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ANALYZING THE EXTENT OF LEACHATE FROM A MAJOR DUMPSITE WITHIN THE CRETACEOUS SEDIMENTS OF IKOM-MAMFE EMBAYMENT, SOUTHEAST NIGERIA

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Abstract: Groundwater resources in the region serve as a vital source of potable water for local communities and are essential for supporting various socio-economic activities. Unfortunately, the infiltration of leachate from dumpsite contributes to the dispersion of contaminants within the cretaceous sediments, posing a potential threat to groundwater quality. This study presents an exhaustive examination of leachate extent emanating from a prominent dumpsite situated within the Cretaceous sediments of the Ikom-Mamfe Embayment, Southeast Nigeria. Employing meticulous soil sampling methodologies and water collection from strategically positioned boreholes near the Ikom dumpsite, advanced techniques such as Electrical Resistivity Tomography (ERT) and Vertical Electric Sounding (VES) were utilized to scrutinize the infiltration of leachate within the site. Laboratory analyses were conducted to evaluate the concentrations of heavy metals, including Lead, Mercury, Arsenic, Nickel, Chromium, and Cadmium, in both soil and borehole water samples. The findings unveiled alarming levels of Lead and Cadmium concentrations in the soil, exceeding established regulatory thresholds, with recorded values ranging from 552.34 to 556.93 mg/kg and 11.88 to 7.46 mg/kg, respectively. Similarly, borehole water analyses in the vicinity of the Ikom dumpsite revealed elevated concentrations of Arsenic, Lead, Cadmium, and Nickel, surpassing WHO limits in specific boreholes (BH2 and BH3), indicative of potential soil porosity issues and unfavorable geological conditions prevalent in the study area. Notably, the use of ERT delineated an inverse resistivity of 5.99 Ωm at a depth of 9.26 m, pinpointing the leachate-infiltrated cretaceous sediments zone, extending laterally from 10m to 40m along the profile. The observed infiltration of leachate at 9.26 m depth underscores its penetration into the sandstone, shale, and dark gray shale strata within the dumpsite. Furthermore, the quantified thickness layer ranging from 1.41 to 4.37 affirmed leachate infiltration within the sandstone, shale, and dark gray shale strata, with implications for its movement and containment dynamics. This study underscores the critical role of layer thickness in influencing the migration and containment of leachate, with thicker layers potentially acting as barriers to its movement, while thinner layers may facilitate more rapid migration. Additionally, the assessment of aquifer protective capacity, denoted by ratings below (<0.1), underscores the poor protective capacity of the aquifer system in the study area. In light of these findings, strategic management, remediation, and vigilant monitoring measures are advocated to mitigate contamination risks and safeguard water quality.

Keywords: Cretaceous Sediments, Dumpsite Leachate, Migration, Heavy Metals, Ikom Dumpsite.

1. INTRODUCTION

The management of solid waste has emerged as a critical issue globally, particularly in rapidly urbanizing regions of developing countries such as Nigeria. With escalating population growth and urbanization rates, the proliferation of municipal solid waste (MSW) has surged, necessitating the establishment of numerous dumpsites across the country. However, these dumpsites engender profound environmental challenges owing to the generation of leachate during organic matter decomposition and rainfall percolation through waste layers.

One of the most paramount concerns among the adverse environmental impacts attributed to dumpsites is the migration of leachate toward underlying aquifers (Abdel-Shafy et al., 2024). Leachate constitutes a complex blend of heavy metals capable of infiltrating the soil and potentially contaminating groundwater resources (Badmus et al., 2022). The movement of leachate towards cretaceous sediments, well-known for their high permeability (Evans, 2019), raises considerable concerns regarding the security and viability of water sources located near dumpsites.

The Ikom dumpsite, situated in Cross River State, Nigeria, epitomises the challenges inherent in solid waste management within urban areas. As population burgeons and economic activities burgeon, the volume of waste generated at the Ikom dumpsite has surged, exacerbating concerns regarding environmental pollution (Igelle & Ekwok, 2018). Despite rudimentary waste management practices being implemented, the dearth of infrastructure and regulatory oversight has precipitated waste accumulation and leachate generation, posing imminent threats to cretaceous sediments and groundwater resources.

Cretaceous sediments are found in various parts of the world and can consist of different types of rock formations, including sandstone, shale, limestone, and chalk (Fello et al., 2024). Understanding the magnitude of leachate migration within cretaceous sediments at the Ikom dumpsite is imperative for assessing the potential risks to groundwater quality. Cretaceous sediments, characterized by their porosity and permeability, play a crucial role in regulating groundwater flow and storage (Devaraj et al., 2020; Sabry et al., 2023). Consequently, contaminants may obstruct pore spaces within the sediment, reducing porosity and permeability, thereby impeding groundwater flow and storage (Wang et al., 2023; Emmarloo et, al., 2024). This depletion can diminish water availability, exacerbate water scarcity, and undermine the sustainability of water resources in affected areas. Nevertheless, cretaceous sediments, with their high porosity and permeability, could facilitate the transport of pollutants over large distances (Xu et al., 2024). Contaminants can migrate horizontally and vertically within the sediment layers, spreading laterally through groundwater flow and vertically through diffusion and advection processes (Mosthaf et al., 2024). This extensive transport can exacerbate contamination risks, affecting distant areas beyond the immediate vicinity of the polluted site (Zeng et al., 2024). The infiltration of leachate into these sediments could compromise the quality of groundwater resources, which serve as a primary source of drinking water for local communities and support various socio-economic activities in the study location.

Some studies have investigated the critical issue of dumpsite leachate locally and across the world. Notably, Sulemanet al., (2023) uses Vertical Electrical Sounding (VES) and 2-D resistivity imaging with Schlumberger and Wenner arrays to assess leachate migration and its impact on groundwater at the Abata Asunkere dumpsite in Ilorin, Kwara State. The research addresses concerns about unregulated waste disposal threatening clean water supplies. The data processing identified five geoelectric layers which include topsoil, clayey sand, weathered basement, fractured basement, and fresh basement. The third layer, characterized by low resistivity values of 2.09 - 3.52 Ωm at depths of 0.9 - 10 meters, indicates leachate contamination. Notably, low resistivity values in the third layer suggest leachate contamination. The results indicate that areas around the dumpsite are at risk of leachate permeating unconfined aquifers, necessitating proper monitoring and control.

Ugbor et al., (2021) uses vertical electrical sounding (VES) and two-dimensional (2D) resistivity tomography to evaluate the impact of a leachate plume on groundwater near a dumpsite along the Onitsha expressway in southeastern Nigeria.

Borehole logs and geophysical data were collected and analyzed using specialized software. The 2D resistivity results indicated low resistivity zones in profiles 1 and 3, suggesting significant leachate contamination, while profiles 2 and 4 showed some leachate impact within certain depths. VES data revealed water table depths ranging from 12.2 to 21.7 meters, with the leachate plume migrating southeast, aligning with the groundwater flow direction.

Ndifreke (2022) focuses on geo-electrical modelling of leachate contamination at a major waste disposal site in south-eastern Nigeria. Vertical electrical sounding (VES) and electrical resistivity tomography (ERT) surveys were conducted at a heavily contaminated waste disposal site in south-eastern Nigeria. The VES results reveal three distinct subsurface layers, with the aquifer situated between the second and third layers. Longitudinal conductance calculations indicate that the aquifer possesses a weak protective capacity, rendering it highly susceptible to leachate contamination. ERT survey models delineate the trajectory of leachate plumes and quantify the extent of leachate penetration into the aquifer. Anomalously low resistivity zones on the ERT models denote the presence of leachate, demonstrating its rapid movement towards the aquifer.

The study conducted by Odong et al., (2024) focused on the groundwater resources in the Ikom-Mamfe Embayment, highlighting significant threats from anthropogenic contaminants and natural processes like carbonate and silicate dissolution. Odong et al., (2024) utilized integrated methods including geoelectrical resistivity and geological indices to assess groundwater vulnerability. Results indicated poorly protected shallow aquifers in certain areas, while others had moderate to excellently protected aquifers, largely influenced by litho-stratigraphic composition. Vulnerability indices supported these findings, indicating moderate to high vulnerability in the central area. However, clay/shale formations in other parts naturally attenuated surface contaminants. Geochemical analyses of groundwater samples revealed concentrations of Ca^{2+}, Mg^{2+}, and Na+, reflecting lithologic influences. Approximately 10% of the area was deemed highly vulnerable, while 90% had adequately protected groundwater. Nevertheless, some areas were unsuitable for drinking due to inherent contaminants, necessitating borehole depths of over 120 meters for potable water. Site-specific geophysical investigations were recommended before drilling, alongside appropriate water treatment measures.

Given the critical need to understand and mitigate environmental contamination, this study addresses a significant issue by focusing on the leachate impact from a major dumpsite within the cretaceous sediments of the Ikom-Mamfe Embayment, Southeast Nigeria. This research uses interdisciplinary approaches, combining hydrological and geophysical techniques to characterize the subsurface environment and evaluate contaminant spread at the lower elevation of the Ikom dumpsite.

By employing vertical electrical sounding (VES) and two-dimensional (2D) resistivity tomography, the study provides a detailed assessment of leachate migration within the cretaceous sediment. This dual-method approach offers a robust framework for identifying low resistivity zones indicative of leachate presence and understanding the interaction between groundwater and contaminant. This study's integration of geophysical and hydrological data not only elucidates the extent of leachate migration but also highlights the environmental vulnerabilities specific to the cretaceous sediments at the Ikom-Mamfe Embayment. The insights gained can inform evidence-based policy interventions and management strategies to mitigate environmental pollution and safeguard water resources in Ikom, Cross River State, Nigeria.

2. STUDY LOCATION

Cross River State, situated within the South-South Geopolitical Zone of the Federal Republic of Nigeria (Figure 1), hosts the Ikom dumpsite, geographically positioned at Latitude 5°56'20.274828" North and Longitude 8°42'39.962304" East. The study location manifests distinct elevations, with an average altitude of 74 meters above sea level (Figure 2). Geological observations reveal the presence of an underlying aquifer within the lithological framework of the study location. The aquifer exhibits confinement with limited aquicludes, delineating two principal water-bearing strata, as elucidated by Edet & Okereke (2002). Specifically, the upper zone, characterized by heightened susceptibility to surface contamination, contrasts notably with the lower zone in terms of vulnerability (Edet & Okereke, 2002). Both surface and groundwater receive replenishment from ample precipitation patterns prevalent in the region. Noteworthy lithological constituents at the dumpsite encompass laterites, sandstone, shale, dark-gray shale, and dark shale.

3. MATERIALS AND METHODS

3.1. Soil Sample Collection and Analysis

The soil sampling methodology adopted in this study follows the approach delineated by Igelle et al., (2024). Utilizing a Global Positioning System (GPS),

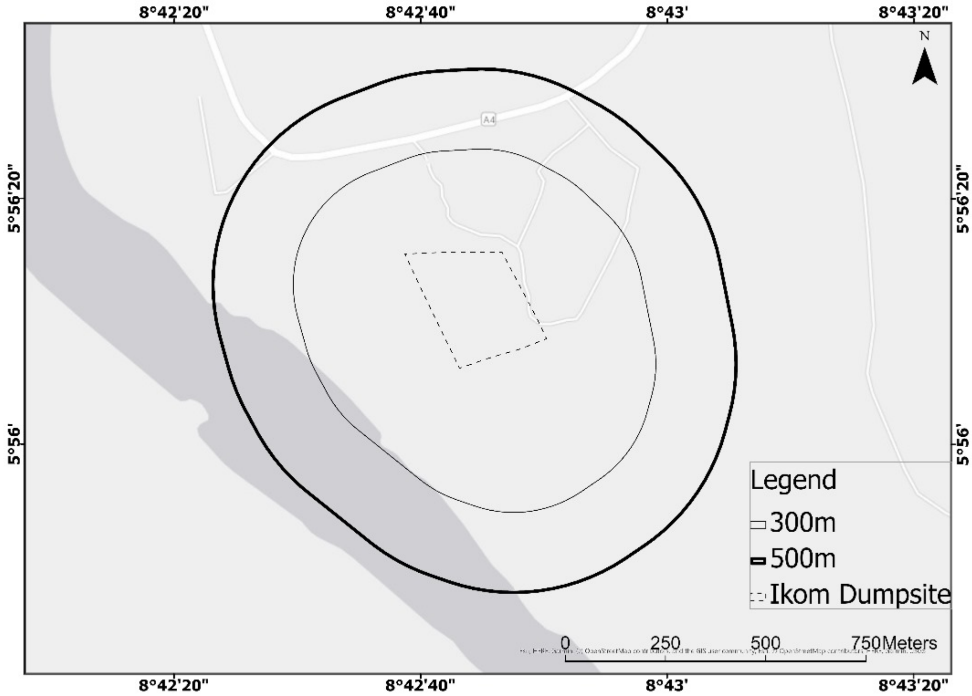

Figure 1: Buffer zone of the dumpsite location.

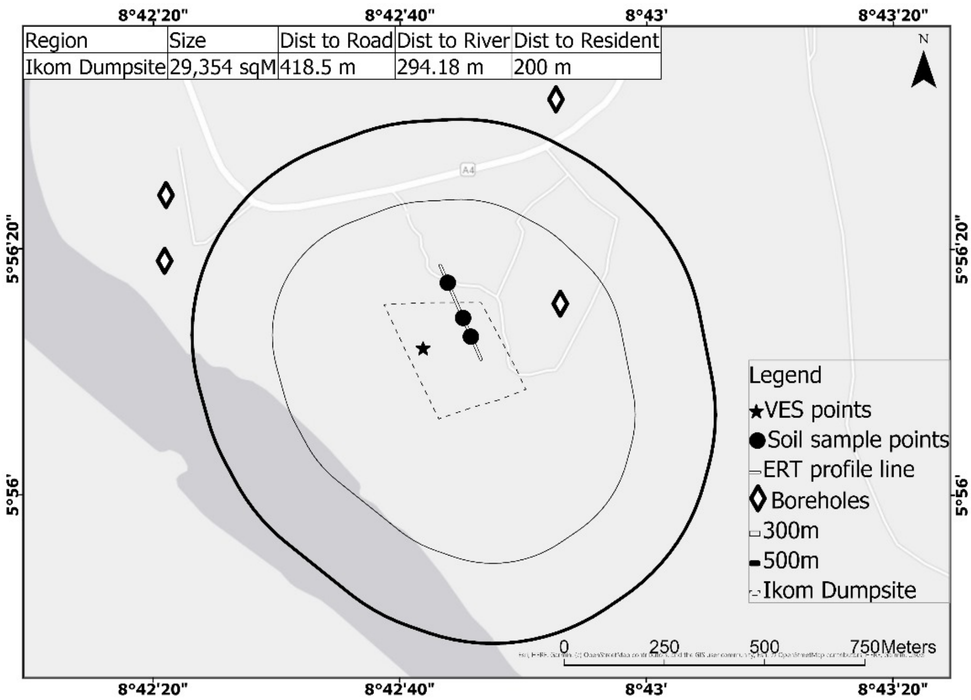

Figure 2. Sampling points at Ikom Dumpsite.

precise coordinates of sampling points were meticulously delineated to ensure spatial accuracy. Soil samples were systematically extracted at depths ranging from 0 to 30 cm using a soil auger, strategically positioned along a linear trajectory to evaluate levels of heavy metal contamination. Specifically, sampling points were strategically positioned at intervals of 5 m, 25 m, and 50 m within the confines of the Ikom dumpsite, with corresponding geographical coordinates meticulously documented (Table 1). At each sampling point, three soil specimens were systematically collected along the lower elevation near the dumpsite, maintaining consistent intervals of 5 m, 25 m, and 50 m. Additionally, for comparative purposes, one control soil sample was procured from a location situated 1 km away from the sampled sites. In total, four soil samples were gathered from the designated study locations. These samples were carefully transferred from the auger to securely sealed and labelled sampling bags. Subsequently, they

Table 1. Coordinates of the sample locations

Sample locations		
Meter	Latitude	Longitude
5m	5°’ 56′ 14.856″ N	8°’ 42′ 43.146″ E
25m	5°’ 56′ 17.218″ N	8°’ 54′ 42.919″ E
50m	5°’ 56′ 17.232″ N	5°’ 56′ 16.375″ E
Water sample’s locations		
Ikom	Latitude	Longitude
Dumpsite location	$5^{0'}$, 56', 20.274828"	$8^{0'}$, 42’, 39.962304"
BH2	$5^{0'}$, 56’, 20.262588"	$8^{0'}$, 42’, 16.810488"
BH3	$5^{0'}$, 56', 26.188332"	$8^{0'}$, 42’, 16.732836"
BH4	$5^{0'}$, 56', 38.423616"	$8^{0'}$, 43’, 2.323632"
BH5	$5^{0'}$, 57', 24.488892"	$8^{0'}$, 42’, 26.91306"
ERT locations		
Distances	Latitude	Longitude
0	5° 56′ 18.056″ N	8° 42′ 43.193″ E
5	5° 56′ 17.880″ N	8° 42′ 43.146″ E
10	5° 56′ 17.725″ N	8° 42′ 43.099″ E
15	5° 56′ 17.542″ N	8° 42′ 43.049″ E
20	5° 56′ 17.376″ N	8° 42′ 42.977″ E
25	5° 56′ 17.218″ N	8° 42′ 42.919″ E
30	5° 56′ 17.066″ N	8° 42′ 42.865″ E
VES location		
VES Points	Latitude	Longitude
Ikom Dumpsite	5°1'59".00N	8°21'55".00E

were stored in a cooler equipped with ice blocks to maintain a temperature of 4°C and promptly transported to the laboratory for thorough analysis of heavy metal concentrations. Notably, the soil sampling activities were conducted in September 2022, thus establishing a specific temporal framework for the study.

The methodology employed herein adhered to the protocols outlined by Al-Hamzawi & Al-Gharabi (2019), alongside guidelines issued by the United States Environmental Protection Agency (2021). To prepare the soil samples for analysis, a systematic procedure was followed. Initially, the soil samples went through drying in an electric oven at 100°C for a duration of 2 hours. Subsequently, the dried samples were grounded using a hand mill and sieved through a fine mesh with a pore size of 75 µm to ensure homogenization in readiness for subsequent laboratory procedures. The prepared soil samples, each weighing 1 gram, were subjected to digestion through the addition of 150 ml of hydrochloric acid (HCl) along with 5 ml of nitric acid (HNO_3). This mixture was subjected to heating in a sand bath for a period of 60 minutes. Following cooling, 5 ml of HCl and 50 ml of distilled water were added to cleanse the container sides from any residual dissolved sample. The resultant mixture was then boiled for 3 minutes, after which the sample was filtered using a filter sheet. The resulting filtrate, comprising a volume of 100 ml, was collected in specialized containers. For the quantification of heavy metal concentrations, specifically Arsenic (Ar), Mercury (Hg), Lead (Pb), Cadmium (Cd), Chromium (Cr), and Nickel (Ni), an Atomic Absorption Spectrometer (AAS) was employed (Al-Hamzawi & Al-Gharabi, 2019; United States Environmental Protection Agency, 2021).

3.2. Borehole Water Sampling Collection

The water sample collection methodology employed in this investigation encompassed both the demarcated buffer zone of 300-500 square meters surrounding boreholes, as stipulated by Igelle et al. (2024), as well as areas extending beyond this prescribed boundary. The rationale behind selecting the 300-500-meter buffer zone was rooted in the proximity of the boreholes to the Ikom dumpsite, affording a targeted spatial scope for sample acquisition. Control water samples, serving as comparative benchmarks, were methodically obtained at a distance of 1 km from the designated borehole water sampling locations. The deliberate selection of water samples cantered on four boreholes proximate to the Ikom dumpsites. The precise coordinates of these boreholes were determined with precision using the Global Positioning System (GPS), as delineated in Table 1. Consequently, the study encompassed the acquisition of four borehole water samples surrounding the dumpsites, along with an additional control sample within the study vicinity, resulting in a cumulative total of five borehole samples. To uphold sample integrity, the collected water samples were expeditiously transferred to a cooler, equipped with ice blocks to maintain a stable temperature of 4°C, and subsequently conveyed to the laboratory for comprehensive heavy metals analysis. It is pertinent to note that the borehole water sampling activities were systematically undertaken in September 2022, thereby establishing a distinct temporal framework for the study.

The methodology adopted in this study aligns with the procedures outlined by Al-Hamzawi & Al-Gharabi (2019), alongside guidelines set forth by the United States Environmental Protection Agency (2021). For the analysis of water samples, 1 ml of nitric acid (HNO_3) was meticulously added to each 100 ml water sample, followed by filtration through filter paper. Subsequently, the mineralized samples were judiciously preserved by storing them in a refrigerator at a controlled temperature of 4°C to ensure their integrity until the time of analysis. The quantification of heavy metal contents, specifically Arsenic (Ar), Mercury (Hg), Lead (Pb), Cadmium (Cd), Chromium (Cr), and Nickel (Ni), in the water samples was conducted through rigorous measurement procedures. Before the analysis, a comprehensive calibration process was undertaken using standard solutions. These solutions were prepared by diluting multi-elemental standard solutions, maintaining a concentration of 100 mg/l, by the methodologies detailed by Al-Hamzawi & Al-Gharabi (2019) and the United States Environmental Protection Agency (2021).

For the analysis of heavy metals, an Atomic Absorption Spectrometer (AAS) AAS-3520 model, manufactured by Wincom, China, was employed. The AAS-3520 model is equipped with an Achromatic C-T monochromator, featuring a grating size of 1200mm. The wavelength range spans from 190 to 900nm, with remarkable wavelength accuracy of ≤±0.2nm and repeatability of ≤0.1nm, ensuring precise and reliable measurement outcomes. The instrument offers flexibility in spectrum bandwidth adjustment, with options ranging from 0.1 to 1.4 nm, catering to diverse analytical requirements. Notably, the precision has a relative standard deviation (RSD) of ≤1%, underscoring its capability to deliver consistent and reproducible results.

3.3. Electrical Resistivity Tomography

The Wenner array, a widely used configuration since its introduction by Wenner in 1916, is notable in geophysical surveys (Wenner, 1916). This methodology demonstrates the efficacy of 2D ERT in producing detailed subsurface depictions spanning over 100 meters, facilitating a nuanced comprehension of subsurface dynamics (Igelle et al., 2024). Resistivity measurements, conducted with a 5-unit electrode spacing, employed the Ohmega 0191 equipment from Allied Associates Geophysical Ltd. The configuration factor for the Wenner array is expressed as $2\pi a\times R=\rho aw$, where π is approximately 3.14, a represents the distance between electrode pairs, C1 and C2 are the current electrodes (corresponding to A and B), and P1 and P2 are the potential electrodes (corresponding to M and N). The variable R denotes the apparent resistance measured in ohms, and ρaw represents the apparent resistivity.

3.4. Vertical Electric Sounding

The Vertical Electric Sounding (VES) method was employed as the primary investigative approach in this study. Within the Schlumberger setup, the central point of the array remained fixed, while measurements were taken by gradually increasing the electrode spacing (Igelle et al., 2024). The electrode spacing was extended to cover a considerable distance within the dumpsite, commensurate with its length. The configuration factor for the Schlumberger array is expressed as $K=4\pi(2L2-a2)$, where π is approximately 3.14, L represents the distance between the current electrodes (A and B), and a is the distance between the potential electrodes (M and N). The apparent resistivity is then calculated using the formula $\rho=K\times R$, where K is the configuration factor for the Schlumberger array, R is the resistance measured in ohms, and ρ is the apparent resistivity in ohm-meters.

3.5. Data analysis

The generated images and depth assessments of leachate contamination in the shallow subsurface of the dumpsites were facilitated by the RES2DInversion software. In tandem, the Earth Imager 1D software played a pivotal role in discerning the subsurface layer geology within the study locations (AGI EarthImager, 2023).

3.6. Longitudinal Conductance of VES

The assessment of Vertical Electric Sounding (VES) data involved the application of longitudinal conductance as a metric, serving to gauge the susceptibility of the aquifer to potential pollution. The first-order geo-electric parameters, derived from the iterative process, were utilized in the development of second-order geo-electric parameters, specifically the Dar Zarrouk parameters (Aladesanmi et al., 2014).

The evaluation of longitudinal conductance serves as a predictive tool for determining the aquifer's protective capacity rating. The formula for longitudinal conductance is expressed as follows:

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

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

4. RESULTS

4.1. Soil parameter values around Ikom Dumpsite

The results of the soil analysis conducted at the Ikom dumpsite, as presented in Table 2, indicate that the concentrations of Lead and Cadmium at all examined distances (5 meters, 25 meters, and 50 meters) significantly exceed the permissible thresholds established by the National Environmental Standards and Regulations Enforcement Agency (NESREA) in the 2011 guidelines. In contrast, Mercury, Arsenic, Nickel, and Chromium concentrations at the same distances fall below the NESREA recommended limits (Table 2).

4.2. Borehole Water Parameter Values of Ikom Dumpsite

The findings from the laboratory analysis of water quality in boreholes proximal to the Ikom dumpsite are presented in (Table 3). The concentrations of Arsenic, Lead, Cadmium, and Nickel in boreholes BH2 and BH3, located around the vicinity of the Ikom dumpsite, exceeded the regulatory thresholds set by the World Health Organization (WHO, 2017).

4.3. Extent of Leachate within the cretaceous sediments around Ikom Dumpsite

The outcomes of the ERT analysis for the study location are delineated in (Table 4, 5, Figures 3 and 4). Specifically, the Ikom dumpsite showcases an inverse resistivity of 5.99 Ωm at a depth of 9.26 m, with the leachate-infiltrated cretaceous sediments zone identified at lateral distances spanning from 10m to 40m along the profile. Notably, the correlation plot between measured and calculated apparent resistivity manifests as a linear straight line, indicative of a robust correlation in resistivity across all ERT models of the dumpsites. The resistivity inverse model was iteratively derived, achieving convergence after 4 iterations with a commendably low Root Mean Square (RMS) error of 6.8% at a 5-meter unit electrode spacing in the study areas (Table 4, Figure 4).

The provided image appears to be the result of an Electrical Resistivity Tomography (ERT) survey conducted at Ikon Dumpsite (Figure 5). The figure shows two resistivity sections derived from inverse modelling with a smoothness constraint. The top section (minimum resistivity) shallow region (up to 5 meters) shows predominantly low resistivity values

Table 2. Heavy metals in soil at Ikom dumpsite.

	Unit	5m	25m	50m	1km Control sample	NESREA
Parameters						
Lead	(mg/kg)	552.34*	557.34*	556.93*	7.3	164
Mercury	(mg/kg)	0.034	0.036	0.031	0.025	4
Arsenic	(mg/kg)	19.34	18.67	16.43	5.94	20
Cadmium	(mg/kg)	8.65*	7.46*	11.88*	0.17	3
Chromium	(mg/kg)	75.11	72.19	74.29	6.76	100
Nickel	(mg/kg)	36.12	32.21	38.44	7.89	70

NESREA= National Standard and Regulation Agency; *=Higher than NESREA Standard; ND=Note Detected.

Table 3. Heavy metals in borehole water around Ikom dumpsite.

Parameter	Unit	Sample codes					
		BH2	BH3	BH4	BH5	WHO	Control sample
Arsenic	(mg/l)	0.053*	0.037*	0.0012	0.0014	0.01	0.0017
Lead	(mg/l)	0.967*	0.78*	0.00014	0.00016	0.01	0.00015
Cadmium	(mg/l)	0.008*	0.005*	0.00017	0.00013	0.003	0.00014
Chromium	(mg/l)	0.0044	0.0031	0.00018	0.00017	0.05	0.00012
Nickel	(mg/l)	0.058*	0.063*	0.00029	0.00034	0.07	0.00023
Mercury	(mg/l)	0.000036	0.000026	0.000016	0.000017	0.006	0.000013

*=Exceeded WHO Standard; ND=Note Detected.

Table 4. ERT profile at the study location

Datum points (63)		Field configuration					Ikom dumpsite
Stations	C1	P1	Midpoints (a)	P2	C2	Electrode spacing	2 πa × R=ρaw
1	0	**5**	**7.5**	**10**	15	5	76.987
2	5	10	12.5	15	20	5	76.987
3	10	15	17.5	20	25	5	74.8534
4	15	20	22.5	25	30	5	76.2453
5	20	25	27.5	30	35	5	74.8534
6	25	30	32.5	35	40	5	76.987
7	30	35	37.5	40	45	5	76.2453
8	35	40	42.5	45	50	5	74.8534
9	40	45	47.5	50	55	5	76.987
10	45	50	52.5	55	60	5	76.2453
11	50	55	57.5	60	65	5	74.8534
12	55	60	62.5	65	70	5	76.987
13	60	65	67.5	70	75	5	74.2453
14	65	70	72.5	75	80	5	63.8534
15	70	75	77.5	80	85	5	66.987
16	75	80	82.5	85	90	5	66.987
17	80	85	87.5	90	95	5	66.2453
18	85	90	92.5	95	100	5	1.765
1	0	**10**	**15**	**20**	30	10	1.365
2	5	15	20	25	35	10	2.0345
3	10	20	25	30	40	10	14.765
4	15	25	30	35	45	10	2.987
5	20	30	35	40	50	10	11.5422
6	25	35	40	45	55	10	1.987
7	30	40	45	50	60	10	2.876
8	35	45	50	55	65	10	28.765
9	40	50	55	60	70	10	28.76
10	45	55	60	65	75	10	56.987
11	50	60	65	70	80	10	56.2453
12	55	65	70	75	85	10	54.8534
13	60	70	75	80	90	10	56.2453
14	65	75	80	85	95	10	54.8534
15	70	80	85	90	100	10	56.987
1	0	**15**	**20**	**25**	40	15	56.2453
2	15	20	25	30	45	15	54.8534
3	20	25	30	35	50	15	76.987
4	25	30	35	40	55	15	56.2453
5	30	35	40	45	60	15	54.8534
6	35	40	45	50	65	15	76.987
7	40	45	50	55	70	15	56.2453
8	45	50	55	60	75	15	54.8534
9	50	55	60	65	80	15	76.987
10	55	60	65	70	85	15	76.987
11	60	65	70	75	90	15	56.2453
12	65	70	75	80	95	15	54.8534
1	0	**20**	**25**	**30**	50	20	76.987
2	20	25	30	35	55	20	56.2453
3	25	30	35	40	60	20	54.8534
4	30	35	40	45	65	20	76.987
5	35	40	45	50	70	20	6.2453
6	40	45	50	55	75	20	4.8534
7	45	50	55	60	80	20	7.987
8	50	55	60	65	85	20	56.2453
9	55	60	65	70	90	20	54.8534
1	0	**25**	**30**	**35**	60	25	76.987
2	25	30	35	40	65	25	56.2453
3	30	35	40	45	70	25	54.8534
4	35	40	45	50	75	25	48.346
5	40	45	50	55	80	25	76.987
6	45	50	55	60	85	25	56.2453
1	0	**30**	**35**	**40**	70	30	54.8534
2	30	35	40	45	75	30	56.77
3	35	40	45	50	80	30	66.34

Table 5. Extent of Leachate within the cretaceous sediments

Locations	Inverse resistivity Ωm	Inverse depth (m)	Unit electrode spacing (m)	RMS error (%)
Ikom dumpsite	5.99	9.26	5	6.8

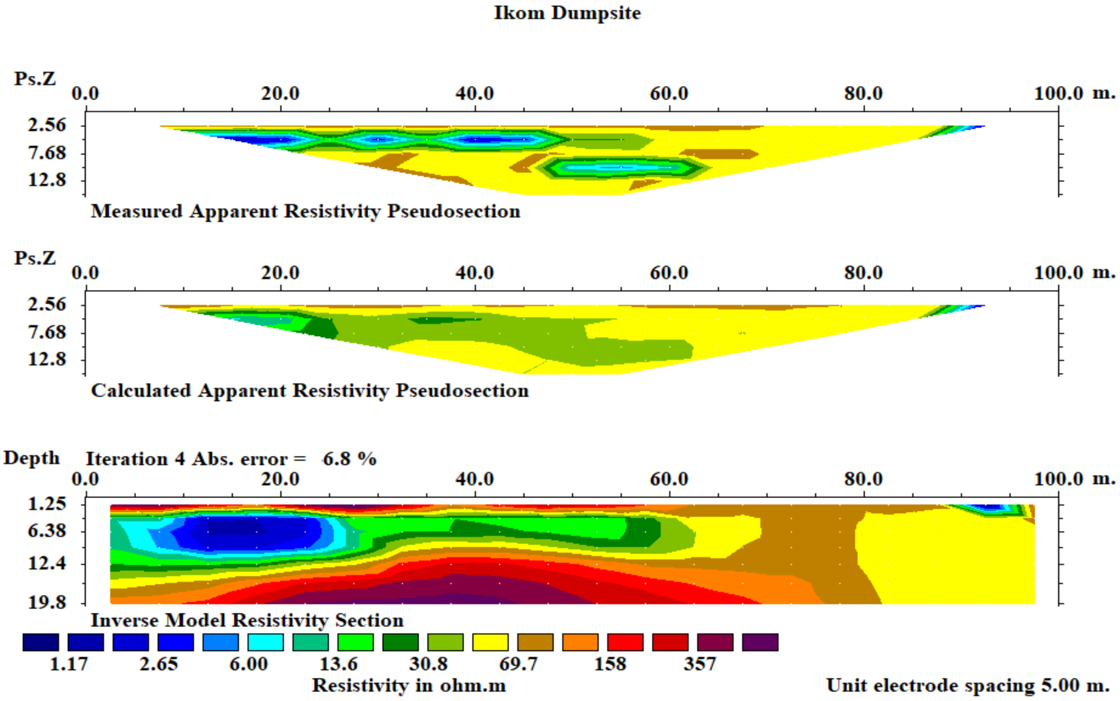

Figure 3. Visual extent of leachate pollution within the cretaceous sediments at Ikom Dumpsite.

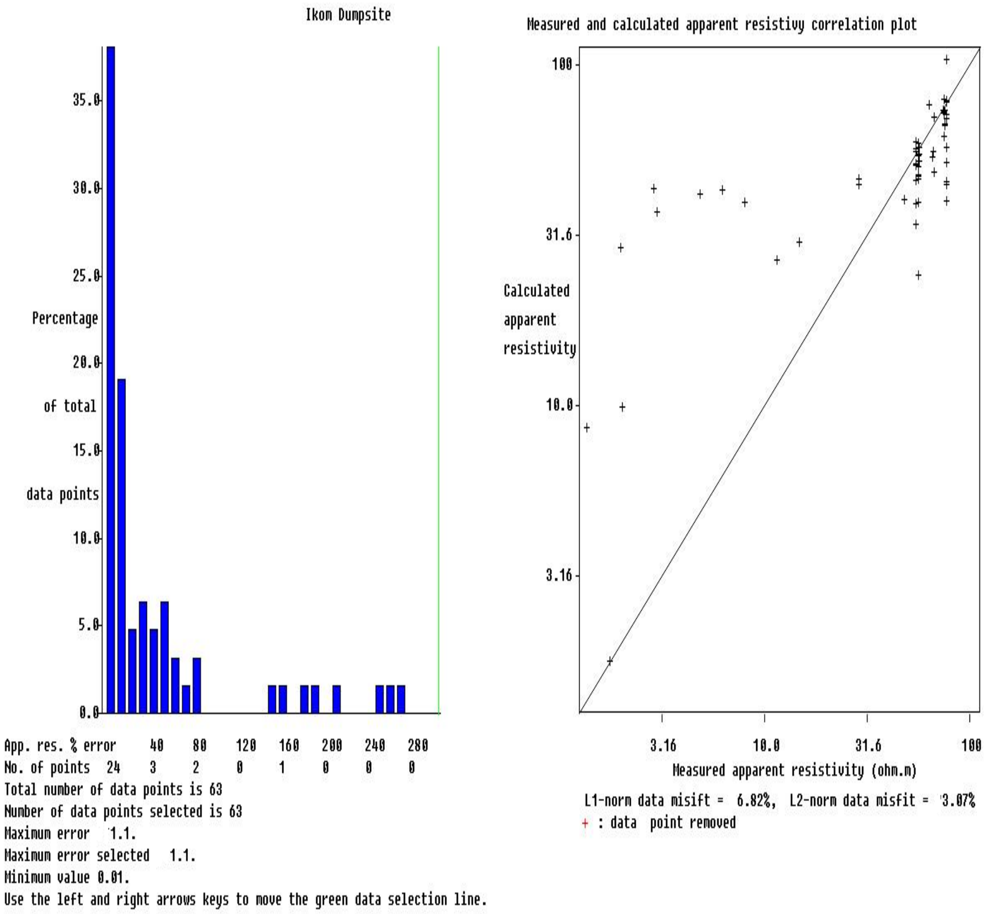

Figure 4. Apparent Resistivity Plot of Leachate Pollution atIkomDumpsite.

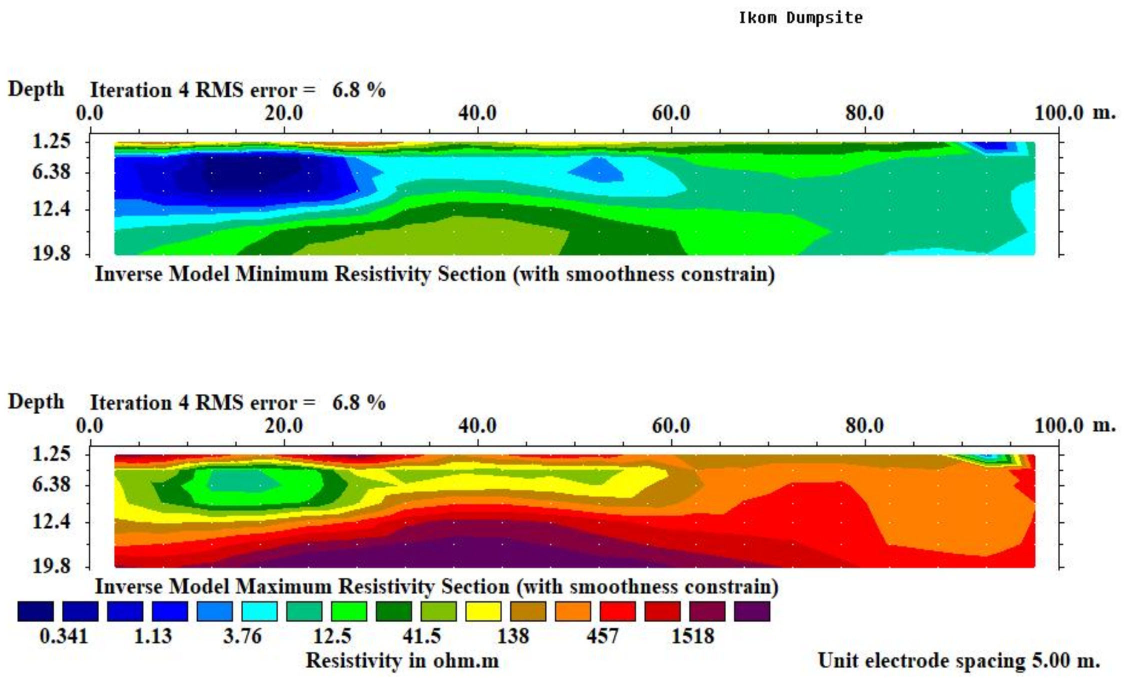

Figure 5. Minimum and maximum extent of Leachate invasion within the cretaceous sediments at Ikom Dumpsite.

(blue and green colors), suggesting the presence of conductive materials, likely indicating water-saturated zones or leachate plume. At greater depths (below 10 meters), resistivity increases slightly but remains relatively low, suggesting less conductive but still moist materials. The bottom section (maximum resistivity) shallow depths show a more complex resistivity distribution with higher resistivity values (yellow, orange, and red colors) dominating. This indicates the presence of more resistive materials such as dry soil or sand. There are significant high-resistivity anomalies, particularly in the central part (around 40-60 meters horizontal distance) and to the right end (80-100 meters). These areas could represent dry, compacted waste, or other resistive materials.

This section shows the uncertainty in the resistivity model (Figure 6). Lower percentage values (blue and green colors) indicate higher confidence in the resistivity values, while higher percentage values (red and brown colors) indicate lower confidence. The confidence zone or shallow to middle depths (0-12 meters) have lower uncertainties (blue to green colors) in most areas, suggesting the resistivity values here are more reliable. Higher uncertainties (red to brown colors) are observed at greater depths (below 12 meters) and towards the edges of the survey line.

4.3.1 Vertical Electrical Sounding and Lithology of the Dumpsites

The VES investigation is detailed in (Table 5, Figure 7). The presented dataset elucidates diverse geological characteristics and lithological compositions at Ikom dumpsites. Apparent resistivity values exhibit a range from 323.79 Ωm to 39.14 Ωm, indicative of varied subsurface resistive properties. Layer thicknesses demonstrate variability, spanning from 1.41 m to ∞ (infinity), signifying undefined thickness for specific strata. Depths extend from 1.41 m to 55 m, providing insights into the subsurface structure. The identified lithology at this dumpsite encompasses laterites, sandstone, shale, dark gray shale, and dark shale, contributing to a comprehensive understanding of the geological composition in the specified location.

Three distinct curve types, denoted as H, K, and Q, are delineated in (Table 7). Regarding Vertical Electrical Sounding (VES) curves, the H curve type is distinguished by its bowl-shaped configuration, characterized by an initial decrease in resistivity followed by an increase. This H-type curve suggests the presence of an intermediate layer with reduced resistivity, indicative of a zone exhibiting consistent resistivity values. The presence of water in this context is contingent upon the specific characteristics of the adjacent materials, potentially indicating the presence of water-bearing layers within the "bowl. "Conversely, the K curve type exhibits bell-shaped curves (bell-type), with the middle layer demonstrating higher resistivity. In contrast, the Q curve type displaysa descending curve, featuring successively decreasing resistivities (Table 6, 7). The Q segment, characterized by a significant reduction in resistivity, implies the presence of highly conductive materials such as saturated sediments or groundwater, which

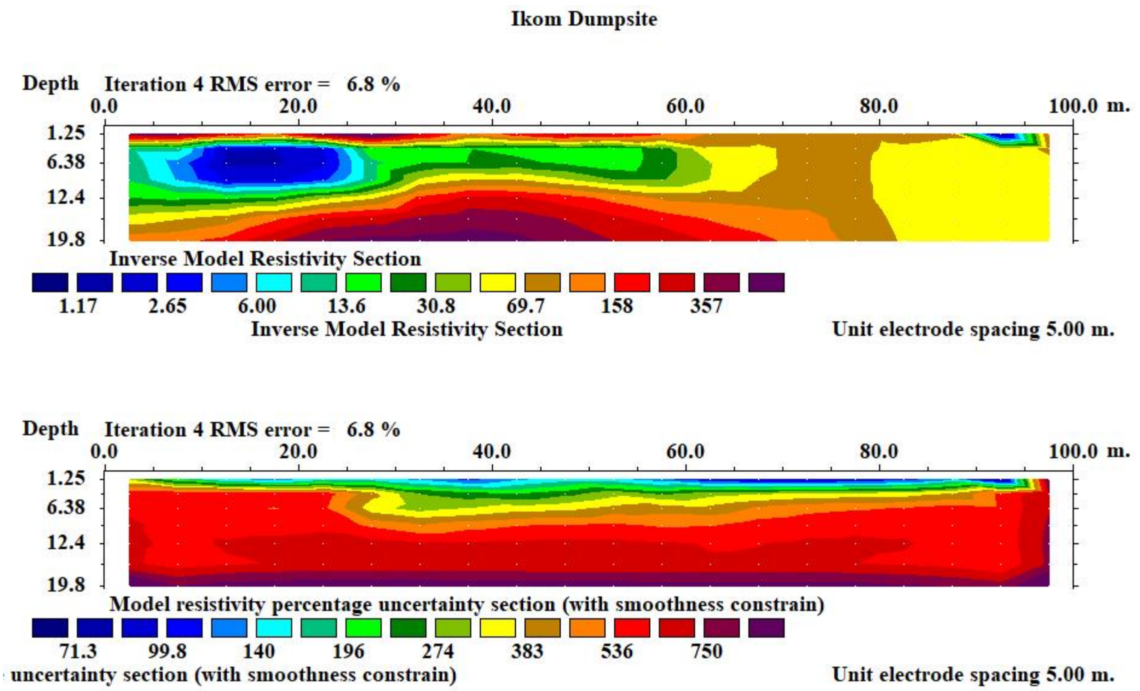

Figure 6: Percentage uncertainty of Leachate invasion within the cretaceous sediments at Ikom Dumpsite.

Table 6. VES at Ikom dumpsite

L	a/2	a	L^2	a^2	L^2-a^2	(L^2-a^2)/a	π/4	π/4(L^2-a^2)/2	R	ρ
6	1	2	36	4	32	16	0.7855	12.568	28.96	363.9693
8	1	2	64	4	60	30	0.7855	23.565	15.85	373.5053
10	1	2	100	4	96	48	0.7855	37.704	10.67	402.3017
10	2	4	100	16	84	21	0.7855	16.4955	5.621	92.72121
12	2	4	144	16	128	32	0.7855	25.136	7.583	190.6063
16	2	4	256	16	240	60	0.7855	47.13	3.537	166.6988
20	2	4	400	16	384	96	0.7855	75.408	4.96	374.0237
20	3	6	400	36	364	60.66667	0.7855	47.65367	3.425	163.2138
30	3	6	900	36	864	144	0.7855	113.112	2.276	257.4429
40	3	6	1600	36	1564	260.6667	0.7855	204.7537	2.669	546.4875
50	3	6	2500	36	2464	410.6667	0.7855	322.5787	1.636	527.7387
60	3	6	3600	36	3564	594	0.7855	466.587	1.362	635.4915
60	10	20	3600	400	3200	160	0.7855	125.68	0.8142	102.3287
70	10	20	4900	400	4500	225	0.7855	176.7375	0.2724	48.1433
80	10	20	6400	400	6000	300	0.7855	235.65	0.3323	78.3065
100	10	20	10000	400	9600	480	0.7855	377.04	0.124	46.75296
120	10	20	14400	400	14000	700	0.7855	549.85	0.1484	81.59774
140	10	20	19600	400	19200	960	0.7855	754.08	0.0683	51.50366
160	10	20	25600	400	25200	1260	0.7855	989.73	0.03822	37.82748
180	10	20	32400	400	32000	1600	0.7855	1256.8	0.1107	139.1278
200	10	20	40000	400	39600	1980	0.7855	1555.29	0.03171	49.31825
200	30	60	40000	3600	36400	606.6667	0.7855	476.5367	0.03822	18.21323

Table 7. Vertical Electric Sounding (VES) apparent resistivity and depth of the lithology in the study areas.

Sounding location	Number of Layer	Apparent resistivity (Ωm)	Layer thickness	Depth (m)	Curve Types	Lithology
Ikom Dumpsite	1	323.79	1.41	1.41	HKQQ	Laterites
	2	165.51	3.38	4.79		Sandstone
	3	312.26	4.37	9.16	$P_1>P_2<P_3>P_4>P_5>P_6$	Shale
	4	66.02	1.60	10.76		Dark gray shale
	5	51.15	10.29	21.04		Dark gray shale
	6	39.14	∞	55		Dark shale

$P_1>P_2>P_3$=Q (descending curve); $P_1<P_2>P_3$=K (Bell curve); $P_1>P_2<P_3$=H (Bowl curve).

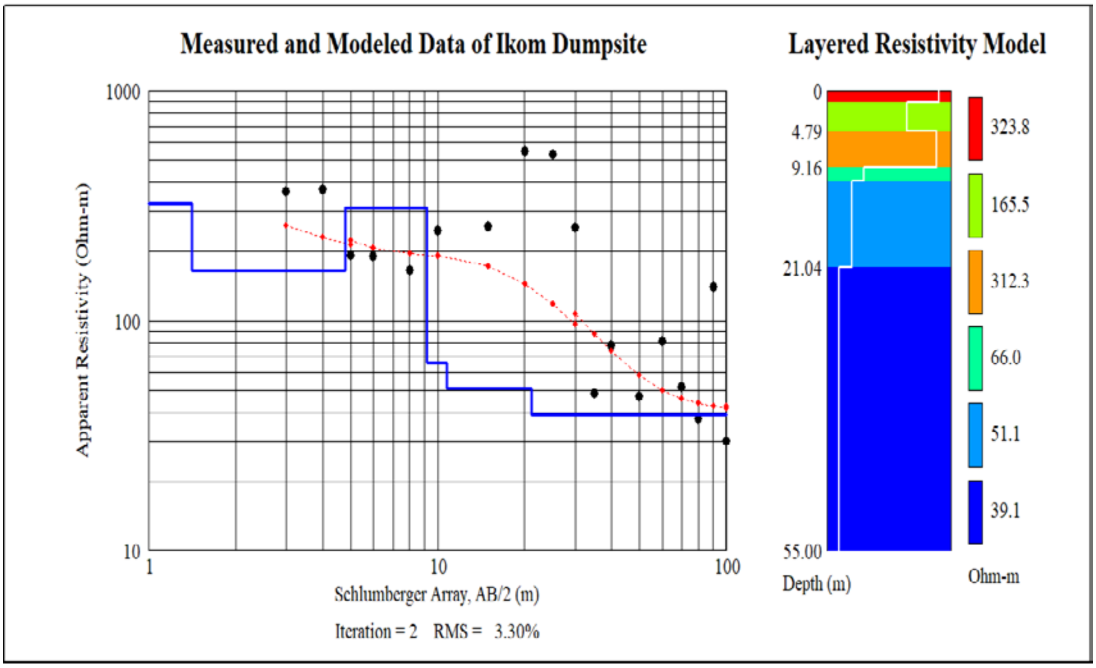

Figure 7. Modelled VES Data at Ikom Dumpsite.

are indicative of a water-bearing layer. Furthermore, it is essential to emphasize that the Ikom dumpsite demonstrates insufficient aquifer protective capacity, as reflected by values below 0.1, as detailed in Tables 8 and 9.

In Figure 7, a chromatic gradient is employed to illustrate the vertical electrical resistivity distribution in the subsurface. Fracture zones are characterized by diminished resistivity in contrast to the hard rock, owing to the inherent moisture content within these fracture zones. This distinction is visually apparent as the blue colour, representing porous and fracture zones.

5. DISCUSSIONS

The findings of the extent of leachate from a major dumpsite within the Cretaceous sediments at Ikom show a revealing investigation in the cretaceous sediments zone. The concentrations of Lead and Cadmium in the soil exceeded regulatory limits, ranging from 552.34 to 556.93 mg/kg and 11.88 to 7.46 mg/kg, respectively, as detailed in Table 2.

Conversely, concentrations of Arsenic, Chromium, and Nickel remained moderate and within the stipulated limits. Various studies, such as those by Handex (2016), Akshay et al., (2017), and Essien et al. (2022), affirm that dumpsites receive diverse materials containing pollutants, leading to soil contamination via leachate percolation and precipitation. The concentrations exceeding regulatory thresholds emphasize the critical need for effective management and remediation strategies to mitigate risks associated with dumpsite leachate. Similarly, borehole water

Table 8. Protective capacity rating of the dumpsites at the study location.

Location	Resistivity (Ωm)	Thickness (m)	Depth (m)	Layers	SL= hi/pi	Longitudinal conductance	Rating
	(pi)	(hi)	(di)				
Ikom	957.87	21.05	47.16	6	0.022	<0.1	Poor

Table 9. 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
<0.1-0.00	Poor

Source: (Igelle et al., 2024).

analysis in the vicinity of the Ikom dumpsite, as detailed in Table 3, reveals that levels of Arsenic, Lead, Cadmium, and Nickel surpass WHO limits in specific boreholes (BH2 and BH3). This suggests potential inadequacies in soil porosity and unfavourable geological conditions within the study location. These results indicate that leachate has permeated the cretaceous sediments surrounding the dumpsite. These findings are consistent with previous studies by (Ševčíková et al., 2021; Igelle et al., 2024), which documented significant contamination in borehole water near the dumpsite. In contrast, the 2D resistivity survey conducted at the lower elevation of the Ikom dumpsite, as shown in Figures 4 and 5, provides crucial insights into the subsurface conditions. The calculated inverse resistivity of 5.99 Ωm at a depth of 9.26 meters indicates a leachate-infiltrated zone at lateral distances of 40m and 80m along the profile. The low resistivity values observed in this survey are likely attributable to the presence of dissolved heavy metals from decomposed waste materials, further indicating leachate penetration into the cretaceous sediments. The correlation plot between measured and calculated apparent resistivity demonstrates a strong linear relationship, underscoring a consistent resistivity pattern across the dumpsite.

The 2D survey indicates that high resistivity areas (top section) likely represent dry, compacted waste, soil, or other resistive materials. Regions exhibiting low resistivity in the upper section imply the presence of conductive materials, such as water-saturated waste or leachate plumes. Conversely, areas of high confidence, primarily located from shallow to intermediate depths (up to 12 meters), indicate that resistivity values in these regions are robust and reliable. In contrast, low confidence areas identified at greater depths and near the survey boundaries suggest reduced reliability of resistivity values, likely due to diminished data resolution in these zones. A related investigation revealed a low resistivity zone indicative of leachte pollution at depths of 0.375 to >7.20m (Ugbor et al., 2021; Bala 2022; 2023; Igelle et al., 2024; Franco et al., 2024). This study aligns with the studies conducted by Ugbor et al., (2021). The low resistivity values were attributed to dissolved compounds from decomposed waste materials, consistent with previous studies (Ganiyu et al., 2016; Abua et al., 2023; Igelle et al., 2024). Additionally, the lithological composition of the Ikom dumpsite, as revealed by VES investigations, consists of laterites, sandstone, shale, and dark gray shale, offering critical insights into the subsurface characteristics (Table 6). While moderate to high current density areas represent rock units. Specifically, the Ikom dumpsite showcases an inverse resistivity of 5.99 Ωm at a depth of 9.26 m, with the leachate-infiltrated cretaceous sediments zone identified at lateral distances spanning from 10m to 40m along the profile. The invasion of dumpsite leachate at 9.26 m depth, shows that leachate has invaded the shale and dark gray shale zone of the dumpsite. The thickness of layer 1.41 to layer 4.37 affirmed the invasion of leachate at the shale and dark shale gray zone. The thickness of each layer can influence the movement and containment of leachate. For instance, thicker layers may act as barriers to leachate migration, while thinner layers may allow for more rapid movement. The aquifer protective capacity ratings below (<0.1) further corroborate the inadequate protective capacity, likely attributable to soil saturation by dumpsite leachate (Emecheta et al., 2023; Sirsat et al., 2023).

Devaraj et al., (2020) and Sabry et al., (2023) affirmed that cretaceous sediments are characterized by their porosity and permeability, and play a crucial role in regulating groundwater flow and storage. Cretaceous sediments have the potential to enable extensive transport of pollutants (Xu et al., 2024). Contaminants can disperse laterally through groundwater flow and vertically through diffusion and advection mechanisms (Mosthaf et al., 2024). Even-though, the VES curves depict distinct resistivity variations indicating a saturated zone at the study location (Table 7, 8). Pollutants can obstruct sediment pore spaces, diminishing porosity and permeability, and thereby hindering groundwater flow and storage (Wang et al., 2023; Emmarloo et al., 2024). This reduction can lead to decreased water availability, exacerbate drinking water scarcity, and compromise the sustainability of water resources in the affected regions. This emphasized potential challenges in safeguarding groundwater resources, necessitating robust management and monitoring measures to prevent contamination and uphold water quality standards.

6. CONCLUSION

In conclusion, the investigation into leachate extent within the Cretaceous sediments at the Ikomdumpsite unveils significant soil contamination, with lead and cadmium concentrations surpassing regulatory limits. While other heavy metals remain within acceptable levels, the presence of contaminants highlights the urgent need for effective management strategies. Borehole water analysis indicates elevated levels of arsenic, lead, cadmium, and nickel in certain locations, suggesting leachate infiltration and unfavourable geological conditions. 2D resistivity surveys further confirm leachate saturation in the cretaceous sediments. The correlation between measured and calculated resistivity underscores the reliability of the survey, aiding in identifying potential leachate zones. Lithological investigations reveal the presence of shale and dark gray shale, influencing leachate movement and containment. Thicker layers may impede migration, while thinner layers facilitate rapid movement. Cretaceous sediments' porosity and permeability play a crucial role in regulating groundwater flow. Pollutants can obstruct sediment pore spaces, diminishing porosity and permeability, and thereby hindering groundwater flow and storage. VES curves indicate distinct resistivity variations, signifying saturated zones and highlighting challenges in safeguarding groundwater. Robust management and monitoring measures are imperative to prevent contamination and uphold water quality standards.

Authors Contribution:

Idaga E. Igelle, **Chinasa Uttah**, and **O. Okang Akim**: Conceptualization and methodology. **H. Izuakolam Kanu**, and **I. Chigbe Ekwok**: Data processing, writing original draft preparation. **Kamal Abdelrahman**, **Hassan ALZAHRANI**, and **Stephen E. Ekwok**: Validation, methodology, reviewing and editing, conceptualization. **Peter Andráš and Jana JANŠTOVÁ**: Review& editing. **Ahmed M. Eldosouky**: Methodology, reviewing and editing, conceptualization. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST:
The authors declare no conflict of interest.

DATA AVAILABILITY STATMENT:
The data used in this study can be made available upon request from the authors. E. IdagaIgelle: evadag003@yahoo.com; igellei@unical.edu.ng. +2349036552684.

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