical investigation indicates potential leachate influence and associated water-quality deterioration around the Kabama dumpsite, Zaria. Six VLF-EM traverses delineated pronounced conductive anomalies from near surface to an apparent depth of approximately 25 m, particularly within and around the central dumpsite area. The hydrochemical results further show substantial increases in several parameters relative to the control well. COD increased from 35 mg/L in the control well to 745–751 mg/L, BOD from 50 to 415–523 mg/L, chloride from 100 to 314–479 mg/L, TDS from 350 to 620–671 mg/L, Pb from 0.011 to 0.051–0.060 mg/L, and Mn from 0.050 to 0.163–0.191 mg/L. Pb, Mn and chloride also exceeded the guideline values reported in the study, while Zn remained below the reported limit. However, the VLF-EM anomalies are not uniquely diagnostic of leachate and

may also reflect clay, saturation, fractures, or buried metallic materials. Thus, the integrated results strengthen the interpretation of potential leachate migration, rather than conclusively proving it.

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