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GEOELECTRIC SIGNATURES FROM A LEACHATE PLUME MAPPED FROM A BASEMENT COMPLEX TERRAIN IN AKURE, NIGERIA

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ABSTRACT

In this study, we investigated the implications of a leachate plume within an aquifer system, unravelling the intricate dynamics that govern contaminant transport and dispersion. An integrated approach of geophysical investigations is used to establish the impact of an open-waste disposal site around Aromed, in a part of Akure, in the Precambrian Basement Complex of Southwestern Nigeria. Investigations using eight (8) Vertical Electrical Sounding (VES) and Double-Dipole Resistivity Tomography (ERT) along two (2) traverses were conducted. The geoelectric interpretation and the inverted two-dimensional electrical resistivity tomography (ERT) images provided insights into the underlying geological composition, identifying three distinct units: the topsoil, the weathered column, and the fractured Basement/fresh Basement bedrock. The geoelectric tomography structures in the 2-D interpretation reveal that the dumpsite area exhibits low apparent resistivity estimated to be between 12 to 71 ohm-m in both the topsoil and the weathered column aquiferous zone. These values closely agree with results from the geoelectric sections, which range between 11 - 68 ohm-m, respectively. The relatively low apparent resistivity results are suggestive to be due to the presence of leachate's chemical composition from the open waste disposal sites, which are suspected to be generated from the dissolution of ions of iron and other conductive minerals producing the leachate plume. The probable leachate depth of migration as revealed by the 2-D tomography structures varies from about <1 – > 14 m beneath the dumpsites. The leachate migration, which is structurally controlled, has a southward flow, majorly in the orientation with the observed structures. The subsurface depression-relief is also attributed to influence the direction of leachate flow. In conclusion, it is suggested that groundwater in the aquiferous zones in the vicinity of the dumpsites have entered a significant pollution level; hence water in the aquifer is not safe for consumption.

Keywords: *Groundwater, Leachate Plume, Electrical Resistivity Tomography, Geoelectrical Resistivity, Basement Complex.*

INTRODUCTION

The activities of man within the environment have often led to grave environmental issues, one of such is groundwater contamination or pollution. This may be due to indiscriminate disposal of household and industrial wastes into water bodies, with attendant degradation of wastes and migration of leachates within the earth (*Figure* 1). Solid waste landfill management in urban centres has been an issue of major concern in developing nations which Nigeria is one. Every day, anthropogenic wastes are produced and discharged off in exposed surface water bodies and landfills without considering the impact on the underground structural systems, local rock types, and its closeness to human habitation. (Ball and Stove, 2002; Bello and Adegoke, 2010; Olowofela *et al.*, 2012; Song *et al.*, 2022). Hence, it is probable that landfill sites will continue to be a significant contributor to groundwater contamination in the immediate and later future (Oni *et al.*, 2020; Ugwu and Nwosu, 2009). Water is therefore vital, as evidenced by the fact that buried waste at landfills endangers aquifers, human health, the environment, and the economy. Non-invasive geophysical methods, e.g. electrical and electromagnetic (EM) methods, seismic refraction, and spontaneous potential (SP), have been used to investigate changes in fluid content, contrasts in density, chemical and mineralogical composition, and temperature variations in the subsurface (Dobrin and Savit, 1988; Keary *et al.*, 2002).

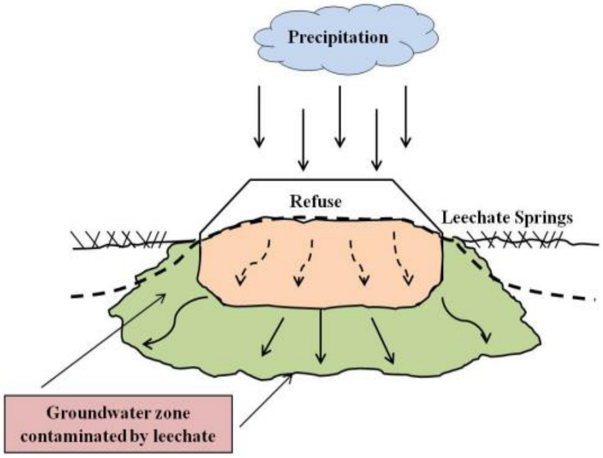


Figure 1: Groundwater contamination generated by leachates from open refuse dumps **(**modified conceptual model by WHO, 2006).

It has been established that several dumpsites, containing organic and inorganic materials, have existed for more than four decades within Akure Metropolis (Bayode *et al.*, 2011), one of which is the Aromed dumpsite. This decomposition generates a leachate plume capable of impairing groundwater's water quality. A considerable segment of the population residing in the urban area relies predominantly on groundwater sourced from manually excavated wells for their household water needs. Consequently, it is imperative to conduct a hydrogeological evaluation to determine the groundwater quality and quantify the magnitude of the dumpsites' influence. Hydrogeophysical investigations are a highly beneficial method for estimating geoelectric characteristics in underground rock water storage systems. Geophysical analyses play a pivotal role in the realm of water management by supplying essential data to comprehend subsurface conditions, assess groundwater resources, and help to better characterise hydrogeological structures (Fleming *et al.*, 2021; Oyeyemi *et al.*, 2023; Adedinni et al., 2023).

The study location is situated within a lowland Tropical rainforest, which is distinguished by well-defined rainy and dry seasons. The average temperature is 27°C through each month, although the average relative humidity exceeds 25 %. Nevertheless, in the northern part of Ondo state, the average temperature in each month and its corresponding variation are approximately 30°C. The average relative humidity each month is below 70 %. Southwards, precipitation occurs consistently throughout the year, although November through January may exhibit comparatively lower levels of rainfall. The average annual precipitation surpasses 2000 millimetres. Nevertheless, in the northern region, a distinct dry season occurs between November through to March, characterised by minimal or negligible precipitation. The annual precipitation in the northern region experiences a significant decrease, amounting to approximately 1800 mm (Osotuyi *et al.*, 2021a). The predominant vegetation in the area is the high forest, characterised by a diverse range of hardwood timber species. The swamp flats encompass the freshwater swamp forests located in the inland regions, as well as the mangrove vegetation units found along the coastal areas. One noteworthy characteristic of the state's flora is the abundance of arboreal crops. The primary tree crops encompass oil palms, cacao, kola, rubber, and citrus. Cacao is notably the predominant crop. The research region exhibits a predominantly level topography, characterised by the presence of horizontally oriented rock exposures. The topography elevation within the research region exhibits variation, ranging from 350 metres (1148 feet) above mean sea level. One notable feature of the drainage systems in regions characterised by Precambrian Basement rocks is the abundant presence of numerous tiny channels of rivers. The smaller river bodies experience prolonged periods of aridity, particularly between the months of November and May. The drainage system in the vicinity of Akure exhibits a dendritic pattern, as observed by Osotuyi *et al.* (2021a). The river known as Ala exerts significant influence over the drainage system within the urban area of Akure, often referred to as Akure Metropolis.

In Southwestern Nigeria, the Precambrian Basement Complex rocks constitute the dominant rock types that underlay the study area (Rahaman and Ocan, 1998; Obaje *et al.*, 2004; Oni *et al.*, 2020; Salako *et al.*, 2019; Osotuyi *et al.*, 2021b). From the reconnaissance survey, Migmatite Gneiss is the main rock lithologic unit that is identified (*Figure* 2). The rock type is observed to be occurring as flat-lying outcrops. The Migmatite Gneiss is observed as relatively flat outcrops in the region of the dumpsite. The Migmatite rock that underlies the dumpsite potentially underwent structural deformation during its geological history. Groundwater is typically located within the weathered layer and the fractured and/or weathered column of basement rocks (Offodile, 1988; Salako *et al.*, 2019; Osotuyi *et al.*, 2021b). The rock outcrops in the study location are predominantly seen on the surface in the northern region and towards the southern parts, as depicted in Figure 2. Typically, structural discontinuities such as joints, faults, shear zones, and fractures within the bedrock have the potential to serve as conduits for the migration of leachate and groundwater (Oni *et al.*, 2020; Osotuyi *et al.*, 2023). Also very dominant are the undifferentiated migmatite rock types. The rocks in numerous locations have undergone significant in-situ weathering, resulting in the occurrence of multiple pockets of weathered sand and sandy clay within the region. This geological phenomenon gives rise to a topography resembling sedimentary basins (Falebita *et al.*, 2018; Salako *et al.*, 2019; Osotuyi *et al.*, 2022). The sand pockets serve as effective aquifers for subterranean water, facilitating the replenishment of the Ala River during periods of low precipitation.

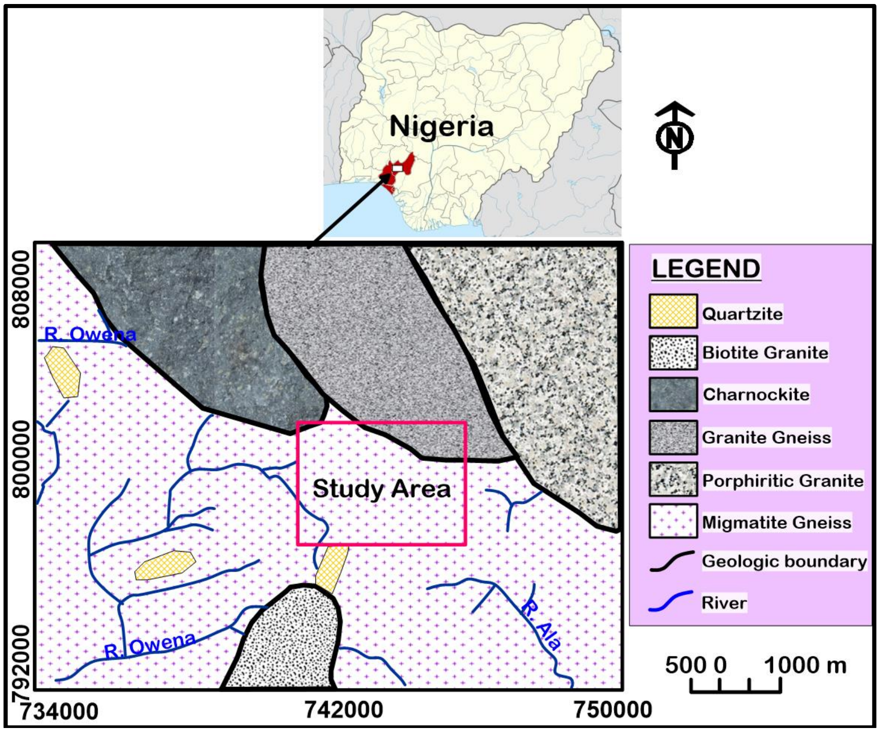


Figure 2: Geological map of around Akure showing the rock distribution and the drainage pattern (developed from the NGSA Geological map sheet with modifications to depict drainages).

The aquifers characteristic of this area, which lies within the Basement Complex terrain, are patchy, irregular, and in the form of shallow subsurface depressions (Offodile, 1988; Salako *et al.*, 2019) and could be single or multilayered. Often, these aquifers could preserve remnants of primary basement rocks. Fractures in crystalline rocks can have a notable influence on groundwater, especially when they are situated at significant depths and are concealed by a thick layer of overburdened material. The presence of this subterranean complex imparts intricate hydrogeological attributes to the terrain. It is typified by highly limited groundwater reservoirs in extent with highly localized aquifers developed from secondary porosity and weathering induced by fracturing and other geological processes (*Odusanya and Amadi, 1990;* Olayinka and Olayiwola, 2001; Salako *et al.*, 2019; Oni *et al.*, 2020; Osotuyi *et al.*, 2021a). This illustration is seen in the UNESCO model presented below in Figure 3.

This study focused on the use of non-invasive surface electrical resistivity measurements involving Vertical Electrical Resistivity drilling (also known as Vertical Electrical Sounding, VES) and 2-D Electrical Resistivity Tomography (ER or ERT) to delineate and characterise the subsurface structures and aquiferous zones in the study area. The geoelectrical resistivity measurements were used to assess both the structural configuration of the geology beneath the study area and the geoelectric parameters of possible fluid flowing beneath the subsurface soil and rock lithologies beneath the waste disposal site.

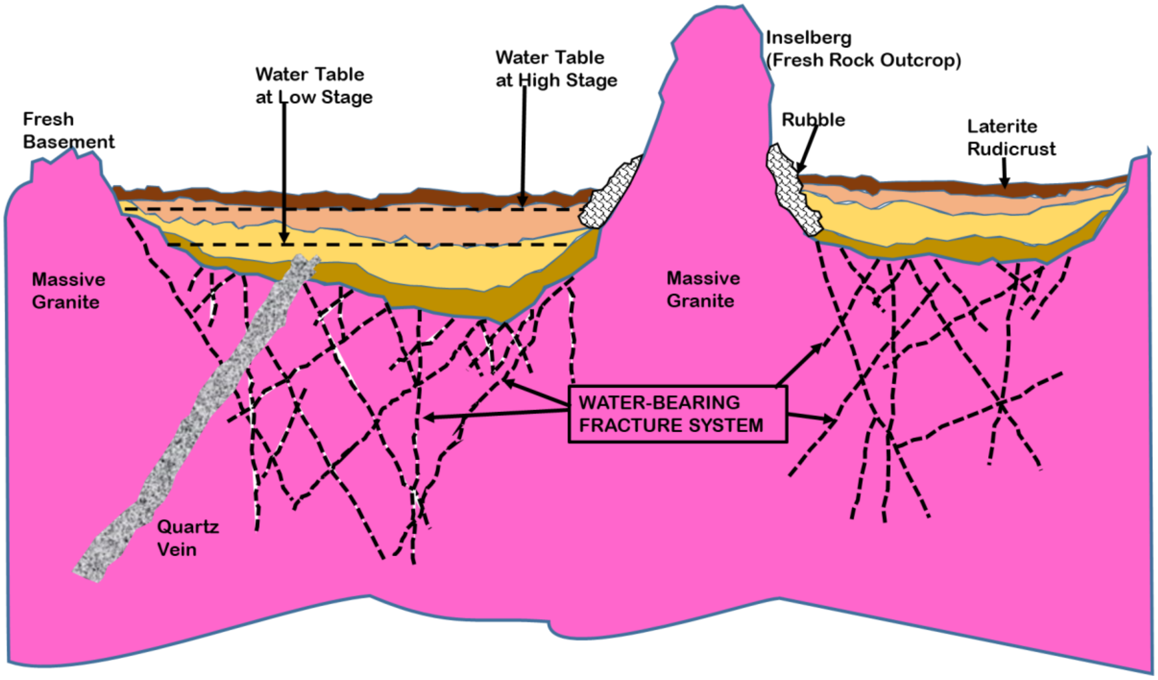


Figure 3: Model of Hydrogeological Characteristics in Basement Complex Terrain (UNESCO, 1994).

MATERIALS AND METHOD

The present investigation incorporates the use of the electrical resistivity (ER) approach, specifically engaging the Vertical Electrical Sounding (VES) and Dipole-Dipole (also referred to as Double-Dipole in other part of this study) horizontal profiling (Electrical Resistivity Tomography, ER or ERT) methodologies. These methodologies offer cost-effective, non-intrusive, and non-destructive techniques for the mapping of underground structural formations. These structures may serve as subsurface migration pathways for fluids (e.g. leachate plume) from open-waste disposal sites located within inhabited residential areas. The contrasts in electrical properties that exist between the host rocks and subsurface geologic structures are advantageous for the applicability of the ER method. This contrast allows for the detection of electrically conductive materials such as leachates and native groundwater (Telford *et al.*, 1990; Keary *et al.*, 2002; Oni *et al.*, 2020; Salako *et al.*, 2020; Song *et al.*, 2022; Zhang *et al.*, 2022). In this research, two traverses, each spanning approximately 18 meters in length, are created in an approximately North-South and East-West orientation. These traverses are positioned along and perpendicular to the strike, as depicted in Figure 4. The two-dimensional subsurface imaging survey was conducted in orthogonal directions approximately aligned with the North-South and East-West axes relative to the dumpsites. The selection of these directions was mostly based on accessibility considerations. The double-dipole array profiling method was employed along the 1st and 2nd traverses, as shown in Figure 4. Inter-electrode spacing of a = 1 metre was used to take the measurements, with the expansion factor (n) ranging from 1 to 5. The inversion of the dipole-dipole data was performed to retrieve a two-dimensional subsurface structure with the aid of the DIPRO inversion tool.

A total of eight (8) Schlumberger resistivity drilling operations were conducted within the designated study region. The distance between the electrodes, denoted as AB/2, was systematically adjusted within the electrode spread of 1 to 40 m. In total, four (4) depth soundings were conducted along each of the two traverses to establish a correlation of the Double-Dipole 2-D subsurface image. The resistivity data was collected via the PASI MODEL 16-GL resistivity metre. The data interpretation of VES entails the application of the partial curve matching approach and 1-D computer-aided forward modelling. This process was carried out using version 1.0 of WinRESIST software, developed by Vander (2004).

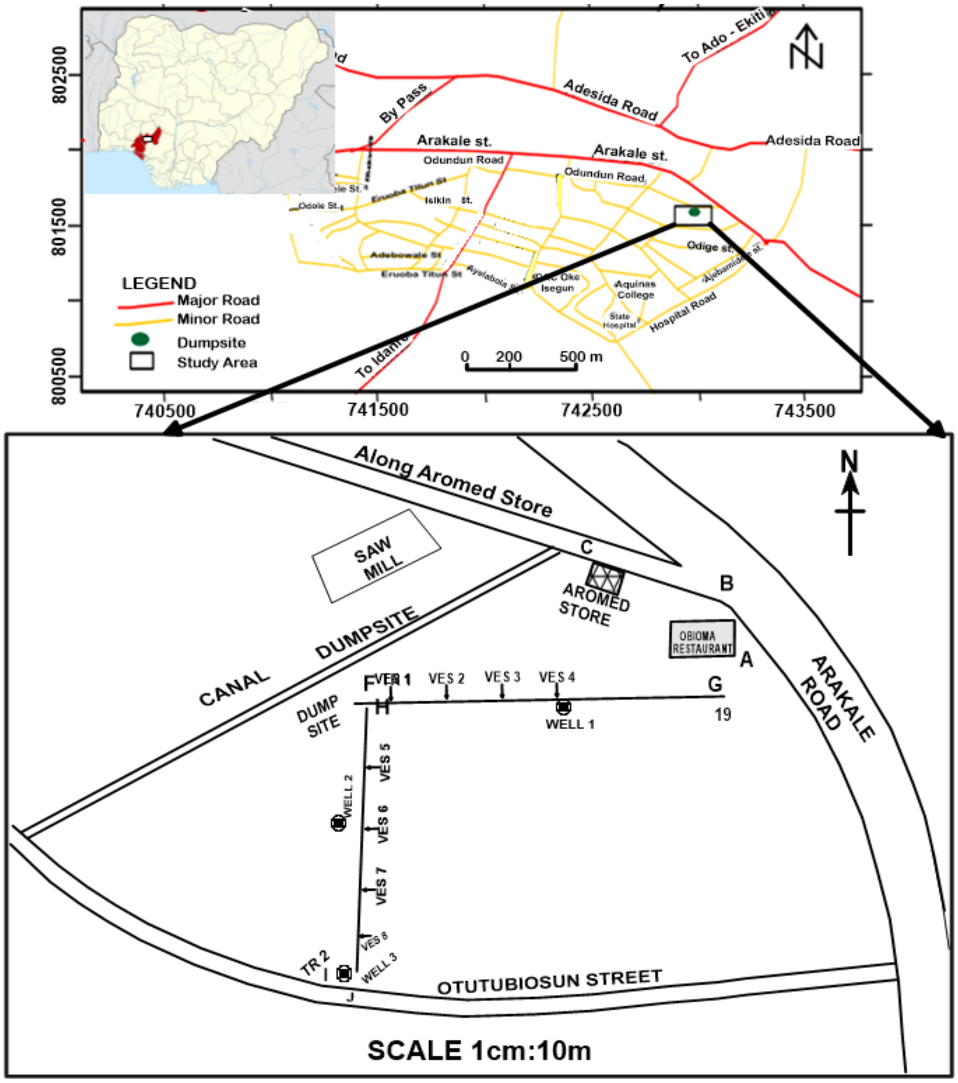


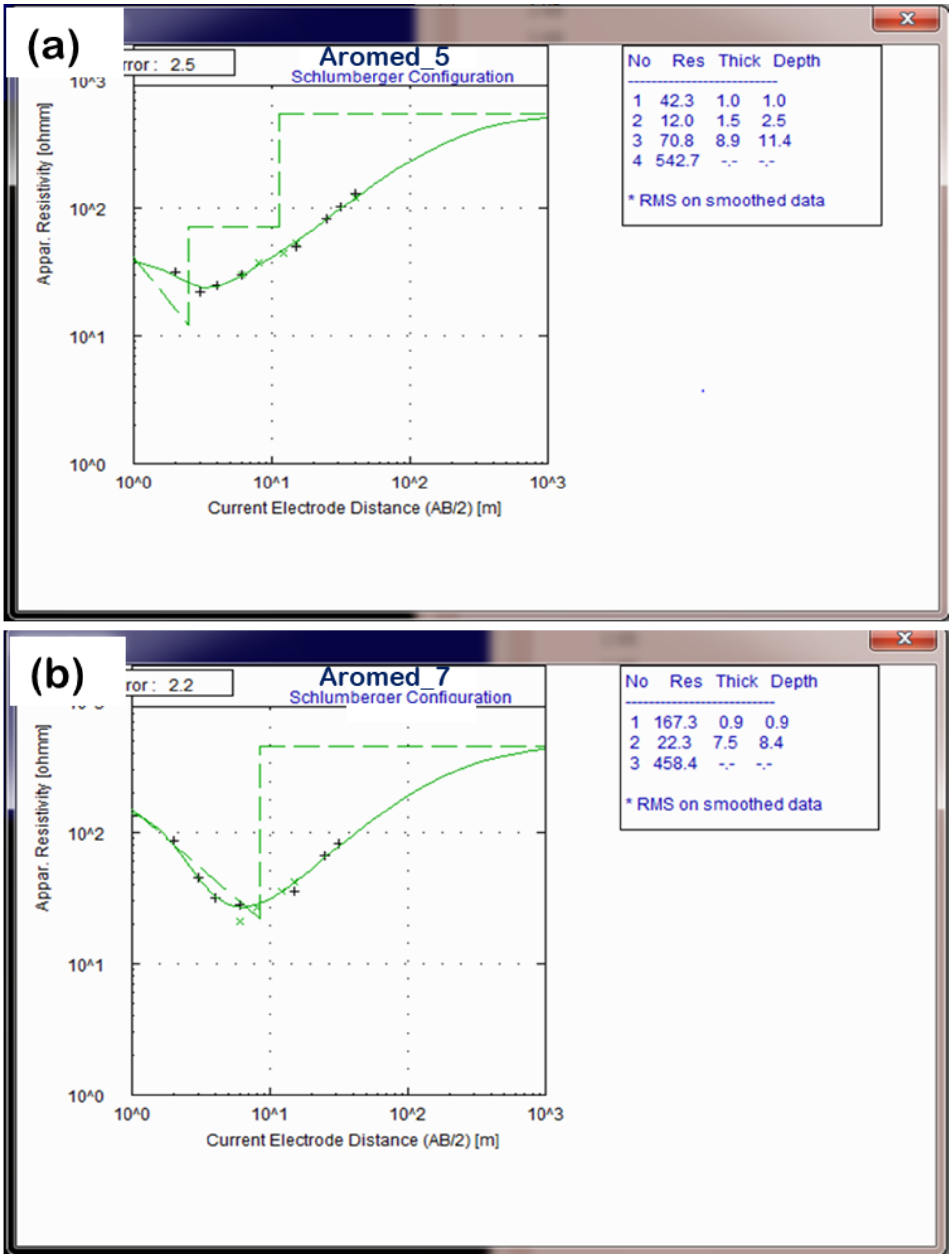
Figure 4: Map of study location and layout of the area under investigation.

RESULTS AND DISCUSSIONS

From the 8 VES stations, interpreted VES data produces predominantly the KH curves (e.g. VES 1) where $\rho_1 < \rho_2 > \rho_3 < \rho_4$, the A type curve (e.g. VES 2) where $\rho_1 < \rho_2 < \rho_3$, and H-type (e.g. VES 3, 4, 5, 6, 7 and 8) where $\rho_1 > \rho_2 < \rho_3$. Figure 5 (a and b) show type-curves obtained from the study site (Aromed VES 5 and VES 7). Three (3) to four (4) subsurface lithologic units are delineated from interpretation including the topsoil, the weathered and/or fractured column, and the Basement bedrock (also referred to as Lithotype 1, Lithotype 2, and Lithotype 3, respectively in Table 1). These three (3) layers are present in VES 2, 3, 4, 6, 7, and four (4) layers are present in VES 1, 5, 8. This is illustrated, as shown in the geoelectric sections, which are produced in an attempt to correlate the equivalent geoelectric layers delineated from the observed VES points along each traverse in the study location (Figure 6). We summarized the geoelectric parameters that are estimated from the VES data from the study area in Table 1. The geoelectric profile reveals vertical variations in the resistivity of the rock layers and changes in the lithology of the rocks of the Basement Complex because of the level of weathering the rocks have been exposed to.

The resistivity and thickness range for the first to third or fourth layers, where applicable, are presented in Table 1. The representative layers are; the topsoil, the weathered column, underlain by the fractured/weathered Basement bedrock. The immediate vicinity beneath and surrounding the dumpsite, as depicted in Table 1, exhibits comparatively low resistivity values. The values of the apparent resistivity from the topsoil vary between 4 to 177 ohm-m, with corresponding column thickness of between 0.7 to 1 m. The apparent resistivity value recorded in the topsoil around the dumpsite along traverse 2 is relatively high, indicating the presence of lateritic clay (Figure 6). The resistivity values encountered in the weathered layer range between 13 to 71 ohm-m with corresponding layer thicknesses between 0.9 to 8.9 m, respectively. The observed low resistivity (< 100 ohm-m) in the surface soil and the weathered substratum is indicative of a probable vertical migration of leachates generated at the dumpsites. This migration is suspected to extend from the surface soil down into the weathered column.

The resistivity values in the layers presumed to be the geoelectric bedrock range from 36 to 2191 ohm-m. The resistivity measurement for unaltered bedrock typically surpasses 1000 ohm-m, yet frequently diminishes to levels below 1000 ohm-m in instances of fracture or shear, as documented by Adepelumi et al. (2005), and Adepelumi et al. (2020), and Osotuyi et al. (2021). This particular incidence has been documented in VES 1, 2, 4, 5, 6, 7, and 8. The results of the 2-D Double-Dipole tomography model along profiles 1 and 2 are depicted in Figures 7 and 8, respectively. Three distinct layers, namely the topsoil, weathered layer, and foundation bedrock are retrieved from the tomography data. The retrieved tomography structure acquired beneath the dumpsite reveals that the top soil has essentially amalgamated with the weathered layer as a result of overlapping resistivity values ranging from low to high. As corroborated by the VES (Table 1), these two layers have relatively thin thicknesses. The topsoil exhibits distinct colour bands ranging from mild to deep shades of bluish, greenish, and yellow, as well as reddish or purple hues. The presence of yellow to reddish/purple colour bands between stations 15 - 18 (75 - 80 m) along profile 2, as depicted in figures 7 and 8, is indicative of the occurrence of topsoil lateritic concretion or fresh basement rock. This observation aligns with the findings from Olayinka and Olayiwola (2001) and Oni et al. (2019). The subsequent stratum is referred to as the weathered layer. The observed characteristic of this phenomenon is the presence of bands with a greenish coloration, as depicted in Figures 7 and 8.



```
No   Res   Thick  Depth
------------------------
 1   42.3   1.0    1.0
 2   12.0   1.5    2.5
 3   70.8   8.9   11.4
 4  542.7   -.-    -.-

* RMS on smoothed data
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```
No   Res   Thick  Depth
------------------------
 1  167.3   0.9    0.9
 2   22.3   7.5    8.4
 3  458.4   -.-    -.-

* RMS on smoothed data
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Figure 5: Representative inverted VES apparent resistivity curves obtained. (a) and (b) are the 1-D models from VES stations 5 and 7, respectively.

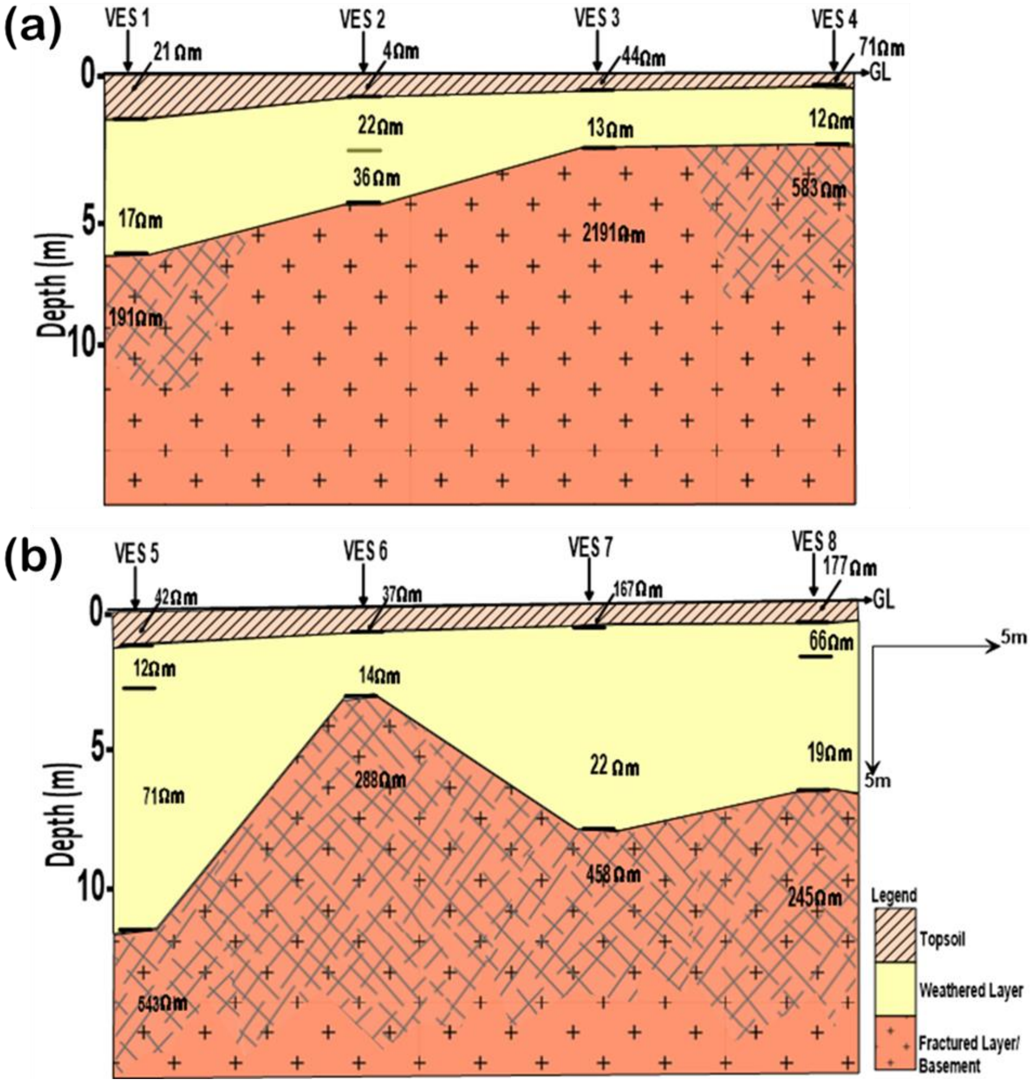

Figure 6: Geoelectric section along Traverse 1 (a) and 2 (b).

Typically, the resistivity values of the layer span a range of 12 to 60 ohm-m. The weathered column thickness range from less than one to eight metres. The geoelectric parameters observed in the 2-D pseudo-section exhibit a correlation with the geoelectric sections depicted in Figures 6 to 8. The 2-D Dipole-Dipole pseudo-resistivity profile displays the presence of a weathered layer that exhibits distinct patches characterised by light to deep-bluish colour bands. These colour bands serve as an indication of low resistivity values, as depicted in Figures 7 and 8. The presence of leachate saturation can be inferred from the zone exhibiting exceptionally low resistivity values, typically falling within the range of 9 to 14 ohm-m. This zone is visually distinguished by bands of light-blue to deep-bluish colours. The phenomena are observed within the range of stations 3 to 10, which corresponds to a distance of 14 to 51 m along profile 2, as depicted in Figures 3, 7, and 8. The plume's migration is observed to have originated from the uppermost layer (i.e. the topsoil).

Table 1: Table showing probable lithology types, apparent resistivity, thickness, and depth.

VES Stations	Layer Apparent Resistivity (Ωm)	Thickness (m)	Depth (m)	Probable Lithology
1	21	0.9	0.9	Lithotype-1
	37	0.8	1.7	Lithotype-2
	17	4.7	6.4	Lithotype-2
	191	∞	∞	Lithotype-3
2	4	0.6	0.6	Lithotype-1
	22	2.2	2.8	Lithotype-2
	36	∞	∞	Lithotype-3
3	44	0.8	0.8	Lithotype-1
	13	2.4	3.2	Lithotype-2
	2191	∞	∞	Lithotype-3
4	71	0.8	0.8	Lithotype-1
	12	2.4	3.2	Lithotype-2
	583	∞	∞	Lithotype-3
5	42	1	1	Lithotype-1
	12	1.5	2.5	Lithotype-2
	71	8.9	11.4	Lithotype-2
	543	∞	∞	Lithotype-3
6	37	1	1	Lithotype-1
	14	2.3	3.3	Lithotype-2
	288	∞	∞	Lithotype-3
7	167	0.9	0.9	Lithotype-1
	22	7.5	8.4	Lithotype-2
	458	∞	∞	Lithotype-3
8	177	0.9	0.9	Lithotype-1
	66	1.3	2.2	Lithotype-2
	19	4.7	6.9	Lithotype-2
	245	∞	∞	Lithotype-3

N.B. Lithotype-1 represents the topsoil, Lithotype-2 represents weathered column, and Lithotype-3 represents the fractured/Basement bedrock.

The last lithology corresponds to the bedrock located in the Basement, as evidenced by the presence of colour bands ranging from yellow to purple (see figures 7 and 8). The resistivity values read from the 2-D tomography structures exhibit a resistivity range spanning from 100 to 2796 ohm-m. The presence of significant discontinuities is observed in the sections between stations 3 and 6 (15 - 30 m) along profile 1, as well as between stations 8 and 11 (40 - 55 m) and stations 13 and 15 (65 - 75 m) along profile 2. The presence of fractured, faulted, or sheared zones is inferred from the examination of the two-dimensional resistivity structure, based on the observed discontinuities (Figures 7 and 8). The regions under consideration demonstrate low resistivity values, as evidenced by the presence of colour bands spanning from light green to deep blue (13 - 80 Ohm-m) on the surface. These zones extend in depth from 8 m to just over 20 m.

The dumpsite under investigation is situated near the reported structural characteristics, specifically cracks and faults, along profiles 1 and 2. The presence of light green to deep blue colour spectrum in the observed structures and their surroundings is believed to be indicative of leachate migration from the waste disposal site into the subsurface structures such as fractures, sheared zones, and faults. This phenomenon suggests the migration of pollution within these features. This finding supports the submission of Bayode *et al.* (2011) in a prior survey that was conducted around a comparable geological setting, which focused on an open-waste disposal site. Nevertheless, the thin thickness of the overburden, ranging from approximately between 3 to 9.5 m, with the existence of compacted subsoil of lateritic composition and/or basement rock (outcropping within the overburden beneath the dumpsite), as evidenced by the 2-D electrical tomography images and geoelectric profile (Figures 6-8), have constrained the accumulation and migration of leachate primarily within the identified structures such as fractures, faults, and shear zones that underlie the dump site.

The comparison and correlation between the 2-D structures from the resistivity tomography and the geoelectric profile (Figures 6 - 8) reveal that the region underlying the waste disposal site has comparatively low resistivity estimates, which vary between 4 to 71 ohm-m. This is vividly exhibited in the topsoil and the underlying weathered column. The observed resistivity properties below 40 ohm-m suggest the presence of dissolved conductive materials, hence indicating the presence of leachate contamination in the vicinity of the landfill site. Observations from the measurement of the water level taken from domestic water wells in the vicinity of the dumpsite, are typically within the range of 0.6 to 2.3 m, hence suggesting the presence of an elevated water table. The shallow depth of the aquifer validates the ease of encroachment of the plume on the underground water.

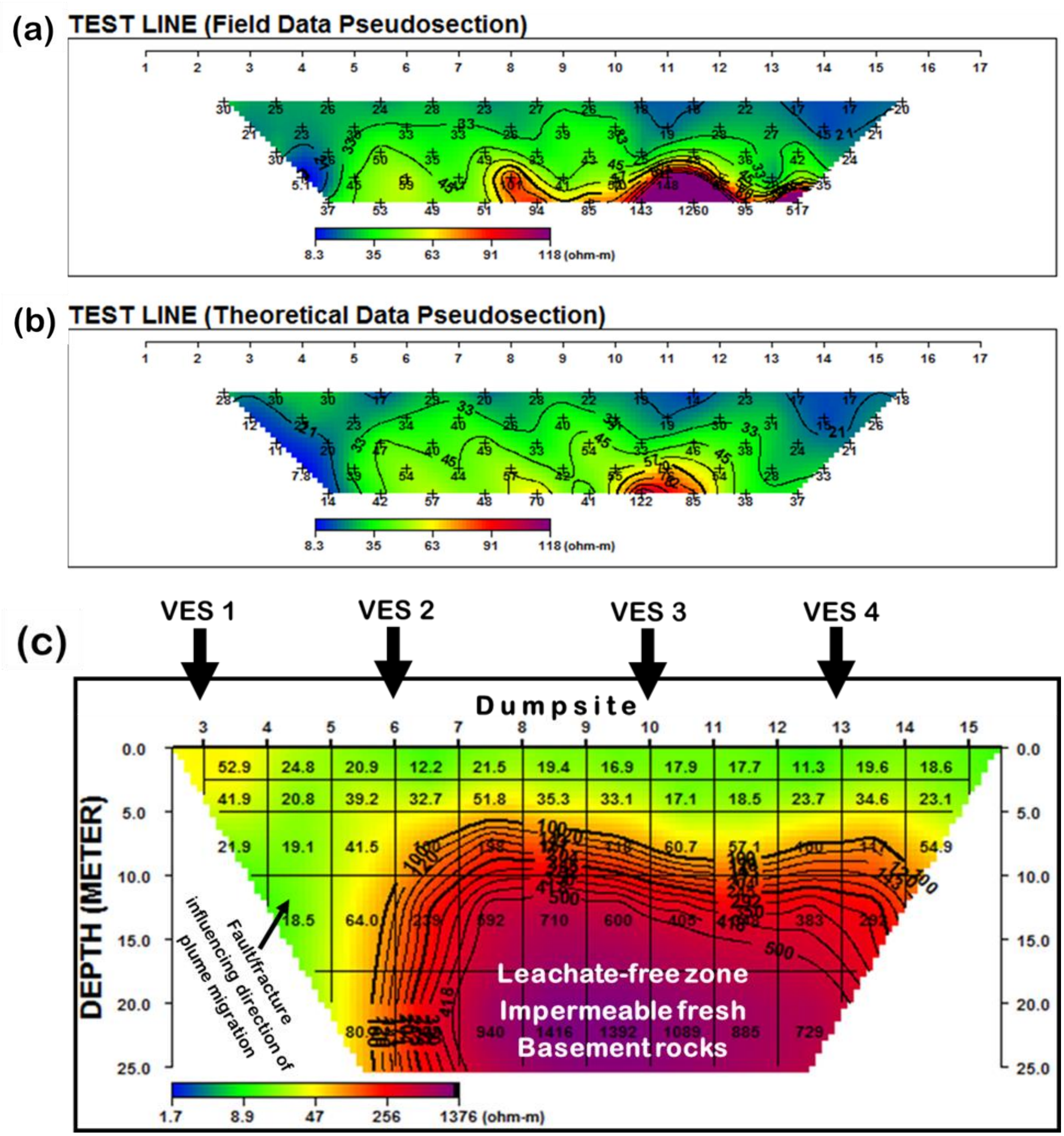

Figure 7: Electrical resistivity tomography image beneath traverse 1. (a) shows the pseudosection from field observation data, (b) shows the pseudosection from computed theoretical data, and (c) shows the 2-D Dipole-Dipole tomography section.

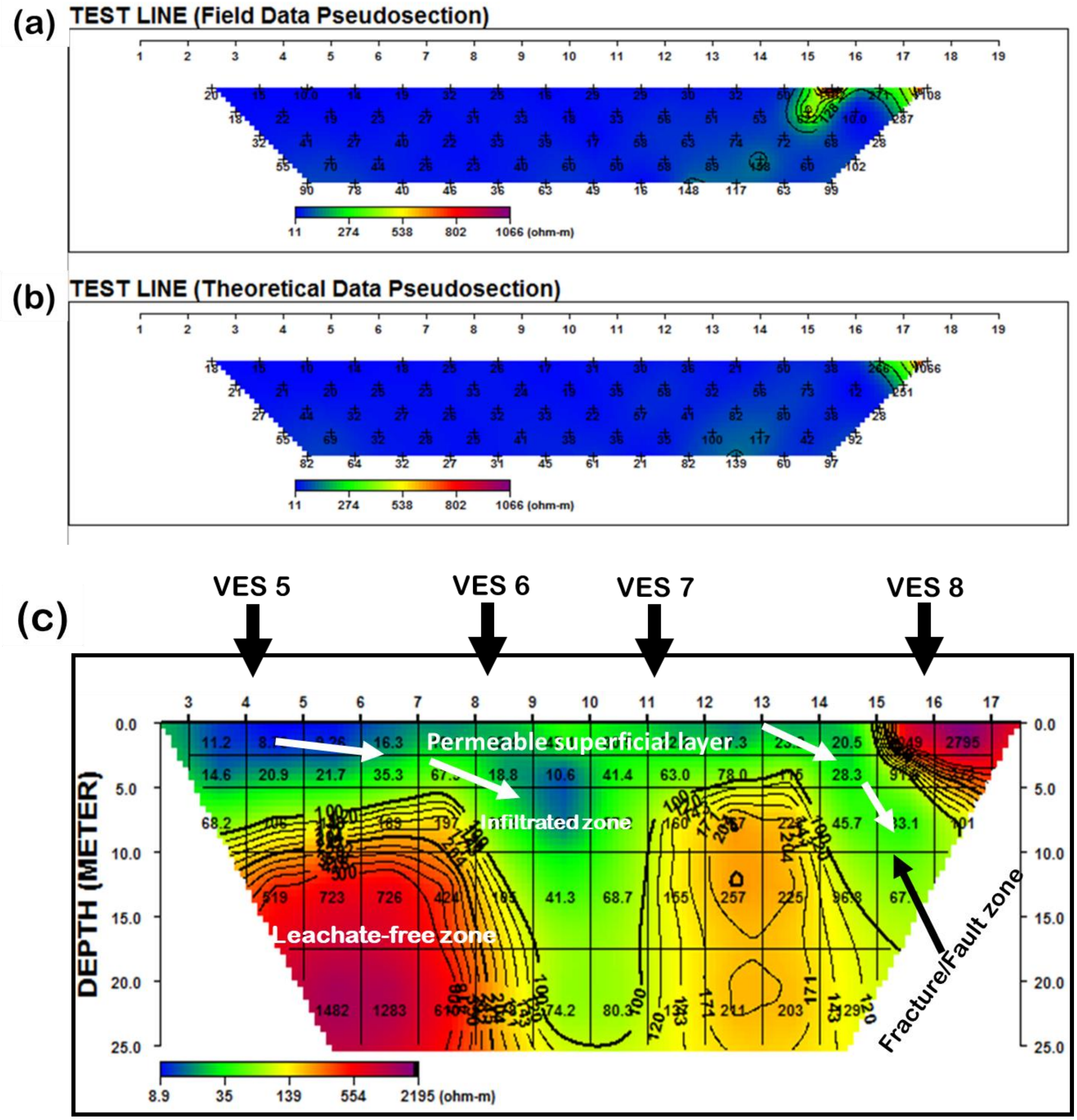

Figure 8: Electrical resistivity tomography image beneath traverse 2. a) shows the pseudo section from field observation data, (b) shows the pseudo section from computed theoretical data, and (c) shows the 2-D Dipole-Dipole tomography section.

CONCLUSIONS

In this study, the Schlumberger VES drilling and Double-dipole tomography profiling were used to investigate the impact of a dumpsite on underground water in a Basement Complex terrain in Akure, Southwest Nigeria. Three lithologic units, notably the topsoil, weathered column, and fractured/fresh Basement were delineated. The presence of leachate incursion into the groundwater has been noted in fractured or faulted rocks, as well as in the shallow porous layer directly beneath the dumpsite which overlies the overburden materials. This is observed from the low resistivity signatures observed within the faulted zones and parts of the weathered zone. Hence, it can be inferred that the movement of the leachate plume is mostly influenced by faulted/fractured zones. Observation from our results shows the migration of leachate pollution exhibits a primarily southward trajectory, aligning with the orientation of the suspected structures and the general trajectory of groundwater movement. Consequently, these zones significantly typify the contamination levels of the aquifer zone at the waste disposal site. The study's results illustrate the utility of electrical resistivity imaging, namely employing the resistivity drilling and Dipole-Dipole tomography profiling methods, as an effective tool for monitoring the spatial and vertical extent of contamination associated with leachate plume originating from the Aromed refuse dump site. It is also effective in delineating the underlying structures that influence the movement of conductive pollution plumes.

RECOMMENDATION

We recommend enhanced waste management protocols to alleviate potential groundwater contamination. Hence, site selection for waste management disposal should be meticulously carried out by conducting a subsoil investigation assessment. This would help in locating subsoils with minimal permeability and/or porosity (primary and secondary) to control the migration of pollutants within the subsoil. To mitigate the impact of leachate contamination, some leachate treatment methods including aerobic biological treatment, evaporation, the pre-treatment of effluent before its release into a municipal wastewater collection system, recycling of leachates, activated sludge, physicochemical processes, and membrane separation are suggested. We also recommend physico-chemical investigations across wells and surface water bodies in the vicinity, and at considerable distances away from the waste disposal site to serve as control. This would help in establishing the extent to which chemical substances have impacted the aquifer system.

CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

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