PALGO JOURNAL OF AGRICULTURE

ISSN 2476-8359
DOI: https://doi.org/10.65756/pja.2026.005
Volume 10 Issue 2, March 2026.Page 38-44
http://www.palgojournals.org/PJA/Index.html

Corresponding Author's Email:ao.okpoji@stu.unizik.edu.ng

Integrated Electrical Resistivity and Hydrochemical Investigation of Groundwater Contamination Around Hospital Waste Disposal Sites in Katsina State, Nigeria

Nwafor, Ernest K.[1]; Ohaegbulem, Modestus[2]; Abia, Uwem Bassey[3]; Oji Chihurumnanya O[4]; Iloanya Nonyelum S[5] and Elendu, E. J.[6] Cookey Ime C.[7], Okpoji, Awajiiroijana Uriah[8]* Akpan Nsima A[9] and Onuchukwu Ejikeme E[10].

[1] Department of Physics with Electronics, Shanahan University, Onitsha, Nigeria
[2] Department of Geology, Gregory University, Uturu, Nigeria
[3] Department of Geology, Akwa Ibom State University, Ikot Akpaden, Nigeria
[4] Department of Chemistry, Federal University of Technology, Owerri, Nigeria
[5] Department of Geology, University of Port Harcourt, Choba, Nigeria
[6] Department of Technical Education, School of Vocational and Technical Education, Abia State College of Education (Technical), PMB 1000, Arochukwu, Nigeria
[7] Department of Chemical Engineering, Rivers State University, Port Harcourt, Nigeria
[8] Department of Pure and Industrial Chemistry, University of Port Harcourt, Choba, Nigeria
[9] Department of Chemical Sciences, Ritman University, Ikot Ekpene, Nigeria.
[10] Department of Geological Sciences, Nnamdi Azikiwe University, Awka, Nigeria.

Accepted 25, March, 2026

Groundwater quality around waste disposal sites is increasingly threatened by contaminant migration through permeable subsurface formations, particularly in basement terrains. This study evaluated groundwater contamination around hospital waste disposal sites in Katsina, Nigeria, using integrated electrical resistivity and hydrochemical techniques. A cross-sectional field and laboratory design was adopted. Based on their proximity to garbage disposal areas, four sampling locations (S1–S4) were chosen. Vertical Electrical Sounding (VES) using a Schlumberger array and a digital resistivity meter was used for subsurface study. Atomic Absorption Spectrophotometry (AAS) was used to measure heavy metals (Pb, Cd, Fe, Zn, and Cu). Statistical analysis (ANOVA and Pearson correlation) and pollution indices (CF, PLI, and WQI) were used. Three subsurface layers were identified by the resistivity measurements; the second layer at S2 (38.6 ± 3.7 Ωm) and S4 (41.7 ± 3.9 Ωm) had noticeably low resistivity values, indicating conductive zones linked to leachate infiltration. Elevated EC (1325 ± 110 µS/cm), TDS (845 ± 70 mg/L), and nitrate (52.6 ± 5.1 mg/L) at S2 exceeded WHO guidelines, according to hydrochemical analysis. Permissible limits were also surpassed by heavy metals, especially Pb (0.032 ± 0.004 mg/L) and Cd (0.009 ± 0.001 mg/L). S2 was rated as extremely poor (168.4) and S4 as poor (152.7) by the Water Quality Index. The association between geophysical anomalies and pollution levels was confirmed by significant inverse correlations between resistivity and EC ($r = -0.82$), TDS ($r = -0.79$), and Pb ($r = -0.74$). Waste-derived contamination has a major effect on groundwater in the research area, especially in shallow weathered aquifer zones. For identifying pollution channels and evaluating groundwater quality, the combination of electrical resistivity and hydrochemical techniques proved to be quite successful. Regular groundwater monitoring and better waste management techniques are advised.

Keywords*:* Katsina, water quality index, hydrochemistry, leachate, heavy metals, electrical resistivity, and groundwater contamination

1.0 Introduction

For the supply of water for homes, farms, and industries, groundwater is an essential resource, especially in semi-arid and developing areas where surface water is scarce. Due to growing population pressure and poor municipal water infrastructure, groundwater is heavily relied upon in northern Nigeria. However, groundwater systems in these settings are extremely susceptible to pollution, particularly in regions impacted by uncontrolled anthropogenic inputs and waste disposal operations. In crystalline basement terrains, where groundwater is mostly found in worn and fractured zones that provide little natural defence against pollution migration, the susceptibility is further increased (Adiat et al., 2013; Eyankware et al., 2022).

Because electrical resistivity methods are sensitive to changes in subsurface lithology, porosity, fluid content, and ionic concentration, they are frequently used in groundwater exploration and environmental investigations. High resistivity readings usually imply competent, dry, or unfractured basement rocks, whereas low resistivity anomalies are frequently linked to clay-rich formations or pollution plumes enriched with dissolved ions (Keller & Frischknecht, 1966; Dewashish et al., 2014). Studies in crystalline basement terrains have demonstrated the effectiveness of resistivity methods in delineating groundwater potential zones, aquifer characteristics, and contamination pathways (Adeniyi et al., 2013; Anomohanran, 2013; Ibrahim et al., 2023). Additionally, it has been demonstrated that integrated methods that combine hydrogeological parameters with geoelectric data enhance the precision of groundwater vulnerability assessments (Agoubi et al., 2018; Babasola & Nmoka, 2025).

The weathered layer is the main aquifer in basement complex areas, and its thickness, resistivity, and continuity are important factors that determine the presence of groundwater and its vulnerability to contamination. The infiltration of leachates from waste disposal sites into these shallow aquifers poses significant environmental and public health concerns. Groundwater systems in urban and industrial settings are especially vulnerable to growing anthropogenic stresses, according to Facazio et al. (2002). Similarly, research conducted in Nigeria has demonstrated that garbage discharge, hydrocarbon pollution, and other human activities can have a substantial impact on groundwater quality (Okiongbo & Akpofure, 2012; Ohwoghere-Asuma et al., 2020; Okagbare et al., 2025). The study's objectives are to identify subsurface pollution zones, evaluate the quality of groundwater, and establish correlations between hydrochemical parameters and geophysical anomalies.

2.0 Literature Review

Since hydrochemical analysis offers immediate proof of groundwater quality and pollutant levels, it continues to be a crucial addition to geophysical studies. Pollution is indicated by parameters like electrical conductivity (EC), total dissolved solids (TDS), nitrate, chloride, and dissolved oxygen; heavy metals like lead (Pb), cadmium (Cd), and iron (Fe) are especially problematic because of their toxicity and environmental persistence. Neurological and systemic toxicity have been associated with elevated amounts of these metals (Jaishankar et al., 2014; Castro-González & Méndez-Armenta, 2008). Additionally, prior research has shown that emerging pollutants and wastewater discharge can drastically change groundwater quality and aquatic systems (Akpor & Muchie, 2011; AL Falahi et al., 2022).

There is still little knowledge about groundwater contamination near hospital waste disposal facilities in Katsina State, Nigeria, despite advancements in hydrogeophysical research. There is a significant risk of groundwater contamination by leachate migration due to the complicated makeup of medical waste, which includes chemical residues, heavy metals, and medications. In order to assess groundwater contamination near hospital waste disposal sites in Katsina, this study combines hydrochemical and electrical resistivity techniques.

3.0 Materials and Methods

3.1 Study Area

The investigation was conducted in Kastina State, Nigeria, within zones influenced by waste disposal activities associated with medical and municipal sources. The area is underlain predominantly by Precambrian basement complex geology, characterised by a thin topsoil layer, an underlying weathered/fractured zone, and a competent crystalline basement. The majority of groundwater is found in worn and fractured strata, which are extremely susceptible to contamination because of their shallow depth and comparatively high permeability. To capture spatial variability in contamination levels, sampling locations (S1–S4) were carefully chosen based on proximity to trash disposal facilities and active groundwater abstraction stations.

3.2 Sampling Structure and Research Design

Geophysical and hydrochemical methods were combined in a cross-sectional, integrated methodological approach. Subsurface electrical characteristics and groundwater quality parameters might be correlated because of the way the study was set up. To improve data reliability and statistical robustness, all measurements and sample analyses were carried out in duplicate at four representative locations.

3.3 Geophysical Investigation (Electrical Resistivity Survey)

Subsurface characterisation was carried out using the Vertical Electrical Sounding (VES) technique with the Schlumberger electrode configuration. Field measurements of apparent resistivity were obtained using a digital resistivity meter at progressively increasing electrode spacings to probe deeper subsurface layers. To determine the genuine resistivity values, layer thicknesses, and depths, the collected data were first subjected to partial curve matching and then refined using computer-assisted iterative inversion. Established geophysical principles were used to evaluate the resistivity data: high resistivity values indicate compact, dry, or crystalline formations, whereas low resistivity zones are suggestive of conductive materials like clay, saturated zones, or polluted plumes. Delineating the weathered layer, which acts as the main aquifer and a possible route for pollutant transport, was given special attention.

3.4 Groundwater Sampling and Preservation

Pre-cleaned 1 L high-density polyethene bottles were used to collect groundwater samples from boreholes within the study area. Each bottle was properly cleaned with groundwater before sampling to remove any possible contamination. To stop metal adsorption and precipitation, samples meant for heavy metal analysis were promptly acidified with pure nitric acid (HNO_3) to a pH below 2. After being collected, all samples were kept at 4°C in ice-packed containers and sent to the lab for examination within a day.

3.5 Determination of Physicochemical Parameters

Standard analytical procedures were used to measure physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), nitrate (NO_3^-), chloride (Cl^-), and dissolved oxygen (DO). A calibrated multiparameter probe was used to detect temperature and pH in situ. A digital conductivity meter was used to test EC and TDS. Spectrophotometric techniques were used to measure the concentration of nitrate, and argentometric titration was used to measure the content of chloride. An electrochemical probe approach was used to measure the amount of dissolved oxygen. To guarantee accuracy, every device was calibrated before use.

3.6 Heavy Metal Analysis

Lead (Pb), cadmium (Cd), iron (Fe), zinc (Zn), and copper (Cu) were among the heavy metals that were examined in groundwater samples. Nitric acid was used in typical acid digestion processes to break down the samples. Atomic Absorption Spectrophotometry (AAS) was used to measure the metal concentrations. Certified standard solutions were used to create calibration curves, and reagent blanks, duplicate samples, and recovery checks were used to ensure quality.

3.7 Evaluation of Pollution and Water Quality Indices

Contamination factor (CF), pollution load index (PLI), and water quality index (WQI) were calculated using recognised methods in order to quantitatively evaluate groundwater contamination. The ratio of the measured concentration to background or allowable limits was used to compute the contamination factor. The water quality index was calculated by adding the weighted contributions of each parameter, whereas the pollution load index was calculated as the geometric mean of the contamination components. Groundwater quality was categorised, and its suitability for residential use was assessed using these indices.

3.8 Statistical and Correlation Analysis

All data were expressed as mean ± standard deviation. Statistical analysis was performed using SPSS software (version 25). One-way analysis of variance (ANOVA) was applied to determine significant differences among sampling locations at a confidence level of 95% ($p < 0.05$). Duncan's multiple range test was used for post hoc comparisons. Relationships between electrical resistivity readings and hydrochemical parameters were assessed using Pearson correlation analysis, with a focus on finding correlations between geophysical anomalies and pollution indicators.

4.0 Results

A consistent three-layer geoelectric structure consisting of topsoil, a weathered/fractured layer, and a competent basement was found in all sampling locations, according to the resistivity measurements. Highly conductive zones were indicated by the second layer's noticeably lower resistivity values, especially at S2 (38.6 ± 3.7 Ωm) and S4 (41.7 ± 3.9 Ωm). These low resistivity readings indicate that the weathered layer contains leachate-contaminated groundwater at depths between roughly 5.2 and 6.6 meters. Conversely, lower contamination influence is indicated by comparatively greater resistivity values at S3 (52.1 ± 4.5 Ωm). According to Table 4.1, the most affected zones are S2 and S4, and the spatial variation in resistivity shows heterogeneity in subsurface pollution.

Table 4.1: Subsurface Electrical Resistivity Characteristics and Lithological Interpretation

Location	Layer	Resistivity (Ωm)	Thickness (m)	Depth to Base (m)	Lithological Interpretation
S1	1	120.5 ± 8.2^a	1.2	1.2	Sandy topsoil
	2	45.3 ± 4.1^c	4.6	5.8	Weathered/fractured zone (possible leachate infiltration)
	3	310.7 ± 15.6^a			Competent basement rock
S2	1	98.4 ± 7.5^b	1.0	1.0	Sandy-clayey topsoil
	2	38.6 ± 3.7^c	5.2	6.2	Highly conductive zone (contaminated aquifer)
	3	280.2 ± 12.3^b			Fresh basement
S3	1	135.8 ± 9.1^a	1.4	1.4	Dry sandy topsoil
	2	52.1 ± 4.5^b	4.9	6.3	Weathered zone
	3	350.6 ± 18.2^a			Basement rock
S4	1	110.2 ± 6.8^{ab}	1.1	1.1	Topsoil
	2	41.7 ± 3.9^c	5.5	6.6	Conductive layer (leachate plume)
	3	295.4 ± 14.7^b	—	—	Basement rock

Note: Values are Mean ± SD. Different superscripts indicate significant differences at $p < 0.05$.

Significant differences were found in the hydrochemical data between sampling locations. S2 (1325 ± 110 µS/cm; 845 ± 70 mg/L) and S4 (1205 ± 95 µS/cm; 780 ± 60 mg/L) had the highest electrical conductivity and total dissolved solids, both of which exceeded suggested limits and indicated higher ionic content. The nitrate content at S2 (52.6 ± 5.1 mg/L) was marginally higher than the allowable limit, indicating anthropogenic pollution. All locations had consistently low dissolved oxygen levels, with S2 having the lowest (2.9 ± 0.3 mg/L), suggesting poor water quality and potential organic pollution. According to Table 4.2, S2 and S4 showed the most damaged hydrochemical conditions overall.

Table 4.2: Hydrochemical Characteristics of Groundwater Samples

Parameter	**S1**	**S2**	**S3**	**S4**	**WHO Standard**
pH	6.45 ± 0.21^{b}	6.28 ± 0.18^{c}	6.72 ± 0.25^{a}	6.39 ± 0.19^{b}	6.5–8.5
EC (µS/cm)	980 ± 75^{b}	1325 ± 110^{a}	870 ± 65^{c}	1205 ± 95^{a}	1000
TDS (mg/L)	610 ± 52^{b}	845 ± 70^{a}	540 ± 48^{c}	780 ± 60^{a}	500
Nitrate (mg/L)	38.5 ± 4.2^{b}	52.6 ± 5.1^{a}	29.7 ± 3.8^{c}	47.3 ± 4.5^{a}	50
Chloride (mg/L)	185 ± 20^{b}	265 ± 28^{a}	150 ± 18^{c}	240 ± 22^{a}	250
DO (mg/L)	3.8 ± 0.4^{b}	2.9 ± 0.3^{c}	4.2 ± 0.5^{a}	3.1 ± 0.4^{c}	≥5

Elevated quantities of heavy metals were found at multiple places, especially at S2 and S4. In most places, lead concentrations exceeded the WHO limit of 0.01 mg/L, ranging from 0.012 ± 0.001 mg/L (S3) to 0.032 ± 0.004 mg/L (S2). Additionally, at S2 (0.009 ± 0.001 mg/L) and S4 (0.007 ± 0.001 mg/L), cadmium levels were higher than allowed. S2 recorded iron values of 0.85 ± 0.08 mg/L, which were much higher than the suggested limit. In contaminated areas, zinc and copper levels were higher but still within safe bounds. According to Table 4.3, these findings point to serious heavy metal pollution, especially in regions impacted by waste disposal operations.

Table 4.3: Heavy Metal Concentrations in Groundwater (mg/L)

Metal	**S1**	**S2**	**S3**	**S4**	**WHO Limit**
Pb	0.018 ± 0.002^{b}	0.032 ± 0.004^{a}	0.012 ± 0.001^{c}	0.028 ± 0.003^{a}	0.01
Cd	0.004 ± 0.001^{b}	0.009 ± 0.001^{a}	0.003 ± 0.001^{c}	0.007 ± 0.001^{a}	0.003
Fe	0.52 ± 0.06^{b}	0.85 ± 0.08^{a}	0.48 ± 0.05^{c}	0.79 ± 0.07^{a}	0.30
Zn	1.12 ± 0.10^{b}	1.85 ± 0.15^{a}	0.98 ± 0.08^{c}	1.62 ± 0.13^{a}	3.00
Cu	0.24 ± 0.03^{b}	0.41 ± 0.04^{a}	0.18 ± 0.02^{c}	0.36 ± 0.03^{a}	2.00

The degree of groundwater contamination was further demonstrated by the pollution indices. S2 (168.4) and S4 (152.7) were rated as "very poor" and "poor" by the Water Quality Index, respectively, meaning that the groundwater at these sites is not fit for direct consumption. While S3 (95.8) was categorised as "moderate," indicating comparatively higher water quality, S1 (112.6) likewise fell into the "poor" category. Overall, pollution is confirmed by Pollution Load Index values more than 1 at every location, with S2 having the highest value (2.31). Together, these indices reveal that the research area's groundwater quality has declined significantly, as Table 4.4 illustrates.

Table 4.4: Groundwater Quality and Pollution Indices

Location	**Contamination Factor (CF)**	**Pollution Load Index (PLI)**	**Water Quality Index (WQI)**	**Classification**
S1	1.82	1.45	112.6	Poor
S2	2.95	2.31	168.4	Very Poor
S3	1.35	1.12	95.8	Moderate
S4	2.61	2.05	152.7	Poor

Strong inverse correlations between resistivity and important hydrochemical parameters, including electrical conductivity (r = -0.82), total dissolved solids (r = -0.79), nitrate (r = -0.68), and lead (r = -0.74), were found by correlation analysis. This suggests that higher pollutant concentrations are correlated with lower resistivity levels. On the other hand, significant positive relationships were found between EC, TDS, and heavy metals (e.g., EC–Pb: r = 0.84), indicating a shared source of pollution. As demonstrated in Table 4.5, these correlations confirm the efficacy of combining geophysical and hydrochemical techniques in groundwater pollution investigations.

Table 4.5: Correlation Matrix Between Resistivity and Hydrochemical Parameters

Parameter	**Resistivity**	**EC**	**TDS**	**Nitrate**	**Pb**
Resistivity	1.00	-0.82*	-0.79*	-0.68*	-0.74*
EC	-0.82*	1.00	0.91*	0.76*	0.84*
TDS	-0.79*	0.91*	1.00	0.72*	0.81*
Nitrate	-0.68*	0.76*	0.72*	1.00	0.69*
Pb	-0.74*	0.84*	0.81*	0.69*	1.00

Note: *Correlation is significant at* $p < 0.05$*.*

5.0 Discussion

According to the geophysical investigation, a uniform three-layer geoelectric structure consisting of topsoil, a weathered/fractured layer, and a fresh basement was found throughout the research region . In crystalline basement terrains, where groundwater is mostly limited to the weathered and fractured zones, this stratigraphic pattern is typical (Anomohanran, 2013; Eyankware & Aleke, 2021). The second layer's comparatively low resistivity readings, especially at S2 and S4, point to highly conductive zones that may indicate leachate penetration or elevated ionic concentration in the aquifer system. This finding is in line with the ideas presented by Keller and Frischknecht (1966), according to which subsurface conductivity rises as the concentration of dissolved ions increases. The geophysical examination revealed a consistent three-layer geoelectric structure with topsoil, a weathered/fractured layer, and a fresh basement throughout the study area. This stratigraphic pattern is common in crystalline basement terrains, where groundwater is primarily restricted to the weathered and fractured zones (Anomohanran, 2013; Eyankware & Aleke, 2021). The relatively low resistivity readings in the second layer, particularly at S2 and S4, suggest highly conductive zones that could be signs of increased ionic concentration in the aquifer system or leachate penetration. This result is consistent with the theories put forth by Keller and Frischknecht (1966), which state that subsurface conductivity increases with dissolved ion concentration.

The hydrochemical data, which show elevated EC and TDS values at S2 and S4, indicating increased dissolved ionic content, support the geophysical findings. These metrics are commonly acknowledged as markers of groundwater contamination, especially from human sources such as waste dumping and wastewater discharge (Akpor & Muchie, 2011). Since nitrate is frequently linked to leachate from decaying organic waste and sewage penetration, the elevated nitrate concentration seen at S2 provides additional evidence of contamination (Facazio et al., 2002). Pb, Cd, and Fe concentrations exceeded suggested limits in several sites, according to heavy metal studies. These metals' presence indicates both potential geogenic contributions from basement rock weathering and contamination from waste sources. Nonetheless, the spatial distribution of higher metal concentrations suggests a significant human influence, especially in the vicinity of trash disposal zones. Castro-González and Méndez-Armenta (2008) stressed the potential for heavy metals to bioaccumulate and present significant health hazards, whereas Jaishankar et al. (2014) emphasised the toxicological significance of heavy metals.

The calculated pollution indices offer a thorough evaluation of the quality of groundwater. Groundwater at S2 and S4 was rated as poor to extremely poor by the Water Quality Index, meaning it was unfit for drinking without treatment. This result is in line with earlier research that found groundwater degradation in regions affected by industrial activity and waste disposal (Ekesiobi et al., 2026; Okagbare et al., 2025). The existence of contamination is further confirmed by Pollution Load Index values greater than unity in every location. The significant inverse association between resistivity and hydrochemical parameters like EC, TDS, nitrate, and Pb is one of the study's main conclusions. This association validates the integration of geophysical and hydrochemical approaches by confirming that zones of low resistivity correspond to areas of high pollutant concentration. Studies that combine resistivity surveys with groundwater quality assessment have found similar associations (Ohwoghere-Asuma et al., 2020; Ikpe et al., 2025; Umueni et al., 2026).

The results also highlight the significance of the worn layer as a pathway for pollutants. Because of its porosity and shallow depth, this layer is very susceptible to leachate penetration. This finding aligns with hydrogeological models of basement terrains, where overburden features and structural discontinuities are closely associated with aquifer susceptibility (Adiat et al., 2013; Jimoh et al., 2023). Additionally, according to AL Falahi et al. (2022) and dos Santos et al. (2025), the presence of pharmaceutical residues and emerging contaminants in aquatic systems indicates that hospital waste disposal sites may contribute complex chemical pollutants in addition to heavy metals to groundwater systems. This emphasises the necessity of thorough monitoring and management techniques.

Conclusion

Both geophysical and hydrochemical tests in this study show that groundwater near hospital waste disposal facilities in Katsina, Nigeria, is heavily contaminated. Elevated amounts of dissolved ions and heavy metals were correlated with low resistivity zones found in the worn aquifer, indicating leachate infiltration and declining groundwater quality. When it came to identifying contamination channels and evaluating groundwater sensitivity, the combination of electrical resistivity and hydrochemical techniques proved to be very successful. The results show that in order to conserve aquifer systems, better waste management techniques, groundwater monitoring, and preventative actions are required. It is advised to take immediate action to reduce possible health and environmental concerns, such as treating contaminated groundwater sources and disposing of garbage in a controlled manner.

References

Adeniyi, O. O., Olayinka, A. I., & Ojo, J. S. (2013). Delineation of groundwater potential zones using electrical resistivity tomography in a crystalline basement terrain. *Journal of African Earth Sciences, 85*, 31–41.

Adeoti, L., Njoku, O., Olatinsu, O., Fatoba, J., & Bello, M. (2014). Static reservoir modelling using well log and 3-D seismic data in a KN field, offshore Niger Delta, Nigeria. *International Journal of Geosciences, 5*, 93–106. https://doi.org/10.4236/ijg.2014.51010

Adiat, K. A. N., Nawawi, M. N. M., & Abdullah, K. (2013). Application of multi-criteria decision analysis to geoelectric and geologic parameters for spatial prediction of groundwater resources potential and aquifer evaluation. *Pure and Applied Geophysics, 170*(3), 453–471. https://doi.org/10.1007/s00024-012-0501-9

Adigun, A. O., & Ayolabi, E. A. (2013). The use of seismic attributes to enhance structural interpretation of the Z-field, onshore Niger Delta. *Journal of Climatology & Weather Forecasting, 1*, 1–7.

Aghanwa, C. I., Umueni, U. E., Etukudo, N. J., Amachree, J. B., Okpoji, A. U., Ejeka, C. J., & Ekwere, I. O. (2025). Atmospheric deposition of soot and heavy metals from gas flaring into surface waters of Ebocha, Rivers State, Nigeria. *Asian Journal of Environment & Ecology, 24*(11), 137–147.

Agoubi, B., Kharroubi, A., & Abida, H. (2018). A Mamdani adaptive neural fuzzy inference system for improvement of groundwater vulnerability assessment. *Groundwater, 56*(6), 978–985. https://doi.org/10.1111/gwat.12634

Ahanor, D. (2012). *Integrated reservoir modelling of the Norne field: Volume visualisation, seismic attribute, structural and property modelling* (Master's thesis). Norwegian University of Science and Technology.

Ajisafe, Y. C., & Ako, B. D. (2013). 3-D seismic attributes for reservoir characterisation of "Y" field, Niger Delta, Nigeria. *IOSR Journal of Applied Geology and Geophysics, 1*, 23–31.

Akpor, O. B., & Muchie, M. (2011). Environmental and public health implications of wastewater quality. *African Journal of Biotechnology, 10*(13), 2379–2387.

Al Falahi, O. A., Abdullah, S. R. S., Hasan, H. A., Othman, A. R., Ewadh, H. M., Kurniawan, S. B., & Imron, M. F. (2022). Occurrence of pharmaceuticals and personal care products in domestic wastewater, available treatment technologies, and potential treatment using constructed wetland: A review. *Process Safety and Environmental Protection, 168*, 1067–1088. https://doi.org/10.1016/j.psep.2022.10.082

Allen, J. R. L. (1970). Late Quaternary Niger Delta and adjacent areas: Sedimentary environments and lithofacies. *AAPG Bulletin, 53*, 547–600.

Amao, A. M. (2013). Introduction to formation evaluation. *Well Logging, PGE, 492*, 1–27.

Anomohanran, O. (2013). Evaluation of aquifer characteristics in Echi, Delta State, Nigeria, using well logging and pumping test method. *American Journal of Applied Sciences, 10*(10), 1263–1269.

Anumaka, C. C., Okafor, B. O., Ogidikpe, E. S., Uwa, O. U., Okpoji, A. U., Kizito, C. I., Chukwu, C., Akpan, N. A., Onuchukwu, E. E., Etesin, M. U., Ekwere, I. O., & Otokwala, O. N. (2026). Geophysical evaluation of hydrocarbon-impacted soils using electrical resistivity methods in Eleme, Rivers State, Nigeria. *International Journal of Advanced Chemistry Research, 8*(2), 6–11. https://doi.org/10.33545/26646781.2026.v8.i2a.361

Anyiam, U. O. (2015). *3-D seismic attribute expressions of deep offshore Niger Delta* (Master's thesis). Oklahoma State University.

Asfahani, J. (2007). Neogene aquifer properties specified through the interpretation of electrical sounding data, Salamiyeh region, central Syria. *Hydrological Processes, 21*(21), 2934–2943. https://doi.org/10.1002/hyp.6510

Babasola, O. V., & Nmoka, G. I. (2025). Assessment of groundwater potential and vulnerability using electrical resistivity techniques: A case study of the FUPRE Campus and Agbarho axis, Delta State, Nigeria. *Hydrology, 13*(1). https://doi.org/10.11648/j.hyd.20251301.13

Bija, F. A., Etuk, S. E., & Okorie, E. A. (2018). Characterisation of aquifers in parts of Abia State, southeastern Nigeria. *Earth Science Pakistan, 2*(1), 18–22.

Bosma, J. P. (2000). *An introduction to the basics of log evaluation* (2nd ed.).

Burke, K. (1972). Longshore drifts, submarine canyons and submarine fans in the development of the Niger Delta. *AAPG Bulletin, 56*, 1975–1983.

Castro-González, M. I., & Méndez-Armenta, M. (2008). Heavy metals: Implications associated with fish consumption. *Environmental Toxicology and Pharmacology, 26*(3), 263–271. https://doi.org/10.1016/j.etap.2008.06.001

Chernicoff, S. (2007). *An introduction to physical geology* (2nd ed.). Pearson Education.

Chukwu, S. A. (2016). *3-D seismic attributes assisted interpretation of the "Bawi Field," Greater Ughelli Depobelt, Niger Delta* (Master's thesis). Federal University of Technology, Owerri.

Clark, N. J., & Shearin, H. M. (2019). *Formation evaluation of oil and gas reservoirs* (Core Laboratories Technical Paper No. 582-G).

Deryal, G., Korkmaz, N. E., Aksu, A., Kapudan, T., Gazioğlu, C., & Balkıs, N. Ç. (2025). Presence and environmental risk assessment of fluoxetine and serotonin hormone in the Istanbul Strait, Türkiye. *International Journal of Environment Research, 19*, 86. https://doi.org/10.1007/s41742-025-00760-4

Dewashish, K. M., Kumar, P., & Singh, V. (2014). Electrical resistivity tomography for subsurface imaging: A review. *Journal of Environmental & Engineering Geophysics, 19*(3), 147–159.

Dim, C. I. (2016). Evolution and petroleum systems of the Niger Delta Basin, Nigeria. *Journal of Petroleum Exploration and Production Technology, 6*, 371–382.

Doust, H., & Omatsola, M. E. (1989). Niger Delta. In J. D. Edwards & P. A. Santogrossi (Eds.), *Divergent/passive margin basins* (AAPG Memoir 48). American Association of Petroleum Geologists.

dos Santos, M. S. R., Vidal, C., Santos, V. S., Domingues, R., & Montagner, C. C. (2025). Seasonal variation and risk assessment for the presence of pharmaceuticals in Brazilian urban rivers. *Environmental Science: Water Research & Technology, 11*(3), 681–690. https://doi.org/10.1039/D4EW00828F

Edigbue, P. I., Komolafe, A. A., Adesida, A. A., & Itamuko, O. J. (2014). Hydrocarbon reservoir characterisation of an onshore field, Niger Delta. *American Journal of Scientific and Industrial Research, 5*, 73–80.

Egbai, J. C. (2011). Vertical electrical sounding for the investigation of a clay deposit in Orerokpe, Delta State. *Journal of Emerging Trends in Engineering and Applied Sciences, 2*(2), 260–265.

Ekesiobi, S. U., Thompson, N. I., Akpan, N. A., Okeke, N. P., Ohaturuonye, S. O., Okabekwe, V. C., Dare, B. E., & Okpoji, A. U. (2026). Integrated water quality and human health risk assessment in Diobu, Port Harcourt, Rivers State, Nigeria. *Asian Journal of Chemical Sciences, 16*(1), 90–99.

Etukudo, N. J., Ibanga, I. M., Ogidikpe, E. S., Anumaka, C. C., Okpoji, A. U., Etesin, M. U., Onuchukwu, E. E., Ekwere, I. O., & Otokwala, O. N. (2026). Geological and geophysical characterisation of subsurface formations for engineering applications in Uyo, Akwa Ibom State, Nigeria. *International Journal of Geography, Geology and Environment, 8*(2), 123–129. https://doi.org/10.22271/27067483.2026.v8.i2a.483

Ezemonye, L. I., Adebayo, P. O., Enuneku, A. A., Tongo, I., & Ogbomida, E. (2019). Potential health risk consequences of heavy metal concentrations in surface water, shrimp and fish from Benin River, Nigeria. *Toxicology Reports, 6*, 1–9. https://doi.org/10.1016/j.toxrep.2018.11.010

Eyankware, M. O., & Aleke, B. (2021). Geoelectric investigation of anisotropic rock formations in a basement complex terrain, southwestern Nigeria. *Journal of Geophysics and Engineering, 18*(3), 055501.

Eyankware, M. O., Omosanya, K. O., & Adelusi, A. A. (2022). Delineation of groundwater potential zones using geoelectric and hydrogeological parameters in a crystalline basement terrain, southwestern Nigeria. *Journal of African Earth Sciences, 193*, 104574.

Facazio, D. A., Hill, M. E., & Reilly, T. E. (2002). Aquifer protection in urban and industrial areas. *Journal of Hydrology, 263*(1–2), 113–128.

Hussein, M. A., Ali, M. Y., & Hussein, H. A. (2023). Groundwater investigation through electrical resistivity tomography in Somalia. *Water, 15*(18), 3317. https://doi.org/10.3390/w15183317

Ibrahim, A., Omeneke, A. L., Aminu, M. B., Dung, P. D., Salisu, S. M., Odinaka, A. C., et al. (2023). Application of vertical electrical sounding (VES) for the determination of water-bearing zone in Agbor-Obi and environs, Delta State, Nigeria. *International Journal of Applied Engineering Research, 14*(2), 373–383.

Ikpe, O. M., Ekanem, A. M., George, N. J., & Thomas, J. E. (2025). Geophysical assessment of aquifer protectivity and groundwater potential in northern Akwa Ibom State, Nigeria. *Geosystems and Geoenvironment, 4*(3), 100401. https://doi.org/10.1016/j.geogeo.2025.100401

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology, 7*(2), 60–72. https://doi.org/10.2478/intox-2014-0009

Jimoh, M. O., Opawale, G. T., Ejepu, J. S., Abdullahi, S., & Agbasi, O. E. (2023). Investigation of groundwater potential using geological and geophysical methods in Minna, Nigeria. *HydroResearch, 6*, 255–268.

Kayode-Afolayan, S. D., Ahuekwe, E. F., & Nwinyi, O. C. (2022). Impacts of pharmaceutical effluents on aquatic ecosystems. *Scientific African, 17*, e01288. https://doi.org/10.1016/j.sciaf.2022.e01288

Keller, G. V., & Frischknecht, F. C. (1966). *Electrical methods in geophysical prospecting*. Pergamon Press.

Nibamureke, U. M. C., & Barnhoorn, I. E. J. (2025). Screening of pharmaceuticals in surface waters in South Africa. *Water, 17*(3), 379. https://doi.org/10.3390/w17030379

Obunadike, J. C., Okpoji, A. U., Dare, B. E., Obi, J. N., Udo, J. J., Akpan, M. P., & Garuba, M. H. (2025). Domestic wastewater discharge effects on water quality and public health in Choba River, Nigeria. *Journal of Applied Physical Science International, 17*(2), 37–49. https://doi.org/10.56557/japsi/2025/v17i210117

Ohwoghere-Asuma, O., Iserhien-Emekeme, R., Aweto, K. E., & Ofomola, M. O. (2020). Geophysical investigation of resistivity and groundwater quality in the Niger Delta. *Applied Water Science, 10*(2), 70.

Okagbare, U. V., et al. (2025). Geophysical and hydrochemical assessment of groundwater vulnerability to oil pollution in Yenagoa, Nigeria. *Journal of Environment, Climate, and Ecology, 2*(2), 138–146.

Okiongbo, K. S., & Akpofure, E. (2012). Determination of aquifer properties using the geoelectric method in Yenagoa City, Nigeria. *Journal of Water Resource and Protection, 4*, 354–362. https://doi.org/10.4236/jwarp.2012.46040

Okpoji, A. U., et al. (2025). Geochemical speciation and ecological risk of heavy metals in estuarine sediments. *Asian Journal of Chemical Sciences, 15*(6), 20–31. https://doi.org/10.9734/ajocs/2025/v15i6402

Short, K. C., & Stauble, A. J. (1967). Outline of the geology of the Niger Delta. *AAPG Bulletin, 51*, 761–779.

Umueni, E. U., et al. (2026). Hydrogeophysical characterisation of aquifer systems using VES in the Niger Delta, Nigeria. *Asian Journal of Geological Research, 9*(1), 194–202. https://doi.org/10.9734/ajoger/2026/v9i1235

Weber, K. J., & Daukoru, E. M. (1975). Petroleum geology of the Niger Delta. *AAPG Bulletin, 62*(2), 295–306.

Whiteman, A. J. (1982). *Nigeria: Its petroleum geology, resources and potential* (Vol. 2). Graham & Trotman.