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Environmental contaminants due to dumpsite leachates and the possible implications on public health

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Abstract

Dumpsite leachate plumes (DLPs) remain one of the major threats to environmental health, compromising the integrity of soil, surface-groundwater systems, and human health. This study exploits three main geophysical methods (electrical resistivity, magnetic survey, and Very Low Frequency) and hydrochemical analysis (HCA) alongside an oral interview to evaluate the impacts of the DLPs on the immediate environment and the associated health risks within Kaduna Metropolis, Nigeria. Based on geophysical investigations, the subsurface resistivities significantly vary between 2.3–9.2 and 17–114 Ωm , the total magnetic intensity (TMI) varies between 37,600–44,500 and 31,095–37,300 nT, while the equivalent current density (ECD) varies between 30.0–45.0 and – 50 to 30, respectively. Low resistivity, high ECD, and high TMI zones were delineated and mapped as leachate plume-accumulated regions, occurring within the depths of 0.0–7.0 m. The geophysical data highlight zones with elevated magnetic anomalies, resistivity contrasts, and conductive anomalies linked to the suspected DLP accumulated zones. HCA examined the contents of trace elements in the leachate plumes and groundwater samples independently, which vary considerably between 11.17–21.73 and 0.017–2.919 mg/l, respectively. The combined data shows that nearly 75% of the populace residing within a 200 m radius of the investigated dumpsites are potentially exposed to trace elements with (Fe > 1.5, Pb > 1.2, Cd > 0.08, Cr > 0.6 mg/l) in groundwater and (Fe > 2.0, Pb > 1.6, Cd > 0.5, Cr > 1.0 mg/l) in surface water. In addition, the leachate plume contaminants have significantly endangered the integrity of the subsurface in nearly 50% of the area within a 200 m radius of the dumpsites to a depth of > 3.0 m, which inversely compromises the regional groundwater and public health systems. Based on the findings of this study, a safe depth/distance was examined and suggested as a temporary solution. Also, for geophysical standardization, it requires that drinking water sources should be located at least 15 m deep in the soil and 100 m away from dumpsites. Similarly, open and unlined dumpsites should be avoided, while sanitary landfills should be sited at least 6 m above the water table. In conclusion, the overall integrity of surface/groundwater and public health status is largely determined by the overall sanitation of its ambient environment.

Keywords Geophysical methods, Hydrochemistry technique, Leachate plumes, Groundwater, Toxic elements, Public health

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Introduction

Today, there are several major environmental challenges, such as air pollution, climate change, loss of biodiversity, ocean health, overpopulation, water pollution, energy use, and weather events, which threaten the existence of man and his environment. However, surface and groundwater pollution by trace elements remains one of the prime challenges across the globe as a result of its toxicity. In the past, oil spillage has been identified as the most devastating and fearful environmental pollution, especially in the oil-producing regions [1–3], which has negatively impacted human health, soil, surface, and groundwater [4, 5]. However, surface/groundwater contamination due to toxic elements emerging from open dumpsites or unlined landfills, especially in developing nations like Nigeria, remains a critical environmental threat [6–8]. There are several studies on the effects of dumpsites on the subsurface in Nigeria [9, 10]. The dumpsite leachate plumes remain a major player in the current global environmental defects, affecting atmospheric conditions, public health, and water resources [11–15]. Environmental contaminants due to oil spillage are restricted to a particular region in Nigeria, while the environmental contaminants due to the uncontrolled dumpsite leachate plumes (DLPs) remain a national challenge as well as a global phenomenon [16]. The elevated heavy metal levels, such as lead, iron, cadmium, and chromium, in the surface and groundwater, can lead to serious health challenges [17].

A study predicted imminent environmental genocide due to the high level of environmental indiscipline and abysmal waste management technology adopted in most developing nations like Nigeria [18]. Citing increased public health risks, the United States Environmental Protection Agency (USEPA) has voiced concerns about the high rate of waste generation that exists today, which shows that the US produces 2 kg of municipal solid waste (MSW) per person per day, and Israel produces about 1.7 kg of garbage per person per day [19]. Worse still, Nigeria's garbage population has increased dramatically from 140 million to over 200 million in the past 14 years, and by 2050, it may surpass 400 million, which may further aggravate the current environmental challenges [19]. Therefore, effective environmental policies and regulatory frameworks are essential for promoting environmental sustainability, ensuring industry compliance, and safeguarding ecosystem health [20–23].

In Nigeria, dumpsites remain the most common technology employed for waste management. However, a poorly managed landfill can generate hazardous impacts when infiltrating the environment [24, 25]. All over the world, dumpsites are often associated with MSW, which can pose significant environmental risks, especially when

interacting with water [26–29]. As a result, a remarkable study suggests the adoption of a rainproof section to be integrated into the construction of modern sanitary landfills [30], especially in tropical regions like Nigeria with higher rain events. The water content of waste items at exposed dumpsites can increase dramatically in Nigeria due to the country's regular and intense rainfall [31]. As a result, trash leaches, and organic and inorganic ingredients dissolve more readily, producing hazardous compounds that seep into the groundwater and soil [32]. Trace elements may become more widely distributed in the landfill because of this process. Thus, the rainproof can minimize the landfill's negative environmental effects. Waste production is typically a natural byproduct of population growth in human evolution [33–36]. Modern waste management technologies (MWMT) have emerged recently as a favored soft land for environmental protection.

Open dumpsites have substantial long-term effects on environmental health even though they are thought to be a cost-effective waste management technique. Sanitary landfills are essential for waste management, according to numerous research [37–39]. Regrettably, there are just two sanitary landfills in Nigeria [38]. However, a source claims that preparations are in motion to close the largest landfill in Africa, Olusosun, while the Epe dumpsite in Lagos, Nigeria, is to be transformed into a world-class sanitary landfill [40]. Nonetheless, the current engineered landfills in Nigeria and other countries were not built to protect the environment from pollution; rather, they were built merely to stop DLPs from penetrating the groundwater. To maintain the general security and health of the environment, this study relies on the knowledge of the immediate environment by applying combined geophysical and hydrochemical methods with physical surveys and oral interviews to evaluate the degree of the HMs contaminants in surface and groundwater commonly used for domestic activities. Therefore, this study focuses on assessing the subsurface impact of DLPs and heavy metal contamination in surface and groundwater due to DLPs and the associated health risks using geophysical and hydrochemical data analysis.

Site description

The ten investigated dumpsites are located within the Kaduna metropolis, which falls within the geographical coordinate of latitude 10° 24' 22.32" N to 10° 32' 47.25" N and longitude 07° 20' 20.76" E to 07° 30' 45.25" E. Kaduna Metropolis has a population of about a million with an average elevation of 650 m. The study cuts across four Local Governments, which include Chikun, Igabi, Kaduna North, and Kaduna South. Open dumpsites are the main waste management technology in Kaduna City.

Some notable dumpsites in Kaduna City include but are not limited to Tirkania, Old Panteka, Sabon Gari, Unguwan Shanu, Badarawa, Zango Road, Mando, Angwan Dosa, Tudun Nupa, Nassarawa Kakuri, Bashama Road, Gumi college, Millennium city, Chechenia market, Unguam Muazu, Christ Ambassadors college Sabo, Kabala West, Abakpa, Malali FGC, Akurki road Tudun Wada, know, Barnawa, Narayi, Isa Kaita road, and Gonin gora (Fig. 1). The sample water from wells and river/

stream, alongside the DLPs, was collected from ten selected dumpsites (Table 1; Fig. 1)to assess the impacts of DLPs in sampled surface-groundwater and the possible associated health risks using geophysical and hydrochemical data.

The study area is located within the Precambrian Crystalline Basement complex rocks, which make up more than half (50%) of Nigeria’s landmass [41]. The regional geology of Kaduna is characterized by the spread of

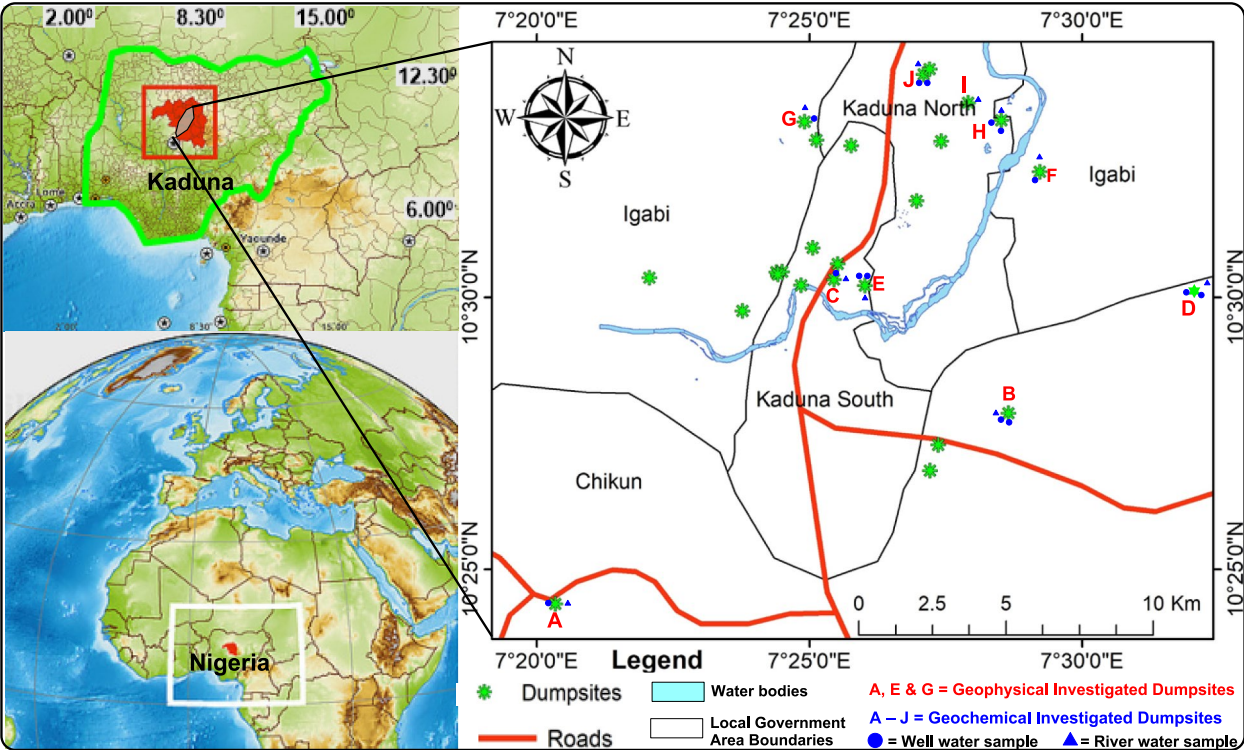


Fig. 1 Map of the study area showing the various dumpsites investigated alongside water samples

Table 1 Description of the ten investigated dumpsites within Kaduna Metropolis

Dump sites	Geographical coordinates Latitude Longitude	Location	Sample(s)		Nearest building	Distance to River (m)	Area (m ²)
			HDW	River			
A	10° 24' 22.32" N, 07° 20' 20.76" E	Goni-Gora	1	1	117	523	9100
B	10° 28' 03.96" N, 07° 27' 05.97" E	Narayan	2	1	159	420	17,500
C	10° 30' 19.72" N, 07° 25' 27.02" E	Bashama road	1	1	198	350	15,100
D	10° 30' 05.50" N, 07° 30' 45.25" E	Millennium City	2	1	200	950	13,000
E	10° 33' 34.56" N, 07° 27' 54.66" E	Barnawa	2	1	147	720	17,000
F	10° 32' 18.31" N, 07° 29' 13.65" E	Sabon Gari	1	1	0.0	800	12,000
G	10° 33' 13.65" N, 07° 24' 54.55" E	Abakpa	1	1	5.0	700	15,000
H	10° 33' 15.11" N, 07° 28' 31.43" E	Malali FGC	2	1	31	550	11,000
I	10° 33' 34.56" N, 07° 27' 54.66" E	Badarawa	1	1	89	650	12,300
J	10° 34' 05.88" N, 07° 27' 05.97" E	Angwan Dosa	2	1	47	470	14,400

complex basement rocks. However, these transparent basement rocks have undergone a range of challenges and varying degrees of deformation over time, resulting in the rocks' folding and fracturing [42]. In addition to the bed fracturing and jointing, this deposit is distinctive due to its undulations. The rocks in the district are occasionally covered by silty soil, mixed laterites, sandstones, and quartzites near the surface. Because of this, the aquifer unit in the area is composed of weathered or clayey sand [41, 43]. There are no outlying geological or terrestrial formations near the dumpsite or its surroundings. In most places, there are significant differences in the topsoil's composition, texture, and color. Regional hydrogeology is often governed and impacted by drainage networks and meteorological variables [44], which in turn affects the types of aquifers and recharge processes. Most of the investigated dumpsites lacks visible drainage systems, and the surface water is usually drained by runoff, infiltration, and evaporation directly, which implies that the drainage system of a terrain might affect leachate influx [6]. The dynamics of surface water, such as evaporation and infiltration, are crucial for groundwater recharge in Kaduna State. Although viable aquifers entirely in bedrock are uncommon due to their poor storage capacity (<1%, [45]), they do exist in basement rocks inside the regolith and fractured bedrock.

Methodology

This study was carried out across the Kaduna metropolis, Nigeria, using three major methods, involving geophysical, hydrochemical and oral interviews. The geophysical methods, which involve electrical resistivity tomography (ERT), ground magnetic survey (GMS), and Very Low Frequency-Electromagnetic (VLF-EM), were applied on three dumpsites, while HCA and oral interview, and a preliminary survey performed across the ten dumpsites labelled A–J (Fig. 1) for adequate investigation and quality reports. The preliminary survey was conducted on ten (10) dumpsites, examining the nearby water bodies, gutters, and areas around the dumpsites. The materials used for this survey include, but are not limited to, the SAS4000 resistivity meter, electrode selector, cables, electrodes, hammer, global positioning system (GPS), magnetometer, terra VLF receiver, 12 V battery, and Atomic Absorption Spectroscopy. Others include shovels, hoes, range poles, beakers, and clean plastic bottles.

ERT data acquisition and processing

A SAS4000 resistivity meter was deployed to acquire the subsurface resistivity data in dumpsites using a Wenner array configuration with electrodes at equidistant positions from each other. The survey was performed on a 2.5 m electrode spacing, which was coaxially laid

on a single survey profile line of 100 m. The electrodes were connected to a control unit of the SAS4000 resistivity meter via electrical cables to measure the values of subsurface layer resistivities along three dumpsites. The acquired resistance values were multiplied automatically by a geometric factor (K) to give apparent resistivity (ρ_a). This K -factor can be expressed by Eq. (1) [46] using the electrode configuration.

$$K = 2a\pi \quad (1)$$

Taking into account the geometry of the electrode array and the variations in subsurface materials, apparent electrical resistivity (AER) can be manipulated using Eq. (2) [46].

$$\rho_a = KR \quad (2)$$

The acquired apparent resistivity values by the 2D ERT measurements were fed into a computer software called RES2DINV [47] for analysis. The results of the RES2DINV program were presented as a pseudo-cross section of apparent resistivity.

GMS data acquisition and processing

A high-resolution magnetometer was used to acquire GMS data on a 5.0 m grid interval, which was subsequently processed and analyzed with Oasis Montaj to identify magnetic anomalies associated with subsurface features. GMS detect leachate plumes by identifying anomalies in total magnetic intensity (TMI) caused by magnetic materials [48]. Leachate plumes influence geophysical properties like TMI, which indicates high magnetic susceptibility and conductivity [48, 49]. Elevated TMI often correlates with magnetic susceptibility, which reflects ferrous materials or microbial activity in waste decomposition, indicating subsurface contamination zones. According to a recent study, magnetic susceptibility is considered a fundamental magnetic property, which reflects the TMI in magnetic surveying [50]. That is, magnetic susceptibility is analogous to density in gravity prospecting. It can take on either negative or positive values. The negative values imply that the induced magnetic field is in the opposite direction as the inducing field, while positive values imply that the induced magnetic field, is in the same direction as the inducing field [50]. Magnetic survey works on the principle of force F between two magnetic poles with strengths of m_1 and m_2 , which are separated by the distance (r) specified by Eq. (3) [46, 51]:

$$F = \frac{\mu_0 m_1 m_2}{4\pi \mu_R r^2} \quad (3)$$

where r is the distance between the two poles, m_1 and m_2 are the strengths of the two magnetic monopoles, and μ_0

and μ_R are constants that represent the relative magnetic permeability of the medium between the poles and the magnetic permeability of the vacuum, respectively. The force is repulsive if the poles are identical, and attractive if they are not. The magnetic field B caused by the pole of strength m at a distance r from the pole is defined as a force applied to a unit positive force at a location by Eq. 4 [46, 52].

$$B = \frac{\mu_0 m}{4\pi \mu h r^2} \quad (4)$$

The relationship between the induced magnetization intensity, I , is proportional to the external field strength, H , and it can be defined by Eq. (5)

$$I = \chi H \quad (5)$$

where χ is the dimensionless proportionality constant for susceptibility for a specific type of magnetic substance. It may assume positive or negative values. Additional analyses were performed using enhanced techniques, such as (i) a Total Magnetic Intensity (TMI) Map to delineate contamination zones, (ii) Euler Deconvolution (ED) to determine the depth of occurrence of the leachate plume, and (iii) Analytical Signal Map (ASM) to adequately map the boundaries of the delineated contamination zone.

VLF-EM data acquisition and processing

A portable terra VLF receiver was used to measure the secondary EM fields generated by subsurface conductive structures when they interact with the primary VLF field [46, 53]. The receiver records the intensity and phase of the secondary field, which was analyzed to infer the orientation and presence of subsurface conductive bodies like leachate plumes [54–56]. This was done by walking along straight lines (profiles) across the dumpsites and their surroundings while taking readings at regular intervals. Theoretically, the conductivity (σ) measured in mS/m, permeability (μ) measured in H/m, the angular frequency (ω), magnetic field (H), and electric field (E), can be expressed by (6):

$$\nabla^2 \left(\frac{E}{H} \right) = i\sigma\mu\omega \left(\frac{E}{H} \right) \quad (6)$$

Tilt angle (θ) and ellipticity (e), in contrast, are computed by Eq. (7) [57].

$$\theta = \tan^{-1} \left(\frac{H_S}{H_P} \sin \alpha \cos \Phi \right) \quad (7)$$

The coupling between the subsurface structure and the transmitter is responsible for α = angle above H_P and

Φ = change in phase angle between H_P and H_S . Equation (4) thus becomes Eq. 8.

$$\theta = \tan^{-1} \left(\frac{H_y}{H_p} \cos \Phi \right) \quad (8)$$

where the real component of the H_S field is $H_y \cos \Phi$, which is in phase. When measured vertically, the tilt tangent angle (θ) is exactly proportional to the actual component (H_S).

Physio-chemical data acquisition and processing

A physicochemical water analysis was conducted on the collected thirty (30) samples, including sample waters from fifteen (15) HDWs, ten (10) rivers/streams, and five (5) DLP samples within a radius of 200 m of the dumpsites. The DLPs were acquired from five (5) dumpsites (A, C, E, G, and I) out of the 10 dumpsites studied. A 0.75-L plastic bottle was used to collect all the samples after being thoroughly washed and rinsed with distilled water. Each water sample and leachate plume obtained was tested for electrical conductivity (EC), chromium (Cr), cadmium (Cd), potential of hydrogen (pH), lead (Pb), and iron (Fe). Atomic Absorption Spectroscopy (AAS) was used for the physicochemical analysis, which is a powerful physicochemical technique to detect trace amounts of HMs in water samples [58, 59]. The AAS typically contains a hollow cathode lamp specific to the metals and is set up to calibrate the instrument using standard solutions of known metal concentrations. To maintain the metals in solution and prevent their adsorption onto the container walls, the samples were acidified to 1% using nitric acid. After being kept, the samples were put into a polypropylene reagent container for AAS analysis. Reagent preparation involved the use of nitric acid, standard stock solutions, and a cesium–lanthanum interference suppression solution. The idea behind AAS is to create contact between matter and radiation. Before calibrating with a calibration curve to determine the unknown concentration of an element (e.g., Pb) using multiple solutions of known concentrations, the AAS lamp was preheated for five minutes to ensure optimal performance.

Result presentations and discussion

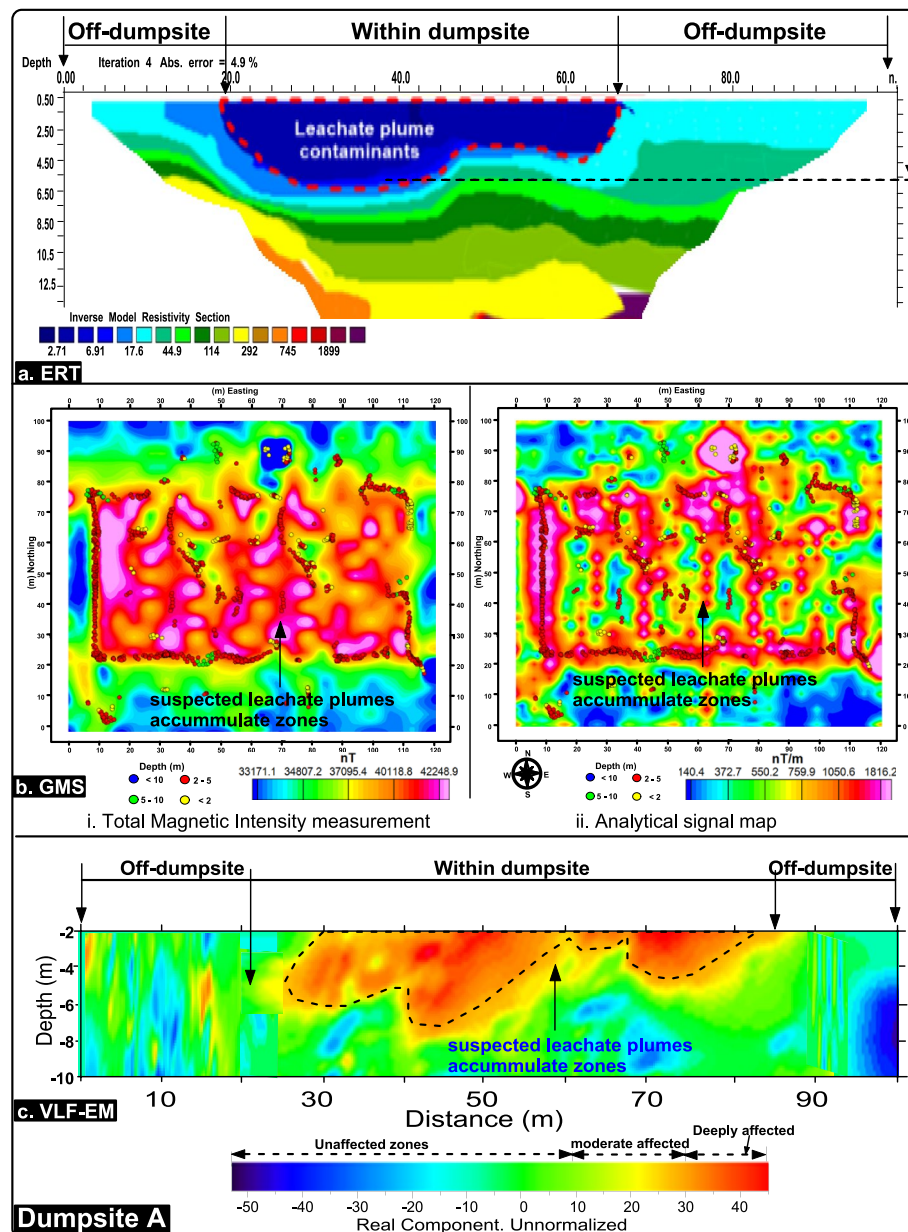
ERT results and discussion

The results from 2D inverse resistivity models reveal the general features of the subsurface, including subsurface layers, shallow conductive zones mapped as accumulated leachate plume zones, and dipping linear conductors delineated as fracture zones within the crystalline basement. Low resistivity values varying between 2.2 and 7.2 Ω m within the dumpsite and 20–73 Ω m off dumpsites

Table 2 Analysis of geo-electrical characteristics in each profile reveals the depth and horizontal distance at which suspected landfill leachate plume contaminants are present

Dumpsites	Electrical resistivity values (Ωm)		Leachate plumes occurrence	
	Off-dumpsites	Within the dumpsites	Distance (m)	Depth (m)
1	17.0–44.0	2.3–9.2	20.0–67.0	0.0–5.5
2	17.2–114.0	2.3–8.5	33.0–73.0	0.0–7.0
3	29.0–75.00	3.0–8.0	40.0–65.0	0.0–2.0

were encountered within the depths of 0.0–7.0 m (Table 2; Figs. 2a, 3a, 4a), aligning with previous studies [6, 60]. The survey was extended to the dumpsite ambient at a minimum distance of 20.0 m, which serves as a control with higher electrical resistivity values greater than 20 Ωm , and this is consistency with the previous studies [24, 61]. This suggests a large percentage of defects (contamination). The electrical results also unveiled the following geoelectric layers comprising four to five distinctive geological sub-layers, including the topsoil layer having about 1.5–6.5 m layer thickness with apparent

**Fig. 2** Geophysical Characterization and Behavioral Maps of Dumpsite A Showing the Subsurface Parameters: **a** 2D ERT Inverse Models, **b** Magnetic maps Due to the accumulated waste/leachate plumes, and **c** 2D KHFFILT program of the VLF-EM Inverse Model for Dumpsite A

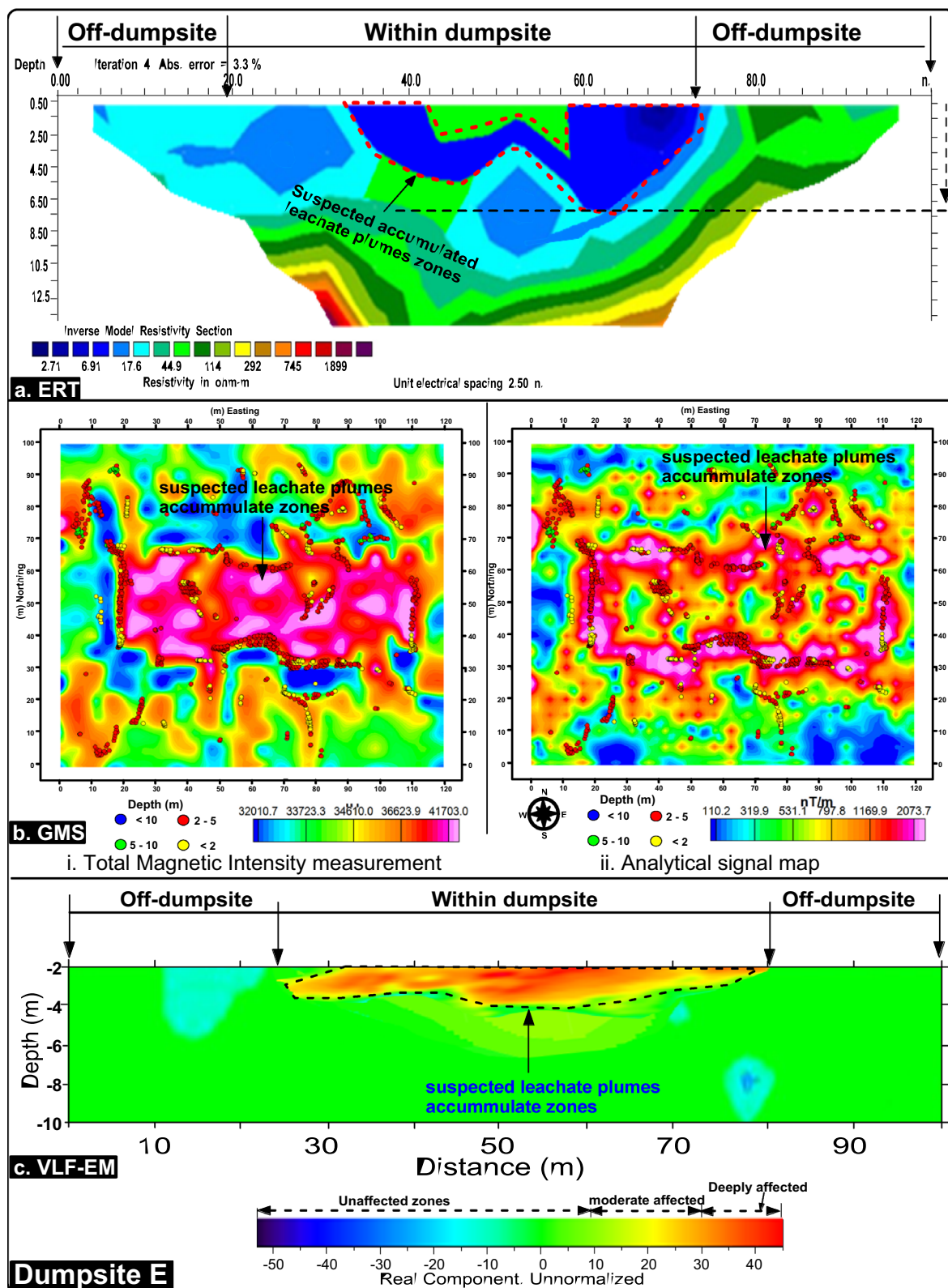


Fig. 3 Geophysical Characterization and Behavioral Maps of Dumpsite A Showing the Subsurface Parameters: **a** 2D ERT Inverse Models, **b** Magnetic maps due to the accumulated waste/leachate plumes, and **c** 2D KHFFILT program of the VLF-EM Inverse Model for Dumpsite E

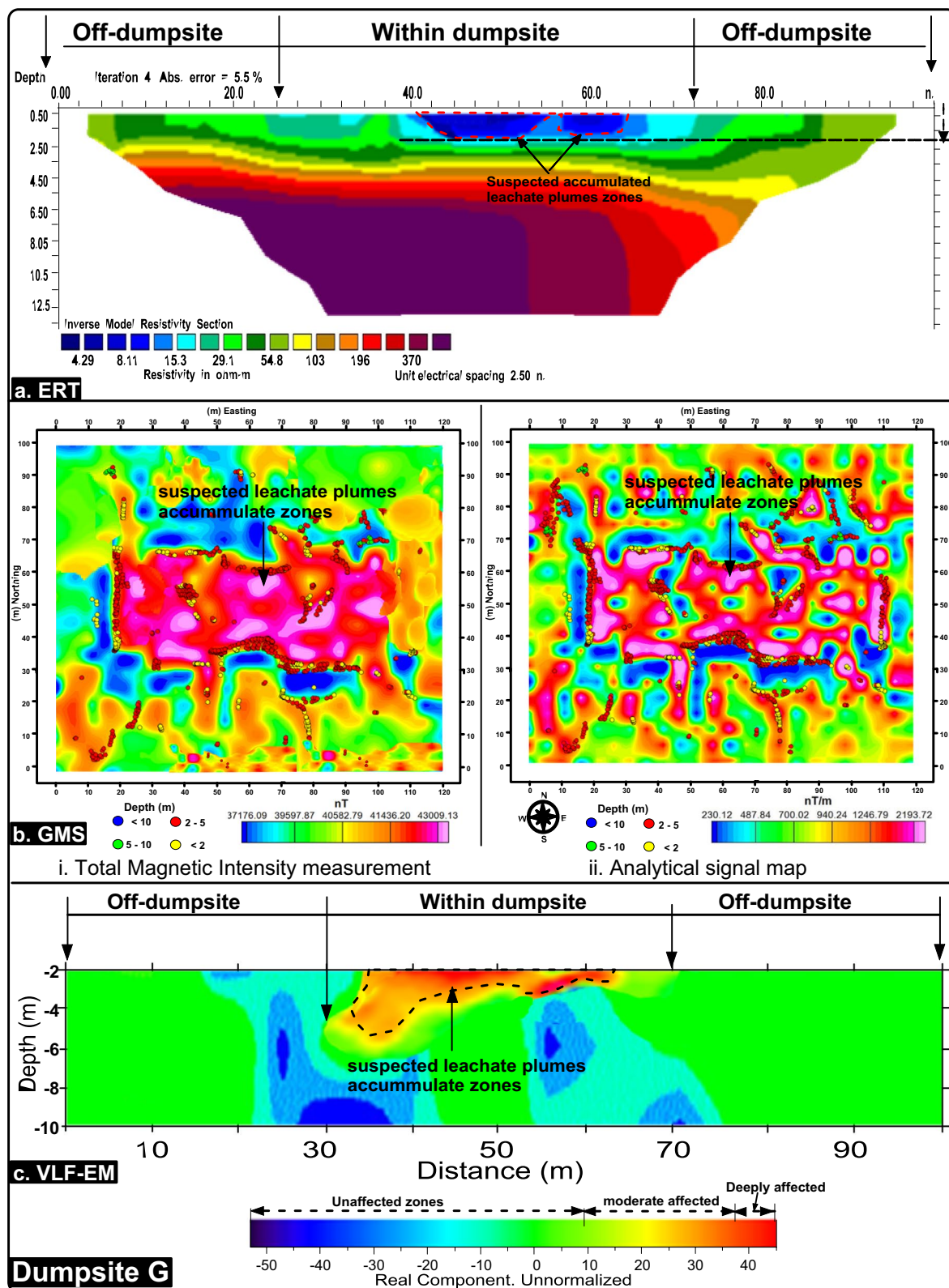


Fig. 4 Geophysical Characterization and Behavioral Maps of Dumpsite A Showing the Subsurface Parameters: **a** 2D ERT Inverse Models, **b** Magnetic maps due to the accumulated waste/leachate plumes, and **c** 2D KHFFILT program of the VLF-EM Inverse Model for Dumpsite G

resistivity values varying between 2.2 and 114 Ωm , followed by silty/clay characterized by about 3.5–11.3 m layer thickness with layer resistivity values varying between 31.8 and 184.0 Ωm . The third layer is delineated to be a weathered/fractured basement, which constitutes the aquifer unit of the study area [42] and has a layer thickness varying from 6.7 to 13.5 m with subsurface resistivity values from 213.5 to 428.5 Ωm . The last layer, believed to be the basement rock of the study area, has resistivity values greater than 1000 Ωm with an infinite thickness. The shallow electrical contrast with resistivity tomography aligned with the solid waste-hipped dumpsites, linked to the infiltration from SW orientation. In addition, the regional borehole (geological well-logs) data provide additional insights into the study area lithologies alongside the previous studies [62, 63], which also serve as a guide for the study.

From the electrical method, four to five distinctive geological sub-layers were delineated. The interpretations show that the dumpsite leachate contaminant plumes were encountered mostly between the first and second layers, which formed the regional aquifer protective soil layers, which appear to have a substantial impact on the AER values of the landfill subsurface stratiform. According to some recent studies, once the integrity of the layers overlying the region is compromised, the regional groundwater is presumed compromised, posing a serious threat to human health [60, 61]. The regions of low resistivity values ($< 7.2 \Omega\text{m}$), usually occurring with depths of 0.0–7.0 m, suggest the presence of leachate contaminant plumes. The resistivity data were compared with the previous studies conducted off-dumpsites within the study area, having high resistivity values (240–1810 Ωm) [63], compared to the current results with 2.2–7.2 Ωm within the dumpsites. In addition, the results (20–73 Ωm) of the extended off-dumpsite surveys indicate slight leachate mixed with the ambient environment, which must have compromised the integrity of soil and groundwater. A consistent increasing trend in subsurface AER values was observed in all the investigated dumpsites with increasing survey distance from the dumpsites, which suggests horizontal migration of the DLPs. However, the low AER noted within the dumpsites and marked as leachate-accumulated regions suggests the presence of HMs in DLPs, which significantly influenced the electrical current flowing in the ground.

Ground magnetic survey results and discussion

A magnetic survey was employed to investigate the dumpsite's leachate plume intrusion based on variations in the Earth's magnetic field. The magnetic method measuring the magnetic properties of the subsurface, such as magnetic susceptibility and remanent magnetization [46],

to identify anomalies that may indicate the presence of contaminants like the DLPs within the dumpsites, which provides insights into the distribution of contaminants in the subsurface [48]. The TMI and analytical signal maps were generated by Oasis Montaj (Figs. 2b, 3b, 4b) with an imposed Euler deconvolution map, which estimated the depth occurrence of the leachate plumes. Based on the TMI and analytical signal maps with an imposed Euler deconvolution map, the magnetic anomalies due to the variations in DLPs within and off the dumpsites vary between 37,600–44,500 nT and 31,095–37,300 nT, respectively. These suspected accumulated leachate plumes were mapped with a depth of 0.0–5.0 m and sometimes extended beyond 5 m based on the imposed Euler deconvolution map. However, other factors or ferro-materials may affect the values of TMI within the dumpsites. Therefore, the results obtained from GMS were complemented by other techniques, such as ERT and VLF-EM. In Figs. 2b, 3b, 4b, a clearer illustration of magnetic anomalies, high-density areas delineated in pink-reddish color, indicative of potential leachate pooling or leachate migration pathways. GMS cannot accurately distinguish ferromagnetic waste-generated versus leachate plume-generated magnetic anomalies.

In addition, most of the locations within the dumpsite showed significant magnetic anomalies, which could be linked to the dumpsite's inhomogeneous material composition and accumulated suspected leachate plumes. The analytical signal map is an enhanced signal map across three dumpsites, which maps the boundaries of the suspected anomalies due to dumpsite leachate [46, 64]. Previous research indicates that the analytic signal map is an enhancement map that produces more nuanced magnetic anomalies surrounding the buried solid waste materials with an improved edge detection anomalous density [50]. The materials at the location cause magnetic anomalies with gradients equal to or greater than 1816 nT/m. The EDM was placed on each map to show the depth distribution of the leachate plume occurrence. The results from the analytical signal show that the magnetic anomalies due to the site's materials and its leachate plumes have a gradient of about 1816 nT/m and above. In addition, there are significant variations in the values of TMI within and off the dumpsites, which seem to always spur maximally within dumpsites and minimized off-dumpsites. This implies that the DLP contaminants leaching into the ground have altered the magnetic properties of the dumpsites and their surrounding soil [48]. Study has shown that elevated TMI, which reflects high magnetic susceptibility, indicates ferrous materials or shallow buried waste decomposition [50]. This becomes more challenging with increasing depth, which may

potentially lead to misinterpretation of survey results. Judging from this and Figs. 2b, 3b, 4b, the occurrence of stronger magnetic anomalies may have indicated a shallow leachate plume.

VLF-EM results

The VLF-EM survey was employed to delineate conductive anomalies associated with leachate plumes. The resistive and conductive zones delineated are imaged using the VLF-EM 2D KHFFILT pseudo-section inversion models (Figs. 2c, 3c, 4c). The results of the VLF data indicate the presence of conductive contrast zones, which are mapped as suspected accumulated leachate plumes within the dumpsites depicted in the reddish color pane, while the dominated resistive region demonstrates the natural inhomogeneity of the site depicted by greenish blueish color pane (Figs. 2c, 3c, 4c). The non-leachate plume-accumulated zones are indicated by the blueish greenish color panes that depict the different resistive or non-conductive areas that stretch from 15 to 30 m horizontally off the dumpsites. This indicates that the groundwater found in these areas is comparatively safe from newly emerging DLPs. The concentrated waste materials were piled between 0.0 and 7.0 m with an ECD of 30.0–45.0 within the dumpsites and – 50 to 30 off-dumpsites, respectively. The VLF-EM identified the landfill leachate plumes at a horizontal distance of 25–85 m. A steady pattern of leachate migration can be seen in the conductive zones, which represent the collected areas of leachate plumes. With a discernible drop in the ECD outward direction of the dumpsites, the zones where leachate plumes accumulated and were shown to be conductive typically occur between 0.0 and 7.0 m below the fault lines.

Conductive zones detected by geophysical methods, such as VLF-EM and ERI, may serve as conduits for the movement of solid waste leachate contaminants into the ground down to the tail water [54], which poses a risk to both the environment and public health due to the hazardous substances. The high conductivity values of the ECD (>30) suggest the presence of leachate plumes, as contaminants, such as heavy metals and organic compounds, which increase the electrical conductivity of the subsurface. The zones of higher ECD, which suggest the presence of leachate contaminant plumes. The significant variation in the values of ECD appears to always emerge maximally and minimally within dumpsites and off-dumpsites, respectively, indicating the dumpsite leachate plume-accumulated and non-leachate plume-accumulated zones [54]. This implies that the solid waste heaped on the open ground has influenced the natural geophysical signature of the dumpsite subsoil due to buried waste.

Hydrochemical analysis results

Groundwater was sampled from 15 HDWs, and 10 river water sample sources were analyzed and presented in Table 3 and Fig. 5. The physical–chemical parameters of the sample DLPs, surface water (rivers/streams), and groundwater for the pH, EC, and HMs values indicate various concentrations, which are dependently influenced by sample sources, wells' depth and distance, as well as dumpsite age. The laboratory results for the sample source are presented below. The hydrochemical parameters readings varied significantly in Groundwater sample as pH (6.4–8.7), EC (0.211–1.831 mg/l), Cr (0.121–1.098 mg/l), Cd (0.021–0.710 mg/l), Pb (0.157–1.479 mg/l), and Fe (0.332–1.811 mg/l), while the concentrations in surface water sample reading considerably for pH (6.9–8.8), EC (2.181–4.009 mg/l), Cr (1.171–1.77 mg/l), Cd (0.192–0.811 mg/l), Pb (1.329–1.917 mg/l), and Fe (2.181–2.919 mg/l). In the leachate plumes sample, the concentration varies considerably for pH (6.6–8.6), EC (21.33–23.73 mg/l), Cr (11.08–12.3 mg/l), Cd (9.44–11.27 mg/l), Pb (9.39–13.01 mg/l), and Fe (12.84–15.44 mg/l). The results suggest that the concentrations of HMs, the values of EC, and pH exceed the World Health Organization (WHO) permitted standard for drinking water [65]. The hydrochemical laboratory test for different substances of the groundwater (HDWs), surface water, and dumpsite leachate sample indicates high concentrations of HMs (such as Cr, Cd, Pb, and Fe), EC, and pH, which provide vital insights into the potential threats posed to human health and the environment vital organs, such as groundwater, air conditions, and soils by the DLPs.

Figure 5 expresses the degree of HMs (Fe, Pb, Cr, and Cd) present in the extracted surface/groundwater systems taken from HDWs, rivers, and streams. The surface water has the highest concentration, followed by HDWs. However, the HDW (W15), which is about 8.0 m in depth and 198 m away from the contaminant source, shows the lowest concentration of HMs, while the river (R3), which is about 32 m away from the contaminant source, has the highest concentration of HMs. Figure 5 shows that the concentration of HMs in the sample water varies significantly in certain consistent trends, with the more the distance, the less the contaminants, with $R3 > R2 > R1 > R9 > R4 > R5 > R6 > R8 > R10 > R7$ in terms of HMs concentrations. A consistent trend of far-distance low concentration and closed-distance high concentration of HMs was noted across all the sample waters analyzed. However, the concentrations of the HMs encountered in the river sample water were unaffected by the depth of the rivers, which are mostly less than 5.0 m. For groundwater samples from HDWs, the concentrations of HMs vary considerably and dependently on their depth and distance,

Table 3 Results of HCA from five (5) leachate plume samples, water samples obtained from fifteen (15) hand-dug wells within ten (10) rivers within 200 m of the disposal sites and the World Health Organization's (WHO) acceptable limits

Parameter measured		EC	pH	Cr	Cd	Pb	Fe
Dumpsites	Wells	ms/cm	-	mg/l	mg/l	mg/l	mg/l
A	W 1	1.320 ± 0.80	6.9 ± 0.31	0.817 ± 0.11	0.097 ± 0.015	0.913 ± 0.29	0.911 ± 0.011
	L 1	21.73 ± 2.12	7.6 ± 0.31	12.31 ± 2.71	10.31 ± 1.80	11.17 ± 1.81	12.31 ± 1.80
	R 1	3.192 ± 0.93	8.8 ± 0.31	1.217 ± 0.13	0.192 ± 0.018	1.711 ± 0.21	2.801 ± 0.073
B	W 2	1.441 ± 0.67	7.3 ± 0.55	0.816 ± 0.23	0.092 ± 0.022	1.012 ± 0.31	1.751 ± 0.072
	W 3	1.023 ± 0.83	6.7 ± 0.31	0.534 ± 0.34	0.089 ± 0.031	1.001 ± 0.43	1.108 ± 0.074
	R 2	3.291 ± 0.82	8.1 ± 0.55	1.656 ± 0.44	0.209 ± 0.014	1.726 ± 0.34	2.675 ± 0.075
C	W 4	1.119 ± 0.22	6.8 ± 0.31	0.715 ± 0.54	0.079 ± 0.025	0.991 ± 0.22	1.111 ± 0.098
	L 2	22.32 ± 2.71	7.7 ± 0.82	11.98 ± 2.77	09.44 ± 1.98	12.08 ± 2.11	15.44 ± 2.377
	R 3	4.009 ± 0.17	7.9 ± 0.31	1.771 ± 0.17	0.53 ± 0.011	1.917 ± 0.44	2.181 ± 0.045
D	W 5	1.831 ± 0.93	7.9 ± 0.55	0.579 ± 0.22	0.301 ± 0.072	1.009 ± 0.52	1.811 ± 0.043
	W 6	0.901 ± 0.27	7.5 ± 0.31	0.591 ± 0.27	0.053 ± 0.044	1.031 ± 0.29	1.298 ± 0.021
	R 4	2.987 ± 0.12	8.9 ± 0.55	1.301 ± 0.39	0.069 ± 0.033	1.552 ± 0.23	2.919 ± 0.083
E	W 7	1.561 ± 0.58	7.1 ± 0.55	0.861 ± 0.33	0.067 ± 0.017	0.729 ± 0.25	1.125 ± 0.019
	L 3	23.73 ± 2.71	8.6 ± 0.22	11.08 ± 2.97	09.730 ± 2.11	13.01 ± 2.21	12.84 ± 2.01
	R 5	2.181 ± 0.12	7.4 ± 0.27	1.332 ± 0.21	0.401 ± 0.037	1.329 ± 0.33	2.771 ± 0.019
F	W 8	1.811 ± 0.66	7.1 ± 0.55	0.666 ± 0.17	0.710 ± 0.041	0.912 ± 0.27	1.211 ± 0.031
	W 9	0.873 ± 0.19	6.8 ± 0.29	1.098 ± 0.11	0.047 ± 0.017	1.479 ± 0.15	1.151 ± 0.031
	R 6	2.801 ± 0.37	7.3 ± 0.49	1.171 ± 0.15	0.097 ± 0.012	1.621 ± 0.34	2.271 ± 0.087
G	W 10	1.024 ± 0.31	7.1 ± 0.37	0.491 ± 0.10	0.029 ± 0.013	0.974 ± 0.20	1.679 ± 0.017
	L 4	21.33 ± 2.34	8.1 ± 0.61	11.11 ± 2.02	11.27 ± 1.99	10.57 ± 2.15	13.55 ± 2.55
	R 7	2.578 ± 0.21	7.8 ± 0.57	1.398 ± 0.29	0.084 ± 0.019	1.401 ± 0.18	2.397 ± 0.098
H	W 11	1.211 ± 0.22	6.4 ± 0.51	0.587 ± 0.07	0.619 ± 0.051	1.173 ± 0.26	1.787 ± 0.077
	W 12	1.231 ± 0.11	7.6 ± 0.55	0.61 ± 0.31	0.071 ± 0.018	0.912 ± 0.25	1.521 ± 0.043
	R 8	2.720 ± 0.41	7.3 ± 0.31	1.337 ± 0.17	0.097 ± 0.015	1.531 ± 0.29	2.701 ± 0.061
I	W 13	1.502 ± 0.17	7.4 ± 0.19	1.017 ± 0.71	0.511 ± 0.11	1.339 ± 0.21	1.711 ± 0.091
	L 5	20.71 ± 2.74	6.6 ± 0.55	10.88 ± 2.11	10.41 ± 2.55	09.39 ± 2.78	12.88 ± 2.41
	R 9	3.001 ± 0.31	6.9 ± 0.27	1.333 ± 0.21	0.771 ± 0.044	1.577 ± 0.33	2.727 ± 0.055
J	W 14	0.931 ± 0.13	8.7 ± 0.47	1.041 ± 0.33	0.331 ± 0.140	1.043 ± 0.11	0.912 ± 0.033
	W 15	0.211 ± 0.09	6.8 ± 0.15	0.121 ± 0.27	0.021 ± 0.011	0.157 ± 0.27	0.332 ± 0.057
	R 10	2.661 ± 0.19	7.8 ± 0.44	1.412 ± 0.37	0.811 ± 0.042	1.441 ± 0.29	2.551 ± 0.051
[65]		0.10–1.000	6.5–8.5	0.030–0.050	0.003–0.005	0.01–0.03	0.300–1.000

W hand-dug wells, R river/stream, L leachate plume

with W5 > W11 > W8 > W13 > W2 > W10 > W12 > W7 > W9 > W1 > W > 4 > W3 > W6 > W14 > W15. For instance, the sample water W15 shows the lowest HM concentration due to its depth (8.0 m) and distance (198 m). This suggests that the distance between the sample water and contaminant sources has a significant impact on the contents of HMs found in the sample water. The HDW (W14), which is about 12 m deep and 57 m away, shows a moderate concentration of HM. In addition, the concentration of individual metals in the water sample consistently followed a specific trend, with Fe > Pb > Cr > Cd. The electrical conductivity encountered in the water sample obtained from both HDWs and rivers varies

between 0.211 and 4.009 mg/l. However, the river water samples indicate extremely high HM contents above the WHO allowable limit for drinking water. Therefore, a safe depth/distance is required in going forward.

In addition, the leachate sample taken from five dumpsites shows more strength in terms of EC and pH values and concentration of HMs, which is about fifteen times that of the concentrations found in both surface and groundwater. According to a remarkable study, leachate plumes with high concentrations of HMs (> 15 mg/l) possess high stopping distance/depth [66]. The high contents of HMs found in the dumpsite leachate samples suggest that the DLPs have a high stopping distance and depth.

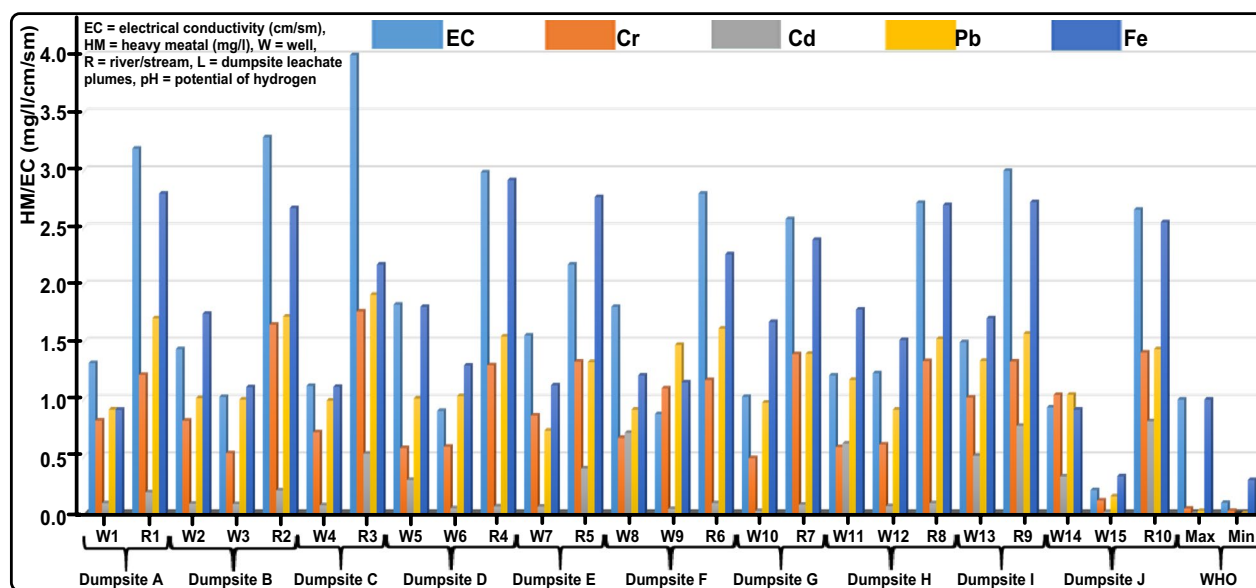


Fig. 5 Degree of heavy metal and electrical conductivity compositions in the regional surface and groundwater systems. Strengths and Limitations

This implies that the DLPs can travel a far distance of depth, polluting a far distance of soil and water before they lose their concentration. However, this impact also depends on specific characteristics, such as the site condition, hydrological factors, and the regional groundwater flow dynamics of the leachate plumes. Furthermore, it was noted that the pH values of the sample leachate plumes pH (6.6–8.6) and water (6.4–8.8) show no significant difference, which indicates moderate rain events and an average composition of acidic and alkaline substances. It also suggests that the microbial activities within the dumpsites generate moderately acidic and alkaline byproducts during the metabolic process.

Integrating ERT, magnetic, VLF-EM, and HCA results provides a comprehensive approach to delineating dumpsite leachate plume contaminants. ERT detects zones of low resistivity ($<7.2 \Omega\text{m}$) within 0–7 m depth, which are indicative of leachate plumes infiltrating subsurface layers. Magnetic surveys identify variations in total magnetic intensity (TMI), correlating anomalies to the presence of contaminants affecting magnetic susceptibility. VLF-EM captures conductive zones with elevated electrical conductivity ($\text{ECD} > 30$), mapping the horizontal and vertical migration of leachates along fault lines. HCA validates geophysical findings by confirming high concentrations of heavy metals (Cr, Cd, Pb, Fe), pH, and electrical conductivity in groundwater and leachate samples, exceeding WHO standards. Together, these methods complement each other: ERT outlines subsurface structure, magnetic surveys refine spatial plume distribution, VLF-EM highlights conductive pathways, and

hydrochemical data confirm contamination, ensuring accurate assessment of environmental risks.

However, while VLF-EM, ERT, and GMS provide a comprehensive insights into the spatial distribution of leachate contaminants within the subsurface, each technique has limitations when assessing leachate plumes' environmental impact. VLF-EM is sensitive to the subsurface conductive anomalies but was challenged in terms of depth resolution, making it difficult to differentiate between different sources of conductivity. In addition to this, VLF-EM could not distinctly map disjoint or minor contaminant plumes like ERT. While ERT provides a detailed stark image of the subsurface, heightening disjoint plumes alongside the plume pathways, the results could be influenced by various factors such as soil water content, leading to potential misinterpretations. On the other hand, GMS detect changes in the subsurface magnetic field but struggles to directly identify leachate plumes from other ferro-materials. GMS is sensitive to shallow subsurface features, making it perfect for identifying near-surface anomalies due to improperly disposed metallic waste [50]. This implies that deeper contaminant sources may not be captured. Also, while GMS by itself is interpretively limited, this agreement with ERT and VLF measurements demonstrates that plume features can be observed through common patterns of anomalies, indicating the utility of combining these techniques in evaluating subsurface pollution of the environment. On the other hand, HCA provides essential elevated levels of toxic elements in the sampled groundwater, yet is limited only to the sampling points, making

it challenging to track migration pathways of the plumes over large areas. Additionally, the dilution effects, flow dynamics, and interactions of groundwater with ambient geology can hinder the comprehensive understanding of the extent of contamination. However, the combined methods enhance the reliability of the findings and minimize uncertainties.

Physical surveys and oral interviews

The physical surveys of the study involve visits to some of the dumpsites within the metropolitan city, which were accomplished with oral interviews with the people living within a 200 m radius. The oral interview shows that over 100 people were interviewed, and about 70–90% of interviewees confirmed frequent malaria and unusual fatigue among the people close to the dumpsites. This implies that individuals living near dumpsites are usually exposed to high public health risks, which include respiratory problems, skin infections, and gastrointestinal illnesses. Based on the physical surveys, more than 20 dumpsites/landfills were visited, about 100% of the visited landfills/dumpsites are open dumping grounds without lining, which heightened the impacts of rain events on the dumpsites, especially during the rainy seasons. The obvious observed trends noted within and outside these dumpsites/landfills include but are not limited to:

- a. Environmental indiscipline: careless waste disposal was noted in all the sites, leading to unnecessary expansion of dumping grounds. According to a remarkable study, environmental indiscipline exacerbates the negative impacts of dumpsites in several ways [18]. Improper waste disposal practices, such as littering and illegal dumping, contribute to the accumulation of waste at dumpsites, leading to overflowing landfills and unsightly surroundings. Inadequate waste segregation and recycling further worsen the environmental burden, increasing pollution levels and health risks. Inadequate enforcement of regulations and lax attitudes toward environmental responsibility perpetuate the cycle of environmental degradation at dumpsites. Addressing environmental indiscipline through education, enforcement, and community engagement is essential to mitigate the detrimental effects of dumpsites on the environment and public health.
- b. Dumping in water bodies, especially in the streams and gutters within the city, can trigger regional and local flooding, pollution, and multiplication of bacteria, rodents, and parasites that can potentially harm the ecosystem and public health.
- c. Rodents within the dumpsites: The dumpsites provide ideal breeding grounds for rodents due to the

abundance of food waste and shelter. The presence of rodents not only poses a nuisance but also increases the risk of disease transmission to humans, creating a public health hazard.

- d. Slope failure: also known as landslides or mass wasting within the dumpsites and across the boundaries, especially the elevated ones, which can potentially lead to the failure of engineering foundations and loss of lives. This implies that improperly or poorly managed dumpsites can lead to slope failures as the accumulation of waste adds weight to the slope, destabilizing it over time. This can result in landslides and erosion, endangering nearby communities and infrastructure.
- e. Unbearable odors: excess odor was noted within and around the dumpsites, affecting the ambient inhabitants. This implies that dumpsites can have detrimental effects on the environment and public health, leading to various issues, such as rodent infestations, slope failures, pollution, and health risks. Here's how dumpsites contribute to each of these problems using persuasive language. Dumpsites contaminate soil, water, and air through the release of harmful chemicals and toxins from decomposing waste. This pollution can have long-lasting effects on ecosystems, wildlife, and human health, leading to respiratory issues, water contamination, and other health problems.

Associated environmental and public health risks

The dumpsite leachate outflow exhibited the highest average values for several parameters, such as pH, EC, Cr, Cd, Pb, and Fe. On the contrary, the extended survey beyond the dump site, which served as the control key, recorded the lowest average values of HMs, EC, and pH. The low contents of HMs suggest that the DLPs are quite young though most of the contents of HMs EC and pH recorded are on the high side compared to WHO's allowable limit for drinking water [65]. The excess contents of these parameters posed a major threat to the environmental vital organs including public health. The elevated toxic substances can infiltrate human health in three major ways including vegetables (food), drinking water, and excessive inhaled of odors emerging from dumpsites or inhaling of smoke from the burning of unsorted waste streams heaped at dumpsites [67, 68]. However, the consumption of these HMs can sometimes provide essential nutrients required in the body. For instance, iron plays a vital role in human health in carrying oxygen through the bloodstream [58]. The production of hemoglobin, the protein in red blood cells that carries oxygen from the lungs to bodily tissues, is another important function

of it. In addition, iron provides the needed energy for the human body when taken according to WHO guidelines for drinking water quality. Chromium contamination in water is often due to industrial waste [69, 70], which could be carcinogenic, linking to the lung cancer and other health issues when taken in excess. However, cadmium in drinking water usually occurs as a result of improper industrial discharges and fertilizers, which can potentially lead to kidney damage and cancer. On the other hand, the lead contaminants in drinking water usually arise from old or rusted pipes and plumbing systems, which can potentially affect the nervous system, especially in children, leading to developmental delays and cognitive impairments.

Based on the result of this study and the above information, the DLPs threaten public health. Excessive consumption and prolonged exposure to these elevated HM levels may cause health issues, such as joint pain, fatigue, and eye disorders, which is supported by the study's oral interview. The elevated HM in water affects not only human health but also impacts aquatic ecosystems and contributes to sedimentation, especially in surface water such as rivers. Individuals living close to dumpsites may be at more risk of exposure to toxic substances making the populace, especially the vulnerable groups such as pregnant women, the elderly, children, and individuals with weak immune systems, more susceptible to the health effects of dumpsite leachate contaminant plumes. Leachate plume contaminants in drinking water can exacerbate the spread of waterborne diseases leading to long-term health effects. The consistent HMs in the soil or water beyond allowable periods may eventually accumulate to a degree that is toxic to plants, animals, microorganisms, and human beings. These contaminant plumes can interact with nutrient uptake by plants, distort soil microbial activity, and eventually alter the overall subsoil chemistry, causing low crop productivity. Additionally, toxic substances, airborne particles, and foul odors emerging from dumpsites may have serious impacts on the well-being of the dumpsite nearby residents. However, further microbial analysis can be carried out on the surrounding water to assess the micro-organism's presence in the regional water.

The sublayer low resistivity contrasts encountered in the geo-electrical survey, the high TMI, and high ECD zones, which characterized the site overburdened topsoil thickness suggest a loose cluster density and poor soil mass. According to a recent study, DLPs can affect the regional subsoil load-bearing capacity [71], which is a sign of potential landslides (slope and structural failures). Based on this fact, a poorly managed dumpsite can lead to landslides, and threaten human existence because one structural failure can claim more than 100 lives. To

weather the storms of DLPs, it is therefore essential to understand the impacts of dynamic leachate plumes and poor waste-managed dumping systems on ground soil, surface water, groundwater, and atmospheric conditions for environmental security because the dumpsites are not just an ugly situation but also hotspots for environmental crises and related potential health issues for effective monitoring, public health interventions, and remediation. This will help us to take controlled measures, such as regular water quality testing, mitigate against excess exposure, establish appropriate remediation strategies, and make informed decisions.

The way forward and recommendations

Going forward, it is essential to address some factors influencing dumpsite leachate contaminant plumes from hydrochemical and geophysical perspectives to provide a soft ground for environmental vital organs. These factors include but are not limited to the depth/distance of drinking water sources, hydrological topography, and geological composition [16]. Based on the geophysical results, these factors play a vital role in the environmental impact of leachate plumes. Thus, the study suggested that a safe depth/distance, safe hydrological topography, safe geological composite, and strong media awareness remain essential in moving forward. A "*safe distance*" in this context is the distance between the contaminant source (landfills) and the water source. Based on the information gathered from the geophysical and physico-chemical data, it is important to know that the distance of wells or boreholes (BHs) from dumpsites can significantly affect the quality of the water within the well due to potential contamination from the landfill. This implies that the closer wells are more polluted, while the farther away water source from landfills is less likely to be affected by leachate, which is in line with the results of previous studies [59, 72]. This is because its far distance permits more dilution and degradation of contaminants as they travel through the soil and rock. However, due to the economic burden of waste management and the lack of adequate planning for dumpsites in developing nations, this study suggests "*safe depth/distance*" as a temporary solution, which emphasizes the need to site wells or boreholes deep down the soil to avoid invasion or intrusion of near-surface contaminant plumes. Safe depth is a depth less prone to near-surface contaminant plumes, in which a borehole or well can be sunk. From the geophysical and physical data, shallow wells are typically more susceptible to near-surface contaminant plumes due to their closer to the surface, where most contaminant plumes are accumulated. Such wells often draw water from aquifers that are not as well filtered through layers of soil and rock, especially where

the landfill leachate plumes have leached into the ground soil and groundwater. For instance, deeper wells that are connected to confined aquifers (aquifers that are isolated from the surface by impermeable layers) [73] are generally less susceptible to surface contaminant plumes compared to shallow wells that access unconfined aquifers.

Another factor to be considered in going forward is “safe hydrological topography and geological composite”, which can significantly influence the groundwater flow and contaminant plume infiltration, respectively. The hydrogeology topography plays a vital role in influencing the direction of groundwater flow [74, 75], which can determine how contaminants from a landfill might travel, the geological composite such as soil composition can also influence the natural filtering soil layers between the landfill and the well. Safe hydrological topography and geological composite are very essential for site wells and landfills in any terrain. The hydrogeological and geological nature of any terrain is quite crucial to determining the flow direction of groundwater, the location of aquifers, and the natural protective layers of soil and rock [60], which will help us to establish safe distances and depths for wells around landfills. The design and management of landfills cannot be adequately done without adequate knowledge of the nature of regional hydrogeology and geology.

In addition, the average safe distance and depth for siting wells around dumpsites can vary depending on several factors such as the waste types in dumped on dumpsites, and local geological and hydrogeological conditions. Based on the results of the combined geophysical investigations, hydrochemical water analysis, and the consistent distance-depth trends encountered in this study, to obtain clean and safe drinking water, HDWs/boreholes should be sited far away from the dumpsite with a resealable depth and distance. Therefore, this study suggests the following distances/depths of 200 m/8 m, 150 m/10, 100 m/12 m, 75 m/15 m, and 50 m/20 m, as safe distances/depths for safe drinking water around the dumpsites based on the results obtained from the integrated geophysical studies and hydrochemical water analysis. Given this fact, a distance less than fifty meters (< 50 m) from dumpsites and a depth less than eight meters (< 8.0 m) from the surface should not be considered when siting wells or boreholes around dumpsites. However, a safe hydrological topography and geological composite should be considered for siting landfills or BHs/HDWs as part of the influential factors. This can temporarily shift the goalpost of the impending environmental disasters due to dumpsite leachate contaminant plumes, especially in developing nations where open dumpings are largely

the only medium of municipal solid waste management. Therefore, to protect well water quality, it is essential to consider these factors (safe distance, safe depth, safe hydrological topography, and geological composition) when setting up a new well or landfill/dumpsite.

Going forward, this study recommends “strong media awareness” to enlighten the public on the implications of uncontrolled landfills on the environment and public health. This will enhance total environmental security and sustainability. Strong media awareness plays a crucial role in addressing environmental indiscipline and promoting environmental protection in several ways, such as (i) education and information dissemination about environmental challenges, such as pollution, deforestation, climate change, and biodiversity loss. (ii) attitudinal change, which can be influenced by strong media awareness, by encouraging environmentally responsible actions. (iii) policy influence, which reshapes public opinion and influences political agendas, where environmental issues become a priority for the electorate, politicians, and government. (iv) global connectivity, especially social media and digital platforms, that can connect people across the globe, facilitating the exchange of ideas, strategies, and best practices for environmental protection. This global network can help spread innovative solutions and create a sense of shared responsibility for the planet. In closing argument, strong media awareness can empower individuals, institutions, and global communities to take action, influence policy, and foster a culture of environmental stewardship, which is quite an essential tool for promoting environmental discipline and protecting natural resources for current and future generations.

Regular environmental monitoring and testing of well water alongside geophysical investigations like this study are also crucial to ensure that any potential contamination is detected early and addressed promptly. However, there is no one-size-fits-all answer or perfect solution, but these suggestions can be adopted by environmental protection agencies and public health authorities to minimize the risk of contamination. However, the average safe distance and depth for wells around dumpsites can vary depending on the specific characteristics of the dumpsite and the nature of the surrounding area. It is important to consider factors such as the type of waste in the dumpsite, the potential for contamination of groundwater, and local regulations and guidelines. In general, it is essential to consult with local environmental authorities and water-related experts/professionals.

Conclusion

This work comprehensively applied combined geophysical and hydrochemical investigations alongside physical surveys and oral interviews to evaluate the environmental impact of DLPs on soil, surface water sources, groundwater, and human health. A consistently increasing trend in subsurface electrical resistivity values was encountered in the investigated dumpsites with increasing survey distance from the dumpsites. A constant decrease in the contents of HMs in sample water was noted with an increased sample water source distance, which suggests horizontal migration and vertical seeping of the DLPs. The combined geophysical studies established the relationship between the depth of wells and contaminant source distance from consistent trends. The hydrochemical data indicate high concentrations of HMs, pH, and EC exceed the WHO standard for drinking water, while oral interviews confirmed suspect impacts of these abnormalities, especially among the people close to the dumpsites, supported by hydrochemical data. A safe depth/distance of 8 m/200 m, 10 m/150 m, 12 m/100 m, 15 m/75 m, and 20/50 m, for siting boreholes/HDWs as a temporary solution was recommended to obtain clean and safe drinking water based on the results of the combined geophysical investigations. The integrity of drinking water sources and waste management methods (unlined landfills) has the biggest impacts on public health, which emphasizes how crucial it is to combine scientific research with local knowledge to resolve environmental challenges. Therefore, landfill standardization may require that landfills be located at least 6 m above the water table. In conclusion, the overall quality and integrity of surface/groundwater sources such as wells, boreholes, or rivers are largely determined by the overall sanitation of their ambient environment. This is because poor waste management and a high level of environmental indiscipline, which constitutes an untidy environment, have paved the way for contaminant materials into the surface/groundwater, especially those around poorly managed dumpsites. Additionally, unchecked leachate seeps necessarily threaten the groundwater quality and public health infrastructure. Neglected dumpsites remain a quiet poison, leaving indelible marks on the groundwater and its host. Therefore, the combined geophysical and hydrochemical data alongside the physical surveys and oral interviews have enhanced the understanding of dynamic leachate plumes and the implications on the environmental health.

Author contributions

Author Contributions: Conceptual framework, Investigation, Data acquisition, Data processing, Analysis, Resources, were done by OJA, OJO, AF, DAA, AAI, and AYB. and Reviewing and Editing of the manuscript were done by all the authors (OJA, OJO, AF, DAA, AAI, AYB, MYD, SUE and DRB), while the manuscript was written by OJA.

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Data availability

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval

I declare that this research is original work carried out by all the authors and that no part of this work has been previously published in any journal. All information provided in this work has been duly acknowledged in the text and the references provided.

Consent for publication

I have read, understand, and agree with the information provided and the terms of the Journal.

Competing interests

The authors declare no competing interests.

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