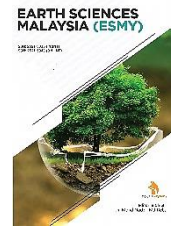


ZIBELINE INTERNATIONAL™  
PUBLISHING

ISSN: 2521-5035 (Print)

ISSN: 2521-5043 (Online)

CODEN: ESMACU



## RESEARCH ARTICLE

**HYDROGEOLOGICAL ANALYSIS OF SUBSURFACE ARCHITECTURE AND AQUIFER VULNERABILITY USING 3D ELECTRICAL RESISTIVITY IMAGING**Nosayaba Avenbuan<sup>a</sup> Osazee Japheth Joh<sup>a</sup>Department of Physical Sciences, Faculty of Science, Benson Idahosa University, Benin City, Nigeria<sup>b</sup>Department of Physics, Faculty of Physical Sciences, University of Benin, Benin City, Nigeria\*Corresponding Author's Email: [navenbuan@biu.edu.ng](mailto:navenbuan@biu.edu.ng); <https://orcid.org/0000-0002-0224-5859>

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## ARTICLE DETAILS

## Article History:

Received 04 November 2024

Revised 6 December 2024

Accepted 10 December 2024

Available online 20 January 2025

## ABSTRACT

This study applies three-dimensional (3D) electrical resistivity imaging (ERI), integrated with borehole log data, to investigate subsurface architecture and aquifer vulnerability at the University of Benin Teaching Hospital (UBTH) Football Field, Edo State, Nigeria. The site, situated within the hydro-geologically significant Benin Formation, revealed a stratified subsurface comprising six distinct layers. Borehole log correlation confirmed the identification of sandy strata between 10.0 m and 17.4 m as primary aquifer zones with high porosity and permeability, underlain by compacted sandstones and crystalline bedrock that serve as structural markers and natural hydraulic barriers. Vulnerability analysis using the GOD model classified the aquifer as moderately susceptible to contamination due to thin clay protective layers and increasing urbanisation pressures. This research underscores the novel application of 3D ERI alongside borehole data to enhance subsurface characterisation and aquifer delineation in complex urban terrains. The findings provide actionable insights for groundwater resource management and environmental protection, with recommendations for multi-method geophysical surveys and hydrogeological modelling to optimise resource utilisation and safeguard aquifers against contamination.

## KEYWORDS

Hydrogeophysical analysis, Subsurface architecture, Aquifer vulnerability, 3D electrical resistivity imaging (ERI), Groundwater management.

## 1. INTRODUCTION

Groundwater is a critical resource for numerous communities, especially in areas such as Benin City, Nigeria. However, the increasing pressures of urbanisation and industrialisation pose substantial risks to aquifer systems, including contamination and depletion. To ensure sustainable management and protection of these vital groundwater resources, a comprehensive understanding of the subsurface architecture and the factors contributing to aquifer vulnerability is essential.

Hydrogeophysical methods have emerged as indispensable tools in the evaluation of subsurface structures and the characterisation of aquifer systems (Fitts, 2002). These methods integrate geophysical principles with hydrogeological frameworks to provide deeper insights into subsurface dynamics. Among the various techniques, three-dimensional (3D) electrical resistivity imaging (ERI) stands out for its high-resolution capabilities, enabling detailed mapping of geological formations and groundwater systems (Zhou et al., 2002). The ability of 3D ERI to delineate aquifer boundaries, assess contamination risks, and offer insights into subsurface architecture has positioned it as a pivotal method in contemporary hydrogeophysical research (Günther, et al., 2006; Raynolds, 2011).

Understanding subsurface architecture is fundamental to hydrogeophysical investigations, as it determines groundwater flow patterns and aquifer properties. Electrical resistivity imaging utilises the contrast in electrical resistivity between various geological materials to map subsurface features (Dahlin and Zhou, 2004). The development of 3D

ERI has significantly advanced this field by offering improved spatial resolution and enabling the accurate delineation of complex subsurface structures. This technique has proven effective in identifying lithological variations, fault zones, and other critical geological features influencing groundwater distribution and quality (Bassey et al., 2019). For instance, studies conducted in Benin City, Edo State, Nigeria, have employed resistivity methods to characterise aquifers and evaluate groundwater potential in regions with diverse lithology (Bassey et al., 2019). Additional research, such as investigations near the University of Benin Teaching Hospital, highlights the utility of resistivity methods in assessing subsurface conditions and ensuring infrastructural safety (Pessu et al., 2021).

Assessing aquifer vulnerability necessitates an in-depth understanding of the factors that influence groundwater susceptibility to contamination (Cardarelli and Filippo, 2004). The incorporation of 3D ERI into vulnerability studies has proven invaluable in identifying contaminant migration pathways and evaluating the protective capacity of overlying strata. By pinpointing low-resistivity zones indicative of clay layers or contamination plumes, 3D ERI helps identify vulnerable aquifers and associated risks (Pessu et al., 2021). Research in African settings, including Benin City, underscores the relevance of ERI in complex hydrogeological environments where human activities significantly threaten groundwater quality.

Recent advancements in 3D ERI technology have enhanced data acquisition and processing capabilities (Loke et al., 2013). Innovations in electrode array configurations and automated systems have improved the efficiency and accuracy of resistivity surveys. Inversion algorithms now

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10.26480/esmy.01.2025.38.42

allow the rapid transformation of resistivity data into three-dimensional models, offering precise visualisations of subsurface structures (Günther et al., 2006). Moreover, integrating 3D ERI with complementary geophysical methods such as seismic and electromagnetic surveys has enabled multi-faceted analyses, resulting in more robust interpretations of subsurface conditions (Cardarelli and Filippo, 2004). These advancements have been applied globally and in Africa to address challenges like water scarcity and contamination (Adepelumi et al., 2009; Pessu et al., 2021).

Applications of 3D ERI in hydrogeophysical studies have demonstrated its effectiveness across diverse geological settings. For example, in Benin City, resistivity methods have been utilised to assess aquifer depth and quality, revealing significant variability in groundwater potential across the region (Alile et al., 2020). In Lagos, Nigeria, 3D ERI has been used to delineate saltwater intrusion, providing critical data for sustainable water resource management (Adepelumi et al., 2009). Investigations near the University of Benin Teaching Hospital further affirm the versatility of resistivity methods in addressing site-specific geotechnical challenges (Pessu et al., 2021). Globally, similar methodologies have been employed in sedimentary basins, contamination zones, and regions affected by climatic stress, showcasing the adaptability and efficacy of 3D ERI in hydrogeophysical research (Jongmans, and Garambois, 2007).

While traditional hydrogeological methods often lack the spatial resolution required to characterise complex subsurface conditions, 3D ERI has demonstrated considerable potential in addressing these challenges. By accurately identifying zones of contamination and variations in lithology, 3D ERI enhances the understanding of groundwater flow and potential pollutant pathways.

Despite advancements in hydrogeophysical techniques, the application of 3D ERI in aquifer vulnerability assessments remains underutilised in this region. Most existing studies in Nigeria have focused on groundwater exploration or aquifer evaluations in other regions, such as Olabisi Onabanjo University in Southwestern Nigeria (Ariyo et al., 2021). This gap underscores the need for dedicated research employing 3D ERI to assess aquifer vulnerability in Benin City. Such research would provide valuable insights into the factors influencing aquifer susceptibility and inform sustainable groundwater management strategies in the region.

### 1.1 Location/Geology Of The Study Area

Figures 1 and 2 show the study location (the University of Benin Teaching Hospital (UBTH) Football Field), situated along the Ugbowo-Lagos Road in Benin City, Edo State, Nigeria. This location, adjacent to the University of Benin, lies within the humid tropical rainforest zone of Southern Nigeria, characterised by its well-defined wet and dry seasons, which significantly influence its geological and hydrological properties.

The UBTH Football Field is underlain by the Benin Formation the some study a dominant lithostratigraphic unit of the Niger Delta Basin (Avenbuan et al., 2020). This formation is comprised predominantly of continental sedimentary deposits, including highly porous and permeable unconsolidated sands interbedded with lenses of clay and occasional gravel. These characteristics make the Benin Formation particularly significant for groundwater exploration and other subsurface investigations, as its depositional environment fosters considerable aquifer development. The sandy units of the formation are known for their excellent water-bearing potential, while the clay intercalations act as confining layers, influencing the hydrodynamic properties of the subsurface.

Topographically, the study area exhibits subtle variations in elevation, ranging from 93.4 metres to 113.1 metres above sea level. These variations reflect the natural undulations typical of the region, which are indicative of fluvial and aeolian processes that shaped the depositional environment of the Coastal Plain Sands. The geographical coordinates of the surveyed area further define the site, providing a clear spatial framework for the geophysical investigations.

The strategic location of the UBTH Football Field, combined with its proximity to critical academic and medical institutions, enhances its value as a research site. It offers a unique combination of accessibility and geological significance, making it ideal for advanced

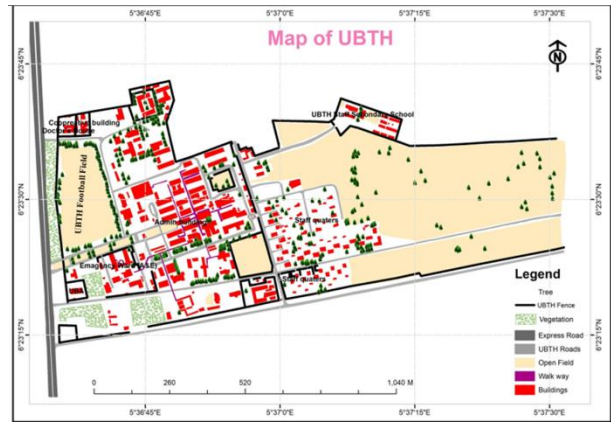


Figure 1: Map of the study Location. (Source: Eguagie-Suyi, 2022).

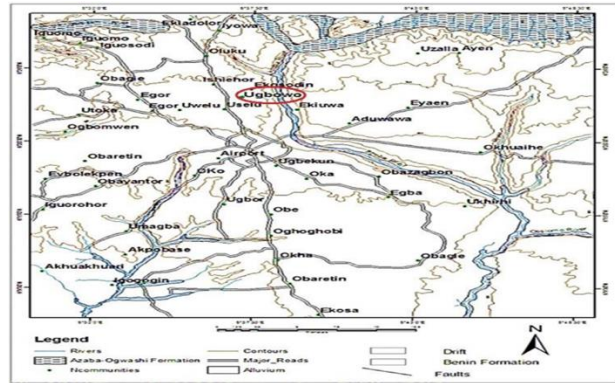


Figure 2: Benin region geological formation (Source: Avenbuan et al., 2020).

Geophysical studies aimed at subsurface characterisation, aquifer delineation, and environmental assessments. The findings from such studies not only provide insights into the geological framework of the region but also contribute to practical applications in groundwater management, environmental planning, and infrastructural development within the Niger Delta Basin.

## 2. FIELD METHODOLOGY/THEORY

To characterize the subsurface structure and evaluate the susceptibility of the aquifer to contamination, Two-Dimension (2D) resistivity data were acquired along six profiles. Three of these profiles were oriented west-east (W-E), while the remaining three followed a south-north (S-N) alignment, as depicted in Figure 3. The 2D data set were collated to form a single 3D resistivity data.



Figure 3: Field Design Adopted For The Data Collection

The 3D resistivity data were processed using RES3DINV software to generate 3D inversion models. These models provide a volumetric representation of subsurface resistivity, visualised as both slice and block diagrams using Voxler software. A flowchart summarising the field design, data acquisition, and analysis is presented in Figure 4. The Wenner-Schlumberger array configuration was employed for data acquisition due

to its ability to achieve a high signal-to-noise ratio and provide extensive horizontal coverage, making it well-suited for the study objectives.

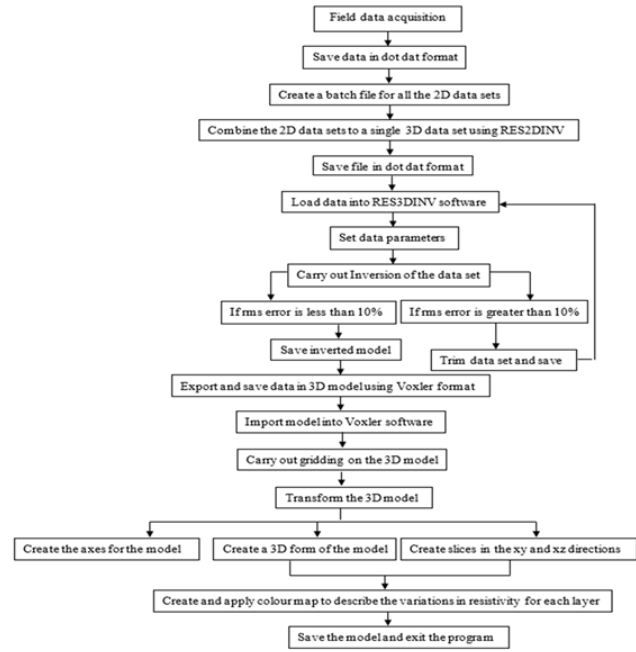


Figure 4: Data analysis flowchart (Source: Avenbuan et al., 2024).

In this method, an electric current is injected into the subsurface through the current electrodes. This current generates an electric field within the subsurface, and the resulting potential difference is measured using a separate pair of potential electrodes

Electrical resistivity ( $\rho$ ) of the subsurface varies based on subsurface lithology, porosity, fluid saturation, and salinity. In this study, the apparent resistivity ( $\rho_a$ ) is determined using the Equation (1):

$$\rho_a = k \frac{\Delta V}{I} \quad (1)$$

where  $\Delta V$  is the measured potential difference,  $I$  is the injected current, and  $k$  is the geometric factor, which depends on the electrode arrangement. Equation (2) gives the geometric factor for the Wenner-Schlumberger configuration.

$$k = \pi \cdot (n+1) a \quad (2)$$

where  $a$  is the base electrode spacing, and  $n$  is a factor that determines the separation between current and potential electrodes.

### 3. INTERPRETATION AND DISCUSSION OF RESULTS

Figures 5 and 6 show the resistivity models derived from the University of Benin Teaching Hospital football field. The results obtained highlights both lateral and vertical resistivity variations, offering detailed insights into lithology, fluid saturation, and structural composition across six distinct layers.

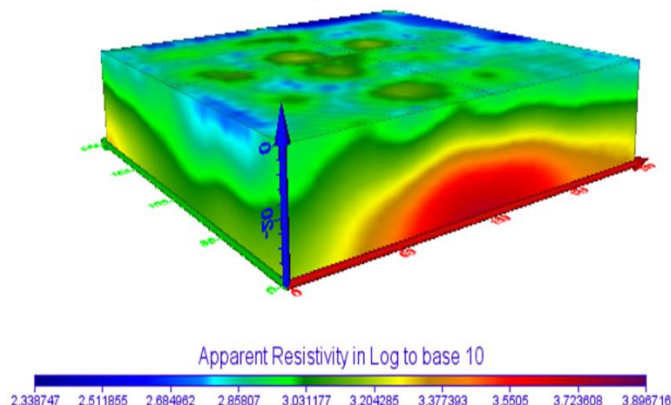


Figure 5: 3D Cube Model of the Subsurface Lithology

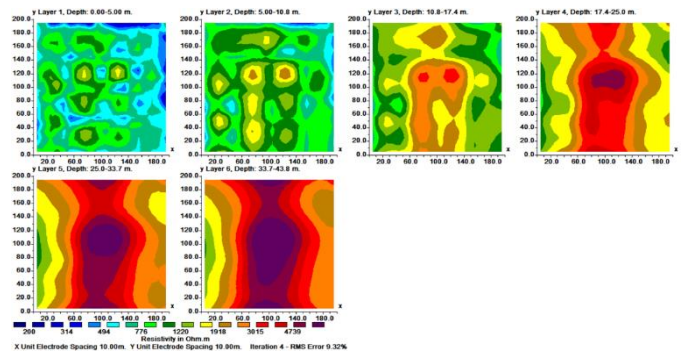


Figure 6: 3D Slice Model of the Subsurface Layers

The first layer, extending from the surface to a depth of 5.00 m, exhibits resistivity values ranging from exactly 173.28  $\Omega$ m to 776.00  $\Omega$ m. This layer likely corresponds to topsoil or lateritic clay interspersed with sand lenses. The moderate resistivity suggests a weathered zone with active surface processes, characterised by moisture and organic content. This zone plays a crucial role in surface infiltration and precipitation interactions, contributing to its heterogeneity.

The second layer spans depths of 5.00 m to 10.00 m, with resistivity values ranging between 500.01  $\Omega$ m and 1220.00  $\Omega$ m. This transitional zone reflects brown laterite to silty sand compositions. Variations in resistivity indicate lateral heterogeneity caused by differences in moisture content and compaction. The sandy fraction suggests increased permeability, marking this layer as a significant transition zone within the subsurface.

At depths of 10.00 m to 17.40 m, the third layer displays resistivity values between 314.00  $\Omega$ m and 2000.00  $\Omega$ m, indicative of a sand-dominated formation. The moderate resistivity range and relatively uniform distribution suggest a porous, semi-saturated layer. This formation represents the primary candidate for groundwater storage due to its higher porosity and permeability. Lateral and vertical continuity of this layer underscores its potential as a viable aquifer.

The fourth layer, extending from 17.40 m to 25.00 m, demonstrates resistivity values ranging from 776.00  $\Omega$ m to 3548.13  $\Omega$ m. This layer comprises compacted sand or sandy clay, with reduced porosity and minimal water saturation. The increase in resistivity compared to overlying layers reflects semi-consolidated material, which acts as a barrier to vertical fluid migration while defining the upper boundary of deeper resistive units.

The fifth layer, occupying depths of 25.00 m to 33.70 m, shows resistivity values between 1220.00  $\Omega$ m and 4739.00  $\Omega$ m. This highly resistive layer is associated with compacted sandstone or fractured rock, characterised by negligible moisture content and minimal porosity. Its uniform resistivity suggests consolidated and stable subsurface material, transitioning toward crystalline formations.

The deepest layer, from 33.70 m to 43.80 m, exhibits resistivity values exceeding 3015.00  $\Omega$ m, peaking at 7883.44  $\Omega$ m. This layer corresponds to crystalline bedrock, a highly resistive and impermeable formation. The abrupt resistivity increase at this depth marks the base of the unconsolidated and semi-consolidated materials, delineating the boundary between the overburden and the geologically stable basement rock.

The findings show lateral and vertical heterogeneity in the subsurface. Shallow layers exhibit significant variability due to lithological composition, grain size distribution, and moisture content. In contrast, deeper layers display uniform resistivity trends, reflecting increasing compaction and lithological homogeneity.

The vulnerability of the aquifer was evaluated using the GOD model, a qualitative tool widely applied in groundwater studies to assess susceptibility to contamination. This method considers three critical parameters: groundwater hydraulic confinement ( $G$ ), overlying lithology ( $O$ ), and depth to groundwater ( $D$ ). Each parameter is assigned a value ranging from 0 (indicating low vulnerability) to 1 (indicating high vulnerability), and the overall vulnerability score is calculated using Equation (3):

$$Vulnerability (V) = G \times O \times D \quad (3)$$

The groundwater hydraulic confinement ( $G$ ) was characterised as semi-confined, based on the lithological sequence, which comprises a sandy clay layer overlying a fine sand aquifer. Semi-confined aquifers offer moderate

resistance to contaminant infiltration. A value of 0.7 was assigned to this parameter, reflecting its intermediate protective capacity.

The overlying lithology (O) was assessed based on the borehole log, which indicates reddish laterite, brown laterite, and sandy clay as the primary overburden materials. While sandy clay provides moderate protection due to its lower permeability, the lateritic materials are relatively permeable, thereby reducing their protective capacity. Consequently, O was assigned a value of 0.6.

The depth to groundwater (D) was determined to be approximately 10 m, based on field data. This depth offers some natural attenuation of contaminants but does not fully eliminate vulnerability. Thus, D was assigned a value of 0.5, reflecting moderate protection from the surface.

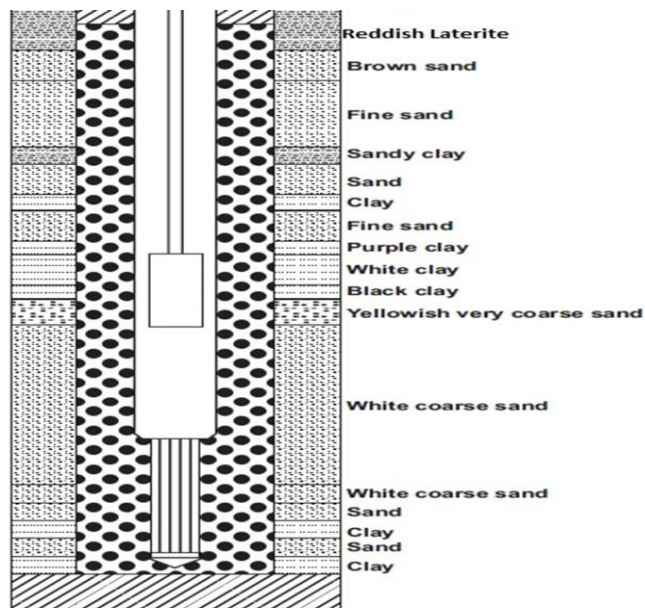
Using these values, the overall vulnerability score was computed as:

$$V = G \times O \times D = 0.7 \times 0.6 \times 0.5 = 0.21$$

This score places the aquifer in the low to moderate vulnerability category, suggesting that while the overburden and semi-confined nature of the aquifer provide some protection, it remains at risk from potential surface or near-surface contaminant sources. This vulnerability underscores the importance of implementing proactive measures to protect the aquifer.

Effective strategies to mitigate risks include controlling land use to minimise contaminant sources, improving waste disposal practices, and conducting regular monitoring of groundwater quality to detect and address contamination promptly (Foster et al., 1998). Such measures are essential to safeguard the aquifer and ensure its continued use as a reliable groundwater resource.

Figure 7 presents the borehole log obtained near the study location. The integration of geophysical results with borehole lithological data highlights both alignments and discrepancies, underscoring the complexity of subsurface characterisation.



**Figure 7:** Borehole log obtained closed to the study area. (Source: Omozeje, 2023).

The upper layer, identified through resistivity data as lateritic clay interspersed with sand lenses, corresponds closely with the borehole description of reddish laterite. This alignment suggests active surface processes, such as infiltration and organic activity, which significantly influence the physical and chemical properties of this layer. The second layer transitions into brown laterite, reflecting increased compaction and reduced organic content, a characteristic supported by its higher resistivity values.

The third layer, interpreted as a porous and permeable sandy unit, likely serves as a significant groundwater reservoir. This interpretation aligns with the borehole's identification of fine sand at the corresponding depth range, reinforcing its role as a primary aquifer. Similarly, the fourth layer, characterised in the resistivity profile as a compacted, low-porosity zone, aligns with the borehole description of sandy clay. This layer likely functions as a semi-confining boundary, restricting vertical water movement.

In contrast, the lower layers exhibit notable discrepancies. The fifth layer,

interpreted from resistivity data as compacted sandstone or fractured rock with minimal porosity, is described in the borehole log as sand. This suggests higher permeability and potential moisture content than implied by the resistivity data. Such a discrepancy could arise from spatial variability within the subsurface or differences in the resolution of geophysical versus lithological methods.

The deepest layer presents the most significant divergence. While resistivity data indicate crystalline bedrock as an impermeable formation, the borehole log describes this layer as clay. This difference may reflect a highly compacted clay layer with resistive characteristics or limitations in the geophysical resolution for capturing finer stratigraphic details. Alternatively, it could suggest localised lithological variations not resolved by the resistivity survey.

These findings emphasise the value of a multidisciplinary approach in subsurface investigations. Resistivity surveys provide a broad-scale perspective on subsurface properties, but their interpretations must be calibrated and refined through direct borehole observations to capture localised variations and finer stratigraphic details. Integrating these methods enhances the reliability of subsurface models, facilitating more precise delineation of aquifer zones, assessment of groundwater potential, and understanding of subsurface heterogeneities. This iterative refinement of models is essential for maximising the utility of geophysical data in environmental and hydrogeological studies.

From a hydrogeological perspective, the second and third layers are particularly significant. Their moderate resistivity and sandy composition suggest potential groundwater storage zones. The third layer, with its higher porosity and relatively uniform distribution, emerges as the most promising aquifer. The compacted nature of the fourth and fifth layers provides structural support, limiting fluid migration and offering stability for engineering purposes. The sixth layer, representing bedrock, serves as the ultimate load-bearing stratum and marks the geological boundary of interest.

This interpretation underscores the site's potential for groundwater exploration and infrastructural development. Further investigations, including borehole drilling and geotechnical analysis, are recommended to validate these findings and optimise resource utilisation.

#### 4. CONCLUSION

This study exemplifies the integration of three-dimensional (3D) electrical resistivity imaging and borehole log data for comprehensive subsurface characterisation and aquifer vulnerability assessment in urban environments. By combining high-resolution geophysical imaging with lithological verification, the research resolved discrepancies in subsurface interpretations, enhancing the reliability of identified aquifer zones. The sandy formations between 10.0 m and 17.4 m were delineated as high-potential aquifers, corroborated by borehole logs, while compacted sandstones and crystalline bedrock were identified as key structural elements providing natural aquifer protection.

The vulnerability analysis, conducted using the GOD model, classified the aquifer system as moderately susceptible to contamination. This underscores the need for proactive measures, including land-use planning, improved waste management, and periodic monitoring to mitigate contamination risks. Furthermore, the findings highlight the utility of combining resistivity imaging and borehole data in urban hydrogeophysical studies, offering a scalable methodology for similar environments worldwide.

Future research should focus on integrating additional geophysical techniques, such as seismic refraction and electromagnetic surveys, with advanced hydrogeological modelling to further refine spatial and lithological resolution. This multidisciplinary approach is crucial for advancing sustainable groundwater exploitation, improving aquifer protection strategies, and addressing the growing demands for water resources in urbanised regions.

#### CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

#### REFERENCES

- Adeplumi, A.A., Ako, B.D., Ajayi, T.R., Afolabi, O., 2009. Delineation of saltwater intrusion into the freshwater aquifer of Lekki Peninsula, Lagos, Nigeria. *Environmental Geology*, 56 (5), Pp. 927-933. <https://doi.org/10.1007/s00254-008-1194-3>,

- Alile, O.M., Ehanire, T., and Edogbanya, O., 2020. Hydrogeophysical characterization of groundwater potential in parts of Benin City, Nigeria. *Nigerian Journal of Environmental Sciences and Technology*, 4 (1), Pp. 55–65.
- Ariyo, S.O., Ajibade, O.M., Coker, J.O., Adeyemi, G.O., Oshagale, B., 2021. And Odugbesan, O.O. "Hydrogeophysical Characterization of Aquifer for Groundwater Potential Evaluation at Ogbere, Southwestern Nigeria". *Journal of Mining and Geology* Vol. 57(1) Pp., 2021. 33 – 40.
- Avenbuan, N., Alile, O. M., and Onobrakpeya, C. U., 2024. "Geoelectrical Investigation of Subsurface Heterogeneity And Influence Of Roots On Infrastructural Planning". *GeoScience Engineering*, 70(2), Pp., 62–70. <https://doi.org/10.35180/gse-2024-0113>,
- Avenbuan, N., Alile, O.M., Iduseri, O.M. "A., 2020. Comparative Study of Subsurface Earth Classification Between Two Dimensional and Three Dimensional Geoelectrical Imaging in University of Benin Teaching Hospital, Benin City, Nigeria". *Nigerian Research Journal of Engineering and Environmental Sciences* 5(2), Pp., 2020 pp. 591-601. [www.rjees.com](http://www.rjees.com),
- Bassey, P.; Lawrence, O. O.; Ailego, J., 2029. eo-electrical Resistivity Evaluation of Groundwater Potential at University of Benin Ugbowo Campus, Benin-City, Edo State of Nigeria, Using the Schlumberger Array". *J. Appl. Sci. Environ. Manage.* Vol. 23 (9), Pp., 1761-1770. DOI: 10.4314/jasem.v23i9.23,
- Cardarelli, E., and Di Filippo, G., 2004. Integrated geophysical methods for the characterization of a landslide". *Journal of Applied Geophysics*, 56(1), Pp., 93-102. <https://doi.org/10.1016/j.jappgeo.2004.06.003>,
- Dahlin, T., and Zhou, B., 2004. A numerical comparison of 2D resistivity imaging with 10 electrode arrays". *Geophysical Prospecting*, 52(5) Pp., 379-398. <https://doi.org/10.1111/j.1365-2478.2004.00423.x>,
- Eguagie-Suyi, P., 2022. Map of UBTH. Digitized the University of Benin Teaching Hospital". [www.google.com](http://www.google.com).
- Fitts, C. R. "Groundwater science". Academic Press, (2002).
- Foster, S. S. D., Hirata, R., Gomes, D., D'Elia, M., and Paris, M., 1998. Groundwater quality protection: A guide for water utilities, municipal authorities, and environment agencies". World Bank.
- Günther, T., Rüker, C., and Spitzer, K., 2006. Three-dimensional modelling and inversion of dc resistivity data incorporating topography—II. Inversion". *Geophysical Journal International*, 166(2) Pp., 506-517. <https://doi.org/10.1111/j.1365-246X.2006.03010.x>, {
- Jongmans, D., and Garambois, S. 2007. Geophysical investigation of landslides: A review." *Bulletin de la Société Géologique de France*, 178(2), Pp., 101-112. <https://doi.org/10.2113/gssgfbull.178.2.101>,
- Loke, M. H., Chambers, J. E., Rucker, D. F., Kuras, O., 2013. And Wilkinson, P. B. "Recent developments in the direct-current geoelectrical imaging method". *Journal of Applied Geophysics*, 95, 135-156. <https://doi.org/10.1016/j.jappgeo.2013.02.017>,
- Omozeje, E. F. "Ugbowo Borehole Section and well design Logged". Benin Owena River Basin Development Authority, 2023.
- Pessu, B., Itiowe, K., and Ikponmwen, M. O., 2021. Application of electrical resistivity tomography for soil competence study in University of Benin Teaching Hospital environment, Edo State, Nigeria". *Asian Journal of Basic Science and Research*, 3(1), Pp 45-58.
- Reynolds, J. M. "An introduction to applied and environmental geophysics". Wiley-Blackwell, 2011.
- Zhou, W., Beck, B. F., and Adams, A. L. 2002. Effective electrode array in mapping karst hazards in electrical resistivity tomography". *Environmental Geology*, 42(8), Pp., 922-928. <https://doi.org/10.1007/s00254-002-0594-z>.

