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Review Article

Geophysical Investigation of Groundwater Contamination in North-Central Nigeria: A Comprehensive Review

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ABSTRACT
Groundwater serves as a critical freshwater resource for North Central Nigeria, yet contamination from agricultural activities, waste dumpsites, industrial effluents, and mining operations poses significant threats to water quality and public health. Geophysical methods, particularly electrical resistivity techniques, were discovered to have emerged as essential non-invasive tools for delineating contamination plumes, assessing aquifer vulnerability, and mapping subsurface hydro stratigraphy. This review synthesizes current knowledge on geophysical investigation approaches, methodological applications, contamination sources, and findings specific to North Central Nigeria, while highlighting research gaps and recommendations for sustainable groundwater management in the region.

Keywords: Geophysical; Groundwater; North Central Nigeria; Research gaps; Safe Water

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INTRODUCTION

North Central Nigeria, comprising states such as Kaduna, Nasarawa, Niger, and Kogi, relies substantially on groundwater resources for domestic, agricultural, and industrial purposes (Imam *et al*., 2023). The region's expanding population intensified agricultural practices, and industrial development have created mounting pressure on groundwater systems. However, inadequate waste management and pollution from anthropogenic sources threaten the sustainability and safety of these vital resources. Access to potable water remains a critical challenge, with studies revealing that more than 55% of groundwater sources in the region are unsuitable for drinking purposes without treatment (Imam *et al*., 2023).

The North Central region faces multiple contamination sources affecting groundwater quality. Agricultural activities involving the extensive use of fertilizers, pesticides, and herbicides constitute significant sources of contamination, particularly in areas such as Kaduna State, where agricultural practices are widespread (Cyril & Abraham, 2025). These chemicals leach into groundwater bodies, generating high biological oxygen demand (BOD) and introducing toxic residues that compromise water quality. In Kaduna State specifically, electrical resistivity tomography investigations have detected distinct low-resistivity zones representing contamination plumes generated by agricultural chemical infiltration (Cyril & Abraham, 2025).

Beyond agriculture, waste dumpsites and refuse disposal sites present formidable contamination threats. Geophysical and hydrochemical investigations in areas such as Nasarawa State have documented that dumpsites generate conductive leachate plumes within the subsurface (Adewoye *et al*., 2025). Abattoir operations in localities such as Keffi, Nasarawa State, also introduce organic and microbial contaminants into groundwater systems, with analyses showing elevated concentrations of sodium, chloride, calcium, nitrate, and sulfate in proximity to these facilities (Ahmed *et al*., 2016). Additionally, mining activities in Adudu, Nasarawa State, have resulted in elevated heavy metal (Lead and Zinc) concentrations in surrounding soils and potential groundwater contamination pathways (Onwuka *et al*., 2024).

GEOPHYSICAL METHODS IN GROUNDWATER EXPLORATION IN NORTH CENTRAL NIGERIA

Electrical Resistivity Techniques

Electrical resistivity methods represent the most extensively applied geophysical approach for groundwater contamination investigation in North Central Nigeria. These techniques, including Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT), exploit variations in subsurface electrical properties to delineate contaminated zones and map aquifer characteristics (Cyril & Abraham, 2025), (Adewoye *et al*., 2025).

Vertical electrical sounding (VES)

Vertical Electrical Sounding employing Schlumberger electrode configuration has been systematically utilized across North Central Nigeria to characterize subsurface geoelectrical structures and assess aquifer properties. This technique involves establishing varying current electrode separations to obtain resistivity values at different depths, enabling the determination of layer thicknesses and resistivity signatures indicative of aquifer composition (Adewoye *et al*., 2025). Studies in Kaduna State have employed VES configurations with current electrode spacing (AB/2) ranging from 1 to 100 meters to acquire sufficient depth penetration for aquifer investigations (Cyril & Abraham, 2025).

The Schlumberger VES technique typically reveals three to four distinct geoelectric layers in the North Central region. These layers characteristically comprise topsoil (commonly displaying resistivity values between 20-100 Ω·m), clay or clayey sand layers (typically exhibiting 50-400 Ω·m), weathered basement or fractured bedrock (ranging from 100-1000 Ω·m), and fresh basement rock (exceeding 1000 Ω·m) (Adewoye *et al*., 2025). Contaminated zones, characterized by leachate plumes, typically display anomalously low resistivity values (often less than 20 Ω·m) that contrast markedly with uncontaminated zones, facilitating visual and quantitative identification of contamination plumes (Adewoye *et al*., 2025).

Two-Dimensional electrical resistivity tomography (2D ERT)

Two-dimensional electrical resistivity imaging employing Wenner, dipole-dipole, or gradient arrays has been increasingly deployed for detailed subsurface mapping and contamination delineation. The Wenner configuration, utilizing equal current and potential electrode spacing, provides superior lateral resolution and is frequently applied for horizontal profiling along survey lines (Adewoye *et al*., 2025). In contrast, the dipole-dipole array enhances vertical resolution, enabling more precise delineation of deep-seated contamination features and layering boundaries (Cyril & Abraham, 2025).

In investigations at Sabo waste dumpsite in Okiti pupa region and other study areas, 2D ERT has successfully delineated subsurface layers and identified low-resistivity zones characteristic of leachate infiltration (Adewoye *et al*., 2025). Data acquisition typically involves electrode spacings ranging from 2.5 to 5 meters with profile lengths extending 80 to 150 meters. Processing and inversion utilizing software such as RES2DINV have produced detailed pseudosections revealing the spatial distribution and depth extent of contamination plumes (Adewoye *et al*., 2025; Cyril & Abraham, 2025).

Integrated Geophysical Approaches

Modern investigations in North Central Nigeria increasingly employ integrated geophysical methods combining electrical resistivity with complementary techniques. Very Low-Frequency Electromagnetic (VLF-EM) surveys have been integrated with electrical resistivity investigations to enhance identification of subsurface conductivity variations and fracture systems that may serve as preferential contaminant migration pathways (OhwoghereAsuma *et al*., 2018). Ground Penetrating Radar (GPR) has been applied in specific studies to supplement electrical methods, particularly for delineating leachate plumes at shallow depths and determining contamination penetration depths (Ojo *et al*., 2021).

SUBSURFACE HYDROSTRATIGRAPHY AND AQUIFER CHARACTERIZATION

Typical Geoelectric Layers

Geophysical investigations across North Central Nigeria have consistently revealed characteristic subsurface sequences. The region's hydrostratigraphy, as delineated through integrated geophysical surveys, typically comprises superficial topsoil layers overlying weathered materials, intermediate clay-dominated formations, fractured bedrock constituting productive aquifer zones, and fresh basement rock (Adewoye *et al*., 2025). In basement complex terrains typical of much of the North Central region, geoelectric sequences often display H or KH curve types according to Schlumberger classification schemes, indicating three to four distinct layers with characteristic resistance patterns (O.o. *et al*., 2023).

Aquifer Properties and Vulnerability Assessment

Geophysical characterization of aquifer properties, including transmissivity and hydraulic conductivity, can be estimated through Dar Zarrouk parameters derived from resistivity data (Okoli *et al*., 2025). These parameters—including longitudinal unit conductance and transverse unit resistance—provide quantitative measures of aquifer protective capacity and groundwater storage characteristics. Studies employing this approach have identified aquifer protective capacity ratings ranging from weak to moderate in many North Central localities (Emeka & Isa, 2025), suggesting heightened vulnerability to surface contamination.

The depth to productive aquifers in North Central Nigeria varies substantially by location, typically ranging between 15 and 120 meters, with significant spatial heterogeneity influenced by basement topography and weathering intensity (Ayua *et al*., 2023). Longitudinal conductance values, computed from geoelectric layer parameters, have provided indices of overburden protective capacity, with values less than 0.2 mhos generally indicating poor aquifer protection against surface contamination (O.o. *et al*., 2023).

CONTAMINATION PLUME DELINEATION AND MIGRATION PATHWAYS

Low-Resistivity Anomalies as Contamination Indicators

A fundamental principle underlying geophysical contamination investigation in North Central Nigeria is that leachate plumes and saturated contaminated zones display anomalously low electrical resistivity values attributable to dissolved ions and ionic species introduced through pollution processes. Agricultural land investigations in Kaduna State have demonstrated that distinct low-resistivity zones (typically displaying values of 2.30×10^1 to 8.20×10^1 Ω·cm) represent contamination plumes originating from fertilizer, pesticide, and herbicide application (Cyril & Abraham, 2025). These anomalies can be reliably distinguished from uncontaminated zones displaying higher resistivity values through careful pseudo-section analysis and 2D inversion modeling.

Leachate Plume Geometry and Migration

Geophysical investigations have effectively mapped the spatial extent and geometry of leachate plumes migrating from contamination sources. At waste dumpsites in the region, leachate plumes have been delineated to depths ranging from 15 to 22 meters below ground surface, with lateral extents dependent on aquifer characteristics, hydraulic gradients, and contaminant transport properties (Adewoye *et al*., 2025). Importantly, 2D resistivity imaging has revealed that leachate migration often follows preferential pathways through more permeable layers, with migration directions controlled by subsurface hydraulic conditions and geological structure.

In contamination studies at Sabo dumpsite, geophysical surveys identified that leachate penetration reached maximum depths of approximately 22 meters, whereas in control traverses positioned away from dumpsite influence, high-resistivity signatures indicated uncontaminated conditions (Adewoye *et al*., 2025). This spatial correlation between low-resistivity anomalies and known contamination sources provides strong validation for the utility of geophysical methods in contamination assessment.

CONTAMINATION SOURCES AND HYDROCHEMICAL CORRELATIONS

Agricultural Contamination

Agricultural activities in North Central Nigeria introduce diverse contaminants into groundwater systems. Investigations in Kaduna State combining geophysical surveys with water quality analysis revealed that fertilizer, pesticide, and herbicide application generate contamination plumes characterized by elevated total dissolved solids (TDS), biological oxygen demand (BOD), and microbial pathogens (Cyril & Abraham, 2025). Biochemical oxygen demand values ranging from 1-10 mg/L and chemical oxygen demand exceeding 2 mg/L were detected in water samples adjacent to geophysically identified contamination zones (Cyril & Abraham, 2025). Furthermore, fecal contamination, including Coliform and Escherichia coli bacteria, was detected above acceptable limits, confirming that agricultural contamination extends beyond chemical constituents to include microbial hazards.

Dumpsite-Induced Contamination

Waste dumpsites represent major groundwater contamination sources throughout North Central Nigeria. Geophysical investigations integrated with water quality analysis have demonstrated strong correlations between low-resistivity anomalies identified through electrical methods and elevated contaminant concentrations in groundwater samples (Babatunde *et al*., 2023). At Apete/Awotan area in Ibadan, electrical resistivity methods revealed high-level chemical contamination within boreholes and wells to distances of 20 meters from dumpsite perimeters, with contamination characterized by elevated anion and cation concentrations (Babatunde *et al*., 2023).

Specifically, hydrochemical analysis of samples from locations adjacent to dumpsite-derived geophysical anomalies showed excessive concentrations of nitrates (NO_3^-), bicarbonates (HCO_3^-), chlorides (Cl^-), and sulfates (SO_4^{2-}) compared to World Health Organization standards and Nigerian standards (Ojo *et al*., 2021). Heavy metal constituents, including lead, zinc, copper, and nickel, were also detected in elevated concentrations within geophysically identified contaminated zones (Ojo *et al*., 2021).

5.3 Industrial and Other Anthropogenic Sources

Beyond agriculture and waste disposal, industrial activities, including abattoir operations and textile manufacturing, introduce contaminants affecting groundwater in North Central locations. Assessments in Keffi, Nasarawa State, demonstrated that abattoir operations influenced groundwater quality within proximity zones, with areas immediately adjacent to abattoirs showing higher concentrations of pollution-related parameters than distant zones (Ahmed *et al*., 2016). Similarly, textile industry effluent discharge in Kaduna State resulted in groundwater quality degradation, with contamination signatures indicative of industrial discharge patterns (Mohammed *et al*., 2015).

AQUIFER VULNERABILITY AND PROTECTIVE CAPACITY ASSESSMENT

Vulnerability Mapping Using Geophysical Parameters

Aquifer vulnerability assessment represents a crucial application of geophysical methods for groundwater protection planning in North Central Nigeria. The protective capacity of aquifer systems, determined from geoelectric layer thicknesses and lithological compositions, provides quantitative measures of resistance to surface contamination. Studies employing Dar Zarrouk parameter approaches have classified aquifer zones into protective capacity categories ranging from poor to good based on longitudinal conductance values (Emeka & Isa, 2025). In the Gauta Buzu area of Keffi, approximately 47% of the aquifer system was classified as weakly protected, with 53% possessing moderate protection (Emeka & Isa, 2025).

Shallow Versus Deep Aquifers

Geophysical investigations have established that shallow boreholes and wells in North Central Nigeria typically access aquifers within weathered and fractured basement zones located at depths between 15 and 40 meters, making them highly susceptible to surface contamination (Emeka & Isa, 2025). Conversely, deeper confined or semi-confined aquifers, accessed at depths exceeding 60-80 meters, generally display improved protective capacity due to intervening clay or clay-rich overburden layers. Depth recommendations for borehole drilling derived from geophysical studies suggest that depths exceeding 30 meters are preferable for accessing groundwater with reduced contamination risk (Olisah & Obiekezie, 2024).

GROUNDWATER CONTAMINATION MONITORING

Agricultural Contamination Studies

Detailed investigations in agricultural areas of Kaduna State, combining electrical resistivity surveys with water quality monitoring, have provided comprehensive documentation of contamination processes and subsurface conditions. Research in Kaura Local Government Area revealed three subsurface layers with distinct resistivity characteristics and identified multiple low-resistivity zones interpreted as contamination plumes derived from chemical applications (Cyril & Abraham, 2025). The study area displayed total dissolved solids concentrations far exceeding Nigerian standards and contained detectable levels of multiple heavy metals (copper, cadmium, nickel, manganese, lead, zinc) along with fecal bacteria, confirming the serious contamination threat posed by uncontrolled agricultural chemical application (Cyril & Abraham, 2025).

Waste Dumpsite Investigations

Comprehensive geophysical and hydrochemical assessments at abandoned dumpsites, such as the Aduramigba-Onibu-Eja Estate facility in the Osogbo area, have demonstrated the long-term persistence of contamination signatures and subsurface migration of leachate over decadal timescales. Comparison of investigations conducted six years apart revealed continued contamination presence, with depths to contamination plumes ranging from 4.1 to 5.9 meters and resistivity values as low as 5.12 $\Omega \cdot m$ in severely contaminated zones (Ojo *et al*., 2021). Ground penetrating radar surveys complementing electrical methods confirmed leachate penetration to depths of 3.5-6.0 meters, corresponding to unconfined aquifer zones vulnerable to contamination (Ojo *et al*., 2021).

Mining Impact Assessments

Lead-zinc mining activities in the Adudu area, Nasarawa State, have introduced elevated concentrations of zinc, chromium, and other heavy metals into surrounding soils, creating a risk of groundwater contamination through infiltration pathways. Ecological risk assessments and contamination factor calculations have identified severely degraded soil conditions proximal to mining operations, with multiple heavy metals exceeding baseline values (Onwuka *et al*., 2024). Geophysical characterization is essential for determining hydrogeological pathways through which mining-derived contaminants can reach groundwater systems.

WATER QUALITY STANDARDS AND HEALTH IMPLICATIONS

Contamination Indicators and Standards Exceedances

Geophysical identified contamination zones in North Central Nigeria frequently display water quality parameters substantially exceeding World Health Organization standards and Nigerian Standards for Drinking Water Quality (NSDWQ). Total dissolved solids concentrations in contaminated zones often range from 300-500 mg/L compared to WHO guidelines of 500 mg/L, while electrical conductivity values frequently exceed 1000 µS/cm (Babatunde *et al*., 2023). Heavy metal concentrations, particularly lead and cadmium, frequently exceed permissible limits by factors of 2-5 (Ojo *et al*., 2021).

Microbial Contamination

Beyond chemical contamination, geophysically mapped contamination plumes frequently contain microbial pathogens representing serious public health threats. Bacterial species, including E. coli, Coliform bacteria, and pathogenic enteroviruses, have been isolated from waters within geophysical identified contamination zones, with concentrations exceeding permissible limits (Cyril & Abraham, 2025). The presence of thermotolerant and fecal coliform bacteria indicates recent and active contamination from organic waste sources, characteristic of agricultural runoff and dumpsite leachate (Cyril & Abraham, 2025).

GEOPHYSICAL METHOD LIMITATIONS AND UNCERTAINTIES

Resolution and Penetration Constraints

While geophysical methods provide valuable information on subsurface conditions, important limitations merit recognition. Vertical resolution of electrical resistivity techniques typically ranges from 1-3 meters for shallow layers to 10+ meters for deeper formations, limiting precise delineation of thin contaminated strata. Additionally, maximum practical investigation depths are restricted to approximately 100-150 meters under typical field conditions, potentially insufficient for assessing deeper confined aquifer systems vulnerable to future contamination (Doro *et al*., 2023).

Hydrogeological Complexity and Ambiguity

North Central Nigeria's basement complex terrain, characterized by highly variable weathering intensity and fracture characteristics, creates subsurface conditions prone to geophysical interpretation ambiguity. Fracture porosity, essential for aquifer function but difficult to resolve geophysically, may not be clearly distinguished from matrix porosity variations (Doro *et al*., 2023). Additionally, natural hydrogeochemical variations, including saline pore waters in certain formations, can produce resistivity signatures similar to contamination-related anomalies, requiring careful integration with hydrochemical data for unambiguous interpretation (Doro *et al*., 2023).

Temporal Variations and Monitoring Challenges

Contamination signatures detected through single-time geophysical surveys provide snapshots of conditions at survey timing. Seasonal variations in water table position, rainfall-induced infiltration fluctuations, and temporal evolution of contamination plumes necessitate repeated surveys for a comprehensive understanding of contamination dynamics (Ojo *et al*., 2021). Multi-temporal geophysical investigations, while providing enhanced understanding, require substantial resource investments often unavailable in resource-limited regions.

RECOMMENDATIONS FOR SUSTAINABLE GROUNDWATER MANAGEMENT

Integrated Geophysical and Hydrogeological Investigations

Future groundwater management strategies in North Central Nigeria should prioritize integrated geophysical investigations combined with comprehensive hydrogeological and hydrochemical characterization. Systematic geophysical surveys utilizing modern VES and 2D ERT techniques should be conducted in priority areas identified by preliminary water quality assessments. Integration of geophysical results with borehole drilling programs, lithological logging, and extended water quality monitoring will enhance the reliability of contamination assessments and management strategy development.

Aquifer Protection and Zoning

Geophysical mapping of aquifer protective capacity should inform land-use zoning and contamination source controls. Areas identified as possessing poor aquifer protective capacity should be restricted from contamination-prone activities, including uncontrolled waste disposal, intensive agricultural chemical application, and hazardous industrial operations. Conversely, areas with moderate protective capacity should implement controlled agricultural practices and engineered waste management systems to minimize contamination risk (Emeka & Isa, 2025).

Water Supply Development Targeting

Geophysical investigations demonstrating depth variations in aquifer vulnerability should guide water supply development strategies. Public water supply boreholes should be designed to access deeper confined or semi-confined aquifer formations displaying reduced contamination vulnerability rather than shallow weathered zone aquifers immediately susceptible to surface contamination (Olisah & Obiekezie, 2024). Minimum borehole depths of 40-60 meters are recommended in areas with established shallow contamination risks (Olisah & Obiekezie, 2024).

Contamination Source Management

Practical contamination control measures informed by geophysical assessments include: (1) engineered waste management facilities replacing open dumpsites, with hydrogeologically-informed siting based on geophysical characterization; (2) establishment of agricultural chemical application standards and practices in areas with high-permeability shallow aquifers; (3) development of industrial wastewater treatment facilities particularly for high-contamination-risk operations including abattoirs and textile manufacturing; and (4) establishment of groundwater quality monitoring networks focused on geophysically identified vulnerability zones (Ahmed *et al*., 2016), (Mohammed *et al*., 2015).

Regulatory and Institutional Frameworks

Effective groundwater management requires institutional frameworks incorporating geophysical investigation results into regulatory decision-making. Development of national and state-level groundwater quality standards informed by hydrogeological and geophysical assessments would enhance protection. Additionally, the establishment of water resource management authorities with technical capacity for geophysical survey supervision and interpretation would strengthen groundwater governance (Doro *et al*., 2020).

RESEARCH GAPS AND FUTURE DIRECTIONS

Limited Data from Geophysical Monitoring Networks

Systematic long-term geophysical monitoring of identified contamination plumes remains extremely limited in North Central Nigeria. Establishment of permanent or semi-permanent geophysical monitoring arrays at priority contamination sites would enable characterization of contaminant migration rates, seasonal variations in contamination extent, and effectiveness of remediation interventions. Time-lapse electrical resistivity imaging, involving repeated surveys over months to years, could provide an unprecedented understanding of contamination dynamics (Ojo *et al*., 2021).

Advanced Geophysical Integration

While electrical methods dominate current practice, limited integration with complementary geophysical techniques has been achieved. Magnetic methods, ground penetrating radar, and controlled-source electromagnetic approaches warrant expanded application in North Central Nigeria for enhanced subsurface characterization. Joint inversion of multiple geophysical datasets, integrating electrical resistivity, electromagnetic, and seismic information, would improve subsurface model reliability and reduce interpretation ambiguity.

Hydrogeological Process Understanding

Fundamental understanding of contaminant transport processes in North Central Nigeria's heterogeneous basement complex terrain remains incomplete. Research coupling geophysical characterization with detailed hydrogeological and hydrochemical process studies would enhance the prediction of contamination fate and transport. Particular emphasis on fracture flow mechanisms, matrix diffusion, and biogeochemical transformations affecting contaminant persistence would improve management strategy effectiveness (Doro *et al*., 2023).

Capacity Building and Technology Transfer

Development of indigenous geophysical investigation capacity within North Central Nigeria, through training programs, equipment acquisition, and research institutional strengthening, represents a priority for sustainable groundwater management. Engagement of academic institutions, governmental water resource agencies, and private sector geophysical service providers in collaborative capacity-building initiatives would enhance the technical foundation for future investigations (Doro *et al*., 2020).

CONCLUSION

Geophysical investigation methods, particularly electrical resistivity techniques, have proven essential for groundwater contamination assessment in North Central Nigeria. Through systematic VES, 2D ERT, and integrated geophysical approaches, subsurface contamination plumes have been successfully delineated, aquifer vulnerability characterized, and groundwater contamination sources identified across the region. Studies have documented contamination originating from agricultural activities, waste dumpsites, industrial operations, and mining activities, with geophysical findings validated through integration with hydrochemical analyses demonstrating elevated contaminant concentrations correlated with low-resistivity anomalies. Despite notable progress, significant challenges persist. Limited monitoring networks, restricted investigation depths in certain terrains, and unresolved interpretation ambiguities in complex basement settings require continued methodological refinement and research investment. Future groundwater management strategies in North Central Nigeria must build upon the substantial foundation of geophysical investigations already completed while establishing systematic monitoring programs, advancing technical capacity within the region, and integrating geophysical results into regulatory frameworks governing groundwater exploitation and contamination source control.

The imperative for sustainable groundwater resource management in North Central Nigeria is substantial, given expanding populations, economic development pressures, and documented contamination threats. Continued investment in geophysical investigations, complementary hydrogeological studies, and integrated management approaches represents the essential pathway toward ensuring the availability of safe, adequate groundwater resources for current and future generations throughout the region.

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