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Assessing aquifer vulnerability near cemeteries using dipole-dipole and vertical electrical sounding methods

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ABSTRACT

An integrated geophysical investigation of the second cemetery in Benin City was conducted with the view to determine the leachate flow direction and the geoelectrical layers that characterized the underlying aquifer. Eight vertical electrical soundings (VES) and two dipole-dipole profiling lines along two transverse sections were carried out. For the dipole-dipole profiling, ABEM Terrameter SAS 300C was employed, while the VES investigation utilized the Schlumberger array. The resistivity data collected during the field investigation were interpreted using DIPROWIN software version 4.01. Leachate plume was identified in the subsurface soil at a depth range of 5 to 20 meters. This was attributed to the soil porosity, aiding the infiltration of necroleachate. The VES results revealed four geoelectric layers: topsoil, lateritic soil, a weathered layer (composed of clay), and medium to coarse sand. The overburden exhibited a thickness range of 0.7762m to 0.8074m, resistivity ranging from 57.318Ωm to 2831.4Ωm, and depths ranging from 0.7762m to 1.5836m. The third geoelectric layer, identified as clay, had an average thickness of 11.48 meters at a depth of 13.06 meters, with a resistivity of 203.52Ωm. Apart from acting as a seal against the downward penetration of leachate, the clay also serves as a filter.

1. INTRODUCTION

For many communities worldwide, groundwater serves as a crucial natural resource and is the primary source of drinking water (Gleeson et al., 2016). However, various anthropogenic activities, including waste disposal practices associated with cemetery activities, pose a potential risk of contaminating groundwater resources (Üçisik & Rushbrook, 1998; Bastianon et al., 2000; Żychowski, 2012). In numerous urban areas, particularly in developing countries, cemeteries are often situated in locations where groundwater supplies are vulnerable to contamination, often adjacent to residential areas (Trick et al., 2005; Lautz et al., 2020). In Nigeria, cemetery operations frequently proceed without proper management procedures, leading to the release of leachate from decomposed organic matter and other waste items into the environment. Groundwater contamination resulting from cemetery activities can have severe consequences for both the ecosystem and public health (Trick et al., 2001; Trick et al., 2005). This raises significant concerns regarding the susceptibility of aquifers to contamination due to cemetery activities, particularly in metropolitan areas where the demand for water is substantial (Aleke et al., 2018; Ekanem et al., 2019; Abu-Bakr & El, 2020; Bon et al., 2020; Ekanem, 2020).

Groundwater is recognized as the most vulnerable receptor of contaminants originating from burial sites. The decomposition of human remains, as well as associated funeral materials, releases biological contaminants such as bacteria and viruses into the surrounding environment (Dian, 2004). Research highlights that poorly sited cemeteries, combined with insufficient measures to prevent contaminant transport, can have detrimental effects on groundwater quality and local ecosystems, particularly through the introduction of pollutants into underlying aquifers (Kabiru et al., 2019).

Aquifer protection is heavily influenced by the permeability of the subsurface materials, which controls the movement of contaminants into deeper aquifer layers (Egbai et al., 2019; Oseji & Egbai, 2019b). The extent and speed of leachate penetration depend on how easily pollutants can move through the subsurface beneath and around cemeteries. While clay-rich, less permeable materials serve as natural barriers, limiting contaminant flow, more permeable sandy materials provide a pathway that allows contaminants to infiltrate more readily, as noted by several studies such as (Ayuk et al., 2013; Awoniyi, 2013; Olla et al., 2015). To assess the impact of nearby cemeteries on the underlying aquifer system, understanding the subsurface soil profile is crucial (Omosuyi & Oseghale 2012). It is essential to note that cleaning up and restoring an aquifer to its original, pristine form is often challenging once it has been polluted (Thirumalaivasan & Karmegam, 2001). Conducting an aquifer vulnerability assessment is crucial for locating potential contamination risk locations near cemeteries. The concept of aquifer vulnerability is based on the idea that groundwater may be protected to some extent from human influences by the physical environment, particularly in terms of contaminants penetrating the subsurface (aquifer). Aquifer vulnerability combines the strata's potential for attenuation with the saturated zone's hydraulic inaccessibility to the entry of contaminants (Foster, 1998; Ehirim & Nwankwo, 2010). To prevent contamination of underlying groundwater supplies, attention might be focused on restricting land use in susceptible zones (Awoniyi, 2013; Eluwole & Ademilua, 2014). Understanding the direction of leachate flow from decomposing corpses can be a solution to groundwater contamination. Once the flow direction is established, government and relevant agencies should prevent residents along this path from locating boreholes. Geophysical approaches, including electrical resistivity imaging, have shown promise in evaluating aquifers' susceptibility to contamination and locating potential hotspots in the aquifer systems' subsurface geology (Ekanem et al., 2019; Bastianon et al., 2000; George, 2020, 2021).

Geophysical methods have proven to be effective for identifying and tracking pollution plumes, assessing their temporal variations, and monitoring aquifer vulnerability to contamination. Numerous studies within environmental engineering have adopted these techniques. For instance, Anomohanran (2011) applied the resistivity method to evaluate groundwater potential in Oleh. Similarly, Oseji and Egbai (2019a) used the resistivity approach to investigate groundwater prospects and the vulnerability of aquifers in Oleh, Delta State, Nigeria. In Irawarea, Lagos State, Ayolabi et al. (2009) utilized the same method to examine aquifer units and groundwater quality. In addition, Oseji et al. (2018) employed the resistivity approach to study the impact of open dumpsites on groundwater quality and aquifer protection in Sapele, Delta State, Nigeria. Egbai et al. (2019) used the resistivity technique to evaluate the aquifer's resilience in Agbor-NTA and its surroundings, while Oseji and Egbai (2019b) characterized aquifers in Issele-Uku, Delta State, and using geoelectric survey data.

While numerous studies have utilized geophysical methods like Vertical Electrical Sounding (VES) and dipole-dipole resistivity for groundwater exploration, few have focused on assessing aquifer vulnerability specifically in proximity to cemeteries. Existing research has often concentrated on broader groundwater quality issues or the impacts of industrial and agricultural activities (Oseji et al., 2018; Anomohanran, 2011). However, the potential contamination risks from necroleachate especially in regions with permeable soils or poor cemetery management practices remain underexplored. The limited research available on this specific subject either lacks spatial accuracy or fails to integrate multiple geophysical techniques to comprehensively assess aquifer vulnerability near burial sites. Consequently, there is a critical need to address the specific ways cemeteries influence aquifer contamination and to develop refined geophysical methods for accurate vulnerability assessment. The uniqueness of this study lies in its dual application of Dipole-Dipole and Vertical Electrical Sounding (VES) geophysical methods to specifically assess aquifer vulnerability near cemeteries, which is a relatively underexplored area in environmental hydrogeology. By integrating these two techniques, the research provides a comprehensive subsurface analysis that captures both shallow and deep aquifer dynamics, enabling a more precise understanding of how contaminants, particularly necroleachate, migrate through various geological layers. Unlike most previous studies that have focused on contamination from industrial or agricultural sources, this research uniquely emphasizes the contamination risks associated with cemeteries.

2. MATERIALS AND METHODS

2.1. Description of study area

The study area is the second cemetery in Benin City, Edo State, Nigeria. Benin City, the capital of Edo State, is one of the largest cities in Nigeria, situated in the southern part of the country. It is positioned between latitude 6°20′17″ N and longitude 5°37′32″ E, with an elevation of 88 meters above sea level. Benin City experiences two main seasons: the wet season (March to October) and the dry season (October to March). The city is predominantly inhabited by the Bini-speaking people of Edo ethnic nationality, with a population of 1.15 million persons according to the last national census in 2006. The projected population of the city, using the National Population Commission’s growth rate of 3.5% per annum for urban centers, is estimated to reach 5.5 million by the year 2050. There are three main public cemeteries in the city: 1st Cemetery, 2nd Cemetery, and 3rd Cemetery. For this study, the 2nd Cemetery was selected. Figure 1 depicts a 3D-study area map, illustrating the location of the cemeteries.

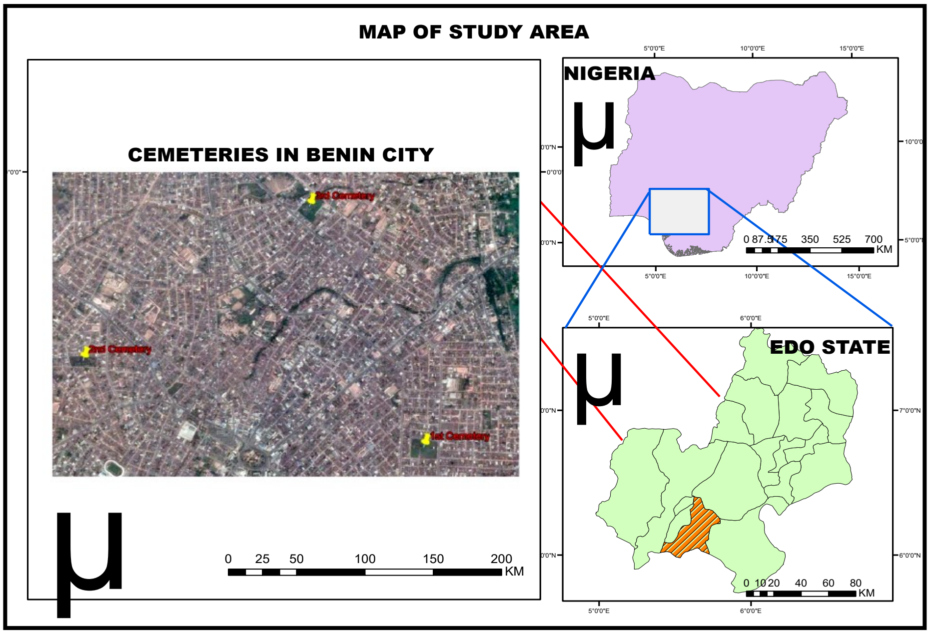


Figure 1. Study area map showing the three cemeteries

2.2. Geology of study area

The Benin region is situated atop the sedimentary formations of the southern sedimentary basin, as highlighted by Ikhile (2016). These formations extend from the west, covering the Niger Delta region and continuing beyond the present coastline. The predominant geological composition of this formation is over 90% sandstone, interspersed with shale layers. The sandstone is typically coarse-grained, sometimes gravelly, and locally fine-grained, with poorly sorted, sub-angular to well-rounded particles. The sediments also contain lignite streaks and wood fragments, reflecting the basin's depositional environment (Idehai & Egai, 2014). Furthermore, the region's geology is characterized by a reddish topsoil, consisting of ferruginized or lateritized clayey sand, which plays a crucial role in the area's surface processes and soil characteristics.

2.3. Methodology of investigation

The VES and ERT resistivity surveys around the second cemetery in Benin City were conducted using several key tools and software programs. The ABEM Terrameter SAS 300C (as shown in Figure 2) was employed for the electrical resistivity measurements. To obtain accurate geographic coordinates and elevation data, Global Positioning Systems (GPS) were used. Data processing and inversion were carried out using DIPRO application version 4.01**,** which is an iterative software program designed for 2-D resistivity inversion. In addition, winRESIST software version 1.0, a computer-assisted tool for 1-D forward modeling, was utilized to interpret the vertical electrical sounding (VES) data. The contouring of resistivity data and the creation of visual representations of subsurface structures were facilitated by the Surfer Software program**,** enhancing the interpretation of the geophysical survey results. These tools collectively allowed for a detailed subsurface analysis around the cemetery site.

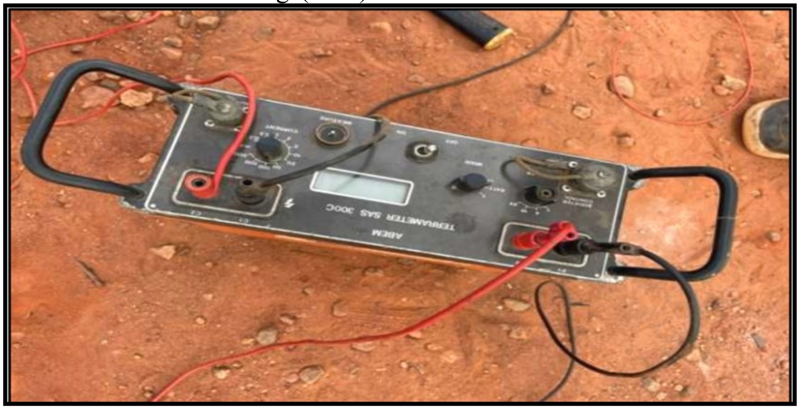


Figure 2. ABEM Terrameter SAS 300C

The study employed a geophysical approach to investigate the subsurface soil around the cemetery, aiming to delineate the geological formations, map subsoil pollution, and assess the hydraulic properties of the underlying soil. These properties include mean apparent resistivity, longitudinal conductance, hydraulic conductivity, transverse resistance, conductivity, and transmissivity (Ugwuanyi et al., 2015; Obiora et al., 2016; Orakwe et al., 2018). The electrical resistivity technique was applied using both 1-D Vertical Electrical Sounding (VES) and 2-D Dipole-Dipole profiling methods. Two transverse lines (TR1-TR2) running in a NE-SW orientation were established, along which 2-D imaging was conducted.

For the 2-D imaging, a Dipole-Dipole array was used, with a dipole length (a) ranging from 0 to 100 meters and an expansion factor (n) between 1 and 5 meters (Lashkaripour & Nakhaei, 2005; Gemail et al., 2011; Orakwe et al., 2018). Four electrodes were inserted into the ground to a depth of 1 meter, spaced 10 meters apart, and connected to the resistivity meter using insulated wires. The resistivity meter monitored the current and voltage for each pair of electrodes (Kearey et al., 2002; Iserhien-Emekeme et al., 2004; Hubbard & Rubin, 2006). Direct current was injected into the ground through the current electrodes (C1 and C2), while the potential electrodes (P1 and P2) measured the resulting potential difference, as depicted in Figure 3. This setup facilitated a comprehensive subsurface survey to analyze the aquifer's vulnerability and pollution patterns.

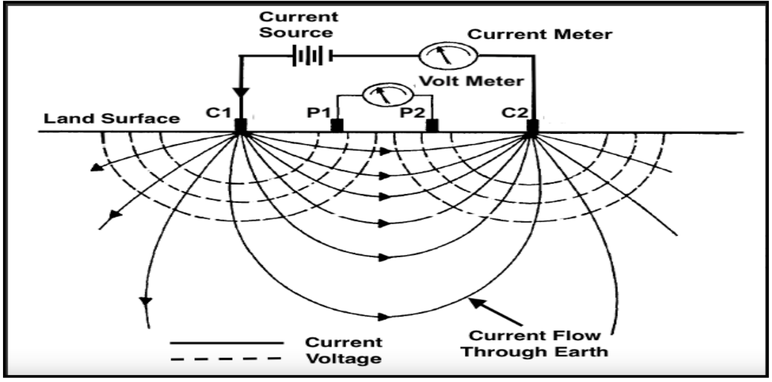


Figure 3. Dipole-Dipole array

During the geophysical investigation, the apparent resistance (Ra) of the subsurface geological materials was recorded using the crystal display of the resistivity meter. The geometrical coefficient (G), which is crucial for translating resistance into resistivity, was calculated based on the electrode spacing in the dipole-dipole array configuration. The equation used for determining the geometrical coefficient (G) is given as per Ekanem (2020), taking into account the distances between the current and potential electrodes. This calculation ensures accurate measurement of resistivity, which is essential for mapping subsurface characteristics and identifying areas of concern, such as potential contamination pathways and aquifer vulnerability.

$$G = \pi\left(\frac{\left[\left\{\frac{C_1C_2}{2}\right\}^2 - \left\{\frac{P_1P_2}{2}\right\}^2\right]}{P_1P_2}\right) \qquad (1)$$

The apparent resistivity (ρ_a) was calculated by multiplying the apparent resistance (R_a) by the geometric factor G, given by the expression in equation (15) (Kearey et al., 2002; Hubbard & Rubin, 2006; Iserhien-Emekeme et al., 2004).

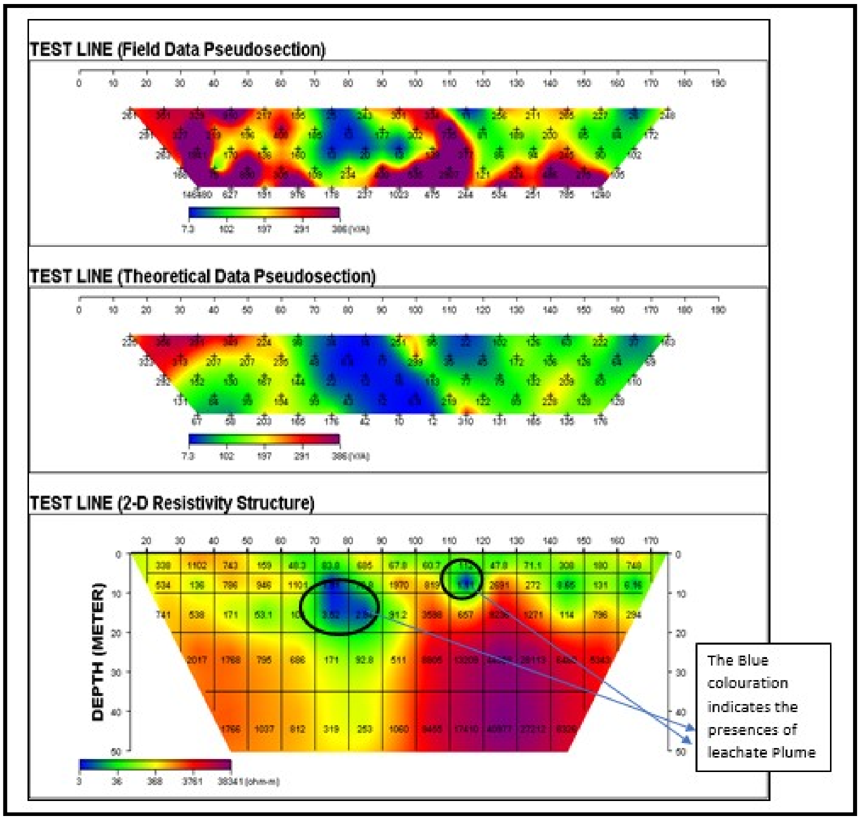
$$\rho_a = \left[GR_a\right] \qquad (2)$$

The DIPRO application version 4.01 was employed to invert the 2-D Dipole-Dipole data into 2-D resistivity profiles. These profiles were crucial for examining subsurface features and identifying probable contamination hotspots. In addition, eight (8) VES were conducted using the Schlumberger array, with a maximum current output of 2 amps and a maximum voltage output of 600 volts. Depth sounding curves generated from the VES stations were quantitatively interpreted using winRESIST software version 1.0. This computer-assisted 1-D forward modeling tool utilizes the partial curve matching technique for data interpretation.

3. RESULTS AND DISCUSSION

3.1. Dipole-dipole investigation

Resistivity data from transverse 1 were employed to generate the 2-D dipole-dipole profile maps presented in Figures 4 and 5.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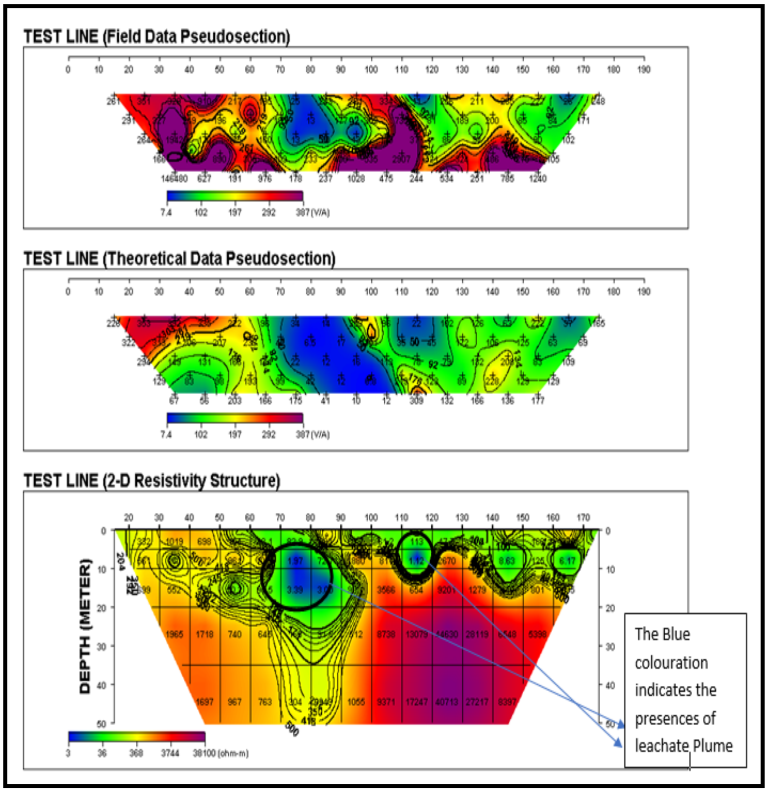
TEST LINE (Theoretical Data Pseudosection)

TEST LINE (2-D Resistivity Structure)

The Blue colouration indicates the presences of leachate Plume

Figure 4. 2-D Resistivity structure based on FEM modeling of transverse 1



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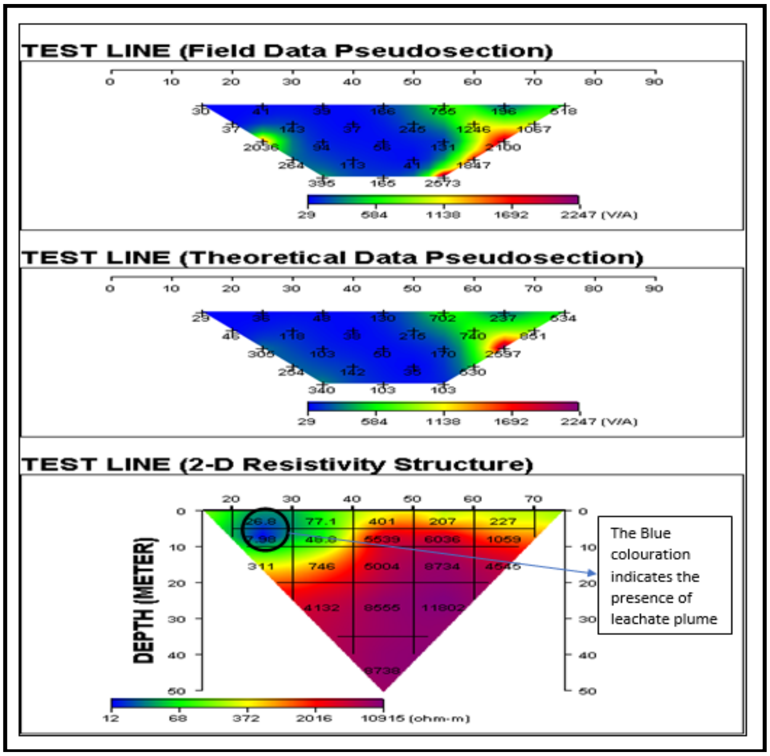
The Blue colouration indicates the presences of leachate Plume

Figure 5. 2-D Resistivity structure with contours based on FEM modeling of transverse 1



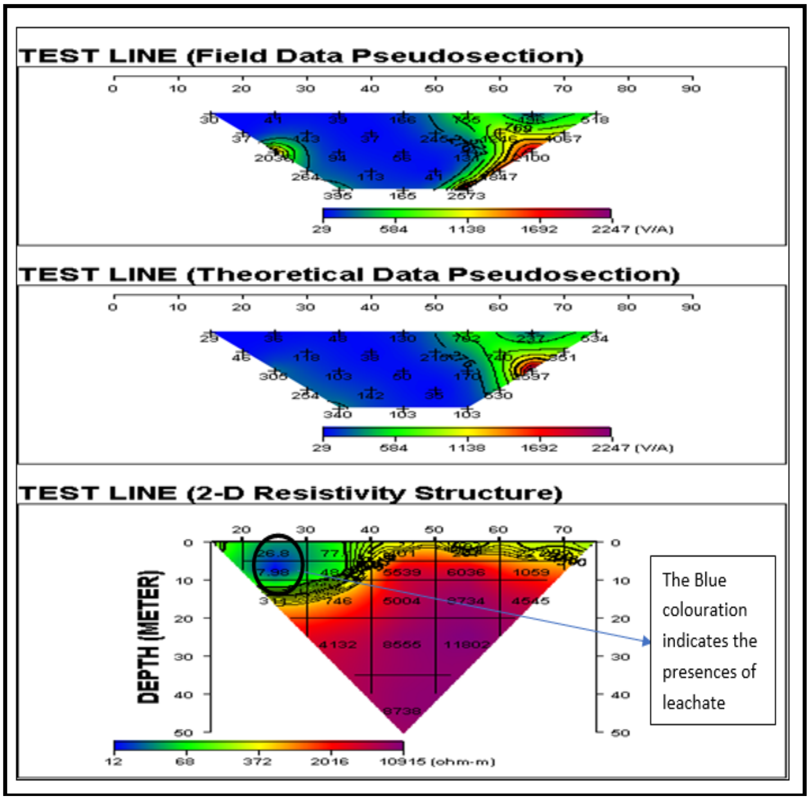
TEST LINE (Field Data Pseudosection)

TEST LINE (Theoretical Data Pseudosection)

TEST LINE (2-D Resistivity Structure)

The Blue colouration indicates the presence of leachate plume

Figure 6. 2-D Resistivity structure based on FEM modeling of transverse 2



The Blue colouration indicates the presences of leachate

Figure 7. 2-D Resistivity structure with contours based on FEM modeling of transverse 2

Observations from the profile maps indicate that the surface of the study area has low resistivity (34Ωm to 180Ωm), which increases with depth. Leachate plumes, observed at depths of 5 to 20 meters, have travelled horizontally to approximately 70m to 120 meters in a northeastern (NE) direction. The topsoil in this horizontal distance range is presumed to be heavily contaminated with necroleachate from cemetery activities. Similarly, resistivity data from transverse 2 were also employed to generate the 2-D dipole-dipole profile maps presented in Figures 6 and 7.

For transverse 2, resistivity data reveals low values (48.8Ωm to 77.1Ωm) at the surface, increasing with depth. Necroleachate was detected at depths of 0 to 10 meters, having traveled horizontally to approximately 20m to 30 meters with a resistivity range of 7.98Ωm to 26.8Ωm. The 2-D dipole-dipole profile map confirms the northeast (NE) direction of leachate movement. The outcome indicates the presence of a necroleachate plume at depths of 5 to 20 meters and 0 to 10 meters, respectively as illustrated in Figures 4, 5, 6 and 7. The profile maps from both traverses confirmed the cemetery operations as the source of the leachate plume, specifically exposing the activities at a depth of 5 to 20 meters for traverse 1 and the presence of the plume from the surface to a depth of 0 to 10 meters for traverse 2. Necroleachate resulting from the decomposition of dead bodies contains heavy metals and other toxic substances due to the decay of coffin material (Spongberg & Becks, 2000; Jonker & Olivier, 2012).

3.2. vertical electrical sounding investigation

To gain insights into the vulnerability of the aquifer around the second cemetery, 1-D geophysical technique known as VES was conducted. Using the acquired VES data, electrical properties of the aquifer, which include apparent resistivity, longitudinal conductance, and transverse resistance, were computed and presented in Table 1 while the layer inversion model based on the VES data showing the lithology of the aquifer is presented in Figures 8 to 15, respectively.

Table1. Summary of electrical properties of aquifer

Sounding points	Mean Apparent Resistivity (Ωm)	Mean Thickness (m)	Conductivity (δ, Ωm^{-1})	Longitudinal conductance (S, Ω^{-1})	Transverse Resistance (TR, Ωm^2)	Hydraulic Conductivity (K)	Transmissivity (Tr, m^2/day)
VES 1	1219.49	11.599	0.0008200	0.009511	14144.8645	0.51069	5.92349331
VES 2	901.3	12.026	0.001109	0.013343	10839.0338	0.67709	8.14268434
VES 3	950.39	10.48	0.001052	0.011027	9960.0872	0.64441	6.7534168
VES 4	1242.78	7.602	0.0008046	0.006117	9447.61356	0.50176	3.81437952
VES 5	1749.93	11.5139	0.0005714	0.006580	20148.5190	0.36463	4.198313357
VES 6	1038.41	12.741	0.0009630	0.012270	13230.3818	0.5933	7.5592353
VES 7	384.55	10.9605	0.0026004	0.028502	4214.86027	1.49871	16.42661096
VES 8	2190.45	7.7891	0.0004565	0.003556	17061.6341	0.29572	2.303392652

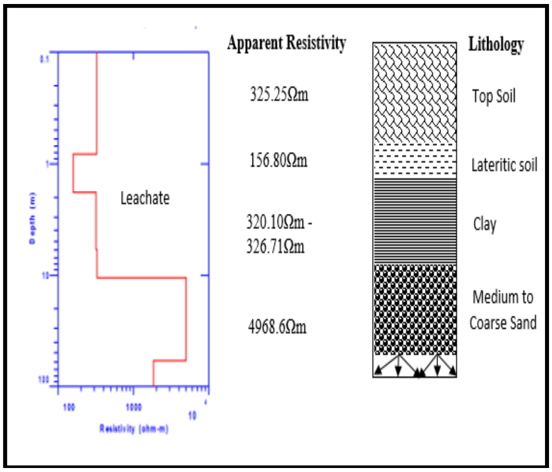


Figure 8. Layered Inversion of VES point 1

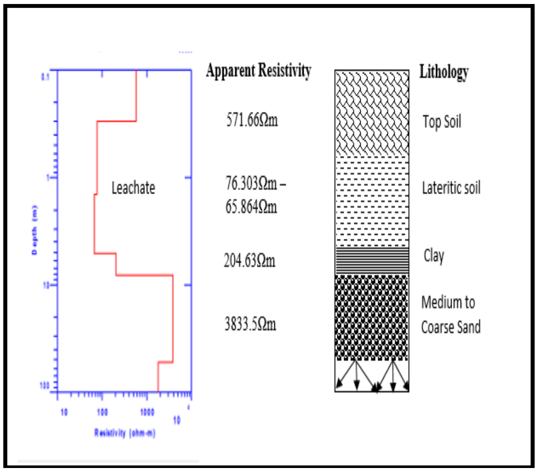


Figure 10. Layered Inversion of VES point 3

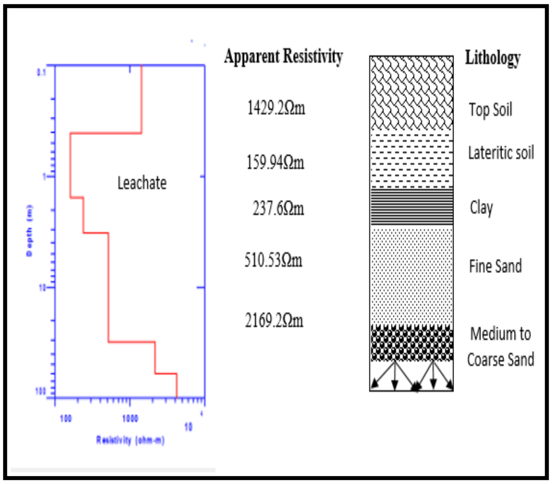


Figure 9. Layered Inversion of VES point 2

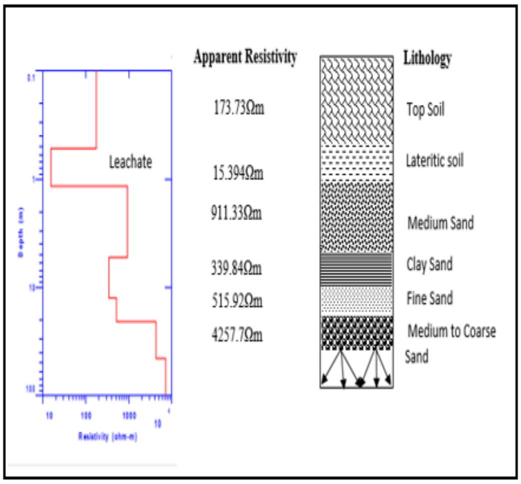


Figure 11. Layered Inversion of VES point 4

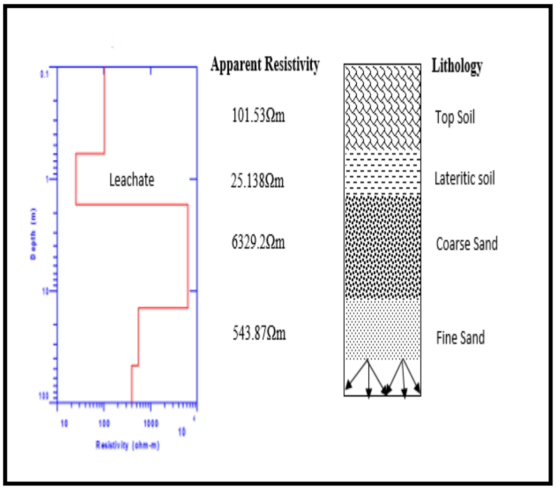


Figure 12. Layered Inversion of VES point 5

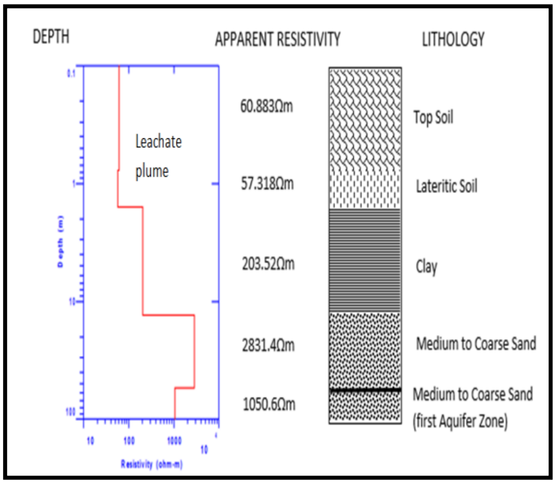


Figure 13. Layered Inversion of VES point 6

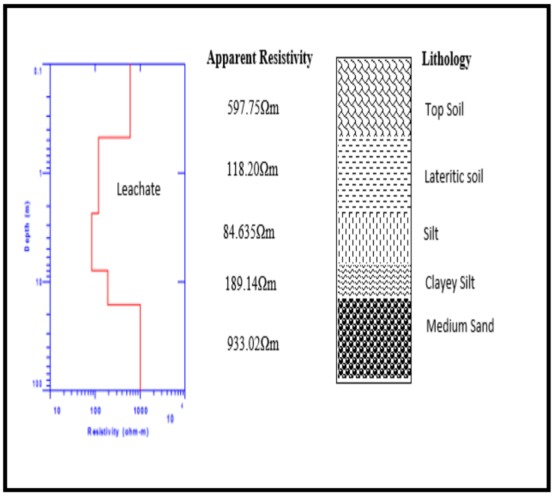


Figure 14. Layered Inversion of VES point 7

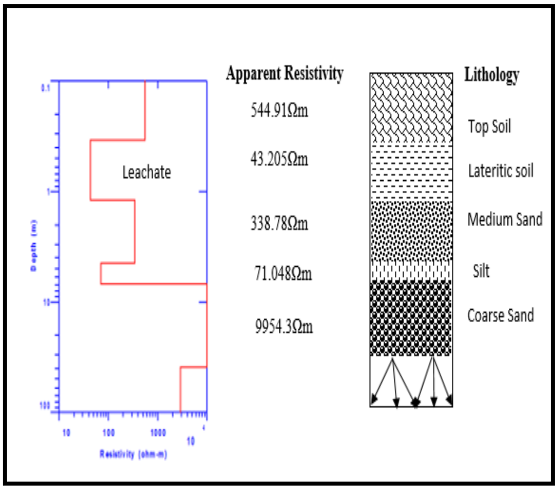


Figure 15. Layered Inversion of VES point 8

The VES modeling conducted across Figures 8 to 15 presents a comprehensive picture of the subsurface geological structure. Across these figures, a consistent pattern emerges, revealing the identification of multiple geoelectric layers, typically around six layers in each case. This systematic approach allows for a detailed exploration of the underground composition. For example, in Figure 8, the resistivity spectrum ranges from 325.25Ωm to 4968.6Ωm, demonstrating a wide variety of underground materials. The fourth layer stands out as primarily Clay, characterized by an average thickness of 4.6280m and a depth of 10.510m, while subsequent layers are predominantly composed of sand. Similarly, Figure 9 depicts resistivity variations ranging from 159.94Ωm to 2169.2Ωm, with the identification of a third clay layer and subsequent layers composed of sand. The trend continues in Figures 10 and 11, with resistivity ranges of 65.864Ωm to 3833.5Ωm and 15.394Ωm to 7144.5Ωm, respectively, further emphasizing the heterogeneous nature of the subsurface. Beyond these figures, figures 12 to 15 uphold the consistent findings, providing additional insights into the geological structure. These findings collectively offer valuable information crucial for various geological and engineering applications, such as groundwater exploration, environmental assessments, and infrastructure development.

4. CONCLUSIONS

The geophysical evaluation emphasizes the crucial significance of comprehending subsurface conditions to ensure efficient groundwater management, especially in sensitive areas like those near cemeteries in Benin City, Edo State, Nigeria.

By employing geophysical techniques, this study has yielded valuable insights into the subsurface conditions and potential risks associated with groundwater contamination in these areas. Both VES and dipole-dipole studies have corroborated the presence of pollution in the topsoil near cemeteries, emphasizing the urgency of addressing this issue. The VES results reveal the existence of four distinct geoelectric layers in the subsurface adjacent to cemeteries, including topsoil, lateritic soil, a weathered layer predominantly composed of clay, and medium- to coarse-grained sand. Notably, the prevalence of clay within the weathered layer serves as a protective barrier, limiting the penetration of leachate and mitigating the risk of contamination deeper into the subsurface. These findings underscore the need for proactive measures to safeguard groundwater quality in such vulnerable areas, informing targeted interventions and management strategies to preserve this vital resource for present and future generations.

5. ACKNOWLEDGMENT

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