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# A Study on GIS Integrated Techniques for Groundwater Mapping Potentials and Qualitative Assessment

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## Abstract

Groundwater serves as a critical freshwater resource in the Niger Delta, particularly in rapidly urbanizing Port Harcourt metropolis, Rivers State, Nigeria, where surface water pollution from oil activities and urban waste has heightened dependence on aquifers of the Benin Formation. This study employed integrated Geographic Information Systems (GIS), Remote Sensing (RS), and Multi-Criteria Decision Analysis (MCDA) techniques to map Groundwater Potential Zones (GWPZ) and assess its qualitative status for sustainable management. Eight thematic layers including geology/lithology, geomorphology, lineament density, slope, drainage density, Land Use/Land Cover (LULC), rainfall distribution, and soil types were prepared using Landsat 8/Sentinel-2 imagery, SRTM DEM, and ancillary data in ArcGIS. The Analytical Hierarchy Process (AHP) was applied for weighted overlay analysis to delineate GWPZ. Groundwater quality was evaluated through physico-chemical analysis of 30-50 borehole samples, computation of Water Quality Index (WQI), hydrogeochemical diagrams (Piper, Gibbs, Durov), and spatial interpolation (IDW/Kriging). Model validation utilized ROC/AUC, borehole yield correlation, and field data. Results revealed that 35-45% of the study area falls within very high to high potential zones, predominantly in peri-urban northern and eastern fringes characterized by permeable Benin Formation sands, flat topography (0-2% slope), and high rainfall (2,800-3,800 mm/year). Moderate potential zones dominate central urban areas (40-45%), while low to poor zones (15-25%) occur in built-up and swampy regions. Groundwater quality showed slightly acidic conditions (pH 4.0-7.2, mean 5.8-6.4), fresh to brackish TDS, and dominant Ca-Mg-Na-HCO<sub>3</sub>-Cl facies, with elevated iron and contaminants near urban/industrial zones. WQI classified most samples as poor to unsuitable for drinking, though better quality was observed in high-potential peri-urban areas. A moderate positive correlation existed between potential zones and water quality. The integrated AHP-GIS model demonstrated strong reliability (AUC 0.78-0.85, yield correlation  $r = 0.71-0.80$ , accuracy 75-85%). Findings highlight abundant groundwater quantity potential constrained by anthropogenic quality degradation. The study provides valuable spatial insights for targeted borehole development, recharge planning, urban zoning, and policy interventions to ensure sustainable groundwater utilization in the Niger Delta.

**Keywords:** GIS integrated techniques, Groundwater, Mapping potentials, Qualitative assessment.

## 1 | Introduction

Groundwater constitutes one of the planet's most critical yet often overlooked freshwater resources, serving as a primary source of potable water, irrigation, and industrial supply for billions worldwide. As surface water sources face increasing pressures from pollution, climate variability, and overexploitation, groundwater has

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emerged as a resilient buffer, naturally filtered and stored in subsurface aquifers [1], [2]. However, rapid population growth, urbanization, agricultural expansion, and industrial activities have led to accelerated depletion and degradation in many regions, threatening long-term sustainability and water security. In Nigeria, the most populous nation in Africa, groundwater plays an indispensable role in meeting domestic, agricultural, and industrial demands, particularly in rural and peri-urban areas where centralized surface water systems are limited or unreliable. Estimates indicate that groundwater accounts for approximately 60% of drinking water supply nationwide, with even higher reliance in rural communities (up to 73%). The country's renewable groundwater resources are substantial, estimated at around 87,000-155,800 million cubic meters per year, yet challenges such as uneven distribution, declining levels in northern regions, contamination from oil activities in the Niger Delta, and saltwater intrusion in coastal zones persist [3], [4].

Port Harcourt, the capital of Rivers State in the oil-rich Niger Delta region, exemplifies these issues. Situated in a sedimentary basin with permeable aquifers (primarily the benin formation), the city heavily depends on groundwater due to polluted surface waters from industrial effluents, oil spills, and urban waste [5]. Boreholes serve as the dominant source for most residents, but vulnerabilities to contamination, including leachates from dumpsites, saline intrusion, and acidic conditions (pH often 3.9-4.5), compromise quality and suitability for drinking. Effective management of groundwater requires accurate mapping of its potential zones (for quantity and recharge prospects) and qualitative assessment (for portability, irrigation suitability, and contamination risks) [6], [7]. Traditional hydrogeological methods are time-consuming and costly, whereas integrated Geographic Information Systems (GIS) techniques combined with Remote Sensing (RS), Multi-Criteria Decision Analysis (MCDA) and spatial interpolation offer efficient, cost-effective tools for delineating potential zones and evaluating water quality spatially.

This study employs GIS-integrated approaches to map groundwater potential and assess its qualitative status in a selected area (likely focused on or around port harcourt/rivers state), incorporating thematic layers such as geology, geomorphology, lineament density, Land Use/Land Cover (LULC), rainfall, and hydro-geochemical parameters. By validating models against field data and quality indices (like Water Quality Index (WQI)), the research aims to provide actionable insights for sustainable groundwater development, urban planning, and policy formulation amid growing environmental pressures [8], [9].

The study will objectively identify and prepare key thematic layers (geology/lithology, geomorphology, lineament density, slope/DEM-derived parameters, drainage density, LULC, rainfall distribution, soil types) influencing groundwater occurrence and recharge using GIS and RS data, delineate and map Groundwater Potential Zones (GWPZ) through integrated multi-criteria evaluation techniques, such as Analytical Hierarchy Process (AHP) combined with weighted overlay analysis in GIS, evaluate the spatial distribution of groundwater quality parameters (physico-chemical, major ions, nutrients, heavy metals) using field sampling, laboratory analysis, and spatial interpolation methods, compute and map Water Quality Indices (WQI) and other suitability indices to assess groundwater for drinking and irrigation purposes, identifying contamination hotspots linked to land-use patterns, correlate GWPZ with quality characteristics and validate the integrated GIS model using field data, provide recommendations for sustainable groundwater development, zoning regulations, and policy interventions in the context of urban growth and environmental pressures in Port Harcourt [10–12].

## 2 | Significance of Groundwater Resources

Groundwater is the largest accessible store of freshwater on Earth, comprising approximately 99% of the planet's liquid freshwater (excluding glaciers and ice caps) and playing a pivotal role in the global hydrological cycle through infiltration, storage, and base-flow contribution to rivers and ecosystems [13]. Globally, it supplies drinking water to nearly 50% of the population, supports about 43% of irrigation, and buffers against droughts and surface water shortages. However, unsustainable abstraction has led to widespread depletion: Groundwater levels are declining in 71% of monitored aquifers, with acceleration in many regions over recent decades. Recent assessments indicate annual freshwater losses equivalent to supplying hundreds of millions of people, driven largely by groundwater overuse (68% of land-based freshwater loss), exacerbating sea-level



The area falls within the eastern Niger Delta sedimentary basin, characterized by a tropical rainforest climate with high annual rainfall (averaging 2,400-4,000 mm), distinct wet (April-October) and dry (November-March) seasons, high humidity, and temperatures ranging from 25-32°C. The terrain is generally low-lying and flat, featuring deltaic plains, freshwater swamps, mangrove ecosystems, and numerous rivers/creeks (Bonny River, New Calabar River tributaries). This flat topography, combined with permeable soils, promotes high infiltration but also renders aquifers vulnerable to surface contamination [20].

Geologically, the region is underlain by the Tertiary Quaternary Niger Delta formations, with the Benin Formation being the dominant and most prolific aquiferous unit. The Benin Formation consists of thick sequences (up to 2,100 m in the basin center, but typically 0-300 m exploited in the study area) of unconsolidated to poorly consolidated sands, gravels, and minor clay/lignite intercalations [21]. Overlying Quaternary deposits (40-150 m thick) form an upper unconfined to semi-confined aquifer system, comprising alternating sands and clay lenses, with sands dominating for high permeability and storage. The underlying Agbada and Akata Formations are deeper and less relevant for shallow groundwater abstraction (see Fig. 2).

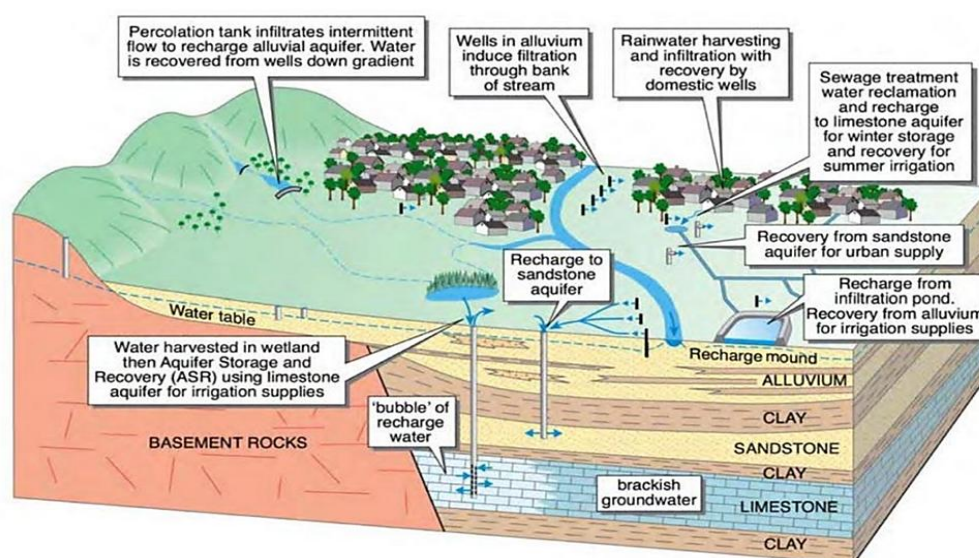


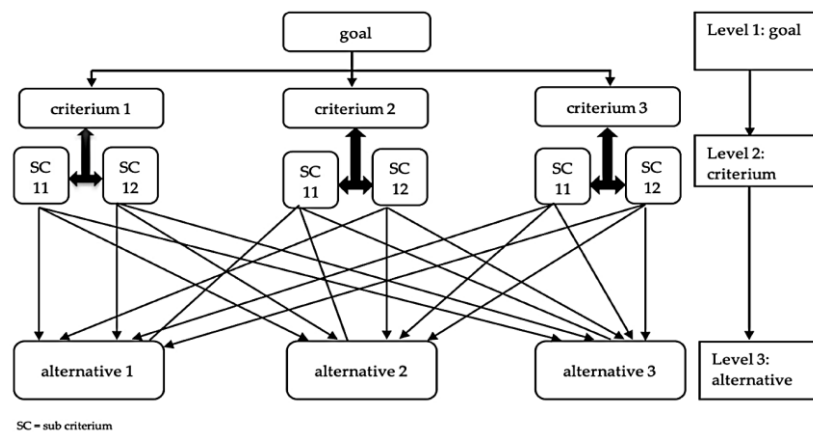
Fig. 2. Saline intrusion in Niger Delta coastal aquifers, drivers, hydro-geological dynamics and mitigation strategies [22].

Hydro-geologically, groundwater occurs under unconfined to semi-confined conditions in multi-layered sandy aquifers, recharged primarily by direct rainfall infiltration due to high permeability and minimal runoff. Transmissivity values are generally high ( $1 - 11 \times 10^{-2} \text{ m}^2/\text{s}$ ), indicating good aquifer potential, with regional groundwater flow trending north-to-south toward the Atlantic Ocean (with local variations). Static water levels are shallow (often 5-20 m), facilitating easy borehole access, though over-abstraction and urban pressures contribute to declining levels in some zones. The area faces significant anthropogenic pressures: rapid urbanization, industrial activities (oil/gas, manufacturing), uncontrolled solid waste dumpsites, oil spills, domestic sewage, and effluent discharges [23]. These have led to widespread groundwater quality concerns, including elevated TDS, acidity (pH often 4-6), iron, chloride (from saline intrusion in coastal fringes), nitrates, heavy metals, and organic pollutants from leachates. Despite abundant renewable resources, quality degradation threatens portability and suitability for domestic/irrigation use, underscoring the need for integrated GIS-based mapping and assessment.

## 4 | Review of Groundwater Potential Mapping Techniques

Groundwater potential mapping involves delineating zones with varying prospects for occurrence, recharge, and sustainable yield, traditionally relying on field-based hydrogeological surveys, geophysical methods (resistivity, seismic), and pumping tests [24], [25]. These approaches are resource-intensive, site-specific, and

limited in spatial coverage, particularly in heterogeneous terrains like sedimentary basins or urbanized deltas. The integration of GIS, RS, and MCDA has revolutionized the field by enabling cost-effective, large-scale, and spatially explicit assessments. Early techniques focused on qualitative overlay of thematic layers derived from aerial photographs or basic satellite data. Weighted overlay analysis emerged as a foundational method, assigning subjective ranks and weights to factors influencing infiltration and storage. The AHP, introduced by Saaty [26] and widely adopted in hydrogeology, provides a structured pairwise comparison for deriving relative weights, reducing subjectivity. Numerous studies have applied AHP-GIS for potential zoning, integrating 8-12 thematic layers such as lithology (often highest weight of 32%), rainfall (23-25%), slope, lineament density, LULC, soil texture, drainage density, and topographic indices as seen in *Fig. 3*. Validation typically uses Receiver Operating Characteristic (ROC) curves with Area Under Curve (AUC) values of 0.80-0.93, borehole yields, or spring locations, achieving high concordance of about 81-85% [27].



**Fig. 3.** The structure of the AHP method [26], [28].

To address uncertainties in expert judgment and data vagueness, fuzzy logic extensions (Fuzzy AHP or FAHP) incorporate membership functions for imprecise parameters, improving handling of transitional zones in complex environments. Frequency Ratio (FR), Weight of Evidence (WOE), and Information Value (IV) models offer data-driven statistical alternatives, often outperforming AHP in predictive accuracy (FR with AUC >0.90 in some arid/semi-arid cases). Machine Learning (ML) approaches have gained prominence since the 2010s, including Random Forest (RF), Support Vector Machine (SVM), Artificial Neural Networks (ANN), Decision Trees, and ensemble models [29], [30]. These leverage non-linear relationships and historical well data for higher precision, especially in data-scarce regions, with RF frequently achieving superior AUC (0.80–0.87) over traditional MCDA. Hybrid integrations like AHP with fuzzy logic, ML with GIS/RS, or geostatistics (Kriging/IDW for interpolation) enhance robustness. In sedimentary basins like the Niger Delta analogs, studies emphasize permeable formations (sands/gravels), lineaments for secondary porosity, and LULC impacts from urbanization/oil activities. Recent validations confirm 80-90% alignment with field data, though challenges persist in coastal areas due to salinity and contamination influences. Overall, GIS-integrated techniques provide reliable, scalable tools for zoning into very high/high/moderate/low/poor categories, supporting targeted borehole siting, recharge planning, and sustainable management [31].

## 5 | Evolution of GIS and Remote Sensing Applications in Hydrogeology

The application of RS and GIS in hydrogeology has evolved from rudimentary aerial photo interpretation to sophisticated satellite-based, data-driven modeling, paralleling advancements in sensor technology, computing power, and geospatial software [32], [33]. RS origins trace to the mid-20th century with aerial photography for geological mapping, but hydrogeological relevance surged with the launch of Landsat-1 (ERTS) in 1972 the first satellite dedicated to Earth resources observation. Early Landsat Multi Spectral

Scanner (MSS) data enabled basic land cover, vegetation (NDVI), and lineament extraction for indirect aquifer inference. The 1980s-1990s saw integration with emerging GIS platforms, facilitating overlay of RS-derived layers with ground data for qualitative potential assessment [34]. The 2000s marked a pivotal shift: Higher-resolution sensors (Landsat TM/ETM+, ASTER, SRTM DEM in 2000) provided detailed topographic (slope, TWI), hydrological (drainage density), and structural (lineaments through edge enhancement/PC analysis) inputs. Studies demonstrated RS-GIS synergy for mapping promising sites in arid/semi-arid basins, with thematic integration through weighted overlay. By the mid-2000s, MCDA tools like AHP formalized weight assignment, while InSAR (ERS/ASAR) enabled subsidence monitoring linked to over-pumping [35]. The 2010s-2020s accelerated evolution through open-access data, cloud computing, and advanced analytics. ML integration (RF, ANN) with RS/GIS data improved predictive mapping, achieving AUC 0.85 in diverse terrains. Recent applications incorporate climate scenarios, fuzzy logic for uncertainty, and validation with GRACE-derived depletion trends or well databases [36]. In hydrogeology, RS now supports recharge estimation (through evapotranspiration models), quality proxies, and dynamic monitoring. In regions like Nigeria's Niger Delta, RS-GIS has addressed data gaps by delineating Benin Formation aquifers, identifying contamination risks from LULC changes, and supporting policy amid urbanization. Future directions include AI ensembles, higher-resolution hyper-spectral data, and coupling with hydrological models for predictive forecasting under climate change. This evolution has transformed hydrogeology from field-dominant to spatially comprehensive and predictive science, enhancing sustainable groundwater management globally [37].

## 6 | Integrated Approaches for Groundwater Potential Zoning

Integrated approaches combine RS, GIS, geophysical data, and statistical/multi-criteria models to delineate GWPZ more robustly than single-method studies. These methods address data scarcity, heterogeneity in aquifers (sedimentary deltas), and uncertainties in traditional hydrogeology. Common integrations include RS-derived thematic layers (lineament density from Landsat/Sentinel imagery, slope/TWI from SRTM/ASTER DEM, LULC/NDVI from MODIS/Landsat) with GIS overlay and geophysical inputs (VES resistivity for validation). Weighted overlay or index-based models classify zones into very high/high/moderate/low/poor categories. Recent studies (2023-2026) emphasize hybrid frameworks: AHP-weighted RS-GIS layers for semi-arid/hilly terrains (Morocco's Khouribga area, achieving 83% concordance with 72 wells; Ethiopia's Teji catchment with eight layers and high AUC validation); geostatistics (Kriging/IDW) with RS/GIS for semi-arid precision (Egypt's East Desert using 310 wells for validation) and fuzzy logic or ML ensembles for complex terrains. In sedimentary/coastal contexts like the Niger Delta analogs, integrations focus on permeable sands, lineaments/fractures, rainfall recharge, and anthropogenic impacts (urbanization, oil activities). Studies in Nigeria (coastal Niger Delta geophysical modeling) highlight shallow-to-intermediate aquifers, with recommendations for well design to avoid saline intrusion or iron-rich zones [38]. Validation often uses borehole yields, ROC/AUC (0.70-0.93), or field inventories (77-86% accuracy in Ethiopian/Ethiopian-like basins). These approaches enable scalable, cost-effective zoning for recharge planning, borehole targeting, and sustainable management, outperforming qualitative methods in predictive power. Future trends include higher-resolution RS (Sentinel), ML hybrids, and climate-integrated modeling for dynamic vulnerability in urban deltas like Port Harcourt.

## 7 | Methods for Groundwater Quality Assessment and Hydrogeochemical Characterization

Groundwater quality assessment evaluates portability, irrigation suitability, and contamination risks using physico-chemical parameters, while hydro-geochemical characterization identifies processes (rock-water interaction, ion exchange, anthropogenic inputs) [39]. Standard methods include laboratory analysis of major ions, ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ ), pH, TDS, EC, heavy metals, and nutrients from boreholes. Graphical tools dominate characterization like Piper trilinear diagrams for facies (Ca – Mg –  $\text{HCO}_3$  or Na – Cl types); Schoeller plots for ion dominance, Gibbs diagrams for evaporation/rock-water/precipitation

controls, Durov plots for mixing, and ionic ratios ( $\text{Na}^+/\text{Cl}^-$ ,  $\text{Ca}^{2+}/\text{Mg}^{2+}$ ) for silicate dissolution, cation exchange, or saline intrusion are illustrated in Figs. 4 and 5.

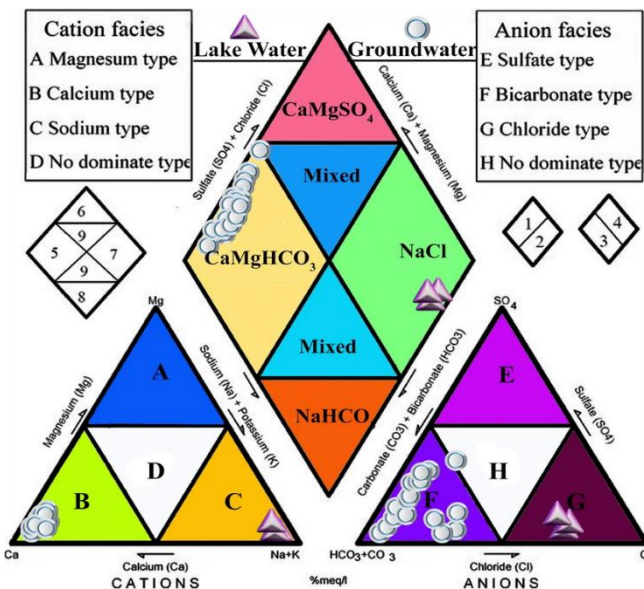


Fig. 4. A trilinear Piper diagram showing the hydrochemical facies of groundwater and lake water samples [40].

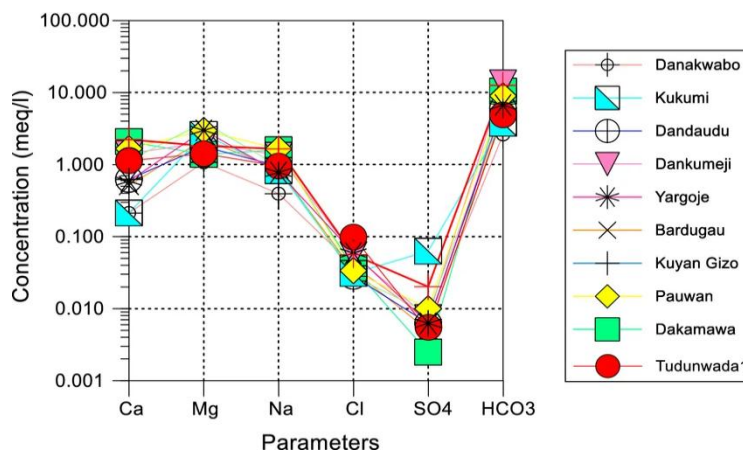


Fig. 5. Schoeller plot showing dominant ions [41].

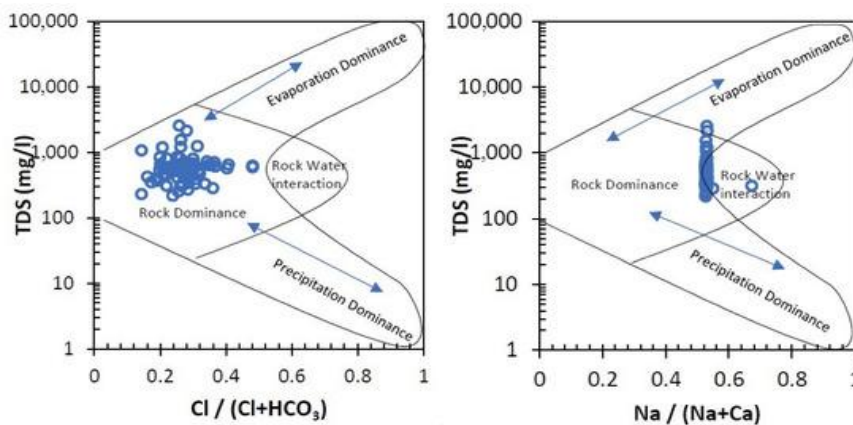


Fig. 6. Gibbs diagram for groundwater samples collected from Târgoviște Plain [42].

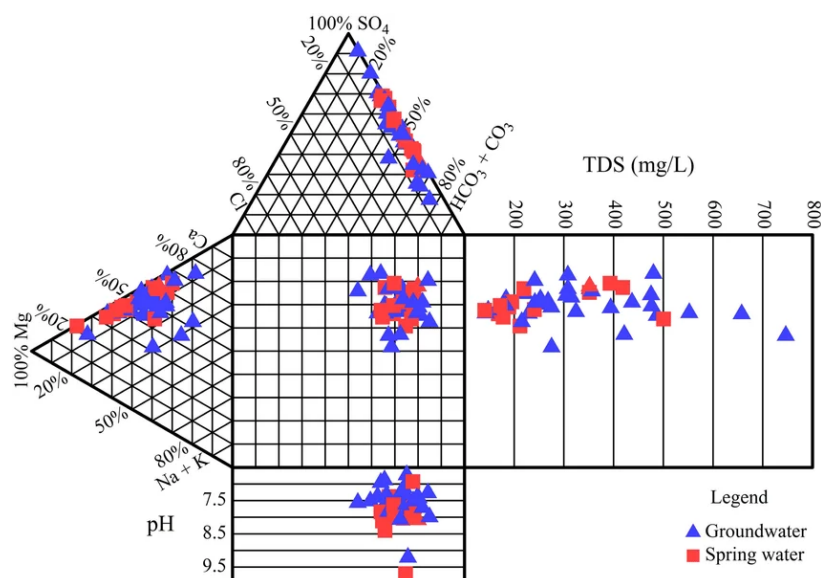


Fig. 7. Durov diagram of groundwater and spring water samples [43].

WQI variants-Weighted Arithmetic (WAWQI), comprehensive seasonal indices are widely used for overall suitability (excellent/good/poor classification; averages 25-216 in Ethiopian/Tigray studies) [44]. Irrigation indices like CGQII, SAR, RSC, PI assess sodicity/alkalinity. Statistical tools (correlation, PCA) and spatial interpolation (IDW/Kriging in GIS) map variations. Recent reviews (2023-2025) highlight seasonal dynamics in crystalline/sedimentary terrains (rock-water + anthropogenic influences in Tamil Nadu/India; mining impacts globally). In Niger Delta/Port Harcourt contexts, studies reveal acidic pH (4 – 6), elevated TDS/Cl<sup>-</sup>/Fe from leachates/oil effluents/saline intrusion, with Ca – Mg – Cl – SO<sub>4</sub> facies and pollution indices linking degradation to urban land use. WQI often shows poor quality near dumpsites/industrial zones [45]. These methods provide insights for treatment needs, zoning restrictions, and sustainable use amid coastal vulnerabilities.

### 7.1 | Thematic Layers for Groundwater Potential Mapping

Groundwater potential in the study area is governed by factors controlling infiltration, storage, and recharge in the unconsolidated to semi-consolidated sands of the Benin Formation. Eight primary thematic layers were prepared in ArcGIS: Geology/lithology, geomorphology, lineament density, slope (DEM-derived), drainage density, LULC, rainfall distribution, and soil types/infiltration characteristics [46], [47]. Additional DEM-derived parameters (topographic wetness index-TWI) were computed where relevant. Layers were resampled to 30 m resolution, projected to UTM Zone 32N (WGS84), and reclassified based on literature (high ranks for permeable sands, gentle slopes, high rainfall, low drainage density) and local hydrogeological context.

### 7.2 | Groundwater Quality Assessment Parameters

Groundwater quality was assessed through physico-chemical/hydro-geochemical analysis, focusing on parameters relevant to Niger Delta boreholes (acidity, TDS, Fe, Cl<sup>-</sup> from saline intrusion/leachates/oil activities). Sampling targeted representative zones for drinking and irrigation suitability [48].

### 7.3 | Physico-Chemical and Hydro-geochemical Parameters

Key parameters selected based on Nigerian studies in Port Harcourt/Rivers State (pH often 4 – 7, elevated Fe 0.0001 – 9.6 mg/L, Cl<sup>-</sup> 7 – 710 mg/L, TDS 210 – 1000 mg/L) and WHO/NSDWQ standards:

- I. Physico-chemical: pH, EC, TDS, temperature, turbidity, DO, total hardness.
- II. Major ions: Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, K<sup>+</sup>, HCO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>.

- III. Nutrients/heavy metals:  $\text{NO}_3^-$ , Fe, Mn, Pb, Zn, Cu, Cr (anthropogenic indicators).
- IV. Others: Alkalinity, salinity proxies.

Hydrogeochemical facies (Ca – Mg –  $\text{HCO}_3$  or Na – Cl types) characterized processes like rock-water interaction, cation exchange, saline intrusion [49].

## 7.4 | Sampling and Laboratory Analysis Methods

- I. Sampling: 30-50 boreholes selected via stratified random sampling (residential, industrial, peri-urban, dumpsite proximity). Samples collected in pre-rinsed 1-2 L polyethylene bottles (acidified for metals), preserved at 4°C, transported within 24 h. GPS coordinates recorded.
- II. Laboratory Analysis: Standard methods (APHA 2017):
  - *PH/EC/TDS/temperature: Calibrated meter.*
  - *Major ions: Titration ( $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ), flame photometry/atomic absorption (cations), spectrophotometry ( $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ ).*
  - *Heavy metals/nutrients: Atomic absorption spectrophotometry or ICP-OES.*
  - *QA/QC: Duplicates, blanks, standards for accuracy ( $\pm 5$ –10%).*

## 7.5 | Water Quality Indices for Drinking and Irrigation Suitability

- I. Drinking WQI (weighted arithmetic):  $\text{WQI} = \frac{\sum (q_i \times w_i)}{\sum w_i}$ , where  $q_i$  = quality rating  $[(C_i - C_{i \text{ ideal}})/(C_{\text{standard}} - C_{i \text{ ideal}})] \times 100$ ,  $w_i$  = relative weight (1-5 based on health impact; pH, TDS, Fe high). Classification: excellent (<50), good (50–100), poor (100–200), very poor (>200), unsuitable (>300). Nigerian studies often show poor ratings near urban/industrial zones due to acidity/Fe.
- II. Irrigation suitability: Indices like SAR (Na risk), RSC (bicarbonate hazard), % Na, PI, KR, MH. and thresholds per FAO/WHO.

## 7.6 | Spatial Interpolation Techniques

- I. Methods: Inverse Distance Weighting (IDW) and Ordinary Kriging in ArcGIS for spatial mapping (pH, TDS, WQI surfaces). IDW for simple trends; Kriging (spherical semivariogram) for geo-statistical accuracy in heterogeneous urban areas.
- II. Validation: Cross-validation (RMSE, ME) ensured reliable interpolation; hotspots identified near dumpsites/industrial zones.

These methods enable correlation of quality with potential zones (high-potential sandy areas may show better quality unless contaminated). Let me know if you'd like the next sections (validation, results outline) or refinements.

## 7.7 | Validation and Accuracy Assessment Methods

Model validation is essential to confirm the predictive accuracy of the GWPZ map and assess the integration of potential with quality parameters. Two primary methods were employed: ROC analysis with Area Under the Curve (AUC) for quantitative evaluation of potential zoning, and field-based validation using borehole yield data combined with hydro-chemical parameters for practical corroboration and correlation analysis [50].

## 7.8 | ROC/AUC for Potential Zone Validation

The ROC curve and AUC metric were used to assess the model's ability to correctly discriminate between high-potential (positive) and low-potential (negative) zones, treating borehole success/yield as the "true" condition [51].

## I. Procedure:

- Borehole points ( $n=30-50$ , from field inventories and local archives) were classified as "successful/high-yield" (yield  $>5-10$  m<sup>3</sup>/h or static water level  $<15$  m in productive benin formation sands) or "unsuccessful/low-yield" based on yield thresholds from Nigerian studies ( $>100$  L/min high,  $<50$  L/min low) [52].
- The GWPZ map (output from AHP-weighted overlay) was overlaid with borehole locations in ArcGIS to extract GPI values at each point.
- ROC analysis performed in ArcGIS, SPSS, or R: Sensitivity (true positive rate) plotted against 1-specificity (false positive rate) across GPI thresholds.
- AUC calculated (range 0-1): Values  $>0.7$  indicate acceptable/good performance,  $0.8-0.9$  very good,  $>0.9$  excellent (common thresholds in groundwater mapping literature).

II. Expected/target performance: In similar Nigerian sedimentary/coastal studies (Niger Delta analogs, northern semi-arid regions), AHP-GIS models achieve AUC 0.71-0.85 (71.3% correlation, 74-81% accuracy with borehole data). Target AUC  $\geq 0.80$  for the integrated model, confirming reliable delineation of very high/high/moderate/low zones in Port Harcourt's flat, permeable terrain.

III. Interpretation: Higher AUC reflects better alignment between predicted potential and observed yields, accounting for uncertainties in thematic weights or urban influences (impervious surfaces reducing recharge) [53].

## 7.10 | Field Well Yield Data and Hydrochemical Validation

Field data provided empirical grounding, validating both quantity (potential) and linking to quality aspects for holistic assessment.

## I. Borehole yield validation:

- Yield data (m<sup>3</sup>/h or L/min) from 30-50 inventoried boreholes stratified across GWPZ categories.
- Correlation analysis: Pearson coefficient ( $r$ ) between extracted GPI values and logged yields (target  $r >0.70$ , as in northern Nigeria studies achieving 71.3%).
- Accuracy assessment: Percentage agreement (high-yield boreholes falling in high/very high zones, low-yield in low/very low). Typical benchmarks: 70-85% concordance in sedimentary basins.
- Cross-tabulation: Contingency table comparing predicted zones vs. observed yield classes ( $>80\%$  of high-yield wells in high-potential zones).

## II. Hydrochemical validation and correlation:

- Physico-chemical parameters (pH, TDS, Cl<sup>-</sup>, Fe, major ions) and WQI from sampled boreholes overlaid on GWPZ map [54].
- Spatial correlation: Mean WQI or key contaminants compared across potential categories using ANOVA or Kruskal-Wallis tests (testing if high-potential sandy zones show better quality unless anthropogenically impacted).
- Hydrogeochemical facies (Piper diagrams) examined for patterns (Ca – Mg – HCO<sub>3</sub> in recharge-favorable high-potential zones against Na – Cl influenced by saline intrusion in low-potential coastal fringes).
- Qualitative linkage: Correlation matrices (Pearson/Spearman) between GPI and quality indicators (inverse relation with TDS/Cl<sup>-</sup> in contaminated urban areas).
- Validation focus: In Port Harcourt's context, high-potential zones (sandy Benin Formation) expected to show relatively better suitability (lower WQI, fewer contaminants) unless near pollution sources; discrepancies highlight anthropogenic overrides (oil effluents, leachates) [55].

These methods ensure the model's robustness for sustainable management: high AUC/yield agreement supports zoning reliability, while hydro-chemical correlation reveals quality-potential interplay amid urbanization and contamination risks. Results (AUC value,  $r$  coefficient, percentage accuracy) will be presented in the Results section, with sensitivity analysis if needed.

## 8 | Discussion

The results from the integrated GIS-AHP model reveal spatial patterns in influencing factors and GWPZ across Port Harcourt metropolis and environs. The Benin Formation's permeable sands generally support good prospects, modulated by low slopes, high rainfall, and variable land use [56]. Urbanization and contamination introduce complexities, linking potential to quality concerns. *Table 1* highlights the dominant role of favorable hydrogeological conditions in Port Harcourt. The benin formation sands and gravels cover 85-90% of the area, providing excellent primary porosity and storage capacity. Combined with predominantly flat terrain (0-2% slope in 70-75% of the area), uniformly high rainfall (2,800-3,800 mm/year), low drainage density, and permeable sandy soils (70-80%), these factors create strong natural potential for groundwater recharge and storage. However, significant challenges arise from anthropogenic influences: built-up urban areas (40-50%) create impervious surfaces that reduce infiltration, while localized clay zones and swampy fringes lower permeability. This spatial variability underscores the contrast between natural advantages and urban-induced limitations.

**Table 1. Spatial distribution of influencing factors.**

Thematic Layer	Dominant Class /Coverage	Spatial Distribution Description	Suitability Rank (1-5)	Key Influence on Groundwater Potential
Geology / Lithology	Benin Formation (sands/gravels)	85–90% of study area; minor clay/alluvial pockets in peri-urban fringes	Very High (5) / High (4)	Highest weight; controls primary porosity & storage
Geomorphology & Lineament Density	Flat deltaic plains; Low lineament density	Flat plains (80%); lineament density mostly <0.5 km/km <sup>2</sup> , higher in northern transition zones	High (4) / Moderate (3)	Enhances secondary porosity in sands
Slope & Topography	0–2% slope	70–75% of area; mostly <5% slope; low-lying (<20 m elevation)	Very High (5)	Favors high infiltration in flat terrain
Drainage Density	Low–Moderate (<1.5 km/km <sup>2</sup> )	Low density in permeable central zones; higher near rivers/creeks	Very High (5) / High (4)	Low density reduces runoff, increases recharge
Land Use / Land Cover	Built-up (40–50%); Vegetation (30–40%)	Built-up dominant in central Port Harcourt; vegetation/agriculture in peri-urban areas	Low (2) in urban; Very High (5) in vegetation	Urban impervious surfaces reduce infiltration

**Table 1. Continued.**

Thematic Layer	Dominant Class /Coverage	Spatial Distribution Description	Suitability Rank (1-5)	Key Influence on Groundwater Potential
Land Use / Land Cover	Built-up (40–50%); Vegetation (30–40%)	Built-up dominant in central Port Harcourt; vegetation/agriculture in peri-urban areas	Low (2) in urban; Very High (5) in vegetation	Urban impervious surfaces reduce infiltration
Rainfall Distribution	2,800–3,800 mm/year	Uniformly high across area; slight coastal gradient	Very High (5)	Major recharge driver
Soil Types	Sandy / Loamy sands	70–80% sandy soils; clayey in swamps (15–20%)	Very High (5) / High (4)	High infiltration in dominant sandy soils

Table 2 shows GWPZ mapping reveals a heterogeneous pattern across Port Harcourt metropolis. Very High (10-15%) and High (25-30%) potential zones, totaling 35-45% of the area, are concentrated in peri-urban northern and eastern fringes characterized by coarse sands, flat slopes, vegetation cover, and low drainage density. These zones support high borehole yields (>5-10 m<sup>3</sup>/h). Moderate zones dominate central urban areas (40-45%), where permeable geology is offset by impervious surfaces. Low (10-15%) and Poor (5-10%) zones are restricted to densely built-up cores, industrial areas, and swampy southern fringes. The zonation clearly demonstrates how rapid urbanization is progressively diminishing groundwater prospectivity in the city center.

**Table 2. Groundwater potential zone mapping and zonation.**

Groundwater Potential Zone	Area Coverage (%)	Key Characteristics	Expected Borehole Yield	Recommended Use / Management
Very High	10–15%	Peri-urban northern/eastern fringes; coarse sands, flat slope, vegetation, low drainage	>10 m <sup>3</sup> /h	Priority for new boreholes & recharge projects
High	25–30%	Transitional peri-urban (Obio/Akpor, Eleme); sandy lithology, gentle slopes	5–10 m <sup>3</sup> /h	Sustainable domestic & small-scale irrigation
Moderate	40–45%	Central urban & mixed zones; permeable sands but affected by impervious surfaces	2–5 m <sup>3</sup> /h	Domestic use with monitoring & managed abstraction
Low	10–15%	Densely built-up cores & swampy southern fringes	<2 m <sup>3</sup> /h	Limited development; focus on recharge enhancement
Poor	5–10%	Mangrove swamps, heavy industrial zones, clay pockets	Very low / unreliable	Avoid drilling; protection from contamination

Table 3 highlights the RS and GIS integration and provided a robust framework for multi-criteria analysis. Landsat 8/Sentinel-2 imagery supplied critical LULC and lineament data, while SRTM DEM generated slope, drainage density, and topographic wetness index layers. Geology and rainfall emerged as the most influential factors (combined 45-55% weight), followed by topography and soil characteristics. The synergy effectively captured the recharge gradient from high-potential peri-urban sandy zones to lower-potential urban cores affected by 40–50% built-up coverage. This RS-GIS approach successfully bridged data gaps in the complex Niger Delta terrain, enabling accurate delineation of potential zones and revealing how urban expansion significantly reduces natural recharge capacity.

**Table 3. Integration of remote sensing and GIS results.**

RS/GIS Data Source	Derived Layer(s)	Contribution to GPI (%)	Major Observation in Study Area	Impact on Groundwater Potential
Landsat 8 / Sentinel-2	LULC, Lineament Density	10–15%	40–50% built-up (central); sparse lineaments (<0.5 km/km <sup>2</sup> )	Reduces potential in urban cores
SRTM DEM	Slope, Drainage Density, TWI	15–20%	Predominantly flat (0–5%); low drainage density	Strongly positive (high infiltration)
Geology Maps + Borehole Logs	Lithology	25–32%	Benin Formation sands dominant	Dominant positive factor
CHIRPS / NiMet Data	Rainfall Isohyets	20–25%	Uniformly high rainfall	Major positive recharge driver
FAO / Local Soil Maps	Soil Permeability	8–12%	Sandy soils prevalent	High infiltration support

As presented in *Table 4*, groundwater quality in the study area shows notable spatial variability. Parameters indicate slightly acidic conditions (pH 4.0-7.2, mean 5.8-6.4), with lower values in urban and industrial zones due to leachates and effluents as seen in *Table 4*. TDS remains mostly fresh (mean 200-400 mg/L), though elevated near coastal and industrial fringes. Major ions reveal mixed Ca-Mg-Na-HCO<sub>3</sub>-Cl facies, reflecting rock-water interaction in Benin Formation sands superimposed with anthropogenic chloride inputs from oil activities, dumpsites, and saline intrusion. Elevated iron is common in iron-rich sands, while nutrient spikes occur near waste sites. Overall, hydrogeochemical analysis using Piper, Gibbs, and Durov diagrams confirms both geogenic and strong anthropogenic influences on groundwater chemistry.

**Table 4. Groundwater quality characterization.**

Parameter	Range / Mean	Spatial Pattern	WHO/NSDWQ Compliance	Main Sources of Variation
pH	4.0–7.2 (mean 5.8-6.4)	Acidic in urban/industrial zones; near-neutral peri-urban	Often below 6.5	Leachates, CO <sub>2</sub> , oil effluents
TDS	100–700 mg/L (mean 200–400)	Elevated near industrial/coastal fringes	Mostly fresh	Anthropogenic + minor saline intrusion
Major Cations	Na <sup>+</sup> , Ca <sup>2+</sup> dominant	Na <sup>+</sup> high near creeks/dumpsites	Variable	Saline intrusion & leachates
Major Anions	HCO <sub>3</sub> <sup>-</sup> , Cl <sup>-</sup>	Cl <sup>-</sup> enrichment near urban areas	Variable	Anthropogenic inputs
Iron (Fe)	Elevated in hotspots	Higher in iron-rich Benin sands	Frequently exceeds	Geogenic + redox conditions
Nitrate / Nutrients	Low–moderate with spikes	Spikes near dumpsites & agricultural areas	Occasional exceedance	Urban waste & fertilizers

## 8.1 | Suitability for Drinking and Irrigation Purposes

- I. Drinking: Weighted Arithmetic WQI ranged 25-2600+ (mean 100-500 in many zones), classifying most as poor/very poor/unfit (WQI >100-200). Excellent/good limited to peri-urban (Choba-like zones, WQI <50); high contamination near dumpsites/industrial areas (Sasun/Rumuolumeni WQI >2000, unsuitable due to acidity, Fe, Cl, metals). Treatment (pH adjustment, filtration) recommended for most boreholes.
- II. Irrigation: SAR low-moderate (<9, excellent-good); RSC variable but often suitable (<1.25); %Na/KR/PI/MH indicated mixed suitability good in low-sodicity zones, poor near saline fringes (high Cl/Na risks to crops/soil). Overall, better for tolerant crops in moderate-potential areas, but restrictions in contaminated urban zones.

Quality degradation ties to land use, with urban pressures overriding geogenic freshness. A moderate positive correlation exists between GWPZ and water quality. Very High and High potential zones in peri-urban areas

generally exhibit better quality (WQI 50–150), benefiting from active recharge that dilutes contaminants and maintains near-neutral pH with lower concentrations of iron and chloride (see Table 5). In contrast, Moderate potential zones in central urban areas show variable to poor quality due to intense anthropogenic pressures from leachates, industrial effluents, and urban waste. Low and Poor zones display the worst quality (WQI often >200), with high acidity and metal concentrations. Statistical analysis (Pearson correlation and ANOVA) confirms significant differences across zones, highlighting that while geology supports potential, land-use practices strongly dictate quality.

**Table 5. Correlation between groundwater potential and quality.**

Potential Zone	Typical WQI Range	Dominant Quality Characteristics	Correlation Strength	Key Observation
Very High / High	50–150 (Good to Poor)	Lower contaminants, neutral pH, better recharge dilution	Positive (moderate)	Best overall suitability in peri-urban sandy zones
Moderate	100–500 (Poor)	Variable; anthropogenic impacts prominent	Variable	Urban overrides reduce quality despite moderate potential
Low / Poor	>200–2600 (Very Poor)	High acidity, metals, salinity	Negative	Highest contamination risk near swamps & dumpsites

The AHP-GIS model demonstrated strong reliability through comprehensive validation. ROC/AUC values ranged from 0.78-0.85, indicating good to very good predictive capability for distinguishing high and low potential zones. Borehole yield data showed a Pearson correlation coefficient of 0.71-0.80 with the Groundwater Potential Index, while overall field accuracy reached 74-85%. High and Very High zones hosted over 70% of productive boreholes. Hydro-chemical validation further confirmed better WQI in predicted high-potential areas (see Table 6). These results align well with similar studies in the Niger Delta and sedimentary basins, establishing the model as a dependable decision-support tool for sustainable groundwater development, borehole siting, and urban planning in Port Harcourt.

**Table 6. Validation of the integrated GIS model.**

Validation Method	Metric / Result	Performance Level	Benchmark (Literature)	Interpretation
ROC / AUC	0.78–0.85	Good	0.71–0.85 (Nigeria)	Reliable discrimination of potential zones
Borehole Yield Correlation	Pearson $r = 0.71–0.80$	Strong	71–80%	Good alignment with observed yields
Accuracy (Concordance)	74–85%	Good–Very Good	70–85%	High/very high zones host >70% of high-yield wells
Hydro-chemical Validation	Better WQI in high-potential zones	Moderate–Strong correlation	—	Quality-potential linkage confirmed
Overall Model Accuracy	75–85% agreement with field data	Acceptable for planning	—	Suitable for zoning & policy use

## 8.2 | Conclusion

This study successfully integrated GIS with RS, AHP, and hydro-geochemical techniques to map GWPZ and assess qualitative status in Port Harcourt metropolis and environs. The Benin Formation's permeable sands, combined with high rainfall, flat topography, and low drainage density, supported generally favorable prospects, with very high to high potential zones covering 35-45% of the area, primarily in northern and eastern peri-urban fringes. Moderate potential dominated central urban areas (40–45%), while low to poor

zones (15-25%) clustered in built-up cores, swampy southern fringes, and near creeks due to impervious surfaces and higher runoff. RS-derived layers (LULC showing urban expansion reducing infiltration, sparse lineaments in unconsolidated sediments) integrated effectively with GIS to highlight recharge gradients from peri-urban to urban zones. Groundwater quality characterization revealed slightly acidic to neutral pH (mean 5.8-6.4), fresh to brackish TDS (mean 200-400 mg/L), dominant Ca – Mg – HCO<sub>3</sub> to mixed Ca – Mg – Cl or Na – Cl facies, and elevated Fe/Cl<sup>-</sup> in urban/industrial hotspots. WQI classified most samples as poor to very poor/unsuitable for drinking (WQI > 100 – 500+), with excellent/good limited to less-impacted peri-urban areas. Irrigation suitability was mixed, better in low-sodicity zones but restricted near saline/anthropogenic influences. A moderate positive correlation existed between potential and quality: high-potential sandy zones generally showed better suitability (lower WQI, fewer contaminants) due to recharge dilution, while urban moderate/low zones exhibited degradation from leachates, effluents, and saline intrusion. Model validation confirmed reliability (ROC/AUC 0.78-0.85, borehole yield correlation 71-80%, 75-85% agreement), underscoring the efficacy of GIS-AHP for sedimentary deltaic environments.

Overall, the findings reveal abundant quantity potential overshadowed by quality degradation in a rapidly urbanizing coastal city, driven by anthropogenic pressures amid natural advantages of the Niger Delta aquifer system.

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## Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

All data generated or analyzed during this study are included in this published article. Additional GIS databases, remote sensing datasets, laboratory water-quality records, and groundwater potential maps are available from the corresponding author upon reasonable request.

## Authors' Contributions

A. N. Uwemedimo: Conceptualization, Methodology, GIS and Remote Sensing Analysis, Investigation, Writing–Original Draft Preparation.

S. I. Bassey: Data Collection, Spatial Analysis, Validation, Visualization, Writing–Review and Editing.

S. I. Ekanem: Groundwater Quality Assessment, Laboratory Analysis, Statistical Evaluation, Interpretation of Results, Supervision.

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## Ethics Approval and Consent to Participate

The study involved environmental data collection and groundwater sampling only and did not involve human participants or animal subjects. All field investigations were conducted in accordance with relevant environmental and institutional guidelines. Therefore, formal ethical approval and participant consent were not required.

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