Heliyon 10 (2024) e30097

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Spatial analysis of leachate penetration at Lemna dumpsite, Calabar: Implications for sustainable waste management in Cross River State

E.I. Igelle [a], P.O. Phil-Eze [b], O.O. Akim [c], H.I. Kanu [d], I.C. Ekowk [e], J.W. Atsa [a], P.A. Ojugbo [a], J.S. Okputu [a], Kamal Abdelrahman [f], S.E. Ekwok [g], P. Andráš [h], Ahmed M. Eldosouky [i,*]

[a] *Department of Environmental Resource Management, Faculty of Environmental Sciences, University of Calabar, PMB 1115, Calabar, Nigeria*
[b] *Department of Geography, Faculty of Social Sciences, University of Nigeria, Postal Code, 410002, Nsukka, Nigeria*
[c] *Environmental Sciences, School of Agriculture and Environmental Sciences, University of Gambia, POBox, 3530, Brikama, Serekunda, Gambia*
[d] *Department of Architecture, Faculty of Environmental Sciences, University of Calabar, PMB 1115, Calabar, Nigeria*
[e] *Department of Geography and Environmental Science, Faculty of Environmental Sciences, University of Calabar, Calabar, PMB 1115State, Nigeria*
[f] *Department of Geology and Geophysics, College of Science, King Saud University, P.O. Box 2455, Riyadh, 11451, Saudi Arabia*
[g] *Applied Geophysics Programme, Department of Physics, University of Calabar, Calabar, PMB 1115, Cross River -State, Nigeria*
[h] *Faculty of Natural Sciences, Matej Bel University in Banska Bystrica, Tajovského 40, 974 01, Banska Bystrica, Slovakia*
[i] *Department of Geology, Faculty of Science, Suez University. P.O. Box: 43221, Suez, Egypt*

A R T I C L E I N F O

Keywords:
Spatial analysis
Leachate penetration
Lemna dumpsite
Soil
Borehole water

A B S T R A C T

This study rigorously investigated the spatial analysis of leachate penetration at Lemna dumpsite, located in Calabar, Cross River State, Nigeria. Purposeful soil sampling, performed at specific intervals (5 m, 25 m, and 50 m) along the Electrical Resistivity profile line within the dumpsite, was augmented by water sample collection from five boreholes near Lemna dumpsite. Utilizing Electrical Resistivity Tomography (ERT) and Vertical Electric Sounding (VES) survey techniques, resistivity data were systematically gathered to comprehensively analyze the Leachate Penetration in the Lemna dumpsite. Laboratory analysis of soil and borehole water quality focused on Benzene, Toluene, Ethylbenzene, and Xylene (BTEX), with paired sample t-tests applied for statistical scrutiny. Analyzing the ERT and VES data employed sophisticated techniques embedded in Resistivity Two Dimension Invasion software and Advanced Geosciences Incorporation Earth Imager software. Substantial disparities ($p < 0.05$) emerged in the paired sample t-tests for BTEX in soil compared to National Environmental Standard Regulation and Enforcement Agency (NESREA) limits. Similarly, BTEX in borehole water displayed significant differences ($p < 0.05$) when compared to World Health Organization (WHO) standards, raising alarming concerns about the safety and portability of groundwater in the area. The examination of dumpsite leachate penetration revealed a resistivity anomaly of 8.01 Ωm and an inverse depth of 12.4 m, underscoring profound environmental implications and necessitating immediate remediation efforts. Additionally, Vulnerability and Aquifer Protective Capacity Index (VES) results, with a rating of <0.1, indicated severely compromised aquifer protective capacity, emphasizing the vulnerability of groundwater resources to further contamination. Our study advocates for strategic

* Corresponding author.
E-mail addresses: dr_a.eldosoky@yahoo.com, Ahmed.Eldosouky@sci.suezuni.edu.eg (A.M. Eldosouky).

https://doi.org/10.1016/j.heliyon.2024.e30097
Received 19 February 2024; Received in revised form 18 April 2024; Accepted 19 April 2024
Available online 26 April 2024

management, remediation, and monitoring measures to prevent contamination and safeguard water quality in the region.

1. Introduction

An open dumpsite is a waste disposal site where wastes are disposed inappropriately on the ground, which may result in open burning and exposure to vectors, rodents, scavengers and increased dumpsite leachate quantity. Dumpsite leachate quantity is on the rise around the globe, due to wastes deposited in poorly constructed open dumpsites [1]. A large quantity of leachate can emanate from open dumpsites. This large quantity of leachate generated from open dumpsites can pollute a large portion of groundwater. Groundwater pollution by dumpsite leachate constitutes a major threat to humans and the environment. Groundwater is considered the most important natural resource to mankind [2]. Groundwater constitutes an important part of the hydrological cycle and is more prone to pollution [3]. Groundwater within and around a dumpsite is highly susceptible to leachates [4]. Groundwater around dumpsites can be vulnerable to dumpsite leachate pollution. Consuming leachate-polluted water may result in inexplicable illnesses and death. Leachate-polluted water may have a wide range of ailments in humans. It has been reported that consuming contaminated

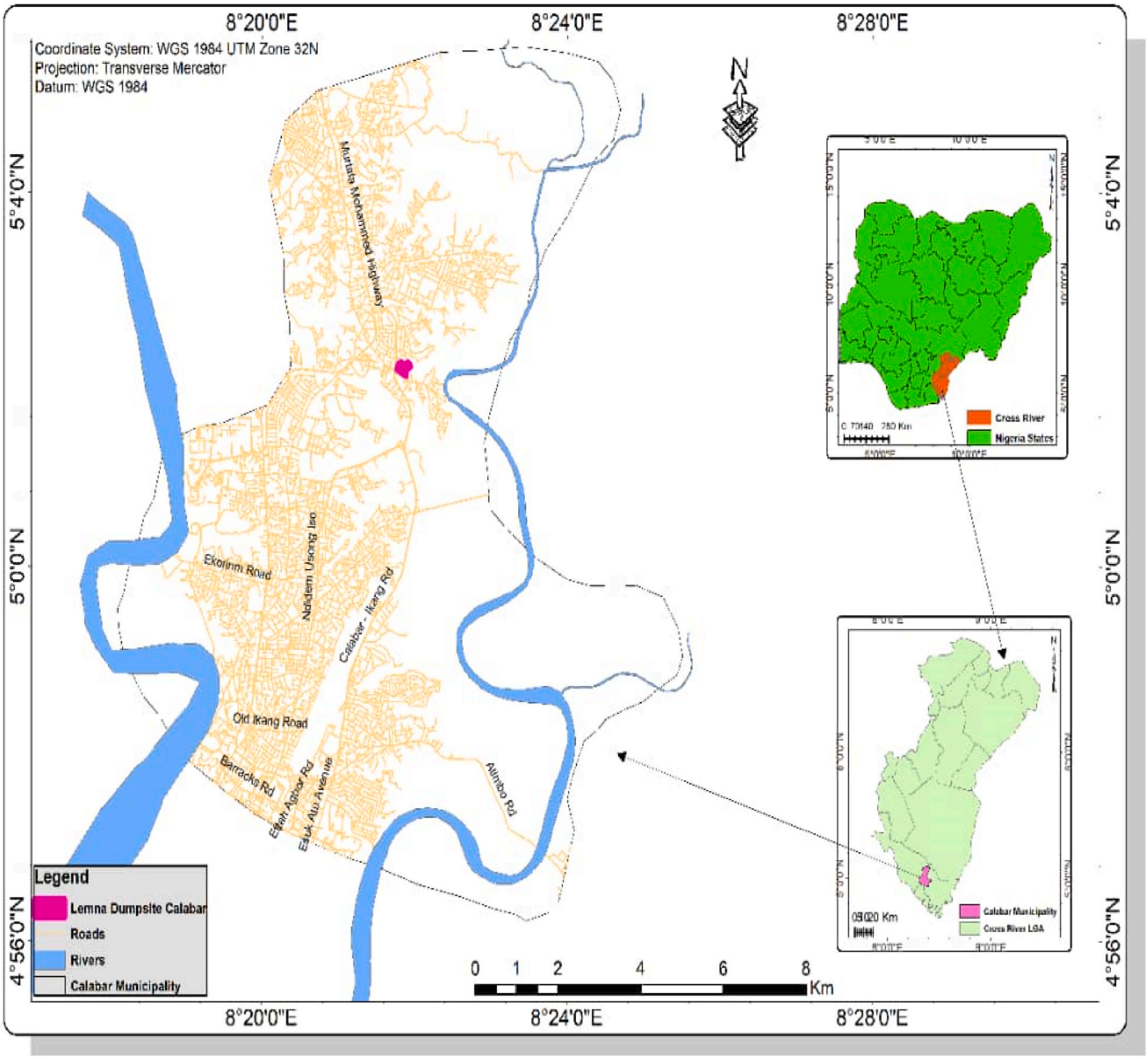

Fig. 1. Cross river state showing location of dumpsites in the study area.
Source: [23].

water may result in diseases such as renal failure, blood-related disorders, anaemia, kidney damage, possible prostate and lung problems, acute kidney failure, anaemia, gastrointestinal bleeding, chronic nephropathy, metabolic syndromes such as heart disease and stroke [5–9].

Seepages of open dumpsite leachate through the soil layers can pollute groundwater, due to its varieties of chemical pollutants [10–13]. The pollution of groundwater occurs whenever a reasonable permeable material exists below the soil strata, especially, where no baselining exists, the leachate may carry along some toxic constituents such as anions, macro elements and heavy metals [14,15]. Dumpsite leachate is a highly complex liquid that can contain contaminants, including heavy metals and Benzene, Toluene, Ethylbenzene, and Xylene (BTEX). Eliminating the devastating effects of dumpsite leachate on the environment depends on the materials underlying the dumpsite, the baselining and the interaction of the leachate [16].

Several research studies, including [17,14,18,19], have investigated the critical issue of dumpsite leachate. Notably [14], conducted a vulnerability assessment of boreholes proximate to the Lemna dumpsite in Calabar Metropolis, Nigeria, revealing that leachates migrate towards groundwater, posing a potential threat to the underlying aquifer. Similarly [17], examined the extent of leachate and pollution from one of the numerous open refuse dumpsites in Lagos metropolis. Qualitative assessment was determined using Electrical Resistivity Tomography (ERT), Vertical Electrical Sounding (VES) and Induced Polarization (IP) software to interpret the data. Both ERT and VES methods revealed persistent low resistivity (1-20 Ω-meter Ωm) of leachate and a depth above 35 m [18]. focused on characterizing the geological features of a former waste disposal site. This approach goes beyond assessing contamination and provides insights into the subsurface structure and bedrock conditions. The study conducted by Ref. [19] did not only assessed leachate contamination but also evaluated the aquifer's protective capacity and vulnerability. This comprehensive analysis provides a more holistic understanding of the potential risks associated with leachate pollution. Their analysis of some physico-chemical parameters indicated values surpassing World Health Organization (WHO) standards. Additionally [20], employed geophysical and geological data to evaluate the spatial distribution of contaminants in Calabar, identifying a localized, low resistivity anomaly (<5 m, <15 Ωm) at the central waste disposal site, suspected to be linked to leachate contamination. This underscores the need for vigilant monitoring to prevent its extension to the aquifers [20].This research lies in its focus on investigating BTEX penetration and aquifer

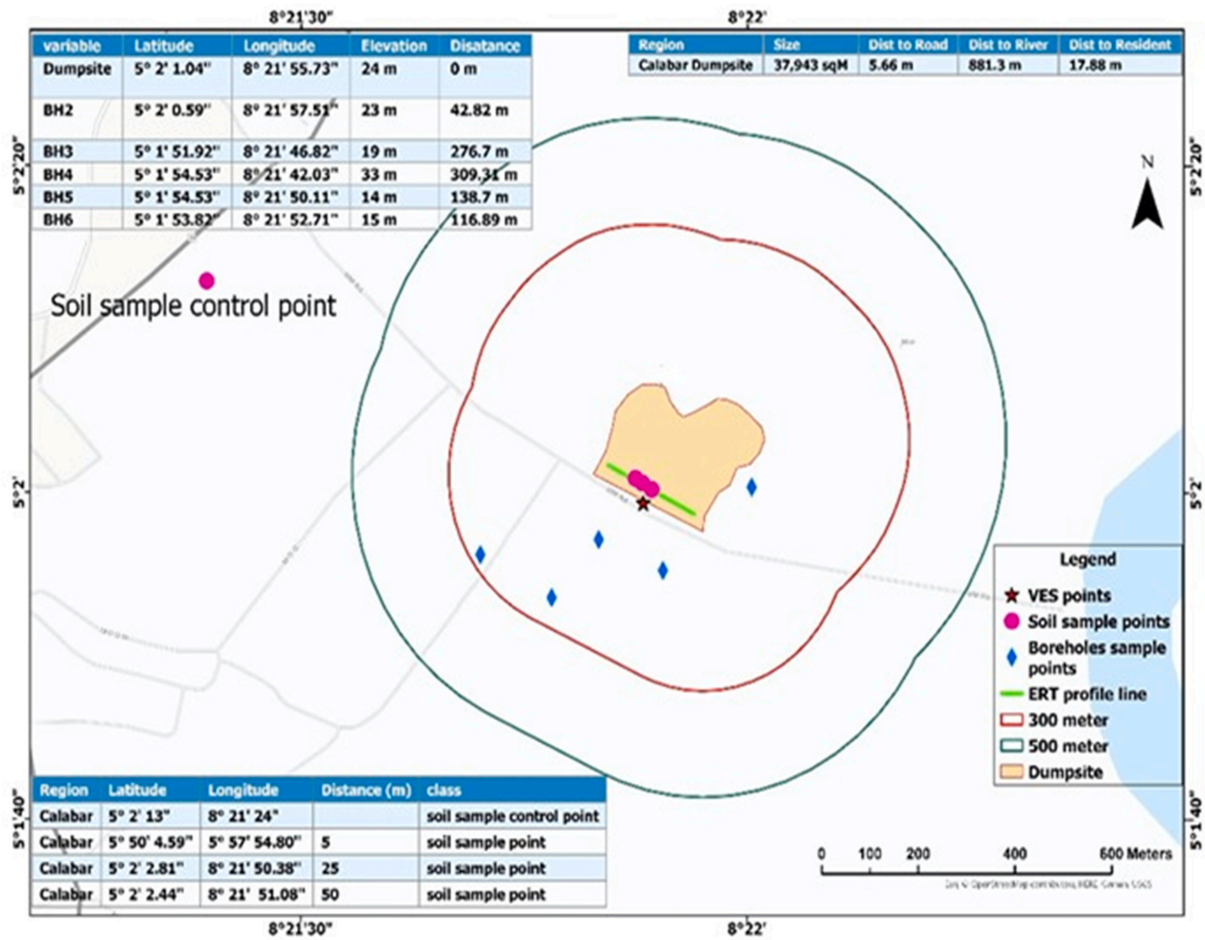

Fig. 2. Overlay Showing Boreholes points, Soil Sample Points, VES Points and ERT Profile Line Locations at Lemna Dumpsite Calabar. Source: [24].

vulnerability at Lemna dumpsite in Calabar, Cross River State, Nigeria. While previous studies have addressed some physico-chemical aspect of dumpsite leachate contamination, this study specifically targets BTEX to assess the depth and spread of leachate infiltration. Moreover, this study integrates soil sample collection along the resistivity profile line at the lower elevation of the dumpsite at 5 m, 25 m and 50 m, to evaluate BTEX spatial distribution of contaminants within the dumpsite. This approach allows for a comprehensive assessment of the subsurface characteristics and leachate penetration pathways, enhancing the accuracy and reliability of the findings. Despite the growing awareness of the environmental and health risks posed by dumpsite leachate contamination, there remains a dearth of detailed studies focusing on BTEX and aquifer vulnerability in the study location. It is on this background the study seeks to examinethe spatial analysis of dumpsite leachate penetration in Lemna dumpsite in Calabar, Cross River State, Nigeria. By honing in on the Lemna dumpsite, the research will provide valuable insights into the spread and depth of leachate penetration, which can inform targeted remediation efforts and groundwater protection measures. By conducting a thorough analysis of leachate penetration in the Lemna dumpsite, the study will contributes to a better understanding of local groundwater pollution dynamics and informs evidence-based decision-making for environmental management and public health protection.

2. The study area

2.1. Location

Cross River State is located in the South-South Geopolitical Zone, Federal Republic of Nigeria. Cross River State is located between latitudes 4° 30′ and 6° 30′ North, and longitudes 8° 00′ and 9° 00′ East, and bounded in the North by Benue State, South by the Atlantic Ocean, South West – Akwa Ibom State, West by Ebonyi and Abia State, and East by the Republic of Cameroon [Fig. 1]. The total landmass is 21,787 sq km [21]. The study area is located in Calabar Urban Areas in Cross River State. The Calabar dumpsite is located at Latitude 5°’, 2′, 1.040928″ Longitude 8°’, 21′, 55.727856’’. The study areas exhibit specific elevations, with Calabar at 24 m [Fig. 2]. The size of the dumpsite is 37,943 m^2 [Fig. 2]. The lithology of the study area is characterized by an underlying aquifer. The surface and groundwater bodies are recharged by high rainfall. The aquifer is confined with few aquicludes, and the two major water-bearing horizons are the upper zone and lower zone [22]. The upper zone is highly vulnerable to surface pollution compared to the lower zone [22]. At the Calabar Dumpsite, the lithology at this dumpsite encompasses clayey laterite, coarse sand, medium sand, fine sand, light brown fine sand, and brownish-white fine sand [22].

Table 1
Coordinates of the study locations.

Coordinates of soil sample collection points in the Study Areas		
Location	Meter	Latitude
Meter	Latitude	Longitude
5 m	5°’, 50′, 4.599″ N	5°, 57′, 54.802’’E
25 m	5°’ 2′ 2.807″ N	8°’ 21′ 50.382″ E
Coordinates of water sampling collection points in the Study Areas		
Lemna, Calabar	Latitude	Longitude
Dumpsite location 1	5°’, 2′, 1.040928’’	8°’, 21′, 55.727856’’
BH2	5°’, 2′, 0.590316’’	8°’, 21′, 57.510504’’
BH3	5°’, 1′, 51.915432’’	8°’, 21′, 46.818216’’
BH4	5°’, 1′, 54.53652’’	8°, 21′, 42.025644’’
BH5	5°’, 1′, 54.530112’’	8°’, 21′, 50.112828’’
BH6	5°’, 1′, 53.81814’’	8°, 21′, 52.713756’’
ERT coordinates points in the study areas		
	Lemna, Calabar	
Distances	Latitude	Longitude
0	5° 2′ 3.131″ N	8° 21′ 49.684″ E
5	5° 2′ 3.088″ N	8° 21′ 49.874″ E
10	5° 2′ 3.023″ N	8° 21′ 49.986″ E
15	5° 2′ 2.958″ N	8° 21′ 50.134″ E
20	5° 2′ 2.882″ N	8° 21′ 50.249″ E
25	5° 2′ 2.807″ N	8° 21′ 50.382″ E
30	5° 2′ 2.735″ N	8° 21′ 50.522″ E
Vertical Electrical Sounding (VES) points		
VES Points	Latitude	Longitude
Lemna, Calabar	5°1′59".00 N	8°21′55".00E

Source: [27].

3. Material and methods

3.1. Lemna dumpsite

One of the main responsibilities of Cross River Urban Development Authorities is to evacuate waste from waste bin at evacuation points [25]. Waste bins are strategically positioned close to residents for waste disposal. Cross River State Waste Management Agency, Cross River State Urban Development Authorities and private partners, collect and disposed all sort of waste at government designated open dumpsites. There are more than a thousand tons of municipal solid wastes deposited annually in Cross River State dumpsites, with a per capita rate of waste generation of 1.2kg/person/day [25,26]. Waste generation in Calabar Municipality is 38,752.59 tons per annum, Calabar South 40,405.31 tons per annum [25]. This implies that waste disposal from Calabar Metropolis is 79,157.9 tons per annum, resulting to 38, 863.28 tons per day. The size of the dumpsite is 37, 943 square meters, 5.66 m close to road, 17.88 m close to some residence, 42,82 m close to some boreholes around the dumpsite [Fig. 2].

3.2. Soil sample collection

A Global Positioning System (GPS) was adopted to locate sampling points. Samples were collected at 0–30 cm using soil auger. Soil samples were collected along the ERT profile line, to identify the level of contaminant of BTEX. If ERT indicates anomalies or areas of concern, soil sampling can confirm the presence and extent of contamination. The soil samples were collected at 5 m, 25 m and 50 m from Calabar, and the coordinate was obtained (Table 1). The sampling positions were within (5 m, 25 m and 50 m along the resistivity profile line of the dumpsites). Three (3) soil samples from the dumpsites were collected and one (1) control points. The control soil sample was collected at 1 km away from the sampled soil. A total of four (4) soil samples were collected in the study areas. The soil samples were transferred from the Auger to sampling bags which were sealed and marked. The samples were stored in a cooler with ice blocks at 4 °C and taken to the laboratory for BTEX analysis. The soil samples were collected in September 2022. Gas Chromatography Flame Ionization Detector (GCFID) equipment was used for the analysis.

For the extraction analysis of BTEX, a 5-g soil sample was mixed with 2 g of anhydrous sodium sulfate ($NaSO_4$) and stirred with a stirring rod. Subsequently, 50 ml of methanol was added to the sample and stirred for approximately 20–30 min. Silica Gel Clean Ups were conducted by placing glass wool at the base of a syringe cartridge, adding 5 g of silica gel to the cartridge, and conditioning the cartridge by rinsing it with 5 ml of methanol. The collected methanol was discarded, and the extract was loaded into the column. An additional 5 ml of methanol was passed through the column to ensure complete removal of any remaining BTEX in the sample. Finally, the resulting extract was transferred to 2 ml flask autosampler vials with Teflon-lined rubber caps. The injection volume of 2 ml flask autosampler vial was1.0 μl [28,29].

3.3. Borehole water sampling collection

Water sample collection was within and outside 300–500 square meters (m^2) buffer zone where boreholes are located. The 500-m buffer zone is chosen because it represents an area near the dumpsite, where there is a higher likelihood of potential contamination of groundwater. The closer the boreholes are to the dump site, the greater the risk of leachate and pollutants infiltrating the groundwater. Control water samples were collected from 1 km away from the sampled borehole water. Water samples were purposively selected from (5) boreholes close to Lemna dumpsites, Calabar. The borehole water samples were collected, and the coordinates were obtained with the Global Positioning System (GPS) [Table 1]. Five (5) borehole water samples were purposively collected around the dumpsites and one (1) control samples in the study areas. A total of six (6) borehole samples were collected. The collected samples were stored in a cooler with ice blocks at 4 °C and taken to the laboratory for BTEX analysis. The borehole water samples were collected in September 2022.

The analysis of Benzene (B), toluene (T), ethylbenzene (E), and xylene (X) extraction was analysed using a Gas Chromatography Flame Ionization Detector GC-FID. A 50 ml of methanol was added to 100 ml of water samples and stirred for 20–30mins. The injection volume of 2 ml flask autosampler vial was1.0 μl [28,29].

3.4. Analytical instrument

The Gas Chromatography Flame Ionization Detector (GC-FID) Agilent 6890 Series instrument boasts a minimum detectable level of less than 1.8 pg C/s, a linear dynamic range exceeding 10^7 with a ±10 % tolerance, data rates of up to 200 Hz accommodating peaks as narrow as 25 ms at half height, standard electronic pressure control (EPC) for three gases (Air: 0–800 mL/min, H2: 0–100 mL/min, Makeup gas He: 0–100 mL/min), and a maximum operating temperature of 450 °C [30]. Pressure is adjusted by increments of 0.01 psi. The dimensions of the oven are 28 cm (length) × 31 cm (width) × 16 cm (height). Operating temperature ranges from +4 °C to 450 °C ambient temperature, with Liquid Nitrogen (LN_2) cryo cooling of −80 to 450 °C and Carbon Dioxide (CO_2) cryo cooling of −40 to 450 °C. Temperature set point resolution 1 °C. Maximum achievable temperature ramp rate 120 °C/min (75 °C/min for 120 V units). Maximum run time of 999.99 min (16.7 h). Oven cools down (from 300 °C to 50 °C in 4.5 min). Ambient temperature rejection <0.01 °C per 1 °C [30].

3.5. Electrical Resistivity Tomography

The Wenner array is one of the most commonly used arrays [31]. Four 2D ERT profile was adopted. The choice of the 2-D Electrical Resistivity Tomography (ERT) was to generate a horizontally extensive (>100 m) high-resolution subsurface image of the area Chambers et al., 2011 [32]. Such subsurface images are expected to serve as a visual aid to the pattern of resistivity changes within the shallow subsurface. The four electrodes (C1, P1, P2, C2) were placed on the surface of the ground along a straight line symmetrically at point 'O' and their coordinate taken [Table 1]. The resistivity measurement was conducted at 5-unit electric spacing. Allied Associates Geophysical Ltd Ohmega 0191 equipment was used to determine resistivity in the study areas. Four Electrodes were used to make electrical contact with the ground. The electrodes comprise two Current Electrodes and two Potential Electrodes (Voltage Electrodes). Therefore, the apparent resistivity (ρaw) configuration is given as:

$$2\,\pi \mathrm{a} \times \mathrm{R} = \rho \mathrm{aw} \tag{1}$$

Where:

ρaw = Apparent resistivity (ρaw)

2 Current electrodes A-B==C1–C2.

2 Potential currents M-N==P1–P2.

R = Apparent Resistance) (ohms)

π = 3.14

a = Distance between the source and the point (pair of electrodes)

3.6. Vertical electric sounding

Vertical Electric Sounding (VES) was adopted in this study. The Schlumberger method was adopted because of the relative sensitivity of vertical changes in the subsurface resistivity below the centre of the array and for its ability to resolve vertical changes [33,34]. The centre of the configuration was kept fixed, and the measurements were made by progressively increasing the electrode spacing. All four electrodes were arranged in a line at equal distances (a), known as electrode separation, and measurements were taken by increasing the electrode separation (a) gradually from a small value, say 5 m to several tens of meters [34,35]. The electrode spacing was extended to cover a reasonable distance in the dumpsite according to the length of the dumpsite. This array is most widely used in electrical prospecting. The four electrodes (A, M, N, B) were placed along a straight line symmetrically over centre point 'O' and the coordinate taken [Table 1]. The separation between potential electrodes (MN) is kept small when compared to the current electrode separation AB. Current is sent through the outer electrodes AB and potential across MN (the inner electrodes) [34,35]. Allied Associates Geophysical Ltd Ohmega 0191 equipment was used to determine resistivity in the study areas. The configuration factor for the Schlumberger array is given as;

$$\mathrm{K} = \pi / 4\left(\mathrm{L}^2 - \mathrm{a}^2\right) / 2 \tag{2}$$

The apparent resistivity calculated formula is given as.Where:

a = Distance between the potential electrodes (M, N)

L = Distance between the current electrodes (A, B)

π = 3.14

ρ = K*R.

K = Configuration factor for Schlumberger array.

R = Resistance (ohms)

ρ = Apparent Resistivity (ohm-m)

3.7. Statistical techniques used for analyzing BTEX concentrations

The difference in the BTEX concentrations was tested with the regulatory standard using the paired sample *t*-test embedded in SPSS tool version 22. The paired sample students' t-test was adopted to compare the deviance in the mean concentration of two independent variables) [36]. The BTEX parameters is compared with the WHO and NESREA guideline limit using paired sampled *t*-test embedded in SPSS version 22 [37,38].

3.8. Techniques used for analyzing ERT and VES data

The RES2DInversion was used to establish the depth of leachate pollution in the dumpsites of the study areas. The RES2DINV software was used to model the Electrical Resistivity Tomography (ERT) data using the Schlumberger method. The RES2DINV software enables the computer to execute finite different modeling [39,40]. The RES2DInversion showed the image of the subsurface and the depth of leachate contamination in the shallow subsurface of the dumpsites. The Earth Imager 1D was used to determine the layer subsurface geology in the study areas. Earth Imager 1D is a cutting-edge inversion modelling software specifically designed for interpreting one-dimensional vertical electric resistivity data, enabling the construction of a detailed layered model of subsurface geology. This 1D software is particularly effective in processing vertical electric sounding (VES) data obtained through well-established techniques like the Schlumberger method Advance Geosciences Incorporation [41]. It provides a clear visualization of the subsurface structures and properties.

3.9. Longitudinal conductance of VES

Longitudinal conductance was used to evaluate the VES data. It rates the vulnerability of the aquifer to pollution. First-order geo-electric parameters obtained from the iteration are used to develop the second-order geo-electric parameters or the Dar Zarrouk parameters [42]. The second-order parameter of interest is the longitudinal unit conductance (Si). Longitudinal conductance Si is derived by hi, the thickness of the aquifer, pi, apparent resistivity and n, the number of layers. The longitudinal conductance is used to predict the protective capacity of the aquifer in an area. It is rated from excellent to poor capacity. Longitudinal conductance is rated as excellent >10, very good 5–10, good 0.8–4.9, moderate 0.2–0.79, weak 0.0–0.19 and poor <0.1 [19,43]. Longitudinal conductance was used to predict the aquifer protective capacity rating. The formula is given as follows;

$$S = \frac{hi}{pi} + \frac{hi}{pi} + \frac{hi}{pi} + \frac{hi}{pi} + \frac{hi}{pi} + \dots + \frac{hn}{pn} = \sum_{n=1}^{n} \left(\frac{hi}{pi}\right) \tag{3}$$

S = Longitudinal conductance
hi = Thickness of the aquifer
pi = Apparent resistivity
n = layers.

4. Results

4.1. Soil parameter values around Lemna Dumpsite

The results of the laboratory analysis of soil heavy metals and BTEX in Lemna dumpsite is presented in [Table 2]. The soil indices tested include Benzene, Toluene, Ethylbenzene and Xylene for all the soil locations. Benzene and Ethylbenzene concentrations at all three distances (5 m, 25 m, and 50 m) are extremely high, significantly exceeding the values recommended in NESREA guideline limits. While Toluene at 25 m and 50 m distances were higher than the NESREA. Xylene was below NESREA limit [Table 2]. The contamination of the soil with BTEX may be due to the type of waste at the dumpsite which may comprise of substances and typical pollutants in dumpsite. The contamination may also be due to the soil porosity.

The paired sample-test of the variation between the returned parameter concentration values of soil and the values recommended in NESREA guideline limits showed that ($p < 0.05$), indicating significant variation [Table 3]. This deviation from guideline limits may be due to the high level of contamination of the soil with BTEX compounds.

4.2. Borehole water parameter values around Lamna dumpsite

The result of the laboratory water quality analysis of the Borehole (BH) water around Lemna dumpsite is presented in [Table 4]. The water quality indices tested were Benzene, Toluene, Ethylbenzene and Xylene for all the boreholes. The water quality analyses of BH2, BH3 BH5 and BH6 around the Lemna Dumpsite revealed elevated concentrations of Benzene exceeding the established limits of the World Health Organization (WHO). Additionally, the presence of Ethylbenzene in BH2 was found to surpass the regulatory limits set by WHO. The contamination of the boreholes may be due to the extension of dumpsite leachate penetration.

The paired sample *t*-test analysis showed that ($p < 0.05$), this implies that there is significant variation between parameter concentration values of borehole water and values recommended in WHO guideline limits. The variation may be due to the high level of BTEX in borehole water [Table 5]. This result highlights the urgent need for remediation and stringent monitoring to mitigate the contamination of the borehole water in the vicinity of the Lemna dumpsite and ensure compliance with the prescribed regulatory limits. Implementing effective measures to safeguard water quality is crucial to protect public health and the environment.

Table 2
Results of soil BTEX in Lemna dumpsite.

BTEX Parameters	Unit	5 m	25 m	50 m	1 km control sample	NESREA
Benzene	(mg/kg)	1.36[a]	1.34[a]	1.32[a]	ND	0.1
Toluene	(mg/kg)	0.017	1.019[a]	1.016[a]	ND	0.1
Ethylbenzene	(mg/kg)	1.28[a]	1.25[a]	1.26[a]	ND	0.1
Xylene	(mg/kg)	0.018	0.016	0.014	ND	0.1

[a] = Exceeded NESREA guideline limit; ND=Note Detected.
Source: [44].

Table 3
Paired samples test soil analysis of BTEX in Lemna dumpsite.

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95 % Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	5m- NESREA	0.56875	0.75271	0.37635	−0.62898	1.76648	1.511	3	0.0228[a]
Pair 2	25 m - NESREA	0.80625	0.60870	0.30435	−0.16233	1.77483	2.649	3	0.0370[a]
Pair 3	50m- NESREA	0.80250	0.60675	0.30337	−0.16297	1.76797	2.645	3	0.0470[a]

[a] = significant at 0.05 % level
Source: [45].

Table 4
Results of heavy metals and BTEX for boreholes around Lemna dumpsite.

BTEX Parameter	Unit	Sample codes						
		BH2	BH3	BH4	BH5	BH6	WHO	Control sample
Benzene	(mg/l)	0.0998[a]	0.0783[a]	ND	0.012[a]	0.013[a]	0.010	ND
Toluene	(mg/l)	0.0086	0.0072	ND	0.0028	0.0018	0.700	ND
Ethylbenzene	(mg/l)	0.53[a]	0.048	ND	0.063	0.0056	0.300	ND
Xylene	(mg/l)	0.0083	0.0062	ND	0.0018	0.0017	0.500	ND

[a] = Exceeded WHO Standard; ND=Note Detected
Source: [46].

Table 5
Paired samples test analysis of BTEX for boreholes around Lemna dumpsite with WHO standard.

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95 % Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	BH2– WHO	−0.21583	0.44514	0.22257	−0.92414	0.49249	−0.970	3	0.0404[a]
Pair 2	BH3 – WHO	−0.34258	0.32790	0.16395	−0.86433	0.17918	−2.090	3	0.0128[a]
Pair 3	BH5 – WHO	−0.35760	0.30493	0.15247	−0.84282	0.12762	−2.345	3	0.101
Pair 4	BH6 – WHO	−0.37198	0.29945	0.14972	−0.84846	0.10451	−2.484	3	0.0890

[a] = Significant at 0.05 % level
Source: [47].

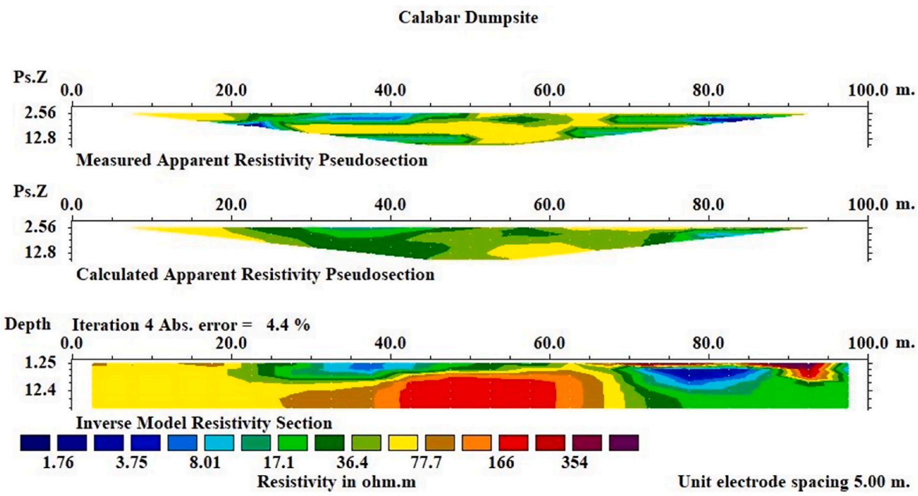

Fig. 3. Spread of leachate pollution in lemna dumpsite, calabar.
Source [48].

4.3. Extent of leachate in the dumpsite

The result of ERT provides data on the inverse resistivity, inverse depth, unit electrode spacing, and Root Mean Square (RMS) error for each dumpsite. The 2D resistivity survey was acquired across the lower elevation of wet and dry surface of Lemna dumpsites. At the Lemna dumpsite, the estimated inverse resistivity is 8.01 Ωm at a depth of 12.4 m [Fig. 3]. The leachate infiltrated zone occurs at lateral distances of 40 m and 80 m along the profile. Meanwhile the measured and calculated apparent resistivity correlation plot showed a linear straight line, indicating a strong correlation of the resistivity in all the ERT model of the dumpsites. The resistivity inverse model was obtained after 4 iterations with a low Root Mean Square (RMS) error of 4.4 %, at 5 m unit electrode spacing in the study areas [Fig. 4].

4.4. Vertical Electrical Sounding and lithology of the dumpsites

The results of the Vertical Electrical Sounding (VES) apparent resistivity and depth of the lithology in the study areas are presented in [Table 6]. The provided data reveals various geological properties and lithologies at different dumpsites in Cross River State. At the Lemna Dumpsite, the apparent resistivity values ranged from 360.93 Ωm to 2173.31 Ωm, with layer thickness varying from 1.39 m to 36.42 m, and depths ranging from 1.39 m to 42.88 m. The lithology at this dumpsite encompasses clayey laterite, coarse sand, medium sand, fine sand, light brown fine sand, and brownish white fine sand.

There are three curve types of VES curves as shown in [Table 6]. The classification of these curves are H, K and A. These symbols correspond respectively to H curve type with a bowl-type curves, which occur with an intermediate layer of lower resistivity. H-type curve resistivity decreases then increases. The H segment suggests the presence of a zone with consistent resistivity values. The presence of water depends on the specific characteristics of the surrounding materials. It might indicate the presence of water-bearing layers within the "bowl." The K curve type has a bell-type curve, where the middle layer is of higher resistivity. The A curve type has an ascending curve, where resistivities successively increase [Table 6].

Additionally, it is noteworthy that Lemna dumpsite exhibited poor aquifer protective capacity ratings, indicated by values below (<0.1) [Table 7]. Longitudinal conductance rates the vulnerability of the aquifer to pollution [Table 8].This indicates potential challenges in protecting groundwater resources in these areas, necessitating appropriate management and monitoring measures to prevent contamination and safeguard water quality.

In Fig. 5, the colour scale represents the vertical electrical resistivity of the subsurface. Fracture zones exhibit lower resistivity compared to hard rock because these fracture zones contain moisture. Lower resistivity indicates the presence of moisture, and this moisture is a better conductor of electricity compared to hard rock. Consequently, the blue areas in these figures indicate the presence

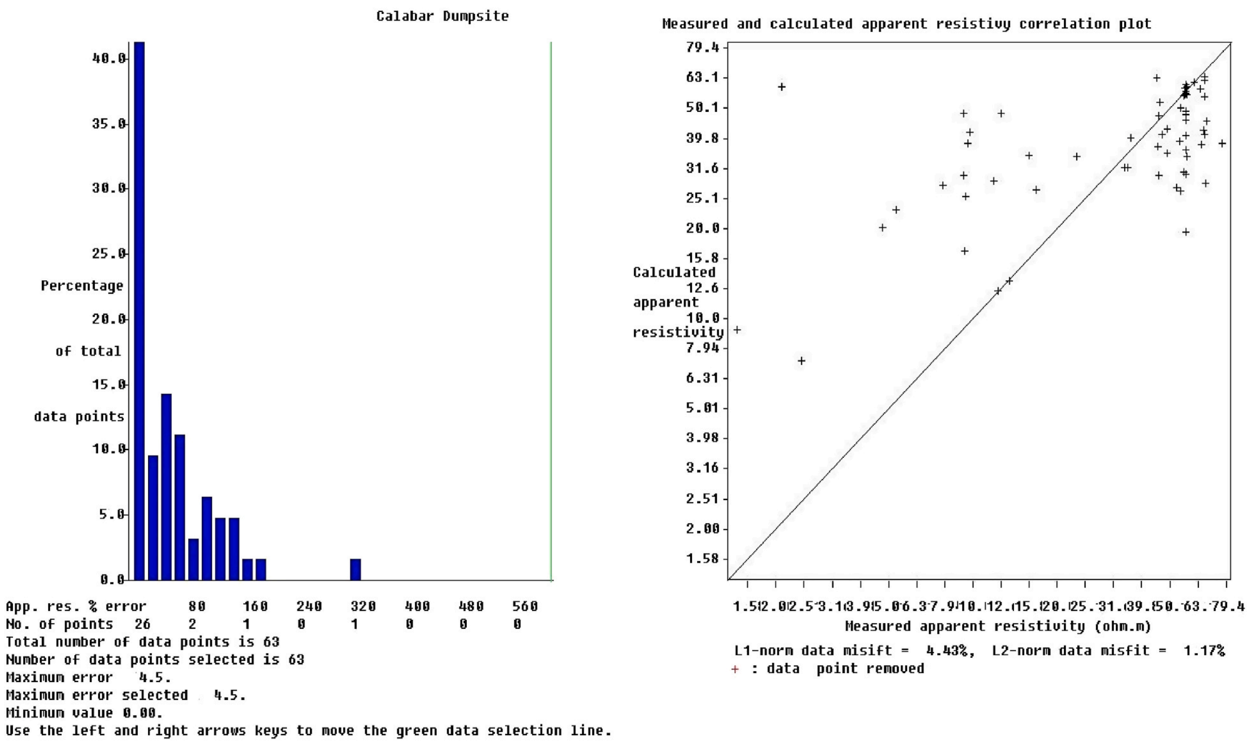

Fig. 4. Measured and calculated apparent resistivity plot of leachate pollution in lemna dumpsite, calabar.
Source: [49].

Table 6
Vertical Electric Sounding (VES) apparent resistivity and depth of the lithology in the study area.

Sounding location	Number of Layer	Apparent resistivity (Ωm)	Layer thickness	Depth (m)	Curve Types	Lithology
Lemna Dumpsite	1	360.93	1.39	1.39	AKHK	Clayey laterite
	2	427.81	0.99	2.37	P1<P2<P3>P4<P5>P6	Coarse Sand
	3	476.30	3.66	6.03		Medium Sand
	4	265.83	0.43	6.46		Fine Sand
	5	2173.31	36.42	42.88		Light brown fine sand
	6	120.88	∞	66		Brownish white fine sand

P1<P2<P3 = A (ascending curve); P1<P2>P3=K (Bell curve); P1>P2<P3=H (Bowl curve)
Source: [50].

Table 7
Protective capacity rating of the dumpsites in the study areas.

Location	Layer resistivity (Ωm)	Layer thickness (m)	Depth to bottom (m)	Number of layers	SL = hi/pi	Longitudinal conductance	Protective capacity rating
	(pi)	(hi)	(di)				
Lemna dumpsite	3825.06	42.89	59.13	6	0.012	<0.1	Poor

Source: [51].

Table 8
Longitudinal conductance of Aquifer.

Longitudinal conductance (mhos)	Protective Capacity rating
> 10	Excellent
5–10	Very Good
0.8–4.9	Good
0.2–0.79	Moderate
0.1–0.19	Weak
<0.1	Poor

Source: [19,43].

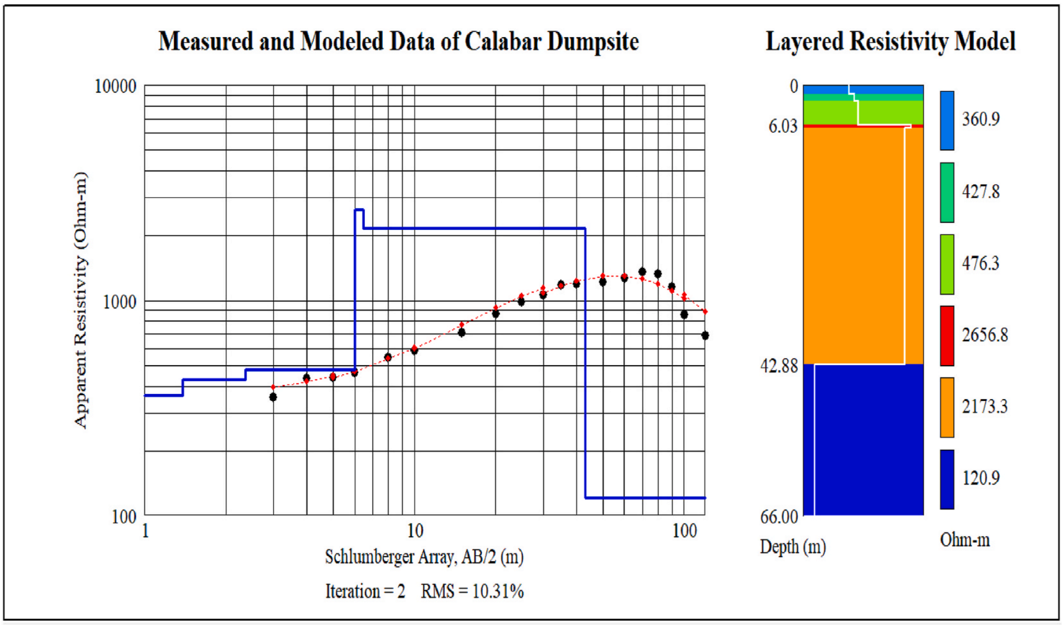

Fig. 5. Measured and modelled VES data of lemna dumpsite.
Source: [52].

of moisture. To detect the presence of moisture within hard rock, it typically requires identifying a vertical anomaly with low resistance. Groundwater is typically found in specific areas within the earth's subsurface, primarily in porous and fractured zones. For instance, sand and gravel beds are porous and can retain water. Similarly, fractures in hard rock formations can also hold water.

5. Discussion

This study examined the Spatial Analysis of Leachate Penetration at Lemna Dumpsite, Calabar. The results of the soil and water quality analyses, as well as the 2D resistivity survey as presented in Tables and Figures, provide valuable insights into the environmental and groundwater conditions around the Lemna dumpsite. This discussion provides a comprehensive overview of the findings and their implications. The study examined soil indices, specifically the concentrations of Benzene, Toluene, Ethylbenzene, and Xylene (BTEX), at various distances from the dumpsite. It was observed that Benzene and Ethylbenzene concentrations at all three distances (5 m, 25 m, and 50 m) as presented in [Table 5] exceeded the recommended limits according to the NESREA guidelines. This finding indicates a severe contamination of the soil with these hazardous compounds. Toluene, on the other hand, exceeded the NESREA limit at 25 m and 50 m distances, while Xylene was below the limit [Table 5]. The contamination of the soil with BTEX compounds can be attributed to the type of waste disposed of at the dumpsite, which may contain these substances and other typical pollutants. Additionally, the soil's porosity allows these compounds to infiltrate and persist. The paired sample *t*-test results revealed a significant variation ($p < 0.05$) between the measured parameter concentrations in the soil and the NESREA limits [Table 6]. This variation further emphasizes the spread of contamination in the soil. The findings align with previous research conducted by Refs. [53,54] which noted that precipitation can facilitate soil contamination, and BTEX compounds can adhere to soil particles potentially migrate to groundwater, especially in porous soil. Similar studies by Refs. [55–57] align with the findings of this study. Similarly, the water quality indices of BTEX compounds in borehole water around the Calabar Dumpsite as indicated in [Table 4] confirmed the presence of BTEX in borehole water. The results revealed elevated concentrations of Benzene and Ethylbenzene in several boreholes, exceeding the established limits of the World Health Organization (WHO) [58–60]. This suggests that the contamination from the dumpsite has extended to the groundwater, affecting the quality of borehole water. The paired sample *t*-test analysis indicated a significant variation ($p < 0.05$) between the parameter concentrations in borehole water and the WHO limits, further confirming the contamination [Table 8]. These findings are consistent with previous research conducted [36,61,62,63]. [63,64] Elucidated that chemical information collected from boreholes in Grindsted, Denmark, revealed the existence of a leachate plume. This plume was observed to gradually descend and increase in size as it moved along the path of groundwater flow away from the dumpsite [63,64]. Moreover, the 2D resistivity survey conducted across the lower elevation of the Lemna dumpsite as indicated in [Fig. 3] provided critical information about the subsurface conditions. The estimated inverse resistivity of 8.01 Ωm at a depth of 12.4 m suggests a leachate infiltrated zone at lateral distances of 40 m and 80 m along the profile. The low resistivity values in this survey are likely due to the presence of dissolved BTEX from decomposed waste materials. The measured and calculated apparent resistivity correlation plot showed a strong linear relationship, indicating a consistent resistivity pattern across the dumpsite. These results are consistent with previous studies [20,65,66] which suggested that low resistivity zones (0–15 Ωm) are indicative of leachate infiltration zone and can affect groundwater resources [20]. Also observed a localized thin low resistivity of (<15 Ωm) at (<5 m) depth suspected to be contamination by leachates. A study conducted illustrated that leachate plume occurs at a depth of 10 m on a 2-D inverse model of real electrical resistivity [67]. However, the 2D resistivity survey, evident in Fig. 4, is in contrast with the study by Ref. [68], which revealed electrical ERT value ranges of 309–40130 Ωm within the depth range of 0–5 m [68]. Nevertheless, low-resistivity zones can indicate the presence of materials that are potentially conductive, such as water-saturated soils, porous soils or fracture bedrock which can be associated with contaminant or ground water [69]. While high-resistivity zones can signify the presence of non-conductive or resistive materials, like dry soils, rocks, or non-porous geological formations, which can be related to the absence of groundwater or low-conductivity minerals [69]. Conversely, the Vertical Electrical Sounding (VES) curves as indicated in [Fig. 5] provide valuable information about the subsurface geology and aquifer characteristics. H-type curves suggest the presence of water-bearing layers within the "bowl," while K-type curves indicate higher resistivity in the middle layer. A-type curves show increasing resistivities. These classifications align with previous studies [70–73]. The VES results further indicate poor aquifer protective capacity, with values below (<0.1), suggesting challenges in protecting groundwater resources in the area [Table 7]. This highlights the urgent need for remediation and strict monitoring to safeguard the quality of borehole water near the Lemna dumpsite. Ensuring compliance with regulatory limits is essential for protecting public health and the environment.

6. Conclusion

In conclusion, the findings of this study reveal significant contamination of both soil and groundwater around the Lemna dumpsite, particularly with BTEX compounds. The soil analysis exposed alarming levels of contamination, primarily from Benzene and Ethylbenzene, at all three distances of the dumpsite. These concentrations significantly exceeded recommended guidelines, indicating a severe problem. Toluene levels were also above limits at certain distances, underlining the extent of pollution. The results of the paired sample *t*-test emphasized this contamination, and it is likely due to the nature of waste disposed of at the site and the porosity of the soil. Urgent measures are needed for effective management and remediation to mitigate the associated risks. Water quality analysis revealed elevated concentrations of Benzene and Ethylbenzene in borehole water, exceeding the World Health Organization's (WHO) limits. This indicates that contamination from the dumpsite has extended to the groundwater, posing a direct threat to public health. The paired sample *t*-test confirmed the significant variation between parameter concentrations in borehole water and WHO guidelines, underscoring the immediate need for remediation and stringent monitoring. The 2D resistivity survey provided essential information about the subsurface conditions, indicating a leachate infiltrated zone at specific depths and lateral distances. The linear correlation of apparent resistivity values of the dumpsite suggests a consistent pattern of resistivity. The Vertical Electrical Sounding (VES) curve classifications further support the understanding of the subsurface geology and aquifer characteristics. It indicates potential challenges in safeguarding groundwater resources, emphasizing the importance of appropriate management and monitoring. These results emphasize the urgent need for effective management, remediation, and stringent monitoring to prevent further contamination and safeguard the environment and public health in the vicinity of the dumpsite.

Funding

No funding received.

Data availability statement

The data used in this study can be made available upon request from the authors. Igelle Evaristus Idagaevadag003@yahoo.com; igellei@unical.edu.ng.

CRediT authorship contribution statement

E.I. Igelle: Investigation, Formal analysis, Data curation, Conceptualization. **P.O. Phil-Eze:** Software, Methodology, Data curation. **O.O. Akim:** Visualization, Validation, Investigation. **H.I. Kanu:** Writing – original draft, Data curation. **I.C. Ekowk:** Writing – original draft, Investigation, Conceptualization. **J.W. Atsa:** Writing – original draft, Visualization, Validation. **P.A. Ojugbo:** Methodology, Investigation, Formal analysis. **J.S. Okputu:** Validation, Software, Investigation. **Kamal Abdelrahman:** Writing – original draft, Funding acquisition. **S.E. Ekwok:** Writing – original draft, Visualization, Supervision. **P. Andráš:** Writing – original draft, Validation. **Ahmed M. Eldosouky:** Writing – review & editing, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was funded by the Researchers Supporting Project number RSP2024R351, King Saud University, Riyadh, Saudi Arabia.

References

[1] S. Mukherjee, S. Mukhopadhyay, M.A. Hashim, B. Sengupta, Contemporary environmental issues of landfill leachate: assessment & remedies, Crit. Rev. Environ. Sci. Technol. 45 (5) (2015) 472–590, 10.1080/10643389.2013.876524, 7/04/2020.
[2] K. Soujanya, R.S. Praveen, Environmental impact of municipal dumpsite leachate on groundwater quality in jawaharnagar, rangareddy, telangana, India, StringerLink 7 (6) (2017) Pp3333–3343, retrieved from, https://link.springer.com/article/10.1007/s13201-016-0480-6, 8/07/2020.
[3] K.B. Soujanya, Characterization of leachate and its effects on ground water quality around Jawaharnagar Municipal open dumpsite, Rangareddy, Telangana, Curr. World Environ. 11 (1) (2016), https://doi.org/10.12944/CWE.11.1.15.
[4] A.J. Omeiza, H.A. Lawal, M.S. Nur, Investigation of groundwater vulnerability to open dumpsites and its potential risk using electrical resistivity and water analysis, Heliyon (2023) e13265, https://doi.org/10.1016/j.heliyon.2023.e13265.
[5] A.T. Jan, I. Murtaza, A. Ali, Q.M.R. Haq, Mercury pollution: an emerging problem and potential bacterial remediation strategies, World J. Microbiol. Biotechnol. (25) (2009) 1529–1537.
[6] C.W. Chen, C.F. Chen, C.D. Dong, Distribution and accumulation of mercury in sediments of kaohsiung river mouth, Taiwan, APCBEE Procedia (1) (2012) 153–158.
[7] J. Monisha, T. Tenzin, A. Naresh, B.B. Mathew, N.B. Krishnamurthy, Toxicity, mechanism and health effects of some heavy metals, Interdiscip Toxicol 7 (2) (2014) 60–72, https://doi.org/10.2478/intox.2014.0009,6/02/2020.
[8] A.-O. Yaw, Rehabilitation, closure and aftercare management of the abloragyei dumpsite. Ga East Municipality, Greater Accra Metropolitan Area, 2018.
[9] H.S. Yun, W.O. Jung, K. Yoon-Ji, K. Youngki, K. Se-Yeong, K. Dongmug, Association between heavy metals, bisphenol A,volatile organic compounds and phthalates and metabolic syndrome, Int. J. Environ. Res. Publ. Health 16 (2019) 671.
[10] D.I. Eni, J.N. Obiefuna, C. Oko, I. Ekwole, Impact of urbanization on subsurface water quality in Calabar municipality, Nigeria, Int. J. Humanit. Soc. Sci. 1 (10) (2011) 167–173.
[11] K.I. Eshiet, J.C. Agunwamba, Contaminant transport from disposal sites and potential impact on groundwater, Journal of Environmental Science and Technology 5 (5) (2012) 306–318.
[12] Md L. Hossain, S. Roy-Das, M.K. Hossain, Impact of landfill leachate on surface and ground water quality, Journal of Environmental Science and Technology 7 (6) (2014) 337–346.
[13] C. Chao-Shi, Tu Chia-Huei, C. Shih-Jen, C. Cheng-Chung, A simulation of groundwater contaminant transport ata decommissioned landfill site—a case study, tainan city, Taiwan, Int. J. Environ. Res. Publ. Health 13 (2016) 467.
[14] D.I. Eni, A.E. Ubi, N. Digha, Vulnerability assessment of boreholes located close to Lemna landfill in calabar Metropolis, Nigeria, International Journal of Physical and Human Geography 2 (2) (2014) 6–15.
[15] C.C. Ejiogu, C.B. Okpara, K.D. Opara, I.O. Onyeocha, C. Azubuike, A.A. Emeh, Effects of solid waste disposal on the physicochemical properties of borehole water along FUTO road, eziobodo, owerri-West, Nigeria, Current Journal of Applied Science and Technology 26 (1) (2018) 1–7.
[16] R.C. Carter, A. Parker, Climate change, population trends and groundwater in Africa, Hydrol. Sci. J. 54 (5) (2009) 676–689.

[17] E.A. Ayolabi, F.F. Adetayo, T.K. Olusola, Integrated geophysical and geochemical methods for environmental assessment of municipal dumpsite System, Int. J. Geosci. 4 (2013) 850–862, https://doi.org/10.4236/ijg.2013.45079,2/09/2019.
[18] S. Eze, O. Orji, A. Onoriode, S. Saleh, M. Abolarin, Integrated geoelectrical resistivity method for environmental assessment of landfill leachate pollution and aquifer vulnerability studies, J. Geosci. Environ. Protect. 10 (2022) 1–26, https://doi.org/10.4236/gep.2022.10900102/06/2023.
[19] F.B. Akiang, G.O. Emujakporue, L.I. Nwosu, Leachate delineation and aquifer vulnerability assessment using geo-electric imaging in a major dumpsite around Calabar Flank, Southern Nigeria, Environ. Monit. Assess. 195 (123) (2023).
[20] A.E. Akpan, A.N. Ugaja, L. Okoye, J.J. Nyankno, Assessment of spatial distribution of contaminants and their levels in soil and water resources of Calabar, Nigeria using geophysical and geological data, Journal Environmental Earth Sciences (1) (2018).
[21] National Bureau of Statistics, Annual Abstracts of Statistics, Federal Republic of Nigeria, 2012.
[22] A.E. Edet, C.S. Okereke, Delineation of shallow groundwater aquifers in the coastal plain sands of Calabar area (Southern Nigeria) using surface resistivity and hydrogeological data, J. Afr. Earth Sci. 35 (3) (2002) 433–443.
[23] Department of Geography and Environmental Science, University of Calabar, GIS Unit, Cross River State Showing Location of Dumpsites in the Study Areas, 2022.
[24] Department of Geography and Environmental Science, University of calabar, GIS unit, calabar ; Overlay of buffer distance showing dumpsite location at Lemna dumpsite calabar; Overlay showing boreholes points, soil sample points. VES Points and ERT Profile Line Locations at Lemna Dumpsite Calabar, 2022.
[25] E.1. IgelleL.B, Obong. Waste to biogas technology in Cross River State, in: G.A. InUgal, A.N. Ndiyo, R.A. Offiong, L.B. Obong (Eds.), Development Imperatives of Contemporary Cross River State, University of Calabar Press, 2019.
[26] World Bank, Solid Waste Management, 2018 retrieved from, https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management20/11/2021.
[27] Researchers' analysis, Coordinates of the Study Locations, 2022.
[28] E. Biose, E. Ogbewi, Assessment of BTEX concentration in soils and earthworm (aporrectodea longa) from two automobile workshops in Benin city, Southern Nigeria, African Scientist 18 (4) (2017).
[29] United States Environmental Protection Agency, Ionic Strength, CADDIS, vol. 2, 2017 retrieved from, https://www.epa.gov/caddis-vol2/ionic-strength.
[30] Agilent technologies, A guide to interpreting detector specifications for gas Chromatography, Printed in the USA (2007) 5989–593290EN. January 24,, https://www.agilent.com/cs/library/specifications/Public/5989-3290EN.pdf/02/03/2022.
[31] F. Wenner, A method of measuring earth resistivity, Bulletin of the Bureau Standard 12 (1916) 469–478, https://doi.org/10.6028/bulletin.282,4/06/2021.
[32] M.H. Loke, I. Acworth, T. Dahlin, A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys, Explor. Geophys. 34 (2003) 182–187.
[33] United States Environmental Protection Agency, Environmental geophysics, retrievedfrom, https://archive.epa.gov/esd/archivegeophysics/web/html/resistivity_methods.html, 2021.
[34] K.R. Ramanuja Chary, T. Gangadhara Rao, A Monograph on Ground Water Exploration by Resistivity, S.P and Well Logging Techniques, 2005.
[35] F. HamedAL.Menshed, Electrical Resistivity Method How to Understand Theoretical Background of Electrical Resistivity Method in A Simple Way, 2018.
[36] International Business Management Statistics Package for Social Sciences (IBM SPSS), Learn how to get the most out of your research and analysis with SPSS software, retrieved from, https://www.ibm.com/analytics/spss-statistics-software, 2021.
[37] National environmental standard and regulation agency, national environmental (Non-metallic minerals manufacturing industries sector) regulations, Federal Government of Nigeria Official Gazzette 98 (2011) B637–B692. Government Notice No 134.
[38] World Health Organization, Guildline for Drinking Water Quality, incorporating the 1st addendum, fourth ed., 2017. retrieved from, https://www.who.int/publications/i/item/9789241549950.2/02/2022.
[39] M.H. Loke, R.D. Barker, Practical techniques for rapid least-squares inversion of apparent resistivity pseudosections using a quasi-Newton method, Geophys. Prospect. 44 (1996) 131–152.
[40] M.H. Loke, I. Acworth, T. Dahlin, A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys, Explor. Geophys. 34 (2003) 182–187.
[41] A.G.I. EarthImager, AGI EarthImager 1D for VES, retrieved from, https://www.agiusa.com/agi-earthimager-1d-ves12/2/2023, 2023.
[42] O. AladesanmiAdedipe, Z. Mohammed Muraina, O. Ayinuola Taiwo, A. Okunade Adenike, Geoelectric investigation of araromi area of akure, Southwestern Nigeria, J. Environ. Earth Sci. 4 (21) (2014) 170–181.
[43] O.A. Olusegun, O.O. Adeolu, F.A. Dolapo, Geophysical investigation of ground water potential and aquifer protective capacity around Osun State University Collage of Health Science, American Journal of Water Resources 4 (6) (2016) 137–143.
[44] Researchers' Analysis, Results of Soil BTEX in Lemna Dumpsite, 2022.
[45] Researchers' Analysis, Paired Samples Test Soil Analysis of BTEX in Lemna Dumpsite, 2022.
[46] Researchers' Analysis, Results of Heavy Metals and BTEX for Boreholes Around Lemna Dumpsite, 2022.
[47] Researchers' Analysis, Paired Samples Test Analysis of BTEX for Boreholes Around Lemna Dumpsite with WHO Standard, 2022.
[48] Researchers' Analysis, Spread of Leachate Pollution in Lemna Dumpsite, Calabar, 2022.
[49] Researchers' Analysis, Measured and Calculated Apparent Resistivity Plot of Leachate Pollution in Lemna Dumpsite, Calabar, 2022.
[50] Researchers' Analysis, Vertical Electric Sounding (VES) Apparent Resistivity and Depth of the Lithology in the Study Areas, 2022.
[51] Researchers' Analysis, Protective Capacity Rating of the Dumpsites in the Study Areas, 2022.
[52] Researchers' Analysis, Measured and Modelled VES Data of Lemna Dumpsite, 2022.
[53] R.T. Akshay, S.V. S.S. Sunil, Sheetal an experimental study of effect of recirculation on leachate characteristics through landfill biofilter, Int. J. Eng. Res. Technol. 10 (1) (2017) 974–3154.
[54] United States Environmental Protection Agency, Ionic Strength, CADDIS, vol. 2, 2017 retrieved from, https://www.epa.gov/caddis-vol2/ionic-strength.
[55] E. Olagunju, B. Olabode, O. Funmilola, M. Babalola, Environmental impact assessment of waste dumpsite using integrated geochemical and physico-chemical approach: a case study of ilokun waste dumpsite, Ado Ekiti, Southern Nigeria, Civil Eng Resource Journal 4 (2) (2018).
[56] Y.N, Q. Wang, Y. Wang, H. Li, Y. Wang, Y. Gao, B. Sun, R. Wang, W. Bian, M. Li, Zhan, Impact of incineration slag co-disposed with municipal solid waste on methane production and methanogens ecology in landfills, Bioresour. Technol. 77 (2023) 128978, https://doi.org/10.1016/j.biortech.2023.128978.
[57] H.F Zhao, S. Wu, H. Zhu, Z. Zeng, X. Zhao, S. Yang, Zhang, Material stock analysis of urban road from nighttime light data based on a bottom-up approach, Environ. Res. 228 (2023) 115902, https://doi.org/10.1016/j.envres.2023.115902.
[58] S, H. Qiu, S. Yang, S. Zhang, S. Huang, X. Zhao, P. Xu, W. He, Y. Zhou, N. Zhao, N. Yan, Nikolaidis. Carbon storage in an arable soil combining field measurements, aggregate turnover modeling and climate scenarios, Catena 220 (2023) 106708, https://doi.org/10.1016/j.catena.2022.106708.
[59] T., B. Zhang, G. Song, H. Han, Q. Zhao, Y. Hu, H. Zhao, Liu, Effects of coastal wetland reclamation on soil organic carbon, total nitrogen, and total phosphorus in China: a meta-analysis, Land Degrad. Dev. 34 (11) (2023) 3340–3349, https://doi.org/10.1002/ldr.4687.
[60] M., V.W. Ma, K.N. Tam, A. Le, W. Butera, X. Li, Wang, Comparative analysis on international construction and demolition waste management policies and laws for policy makers in China, J. Civ. Eng. Manag. 29 (2) (2023) 107–130, https://doi.org/10.3846/jcem.2023.16581.
[61] C., B. Hu, H. Dong, J. Shao, Y. Wang Zhang, Toward purifying defect feature for multilabel sewer defect classification, IEEE Trans. Instrum. Meas. 72 (2023) 1–11, https://doi.org/10.1109/TIM.2023.3250306.
[62] Z., Z. Liu, X. Xu, L. Zhu, Z. Yin, X. Yin, W. Li, Zheng, Calculation of carbon emissions in wastewater treatment and its neutralization measures: a review, Sci. Total Environ. (2023) 169356, https://doi.org/10.1016/j.scitotenv.2023.169356.
[63] A.O. Olorunfemi, A.B. Alao-Daniel, T.A. Adesiyan, C.E. Onah, Geochemical assessment of heavy metal impact on soil around ewu-elepe dumpsite, Lagos state, Nigeria, IFE J. Sci. 22 (3) (2018).
[64] P.K. Maurya, V.K. Rønde, G. Fiandaca, N. Balbarini, E. Auken, P.L. Bjerg, A.V. Christiansen, Detailed landfill leachate plume mapping using 2D and 3D electrical resistivity tomography - with correlation to ionic strength measured in screens, J. Appl. Geophys. 138 (2017) 1–8, https://doi.org/10.1016/j.jappgeo.2017.01.019.

[65] O. Iyoha, J.E. Ighodalo, P.N. Okanignuan, Geophysical investigation of waste plume in waste disposal site: a case study of Otofure dumpsite Ovia North-east Local Government Area of Edo State, Nigeria using 3-D electrical resistivity tomography, BIU Journal of Basic and Applied Sciences 5 (1) (2020) 15–26.

[66] A.J. Omeiza, H.A. Lawal, M.S. Nur, Investigation of groundwater vulnerability to open dumpsites and its potential risk using electrical resistivity and water analysis, Heliyon (2023) e13265, https://doi.org/10.1016/j.heliyon.2023.e13265.

[67] G.O. Mosuro, K.O. Omosanya, O.O. Bayewy, M.O. Oloruntola, T.A. Laniyan, O. Atobi, M. Okubena, E. Popoola, Assessment of groundwater vulnerability to leachate infiltration using electrical resistivity method, Appl. Water Sci. 7 (5) (2017) 2195–2207, https://doi.org/10.1007/s13201-016-0393-4.

[68] D.A. Babaiwa, M.O. Ikponmwen, Application of 2D and 3D electrical resistivity tomography (ERT) in predicting soil erodibility in oredide village, auchi in etsako west LGA of edo state, Southern Nigeria, J. Appl. Sci. Environ. Manag. 25 (6) (2021) 1073–1079.

[69] W.E. Wightman, F. Jalinoos, P. Sirles, K. Hanna, Application of geophysical methods to highway related problems. Federal Highway Administration, Central Federal Lands Highway Division, 2003. Lakewood, CO, Publication No. FHWA-IF-04-021, http://www.cflhd.gov/resources/agm/10/09/2022.

[70] G.K. Anudu, B.I. Essien, S.E. Obrike, Hydrogeophysical investigation and estimation of groundwater potentials of the Lower Palaeozoic to Precambrian crystalline basement rocks in Keffi area, north-central Nigeria, using resistivity methods, Arabian J. Geosci. 7 (2012) 311–322, https://doi.org/10.1007/s12517-012-0789-x.

[71] United States Environmental Protection Agency USEPA, Resistivity Methods Environmental Geophysics, 2016 retrieved from, https://archive.epa.gov/esd/archivegeophysics/web/html/resistivity_methods.html10/09/2022.

[72] A.S. Ogungbe, E.N. Unanka, A.A. Alabi, J.O. Coker, E.O. Onori, Geophysical assessment of leachate migration and aquifer protective capacity of cassidy dumpsite, ojo, Lagos state, Nigeria, Ilorin Journal of Science 9 (2) (2022) 137–161.

[73] E. S, U.C. Ekwok, A.M. Ben, S.Qaysi Eldosouky, A.E. Akpan, P. Andráš, Towards understanding the extent of saltwater incursion into the coastal aquifers of Akwa Ibom State, Southern Nigeria using 2D ERT, J. King Saud Univ. Sci. 34 (8) (2022) 102371.