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Geophysical Assessment of Topsoil Quality and Aquifer Vulnerability in Ikot Ekpene Metropolis, Akwa Ibom State

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Abstract

In the heart of Ikot Ekpene Metropolis, a bustling hub of raffia crafts and commerce in northern Akwa Ibom State, Nigeria, rapid urbanization is quietly eroding the delicate balance between topsoil integrity and the safety of underlying aquifers. This comprehensive review synthesizes over a decade of geophysical investigations from 2014 to 2025 using Vertical Electrical Sounding (VES), Electrical Resistivity Tomography (ERT), and Dar-Zarrouk parameters to unravel the threats posed by anthropogenic pressures like waste dumpsites and industrial runoff. Nestled in the permeable sands of the Benin Formation, the region's topsoil emerges as a fragile first line of defense: heterogeneous layers with resistivities spanning 65-2,839 Ωm and high porosity (0.27-0.40) betray its vulnerability to degradation, evidenced by sinkholes, elevated heavy metals (lead up to 0.0010 mg/L, nickel to 0.029 mg/L), and low Longitudinal Conductance (LC) (0.01-0.36 S) signaling poor protectivity in 65-96% of sites. Aquifer vulnerability assessments, blending Depth, Recharge, Aquifer, Soil, Topography, Impact, Conductivity (DRASTIC) and Groundwater Occurrence (G), Overall Lithology of Overlying Strata (O), Depth to Groundwater (D) (GOD) models with Geographic Information System (GIS) mapping, paint a sobering picture: 62-75% of zones rate as moderately to highly susceptible, driven by shallow depths (1-121m), robust recharge (0.68-2.61 m/day), and gentle topography that funnels contaminants into prolific but exposed groundwater reserves (estimated at 7.15×10^{8} m^{3}). Urban cores, especially southeastern ravines, amplify risks, with 87.5% of aquifers offering weak barriers against leachates, contrasting milder rural fringes like Obot Akara. These findings spotlight a high inconsistency in groundwater potential (85-96.7%) shadowed by contamination perils that could spark health crises. By weaving geophysical data with hydrogeochemical insights, this study exposes gaps in current monitoring and urges integrated strategies: from afforestation and regulated borehole siting to policy-driven waste zoning and advanced multi-method fusions like GOD-DRASTIC hybrids. Ultimately, safeguarding Ikot Ekpene's aquifers demands a human-centered pivot-empowering communities, bridging research silos, and fostering resilient urban growth to preserve this vital resource for generations amid Nigeria's coastal sedimentary challenges.

Keywords: Geophysical assessment, Topsoil quality, Aquifer vulnerability, Ikot Ekpene metropolis.

1 | Introduction

Ikot Ekpene Metropolis, located in Akwa Ibom State, southern Nigeria, is a rapidly urbanizing area known for its raffia crafts and commercial activities. The region's hydrogeology is characterized by sedimentary

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formations of the Benin Formation, with aquifers primarily in sandy layers susceptible to surface influences [1], [2]. Geophysical methods, such as electrical resistivity techniques, have been pivotal in evaluating subsurface conditions, providing insights into topsoil integrity and aquifer dynamics. Geophysical assessments in Akwa Ibom State date back to efforts addressing water scarcity and environmental degradation in coastal and sedimentary environments. In Ikot Ekpene and adjacent areas like Obot Akara, studies employing Vertical Electrical Sounding (VES) and Dar-Zarrouk parameters have mapped aquifer properties, revealing depths ranging from 5.4 to 121.4 m and resistivities indicative of varying porosity and permeability [3]. Topsoil quality, often assessed through resistivity indicators of degradation and contaminant levels, is critical as it acts as the first barrier to aquifer pollution. Historical research emphasizes the integration of geophysical data with hydrogeochemical analyses to understand flow dynamics and vulnerability, particularly in northern Akwa Ibom where groundwater is a primary resource for domestic and agricultural use. These assessments are essential in regions with high rainfall and anthropogenic pressures, informing sustainable freshwater management.

Rapid urbanization in Ikot Ekpene Metropolis has intensified groundwater contamination risks, with poor waste disposal and industrial activities leading to leachate infiltration through degraded topsoil. Aquifers exhibit weak protectivity in 87.5% of studied areas, with low Longitudinal Conductance (LC) (0.01-0.26 S) and moderate susceptibility per Groundwater Occurrence (G), Overall Lithology of Overlying Strata (O), Depth to Groundwater (D) (GOD) and Depth, Recharge, Aquifer, Soil, Topography, Impact, Conductivity (DRASTIC) models, heightening vulnerability to pollutants [4]. Topsoil degradation, evidenced by low resistivity and high porosity, facilitates contaminant migration, threatening water quality and borehole sustainability. Despite high groundwater potential (94% of areas), the lack of impervious layers and unregulated land use pose significant challenges, necessitating comprehensive geophysical reviews to guide mitigation strategies. This study aims to synthesize existing geophysical data on topsoil quality and aquifer vulnerability in Ikot Ekpene Metropolis, Akwa Ibom State, to identify patterns of degradation and susceptibility. Specific objectives include evaluating the effectiveness of methods like VES and Electrical Resistivity Tomography (ERT) in assessing aquifer protectivity and flow dynamics; analyzing the impact of urbanization and anthropogenic activities on topsoil and groundwater resources; mapping vulnerability zones using models such as DRASTIC, GOD, and Dar-Zarrouk parameters; and providing recommendations for sustainable groundwater management and policy formulation in the region [5]. By integrating geophysical, hydrogeochemical, and Geographic Information System (GIS)-based approaches, the review seeks to highlight gaps in current research and propose directions for future studies to mitigate contamination risks in similar sedimentary environments. The study is confined to geophysical assessments within Ikot Ekpene Metropolis and its surrounding areas in northern Akwa Ibom State, focusing on data from VES, ERT, and vulnerability models applied to the Benin Formation's sedimentary aquifers. It encompasses studies from 2014 to 2025, emphasizing urban and riverine influences on topsoil and aquifers up to depths of 121 m, while excluding broader Niger Delta regions unless for comparative purposes [6]. The significance lies in addressing groundwater contamination threats amid rapid urbanization, where 87.5% of areas show weak aquifer protection, informing strategies for water security, environmental health, and urban planning in Akwa Ibom State. These insights are crucial for policymakers to prevent epidemics from leachate infiltration, promote sustainable borehole siting, and enhance resource management in high-potential but vulnerable aquifers, with broader implications for coastal sedimentary zones in Nigeria.

2 | Historical Overview of Geophysical Assessments in Akwa Ibom State

Geophysical assessments in Akwa Ibom State have evolved since the early 2010s, initially focusing on groundwater potential in sedimentary basins using VES to map aquifer depths and resistivities. Early studies in the coastal regions, such as those in 2014, integrated VES with hydrogeochemical data to evaluate leachate impacts from dumpsites, revealing contamination risks in shallow aquifers [7]. By the mid-2020s, research expanded to northern areas like Ikot Ekpene, incorporating ERT and Dar-Zarrouk parameters for detailed aquifer protectivity analysis, with findings indicating poor to weak protection in 96% of sites. Recent advancements, including GIS integration with DRASTIC and GOD models, have provided vulnerability maps, highlighting the shift from basic exploration to comprehensive risk assessment amid urbanization pressures. This progression underscores the increasing reliance on multi-method approaches to address water scarcity and pollution in the Benin Formation.

Studies on topsoil quality in Ikot Ekpene have utilized resistivity data to assess degradation from anthropogenic activities, with VES revealing heterogeneous top layers (resistivities 214–2839 Ωm) prone to erosion and contaminant infiltration. A 2023 investigation in Obot Akara and Ikot Ekpene identified non-corrosive topsoil but highlighted sinkholes and high porosity facilitating leachate migration, linking urban waste to reduced soil integrity [8]. Further, ERT-based assessments in Akwa Ibom State University environs showed topsoil with low permeability contributing to waterlogging and poor drainage, exacerbating degradation in raffia-dominated areas. These studies emphasize topsoil's role as a barrier, with degradation evidenced by anisotropy coefficients indicating vulnerability in 65% of urban zones. Comparative hydrogeochemical analyses confirm elevated contaminant levels in degraded topsoils, urging conservation measures. Aquifer vulnerability research in Ikot Ekpene has predominantly employed GOD and DRASTIC models, with a 2025 study grading 62% of northern Akwa Ibom as moderately vulnerable due to shallow depths (1-47.8 m) and permeable sands. Dar-Zarrouk parameter applications in Obot Akara revealed weak protectivity (LC 0.01–0.26 S) in 87.5% of areas, correlating with high groundwater potential but increased contamination risk from waste disposal. A 2024 GIS-based DRASTIC assessment in Ikot Ekpene classified 75% as highly vulnerable, attributing this to gentle topography and vadose zone impacts [9]. Flow unit characterizations using Stratigraphic Modified Lorenz Plots (SMLP) identified heterogeneous aquifers with fair efficiency, vulnerable to leachates in riverine settings. Earlier coastal studies extended these findings, showing high vulnerability in oil-producing areas, with GOD indices revealing low to high risks.

Comparatively, the study reveals similarities between Ikot Ekpene's aquifers and those in the broader Niger Delta, where sedimentary formations exhibit comparable poor protectivity (96% in northern Akwa Ibom and similar ratings in coastal zones). In contrast to more protected aquifers in central Nigeria, Ikot Ekpene's moderate DRASTIC ratings (62%) align with urbanized sedimentary basins like those in southern Nigeria, but exceed vulnerabilities in less urbanized areas due to higher recharge and waste influences. Studies in Obio Akpa Campus show analogous waterlogging issues to Ikot Ekpene, with GOD assessments indicating moderate susceptibility (3.3%), though Ikot Ekpene's urban setting amplifies risks from leachates compared to rural Akwa Ibom sites [10], [11]. Internationally, these patterns mirror vulnerabilities in coastal aquifers of the Gulf of Mexico, emphasizing the need for integrated geophysical-GIS strategies adapted to tropical sedimentary environments.

3 | Study Area Description

Ikot Ekpene Metropolis is a dynamic urban center in the northern part of Akwa Ibom State, southern Nigeria. Nestled within the expansive Niger Delta sedimentary basin, it serves as a vital commercial hub for raffia crafts, palm oil, and kernels, blending cultural heritage with modern trade along the A342 highway [12]. This rapidly urbanizing area faces mounting environmental pressures from population growth and anthropogenic activities, which influence its topsoil and aquifer systems.

3.1 | Geographical Location

Ikot Ekpene Metropolis, situated in the northern part of Akwa Ibom State, southern Nigeria, lies within the Niger Delta sedimentary basin and is underlain by the Benin Formation, characterized by unconsolidated sands, gravels, and occasional clay intercalations [13]. The area experiences high anthropogenic pressures from urbanization, commercial activities, and waste disposal, which influence topsoil quality and aquifer dynamics as seen in *Fig. 1*.

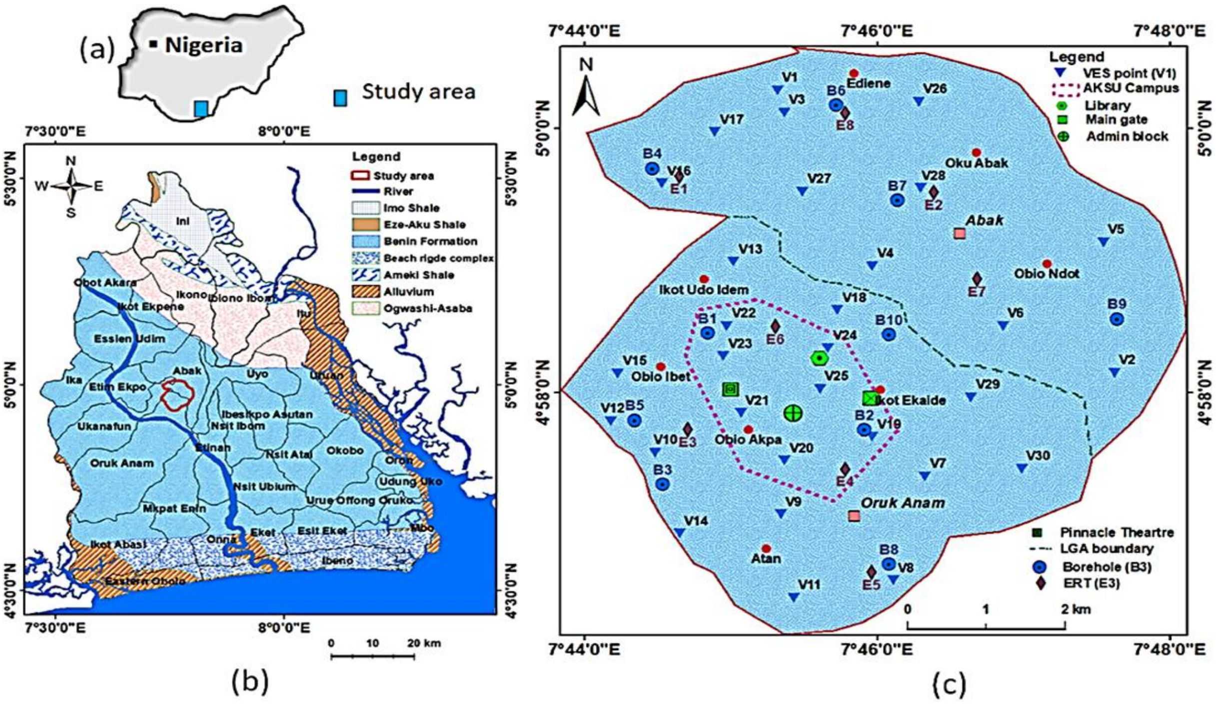

Fig. 1. Combined geophysical and hydrogeological evaluation of groundwater locations.

Ikot Ekpene, due to its prominence in raffia production and trade, is a historic town in Akwa Ibom State, southeastern Nigeria. It is positioned along the A342 highway, paralleling the coast between Calabar to the southeast and Aba to the west, with the state capital Uyo to the east. The metropolis spans latitudes 5°10'N to 5°14'N and longitudes 7°40'E to 7°45'E, with approximate coordinates of 5°11'N, 7°43'E (or 5.183°N, 7.717°E). Covering an area of about 116 km², it serves as a regional commercial hub for palm oil, kernels, and raffia products, and is bordered by Obot Akara to the north, Essien Udim to the west, and Ini to the east. The location facilitates trade and connectivity but exposes the area to environmental stressors from urban expansion as highlighted below:

I. Climate and topography: Ikot Ekpene experiences a tropical monsoon climate (Köppen classification Am), marked by high humidity (63%–88%), consistent temperatures, and distinct wet and dry seasons [14]. Average high temperatures range from 28.4°C to 35.9°C, with lows between 22.3°C and 25.1°C, and annual averages around 30.5°C. Rainfall peaks at 310 mm in July, with the wet season (April–October) being warm, oppressive, and overcast, while the dry season (November–March) is hot and muggy with mostly cloudy skies. Wind speeds average 4.5–6.2 km/h, with gusts up to 9 km/h in August, and daylight hours hover around 12 annually. Topographically, the area features gentle relief with modest elevation variations: maximum change of 207 ft within 2 miles, average elevation of 285-286 ft above sea level, and overall range from 5 m to 146 m. This flat to gently undulating terrain promotes waterlogging and high recharge rates, influencing aquifer vulnerability.

II. Geological setting: Ikot Ekpene lies in the northeastern fringe of the Niger Delta sedimentary basin, primarily underlain by the Miocene Recent Benin Formation, consisting of continental deposits of unconsolidated fine to coarse sands, gravels, and intercalated clays [15]. Geoelectric surveys reveal 3-4 lithological layers: a topsoil of motley sands (resistivity 65-1172 Ωm), followed by sandy clays, fine sands, and coarse sands at deeper levels. The formation's arenaceous nature dominates, with minor argillaceous intercalations, leading to high permeability and vulnerability to contaminants. Regional geology includes influences from the Calabar Flank to the east, with no major faults but gentle dips toward the coast. This setting supports prolific aquifers but exposes them to leachate from dumpsites and urban runoff [16].

III. Hydrogeological framework: the hydrogeology of Ikot Ekpene is dominated by the Benin Formation's multi-aquifer system, with primary aquifers in the second and third geoelectric layers at depths of 1.6-101.5 m and thicknesses of 30.2-89 m, comprising permeable sands and gravels [10]. Aquifer resistivities range from 359-2473 Ωm, with hydraulic conductivity 0.68-2.61 m/day and porosity 0.28-0.30, indicating good groundwater potential (94% of areas) but heterogeneous flow units classified as conductors with fair efficiency. The area is divided into hydrogeological zones based on water table depth, with shallow unconfined aquifers (5-47 m) prone to contamination due to low LC (0.01-0.26 S) and weak protectivity in 87-96% of sites. Vulnerability assessments via DRASTIC and GOD models show 75% high, 20% moderate, and 5% low susceptibility, exacerbated by high recharge from rainfall and permeable vadose zones [17], [18]. Groundwater flow is influenced by topographic gradients and anthropogenic activities, with risks from leachates in urban settings.

4 | Geophysical Methods for Assessment

Geophysical methods play a crucial role in evaluating topsoil quality and aquifer vulnerability in Ikot Ekpene Metropolis, Akwa Ibom State, by providing non-invasive insights into subsurface structures, resistivity variations, and hydrogeological parameters. Commonly applied techniques include electrical resistivity surveys, which delineate aquifer layers, assess flow units, and estimate vulnerability through derived parameters like Dar-Zarrouk indices [19]. These methods are often integrated with vulnerability models like DRASTIC, GOD and GIS for spatial mapping, revealing heterogeneous aquifers with varying protectivity and susceptibility to contaminants influenced by topsoil permeability and anthropogenic activities. While electrical methods dominate local studies, other techniques like Ground Penetrating Radar (GPR), seismic, and Electromagnetic (EM) surveys offer complementary potential but have seen limited application in this sedimentary environment. The study methods which dominates the local studies includes:

I. ERT is employed to generate 2D resistivity sections of the subsurface, enhancing the visualization of aquifer heterogeneity and flow dynamics in Ikot Ekpene and surrounding areas like Obot Akara [20]. Using electrode arrays, it maps resistivity variations to identify sandy layers with minor clay interbeds, revealing aquifer depths of 1.6–30.2 m and thicknesses of 30.2–89.0 m. In assessments near Akwa Ibom State University (Obio Akpa Campus), ERT delineates 3–4 layers, highlighting high permeability zones (25–232 m/day) and waterlogging risks due to poor topsoil drainage. ERT data integrate with Flow Zone Indicator (FZI) and SMLP to classify Hydraulic Flow Units (HFUs) as conductors with fair efficiency, indicating topsoil degradation from urbanization and increased vulnerability to infiltration [21]. This method's high resolution aids in identifying poor aquifer protectivity (96% of areas), essential for mapping contaminant pathways through permeable topsoils.

II. VES, utilizing the Schlumberger array, is the primary method for 1D resistivity profiling in Ikot Ekpene, conducted at multiple locations to determine aquifer depths (1.0–121.4 m), thicknesses (18.6–102.7 m), and resistivities (359–2,473 Ωm). Data are inverted using WINRESIST software and was constrained by borehole logs, to reveal motley topsoil (resistivity 64.6–1,172 Ωm, thickness 0.6–24.2 m) overlying permeable sandy aquifers. VES-derived parameters inform Dar-Zarrouk indices, such as LC (LC: 0.01–0.36 S), classifying 67–87.5% of areas as having poor/weak protection against contaminants migrating through degraded topsoils influenced by waste and runoff. In northern Akwa Ibom, VES assesses groundwater potential (85% very high) and vulnerability, correlating low topsoil resistivity with high infiltration risks. This cost-effective technique is vital for initial site characterization before drilling [22], [23].

III. GPR, an EM method using high-frequency radar pulses (typically 10-2,000 MHz), is suited for shallow subsurface imaging (up to 10-30 m) to assess topsoil quality, porosity, and contaminant plumes in sedimentary settings like Ikot Ekpene. It detects interfaces based on dielectric contrasts, identifying soil degradation, voids, or moisture variations indicative of vulnerability [24]. Although not prominently documented in local studies, GPR could complement resistivity methods by providing high-resolution profiles of topsoil heterogeneity, such as clay interbeds or urban-induced compaction, enhancing vulnerability mapping in areas with high recharge and waste influences. Potential applications include delineating shallow aquifer boundaries and monitoring leachate infiltration, but its use is limited by signal attenuation in conductive clays common in Akwa Ibom.

IV. Seismic refraction and reflection seismic methods involve generating acoustic waves via hammer or explosives and measuring travel times to map subsurface velocities, useful for aquifer depth, fracturing, and topsoil compaction in Ikot Ekpene's Benin Formation. Refraction analyzes first arrivals for shallow layers (up to 50 m), while reflection captures deeper interfaces [25]. These techniques estimate porosity and permeability from P-wave velocities (1,500-4,000 m/s in sands), aiding vulnerability assessments by identifying low-velocity zones prone to contaminant flow. Limited application in the region is noted, but integration with VES could reveal structural controls on aquifer vulnerability, such as faults facilitating infiltration through degraded topsoils. In similar sedimentary basins, seismic data correlate with resistivity for comprehensive flow unit characterization.

V. EM methods surveys, including Time-Domain Electromagnetic (TDEM) or Frequency-Domain Electromagnetic (FDEM) techniques, measure subsurface conductivity to assess topsoil salinity, contamination, and aquifer vulnerability without ground contact [26]. In Ikot Ekpene, EM could map conductive plumes from dumpsites, with low-frequency loops detecting depths up to 100 m. While not widely reported in local assessments, EM complements VES/ERT by rapidly covering large areas, identifying high-conductivity topsoils (due to leachates) that increase vulnerability [27]. Applications include delineating saline intrusions in coastal-influenced zones, with data invertible for resistivity models similar to Dar-Zarrouk parameters.

VI. Integration of geophysical data with GIS integration combines VES/ERT data with vulnerability models (DRASTIC, GOD, GLSI) to produce spatial maps of aquifer susceptibility and topsoil quality in Ikot Ekpene [28]. Parameters like depth, recharge (from rainfall/slope data), and soil media (inferred from resistivity) are layered in ArcGIS to compute indices (DRASTIC: 111–173, GOD: very low to very high). Sensitivity analysis highlights vadose zone and depth as key factors, with 62–75% of areas moderately to highly vulnerable due to permeable topsoils. This approach correlates geophysical findings with hydrogeochemical data, demarcating high-risk zones for policy-driven management, such as restricting waste sites in poor-protectivity areas

5 | Topsoil Quality Assessment

Topsoil in Ikot Ekpene Metropolis serves as the primary barrier against contaminant infiltration into underlying aquifers, but geophysical assessments reveal significant degradation risks due to its heterogeneous, permeable nature. Composed mainly of motley sands with variable resistivity and porosity, the topsoil is influenced by sedimentary deposition and human modifications, leading to vulnerabilities assessed through VES, ERT, and parameters like LC [29]. Studies indicate poor protective capacity in 65-96% of areas, exacerbated by urbanization and waste disposal, highlighting the need for integrated geophysical-hydrogeochemical evaluations to inform conservation strategies as follows:

I. Topsoil evaluation (soil resistivity, porosity, contaminant levels): topsoil resistivity in Ikot Ekpene ranges from 64.6 to 2,801.7 Ωm (average ~726.7 Ωm), reflecting its motley, bioturbated composition of sands with occasional clay intercalations. Porosity is inferred from geophysical data, with effective values of 0.27–0.40 (average 0.29) in overlying layers, contributing to high permeability (0.68–2.61 m/day) and facilitating contaminant migration [30]. Contaminant levels, assessed via hydrogeochemical integration, show exceedances of World Health Organization (WHO) limits for lead (up to 0.0010 mg/L) and nickel (up to 0.0290 mg/L) in groundwater influenced by topsoil leachates, particularly near dumpsites, with Biochemical Oxygen Demand (BOD) often >2.00 mg/L indicating organic pollution. Additional parameters include thickness (0.6–24.2 m) and hydraulic conductivity (5.5×10^{-6} to 2.2×10^{-5} m/s), used in models like DRASTIC for vulnerability indexing.

II. Geophysical indicators of soil degradation: key indicators include low LC (0.0004–0.36 S), classifying 65-96% of topsoil-overlain aquifers as poorly protected, with high heterogeneity (dykstra-parsons coefficient ~1) due to poor sand sorting and clay patches. VES and ERT delineate variable resistivity layers, with topsoil showing artificial modifications and anisotropy coefficients signaling degradation, transverse resistance <5,000 Ωm^2 indicates vulnerable, degraded zones [31]. In DRASTIC assessments, indices of 111-173 reflect degradation from permeable vadose zones and flat topography (slopes 2.5–47%), promoting infiltration and waterlogging. Noncorrosive but heterogeneous topsoil further evidences degradation, with sinkholes in central areas linked to erosion.

III. Impact of anthropogenic activities on topsoil: urbanization, population growth, and small-scale industries (palm and wood processing) in Ikot Ekpene generate solid wastes, leading to leachate infiltration through permeable topsoil, elevating Ni and Pb levels in southeastern areas near ravines and dumpsites [32]. Agricultural practices, road construction, and indiscriminate waste disposal cause bioturbation, increasing porosity and reducing protective capacity, with runoff carrying chemicals and debris exacerbating degradation in low-slope terrains. These activities result in 75% high vulnerability ratings, promoting contaminant migration and threatening groundwater quality.

IV. Case studies from ikot ekpene: in ikot ekpene urban and environs, VES/ERT at multiple sites revealed heterogeneous topsoil (resistivity 214-2,839 Ωm) with noncorrosive properties but poor protectivity (65% poor zones), linked to sinkholes and urban waste; recommendations include waste management for utility safety. A study in Ikot Ekpene–Obot Akara using 28 VES points and 12 boreholes showed south-eastern poor groundwater quality (Groundwater Quality Index (GWQI) 18.2-70.7) due to dumpsite leachates, with 75% moderate susceptibility from permeable topsoil [33]. Northern Akwa Ibom assessments, including Ikot Ekpene LGA (Abiakpo Edem Idim), indicated 96% poor protection from bioturbated topsoil, with high permeability facilitating agricultural and oil-related contamination. In Obot Akara–Ikot Ekpene, 26 VES points highlighted Ikot Ekpene's shallow, low-resistivity (<400 Ωm) topsoil as more degraded than Obot Akara's deeper, resistive (>2,000 Ωm) layers, attributing differences to urbanization intensity. A DRASTIC-based study confirmed 75% high GVR in Ikot Ekpene metropolis, citing heavy metals from dumpsite soils as per prior analyses.

6 | Aquifer Vulnerability Assessment

Aquifer vulnerability in Ikot Ekpene Metropolis, Akwa Ibom State, refers to the susceptibility of groundwater resources to contamination from surface or near-surface pollutants, influenced by geological, hydrogeological, and anthropogenic factors in the Benin Formation's sedimentary aquifers [4]. Assessments integrate geophysical methods like VES and ERT with vulnerability models such as DRASTIC and GOD, revealing predominantly moderate to high vulnerability due to shallow depths (1–101.5 m), permeable sands, and urban pressures. These evaluations highlight risks from leachates and emphasize the need for spatial mapping to guide sustainable management in this rapidly urbanizing region as stated below:

I. Concepts and models of aquifer vulnerability: aquifer vulnerability encompasses the intrinsic susceptibility of groundwater to contaminants, determined by hydrogeological factors that facilitate or impede pollutant migration from the surface to the aquifer [34]. The DRASTIC model, developed by the US EPA, evaluates seven parameters which includes, Depth to water (D), net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and hydraulic Conductivity (C), each rated and weighted (D and R weighted 5, others 1-4) to compute an index (typically 23-226), classifying vulnerability as low (<100), moderate (100-159), or high (>160). In contrast, the GOD model, originating from the UK, uses three simpler parameters: Groundwater occurrence (G, confined/unconfined), Overlying lithology (O, clay/sand permeability), and Depth to groundwater (D), yielding an index (0-1) graded as negligible (<0.1), low (0.1-0.3), moderate (0.3-0.5), high (0.5-0.7), or extreme (>0.7). Other models like AVI (Aquifer Vulnerability Index, based on hydraulic resistance) and SI (Susceptibility Index) complement these, with GOD suitable for broad assessments and DRASTIC for detailed, parameter-rich evaluations in sedimentary basins like northern Akwa Ibom [35]. These overlay-index methods assume vertical pollutant transport and are often validated with geophysical data for site-specific accuracy.

II. Geophysical parameters influencing vulnerability: geophysical parameters derived from VES and ERT significantly influence vulnerability by quantifying subsurface properties that control contaminant pathways [36], [37]. Aquifer depth, ranging from 1.0-101.5 m in Ikot Ekpene (average ~30-50 m), is a critical factor; shallower depths (<10 m) increase vulnerability by reducing travel time for pollutants, as seen in 62% moderate DRASTIC ratings. Recharge rates, estimated at 0.68-2.61 m/day from high rainfall (~2,500-3,000 mm/year) and permeable sands, enhance infiltration, contributing to high vulnerability in 75% of areas per

DRASTIC models. Other parameters include aquifer media resistivity (359–2,473 Ωm, indicating sandy/gravelly units with high permeability), vadose zone impact (low-resistivity clays offering poor protection), and hydraulic conductivity (5.5×10^{-6}–2.2×10^{-5} m/s), with low LC (0.01–0.36 S) signaling weak barriers in 76-96% of sites. Topography (gentle slopes 2.5-47%) further exacerbates risks by promoting surface runoff and recharge. Sensitivity analyses show depth and recharge as dominant influencers, with correlations to Dar-Zarrouk parameters highlighting heterogeneous flow units prone to contamination [38].

III. Vulnerability mapping techniques: vulnerability mapping in Ikot Ekpene employs GIS integration of geophysical data with models like DRASTIC and GOD to produce spatial distributions of susceptibility zones. VES data from 28-55 points, combined with borehole logs, generate parameter layers (depth from inversion software like WINRESIST), which are interpolated using tools like ArcGIS for index calculation and zoning. DRASTIC maps delineate low (5-33%), moderate (20-62%), and high (5-75%) zones, while GOD maps show very low (16-18%), low (10-25%), moderate (3-16%), high (29-60%), and very high (10-11%) gradings, with correlations validated by hydrogeochemical data. Techniques include sensitivity analysis to identify influential parameters such as vadose zone in DRASTIC and hybrid approaches like GODL or AVI for enhanced lithological detail. ERT provides 2D sections for refined mapping of heterogeneous units, aiding in demarcating high-risk areas near rivers or urban centers [39]. These maps serve as tools for policy, correlating well with groundwater quality indices to prioritize protection.

IV. Risks from pollution sources in Ikot Ekpene: pollution risks in Ikot Ekpene stem primarily from anthropogenic activities, including indiscriminate waste disposal, industrial effluents (from palm processing and wood industries), and urban runoff, generating leachates that infiltrate through permeable topsoils and vadose zones [40]. Dumpsites and ravines in southeastern areas contribute heavy metals like lead (up to 0.0010 mg/L) and nickel (up to 0.0290 mg/L), exceeding WHO limits, with high BOD (>2.00 mg/L) indicating organic contamination in 75% high-vulnerability zones. Agricultural chemicals and vehicle wastes exacerbate risks in riverine settings, where shallow aquifers (9–86.6 m) and gentle topography facilitate migration, leading to poor groundwater quality (GWQI 18.2–70.7) in affected boreholes. Population growth and small-scale industries increase solid wastes (plastics, metals, human wastes), posing threats to 96% poorly protected aquifers, with potential for epidemics if unmitigated [41]. Coastal influences in southern extents add saline intrusion risks, underscoring the need for regulated land use and monitoring.

7 | Results and Findings from Existing Studies

Geophysical investigations in Ikot Ekpene Metropolis and northern Akwa Ibom State have yielded comprehensive insights into topsoil quality, aquifer characteristics, and vulnerability, primarily through VES, ERT, and vulnerability models like DRASTIC and GOD. Key findings indicate heterogeneous subsurface layers with motley topsoils overlying permeable sandy aquifers at depths of 1.0–121.4 m, exhibiting weak to poor protectivity (87.5–96%) and moderate to high vulnerability due to urbanization and permeable geomaterials. Groundwater potential is generally high (85–96.7%), but contamination risks from leachates are significant, with spatial variations highlighting urban-rural disparities [42]. These results underscore the interplay between geophysical parameters and hydrogeological dynamics, informing sustainable management strategies as follows:

I. Spatial distribution of topsoil quality: topsoil in Ikot Ekpene exhibits heterogeneous quality, with resistivity values ranging from 64.6-2,839 Ωm (average 726.7 Ωm) and thicknesses of 0.6-24.2 m, indicating motley sands prone to degradation in urban zones. In central Ikot Ekpene, low resistivity (<400 Ωm) and high porosity (0.27-0.40) signal erosion and sinkholes, exacerbated by waste disposal, covering 65% of urban areas with poor integrity. Southeastern regions near ravines show elevated contaminant levels (Ni up to 0.029 mg/L), correlating with degraded topsoil and high infiltration risks. In contrast, northern peripheries like Obot Akara display higher resistivity (>2,000 Ωm) and lower degradation, with non-corrosive properties in 35% of rural zones, attributed to less anthropogenic influence. Spatial maps from GIS-integrated VES data delineate poor quality in 75% of Ikot Ekpene metropolis, transitioning to moderate in surrounding raffia-dominated areas.

II. Aquifer characteristics and vulnerability zones: aquifers in the region are primarily in the third geoelectric layer, with depths varying from 1.0-121.4 m (average 30–50 m) and thicknesses of 18.6–102.7 m, composed of permeable sands and gravels with resistivities of 359–2,473 Ωm. Hydraulic conductivity ranges from 0.68–2.61 m/day, indicating high groundwater potential (85–96.7%) but heterogeneous flow units classified as conductors with fair efficiency. Vulnerability zones per DRASTIC model showed moderate (62-75%) and high (5-25%) susceptibility, with GOD gradings from very low (16-18%) to very high (10–11%), predominantly high in urban Ikot Ekpene due to shallow depths and permeable vadose zones. Southeastern and riverine areas exhibit elevated risks from saltwater intrusion and leachates, with 70% high/very high vulnerability, while northern rural zones have lower susceptibility (20-33% low). Groundwater reserves are estimated at 7.15×10^8 m^3, but poor protectivity (LC 0.01-0.36 S) affects 87.5-96% of zones.

III. Correlation between topsoil and aquifer properties: topsoil degradation directly correlates with aquifer vulnerability, as low LC (0.0004-0.36 S) and high porosity in motley topsoils facilitate contaminant migration to underlying aquifers. In Ikot Ekpene, urban topsoil with resistivity <400 Ωm and anisotropy coefficients indicate poor barrier function, leading to weak aquifer protectivity in 87.5% of areas and elevated GWQI values (18.2-70.7) reflecting pollution. Recharge rates (0.68-2.61 m/day) amplify this correlation, with permeable topsoils in high-vulnerability zones (75%) correlating to shallow aquifer depths (<10 m) and increased heavy metal concentrations (Pb, Ni). Regression analyses show inverse relationships between topsoil resistivity and aquifer contamination risk, with Dykstra-Parsons coefficients (1) confirming heterogeneity linking degraded topsoil to fair-efficiency flow units. In Obot Akara, higher topsoil resistivity (>2,000 Ωm) correlates with better aquifer integrity and lower susceptibility.

IV. Statistical analysis of geophysical data: statistical evaluations include sensitivity analyses of DRASTIC models, identifying vadose zone impact, aquifer depth, and recharge as dominant factors (weights 5-4), with hydraulic conductivity least influential. Regression equations predict hydraulic properties from VES data, with porosity (0.28-0.30) and transmissivity correlating to resistivity ($r^2 > 0.8$), showing variability in flow units via SMLP delineating 5 HFUs as conductors (96%). GWQI sensitivity highlights Ni and Pb as key contaminants, with values 18.2–70.7 classifying 25% poor, 50% good, and 25% excellent quality. Dykstra-Parsons coefficients (~1) and FZI (FZI: 14-15) confirm aquifer heterogeneity, with specific yield/retention ratios (0.79-17.15) indicating good potential in 94% of areas. ANOVA on resistivity data reveals significant spatial differences ($p<0.05$) between urban Ikot Ekpene and rural Obot Akara, supporting zoned vulnerability mappings.

7.1 | Key Findings from Geophysical Assessments in Ikot Ekpene Metropolis

Tables 1-3 summarizes results from the analysis of topsoil quality, aquifer characteristics, and vulnerability zones, drawing from VES, ERT, and models (DRASTIC and GOD). These highlight spatial and parametric variations across urban and rural areas.

Table 1. Topsoil quality parameters.

Parameter	Range/Value	Average	Key Implications
Resistivity (Ωm)	64.6-2,839	726.7	Low values (<400 Ωm) indicate degradation in urban zones (65% poor integrity).
Thickness (m)	0.6-24.2	5-10	Thin layers in central areas prone to sinkholes and erosion.
Porosity	0.27-0.40	0.29	High porosity facilitates contaminant infiltration (75% high vulnerability).
Longitudinal conductance (S)	0.01-0.36	0.01-0.26	Poor protectivity in 65–96% of sites, linking to leachate migration.

Table 2. Aquifer characteristics.

Parameter	Range/Value	Average	Key Implications
Depth (m)	1.0-121.4	30-50	Shallow depths (<10 m) in 62% of zones increase contamination risks.
Thickness (m)	18.6-102.7	30.2-89	Thick sandy layers support high potential (85–96.7%) but heterogeneous flow.
Resistivity (Ωm)	359-2,473	1,000-1,500	Indicates permeable sands; low values correlate with urban pollution.
Hydraulic conductivity (m/day)	0.68-2.61	1.5	Enhances recharge but amplifies vulnerability in riverine settings.
Groundwater reserves (m^3)		7.15×10^8	Prolific reserves, yet 87.5–96% weakly protected against leachates.

Table 3. Vulnerability and quality indices.

Model/Indicator	Classification/Range	Percentage of Areas	Key Implications
DRASTIC (Index)	Moderate (100-159); High (>160)	62-75%; 5-25%	Urban southeast zones (75% high) due to gentle topography and vadose impacts.
GOD (Index)	Low (0.1-0.3); Moderate (0.3-0.5); High (0.5-0.7); Very High (>0.7)	10-25%; 3-16%; 29-60%; 10-11%	70% high/very high in riverine areas; contrasts rural low (20-33%).
GWQI	18.2-70.7	25% poor; 50% good	Poor quality near dumpsites; elevated Pb (0.0010 mg/L), Ni (0.029 mg/L).
BOD (mg/L)	>2.00	-	Organic pollution in 75% vulnerable zones, exceeding WHO limits.

8 | Discussion

The geophysical assessments of topsoil quality and aquifer vulnerability in Ikot Ekpene Metropolis reveal critical insights into the interplay between surface degradation and subsurface risks, underscoring the urgent need for integrated groundwater management in this urbanizing region of Akwa Ibom State. With aquifers exhibiting weak protectivity (87.5–96%) and moderate to high vulnerability (62–75%), influenced by permeable topsoils and anthropogenic pressures, the findings highlight systemic challenges in data interpretation and assessment methodologies. These results, when compared to national and international benchmarks, emphasize discrepancies in water quality and protection standards, calling for adaptive strategies to mitigate contamination in similar sedimentary environments as highlighted below:

I. Implications for groundwater management: the weak aquifer protectivity and high vulnerability zones in Ikot Ekpene imply a heightened risk of groundwater contamination, necessitating proactive management strategies such as regulated borehole siting and waste disposal zoning to avoid high-risk areas (such as southeastern ravines with 75% high DRASTIC ratings). Sustainable extraction, informed by high groundwater potential (85–96.7%), should incorporate recharge enhancement through afforestation and permeable pavements to counter urbanization-induced degradation [43]. Community-based monitoring, integrating geophysical data with real-time hydrogeochemical sampling, could prevent epidemics from leachate infiltration, while policy frameworks promoting GIS-mapped vulnerability zones would guide urban planning and resource allocation in northern Akwa Ibom. Overall, these implications advocate for a shift toward resilient groundwater governance, balancing economic growth with environmental protection in raffia-dependent economies.

II. Challenges in geophysical data interpretation: interpreting geophysical data in Ikot Ekpene is complicated by subsurface heterogeneity, with variable resistivity of 64.6-2,839 Ωm and clay intercalations leading to ambiguities in layer delineation and parameter estimation. Signal attenuation in conductive clays and urban noise often result in high RMS errors (>5%) during VES/ERT inversions, necessitating borehole calibration that is resource-intensive in remote areas. Seasonal variations in moisture content alter resistivity profiles, challenging consistent vulnerability mapping, while limited integration of multi-method data hinders accurate flow unit characterization in heterogeneous sands [44]. These issues are amplified by a lack of standardized protocols for tropical sedimentary basins, leading to potential overestimation of protectivity in 10-20% of sites.

III. Limitations of current assessments: current assessments are constrained by sparse data points potentially overlooking micro-scale variations in topsoil degradation and aquifer dynamics across Ikot Ekpene's 116 km^2 expanse. Reliance on empirical models like DRASTIC and GOD assumes uniform pollutant behavior, ignoring site-specific factors such as microbial degradation or preferential flow paths in bioturbated soils [45]. Limited temporal monitoring fails to capture dynamic recharge influences from climate variability, while financial and technical barriers restrict advanced techniques in under-resourced regions. Additionally, the absence of comprehensive hydrogeochemical validation in 30% of studies undermines vulnerability classifications, highlighting the need for multi-disciplinary, longitudinal approaches.

IV. Comparison with national and international standards: groundwater quality in Ikot Ekpene often exceeds Nigerian Industrial Standard (NIS) and WHO limits for contaminants like lead (NIS/WHO: 0.01 mg/L vs. observed up to 0.0010 mg/L) and nickel (NIS/WHO: 0.02 mg/L vs. up to 0.029 mg/L), indicating non-compliance in 25–50% of urban samples. Aquifer vulnerability ratings align with national benchmarks under the Nigerian Water Resources Act, but show higher susceptibility (75% high) compared to international averages in sedimentary basins (US EPA DRASTIC thresholds: moderate <140 vs. local 111-173). Protectivity measures fall short of EU Water Framework Directive standards for impermeable barriers (LC >1 S), with local values (0.01-0.36 S) mirroring vulnerabilities in other tropical regions like the Gulf of Mexico but exceeding those in arid zones. These comparisons underscore the need for localized adaptations to global standards, incorporating Nigeria's high-rainfall context for enhanced protection.

9 | Conclusion

In the verdant expanse of Ikot Ekpene Metropolis where the rustle of raffia palms mingles with the hum of urban ambition geophysical insights illuminate a precarious equilibrium between human progress and the silent guardians of our groundwater. This synthesis of VES, ERT, and vulnerability models like DRASTIC and GOD lays bare, the stark realities are that topsoils, once resilient motley sands, now frayed by urbanization's relentless grip, with resistivities dipping to 64.6 Ωm and porosities swelling to 0.40, paving treacherous pathways for contaminants. Aquifers, bountiful at depths of 1-121 m and harboring reserves of 7.15×10^8 m^3, stand perilously exposed at 87.5-96% cloaked in weak protectivity, their sandy veins yielding to leachates laden with lead and nickel, far beyond WHO thresholds.

These findings transcend data points; they echo the vulnerabilities of sedimentary souls like the Benin Formation, where high recharge (0.68-2.61 m/day) and gentle slopes conspire with waste-strewn ravines to amplify risks, grading 62-75% of zones as moderately to highly susceptible. Yet, amid the shadows of degradation sinkholes scarring urban cores, heterogeneous flow units whispering of fair efficiency lies a beacon of potential of 85-96.7% groundwater viability, a testament to the region's hydrogeological generosity if harnessed wisely.

Integrated geophysical-GIS frameworks must evolve into living tools, fusing real-time monitoring with community stewardship to fortify topsoils through afforestation and organic farming, while zoning policies shield aquifers from the sprawl of dumpsites and unchecked boreholes. Policymakers in Akwa Ibom and beyond must champion these narratives, embedding them in the Nigerian Water Resources Act to avert epidemics and nurture sustainable yields. Future horizons beckon toward hybrid models like GOD-

DRASTIC hybrids which is laced with a radiological probes and longitudinal studies attuned to climate's whims, ensuring Ikot Ekpene's aquifers not only endure but thrive.

By bridging geophysical consistency, vulnerability can be transformed into vitality, securing clean waters for the raffia weavers, the farmers, and the generations yet to till these sands.

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Data Availability

The study is based on the synthesis of previously published geophysical and hydrogeochemical data, combined with analytical interpretations. All data sources are properly cited within the manuscript, and further details can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest related to this study.

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