

The Integrated Groundwater Health Risk (IGHR) Decision-Support Model: Integrating Hydrogeological, Environmental, and Knowledge, Attitude and Practice Indicators for Groundwater Health Risk Prediction in Abeokuta, Nigeria

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Abstract

Groundwater contamination from petroleum filling station (PFS) activities poses an increasing environmental and public health challenge in rapidly urbanizing regions where groundwater constitutes a major source of domestic water supply. Existing groundwater risk assessment approaches primarily focus on hydrogeological vulnerability or water quality and often overlook the influence of community behavioural factors on human exposure. This study developed and evaluated an Integrated Groundwater Health Risk (IGHR) Decision-Support Model that combines hydrogeological, environmental, and Knowledge Attitude Practice (KAP) indicators to predict groundwater-related health risks in Abeokuta Urban, Ogun State, Nigeria. A mixed-methods approach was adopted, comprising hydrogeological assessment, groundwater quality analysis, household surveys, Geographic Information System (GIS)-based spatial analysis, and statistical modelling, to sample a total of 187 geo-referenced groundwater sources surrounding 19 PFS transects alongside 374 household respondents spatially linked at a 2:1 sampling ratio. Significant spatial variability was observed across physicochemical parameters (pH, EC, TDS, BOD, COD, Cl⁻, NO₃⁻; $p < 0.001$). Heavy metals (Pb, Cd, Cr, Ni, As, V, Ba) differed significantly across vulnerability classes ($p < 0.001$), with Lead (29.4%) and Cadmium (33.2%) frequently exceeding WHO drinking water guidelines. Household surveys revealed moderate knowledge (41.9%) and positive attitudes (56.1%) but poor protective practices (37.4%), with regression analysis confirming that attitudinal disposition and education significantly drive water protection practices ($R^2 = 0.285$, $p < 0.001$). The IGHR Decision-Support Model integrated the normalized sub-indices using a weighted additive structure: $IGHRI = 0.20(HVRI_N) + 0.30(WQI_N) + 0.35(HMI_N) + 0.15(1 - KAPI_N)$. Using site-wide sub-index mean values $HVRI_N$ (0.233), WQI_N (0.366), HMI_N (0.482), and $KAPI_N$ (0.438), the composite index yielded an overall score of 0.4094. The Heavy Metal Index represented the largest weighted contributor (0.1687) to the composite score. Based on equal-interval threshold boundaries (0.401–0.600), the study area is categorized as Moderate Risk, indicating a need for continuous water quality surveillance and targeted community risk communication. Spatial hotspot analysis identified elevated risks down-gradient of PFSs where hydrogeological vulnerability, heavy metal accumulation, and behavioral deficits converged. Model validation against USEPA Non-Carcinogenic Hazard Index scores demonstrated strong spatial predictive accuracy (ROC-AUC = 0.824, $p < 0.001$). Conclusively, the IGHR model offers a practical spatial decision-support tool for groundwater protection and public health management in petroleum-impacted urban environments.

Keywords: Abeokuta; Contamination; Decision-Support Model; Health Risk; KAP; Underground Storage Tanks.

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INTRODUCTION

Groundwater is one of the world's most valuable freshwater resources, providing drinking water for approximately half of the global population and supporting domestic, agricultural, industrial, and ecosystem needs (Khilchevskiy & Karamushka, 2022; Pointet, 2022). In developing countries, particularly across sub-Saharan Africa, groundwater serves as the principal source of potable water because of inadequate public water supply infrastructure, rapid urbanization, and increasing population growth (MacDonald & Davies, 2013) cited in (Gaye & Tindimugaya, 2019). In Nigeria, groundwater obtained from boreholes and hand-dug wells remains the predominant source of domestic water supply in almost all rural, urban and peri-urban communities (Danert & Healy, 2021; Ogbale et al., 2025). However, increasing anthropogenic activities have raised growing concerns regarding groundwater quality deterioration and the associated environmental and public health consequences (Akhtar et al., 2021; Ravindiran et al., 2023).

Among the numerous anthropogenic sources of groundwater contamination, petroleum filling stations have emerged as important environmental risk points. Leakages from underground storage tanks (USTs), corroded pipelines, accidental fuel spillages, poor maintenance practices, and surface runoff introduce petroleum hydrocarbons and heavy metals into surrounding soils, where contaminants may migrate through the vadose zone into underlying aquifers (Fei-Baffoe et al., 2024). The persistence and mobility of these contaminants threaten groundwater quality, particularly in densely populated urban areas where petroleum filling stations are located close to residential neighbourhoods that rely heavily on groundwater for drinking and other domestic purposes (Adediji et al., 2021; Omokpariola et al., 2025; Oyebamiji et al., 2025; Alao et al., 2026).

The rapid expansion of petroleum retail business in Nigerian cities has increased the potential for groundwater contamination. In Abeokuta Urban, Ogun State, and similarly in other parts of Nigeria numerous petroleum filling stations operate in proximity to residential communities where boreholes and shallow wells constitute the major sources of potable water (Adediji et al., 2022; Ulakpa et al., 2022; Akinyosoye & Balogun, 2023; Gbadebo et al., 2024). Previous studies have demonstrated that groundwater surrounding petroleum facilities may contain elevated concentrations of petroleum-derived contaminants and heavy metals, including lead, cadmium, chromium, copper, and zinc, which have been associated with neurological disorders, kidney dysfunction, developmental abnormalities, reproductive impairment, and carcinogenic risks following prolonged exposure (WHO, 2022; Gbadebo et al., 2024; Fei-Baffoe et al., 2024). These findings emphasize the need for comprehensive groundwater health risk assessment approaches capable of identifying contamination pathways and supporting effective environmental and water management.

Several groundwater vulnerability and health risk assessment models have been developed to evaluate contamination risks (Kumar and Pramod Krishna, 2020; Moges and Dinka, 2022; Lu et al., 2025; Salem et al., 2025; Thomas, 2026). Furthermore, Hydrogeological models such as DRASTIC, GOD, and SINTACS primarily assess aquifer susceptibility using environmental characteristics including depth to groundwater, recharge, soil properties, aquifer media, topography, and hydraulic conductivity (Shah et al., 2021; Assefa and Dinka, 2023; Ekanem and Udosen, 2023; Idir et al., 2024; Udosen et al., 2024). Similarly, conventional human health risk assessment frameworks recommended by the United States Environmental Protection Agency (USEPA) estimate carcinogenic and non-carcinogenic risks based on contaminant concentrations, exposure pathways, and toxicological reference values (Shetty et al., 2024;

Wang et al., 2024; Sedghi et al., 2026; USEPA, 2004). Although, these approaches have significantly advanced groundwater protection, focusing predominantly on environmental and hydrogeological conditions while largely overlooking behavioural factors that influence actual human exposure and health outcomes.

Beyond these environmental and hydrogeological considerations, studies by Abdoulaye et al. (2025), Jeffrey et al. (2025), Mahé et al. (2026), and Waswala-Olewe et al. (2026) have increasingly recognized Knowledge, Attitudes, and Practices (KAP) as fundamental determinants of environmental health because they influence how individuals perceive environmental hazards, select drinking water sources, adopt household water treatment measures, respond to contamination events, and comply with public health recommendations. This perspective is consistent with evidence from the Water, Sanitation, and Hygiene (WASH) literature, which demonstrates that inadequate KAP is a major contributor to the transmission of water-related infectious diseases (Dreibelbis et al., 2013, as cited in Berhe et al., 2020). Moreover, the effectiveness of WASH interventions depends not only on the availability of safe water and sanitation infrastructure but, more importantly, on individuals' willingness and ability to adopt appropriate behaviours. Consequently, access to water and sanitation services alone is insufficient to reduce health risks unless accompanied by adequate knowledge, positive attitudes, and safe practices regarding water use and hygiene (Barnard et al., 2013, as cited in Berhe et al., 2020). By extension, these findings provide strong empirical support for incorporating KAP into groundwater management and health risk assessment frameworks, as behavioural factors significantly influence exposure pathways, the adoption of preventive measures, and the overall effectiveness of interventions aimed at protecting groundwater quality and public health.

Communities with poor knowledge of groundwater contamination may unknowingly consume unsafe water, neglect routine water quality monitoring, or fail to implement preventive measures, thereby increasing their susceptibility to adverse health outcomes. Conversely, adequate environmental knowledge and positive behavioural practices can substantially reduce exposure and strengthen community resilience. Despite their importance, KAP indicators have rarely been incorporated into groundwater health risk assessment models, resulting in an important methodological gap between environmental assessment and human health protection.

Recognizing this limitation, the present study develops the Integrated Groundwater Health Risk (IGHR) Decision-Support Model, a multidimensional framework that integrates hydrogeological, environmental, and behavioural indicators into a unified groundwater health risk prediction system. The model conceptualizes groundwater contamination as a dynamic interaction between the source of pollution, environmental pathways, community behavioural characteristics, and public health outcomes. Specifically, the framework integrates groundwater vulnerability, physicochemical water quality, heavy metal contamination, and residents' Knowledge, Attitudes, and Practices (KAP) to generate an integrated groundwater health risk index capable of supporting environmental monitoring, groundwater protection, and evidence-based decision-making.

Unlike existing groundwater assessment models that primarily quantify environmental contamination, the IGHR Decision-Support Model explicitly incorporates behavioural determinants as modifiers of groundwater health risk. This integration acknowledges that the magnitude of health risk is influenced not only by contaminant concentrations but also by how communities perceive, utilize, and manage groundwater resources. Consequently, the proposed

model provides a more comprehensive environmental health assessment framework that bridges hydrogeology, environmental science, and public health.

Meanwhile, Abeokuta Urban, Ogun State, Nigeria, provides an appropriate case study for developing and validating the IGHR Decision-Support Model because of its (increasing urbanization, dependence on groundwater for domestic water supply, and growing density of petroleum filling stations located within residential area (Adedeji et al., 2022; Bankole et al., 2022; Fei-Baffoe et al., 2024; Taiwo et al., 2026) By integrating environmental and behavioural dimensions into a single decision-support framework, this study contributes a novel methodological approach for groundwater health risk prediction that can inform groundwater management, environmental policy, and public health interventions in Nigeria and other groundwater-dependent urban environments.

Aim of the Study

To develop and validate the Integrated Groundwater Health Risk (IGHR) Decision-Support Model by integrating hydrogeological, environmental, and Knowledge Attitude Practice (KAP) indicators for groundwater health risk prediction in Abeokuta, Nigeria.

Specific Objectives

1. To develop an Integrated Groundwater Health Risk Index (IGHRI) Decision-Support Model by integrating hydrogeological vulnerability, groundwater quality characteristics, petroleum-related heavy metal contamination, and community Knowledge Attitude Practice (KAP) indicators into a unified groundwater health risk assessment framework.
2. To evaluate the integrated groundwater health risk status and demonstrate the applicability of the IGHRI Decision-Support Model for groundwater risk classification, spatial risk interpretation, and evidence-based environmental health decision-making in petroleum-impacted urban communities in Abeokuta, Nigeria.

MATERIALS AND METHODS

Study Area

The study was conducted in Abeokuta Urban, Ogun State, southwestern Nigeria, a rapidly urbanizing city located between latitudes approximately 7°03'-7°13' N and longitudes 3°15'-3°28' E. Abeokuta lies within the Precambrian Basement Complex terrain, characterized predominantly by granite gneiss, migmatite, schist, and quartzite formations. Groundwater occurs mainly within the weathered overburden and fractured basement aquifers, which constitute the principal sources of domestic water supply through boreholes and hand-dug wells.

Rapid urban growth and increasing commercial development have resulted in the establishment of numerous petroleum filling stations within residential neighbourhoods. The close proximity of groundwater abstraction points to petroleum facilities has heightened concerns regarding groundwater contamination arising from leaking underground storage tanks (USTs), fuel spillages, and runoff. Consequently, Abeokuta Urban provides an appropriate setting for developing and validating an integrated groundwater health risk assessment framework.

The spatial distribution of the selected petroleum filling stations and groundwater sampling locations is presented in Figure 1.

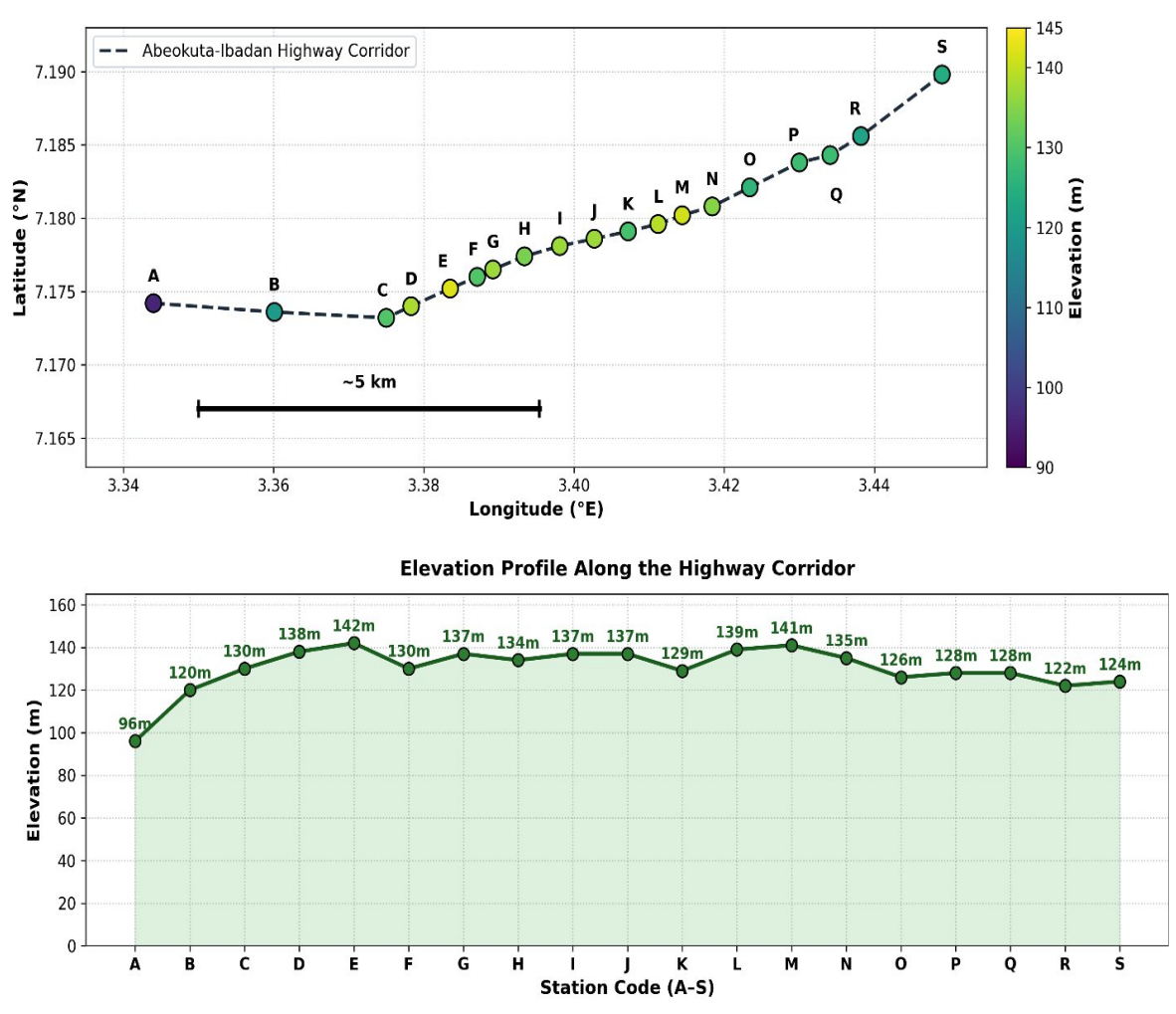


Figure 1: Selected petroleum filling stations GPS locations

Study Design

This study adopted a cross-sectional integrated environmental health modelling approach for developing the Integrated Groundwater Health Risk (IGHR) Decision-Support Model. The framework combined hydrogeological vulnerability assessment, groundwater quality analysis, heavy metal assessment, residents' Knowledge Attitude Practice (KAP) assessment, Geographic Information System (GIS)-based spatial analysis, and statistical modelling to predict groundwater health risks associated with petroleum filling station environments.

Unlike conventional groundwater assessment studies that evaluate these components independently, the present study integrated them into a unified decision-support framework for groundwater health risk prediction.

The study consisted of five sequential stages: (1) Field survey and spatial data acquisition; (2) Groundwater sampling and laboratory analysis; (3) Household Knowledge Attitude Practice (KAP) survey; (4) Development of the IGHR Decision-Support Model; and (5) Spatial prediction of groundwater health risks using Geographic Information System (GIS).

Groundwater Sampling Strategy

A systematic, multi-stage spatial sampling framework was implemented to select petroleum filling stations and associated groundwater abstraction points:

1. **PFS Selection:** Nineteen (19) operational commercial petroleum filling stations (coded Stations A through S) were selected along one of the major interstate highways in Abeokuta Adatan-Asero-Obantoko-Camp-Osiele axis based on proliferation of PFSs and residential density.
2. **Spatial Cluster Radius:** Petrol filling stations (PFS) with functional boreholes or hand-dug wells were first identified, and only those whose management granted access for sampling were selected. Around each selected PFS, a spatial sampling boundary with a radius of 200 m to 500 m was delineated using QGIS 4.0. Within each cluster, residential buildings around the station were then selected.
3. **Inclusion/Exclusion Criteria:** Eligible groundwater sources were active, functional domestic boreholes and shallow hand-dug wells utilized daily for household drinking or cooking. Abandoned wells, non-functional points, and purely commercial industrial wells were excluded.
4. **Synchronized Sampling Survey:** To avoid seasonal hydrogeological fluctuations confounding the hydrochemical data, all 187 groundwater samples were collected in one synchronized field survey during the dry season.

Laboratory and Quality Control (QC) Procedures

Groundwater sampling and laboratory analysis adhered strictly to USEPA (2004) and APHA (2017) standard analytical methods:

1. **Boreholes were purged** for 10 to 15 minutes prior to sampling to ensure the collection of representative groundwater, and purging continued until in-situ parameters (pH, temperature, EC, and TDS) stabilized. Samples were collected in pre-cleaned 1-litre HDPE bottles, and physicochemical parameters were measured on site with a portable multiparameter meter. Colour and odour were evaluated in situ through sensory assessment.
2. **Preservation & Transport:** Samples designated for heavy metal analysis were acidified immediately on site with ultra-pure nitric acid (HNO_3) to $\text{pH} < 2.0$ to prevent metal precipitation and wall adsorption. Samples were stored in insulated coolers packed with ice at $< 4^\circ\text{C}$ and transported to the laboratory within 24 hours.
3. **Analytical Instrumentation:** Seven heavy metals (Pb, Cd, Cr, Ni, As, V, Ba) were quantified using Atomic Absorption Spectrophotometry (AAS). Physicochemical parameters (DO, BOD, COD, TDS, Cl^- , NO_3^-) were measured using calibrated digital meters and titrimetric methods.
4. **Quality Assurance/Quality Control (QA/QC):** Quality control measures included reagent blanks, matrix spikes, multi-point standard calibration curves ($R^2 > 0.995$), and field duplicates (10% of total sample volume). Analytical recovery rates for spiked samples ranged between 92% and 105%, and instrument detection limits were established at 0.001 mg/L for trace metals.

Household KAP Survey Design, Sample Size, and Spatial Linkage

To quantify residents' behavioral protection, a household Knowledge, Attitude, and Practice (KAP) survey was administered alongside with water sampling:

1. **Spatial Linkage (2:1 Ratio):** Exactly 374 household respondents were surveyed across the 187 groundwater sampling locations, establishing a uniform 2:1 spatial ratio (2 households per sampling point). Sampled households were located within a 50 m radius of the specific geo-referenced sources.
2. **Instrument Structure:** The structured questionnaire evaluated three core behavioral domains across 18 items: Knowledge regarding contamination pathways and health risks (5 items), Attitudes toward groundwater protection and regulatory enforcement (5 items), and Practices regarding boiling, filtration, wellhead sealing, and pollution reporting when they suspect or observe contamination (8 items).
3. **Spatial Aggregation:** Individual household KAP scores were aggregated and averaged at each groundwater sampling point, yielding site-specific KAP_{IN} scores (0.00 to 1.00) that were interpolated in QGIS to generate continuous behavioral risk layers.

Ethics Statement and Participant Protection

The survey protocol and human subject methodology received formal ethical approval from the Centre for Research and Development, Kwara State University Institutional Health Research Ethics Committee (Approval Number: KWASU/CR&D/REA/2025/00131). The study complied strictly with the ethical principles of the Declaration of Helsinki. Informed consent (verbal) was obtained from all 374 adult respondents (≥ 18 years) prior to questionnaire administration. Participation was entirely voluntary, anonymous, and respondents were assured of the right to withdraw at any stage without penalty. To maintain confidentiality, household records were anonymized using alphanumeric identification codes linked solely to geo-referenced groundwater sampling points.

Sub-Indices Mathematical Derivation

The multi-criteria model integrates four mathematically normalized sub-indices (ranging from 0.00 to 1.00):

Hydrogeological Vulnerability Risk Index (HVRI)

HVRI evaluates aquifer susceptibility to petroleum leakage based on UST age (A , weight = 0.40), source-to-station proximity distance (D , weight = 0.30), and hydraulic position relative to groundwater flow (H , weight = 0.30; up-gradient = 1, lateral = 2, down-gradient = 3):

$$HVRI = 0.40A + 0.30D + 0.30H \quad (\text{Eq. 1})$$

$$HVRI_N = (HVRI - 1.0) / (3.0 - 1.0) \quad (\text{Eq. 2})$$

Water Quality Index (WQI)

WQI evaluates physicochemical suitability across 11 parameters relative to World Health Organization (WHO) permissible limits (S_i):

$$W_i = K / S_i, \text{ where } K = 1 / \sum (1 / S_i) \quad (\text{Eq. 3})$$

$$Q_i = (C_i / S_i) \times 100 \quad (\text{Eq. 4})$$

$$WQI = \sum (W_i \times Q_i) \quad (\text{Eq. 5})$$

$$WQI_N = (WQI - WQI_{\min}) / (WQI_{\max} - WQI_{\min}) \quad (\text{Eq. 6})$$

Heavy Metal Index (HMI)

HMI quantifies toxic metal burden across 7 heavy metals (Pb, Cd, Cr, Ni, As, V, Ba) evaluated against WHO drinking water thresholds:

$$HMI = \sum (W_i \times (C_i / S_i) \times 100) \quad (\text{Eq. 7})$$

$$HMI_N = (HMI - HMI_{\min}) / (HMI_{\max} - HMI_{\min}) \quad (\text{Eq. 8})$$

Knowledge, Attitude, and Practice Index (KAPI)

Site-specific KAPI reflects community protective behaviors evaluated across 18 survey items:

$$KAPI = \text{Total Observed Score} / \text{Maximum Obtainable Score (18)} \quad (\text{Eq. 9})$$

Composite IGHR Model Weighting Scheme and Risk Classification

The normalized sub-indices were integrated into the final composite Integrated Groundwater Health Risk Index (IGHRI) using an additive linear model:

$$IGHRI = 0.20(HVRI_N) + 0.30(WQI_N) + 0.35(HMI_N) + 0.15(1 - KAPI_N) \quad (\text{Eq. 10})$$

Weights were established based on toxicological severity, environmental persistence, and exposure buffering. HMI_N receives the highest weight (0.35) due to the non-biodegradable, bioaccumulative, and carcinogenic health risks associated with heavy metals (Pb, Cd). WQI_N (0.30) represents acute physicochemical degradation, $HVRI_N$ (0.20) models hydrogeological pathway vulnerability, and $(1 - KAPI_N)$ (0.15) captures the human exposure deficit buffer.

Then, the composite IGHRI score domain (0.000 to 1.000) is structured into five equal-interval risk levels (Table 1).

Table 2.1. Classification of groundwater health risk based on IGHRI scores.

IGHRI Score Range	Risk Status	Public Health & Management Interpretation
0.000 – 0.200	Excellent	Minimal groundwater risk; suitable for domestic use.
0.201 – 0.400	Good	Low risk; acceptable quality requiring routine observation.
0.401 – 0.600	Moderate Risk	Measurable risk; requires continuous surveillance & preventive controls.
0.601 – 0.800	Poor	High risk; requires treatment prior to domestic consumption.
0.801 – 1.000	Critical	Severe risk; immediate intervention & alternative supply required.

Statistical Analysis, Spatial Interpolation, and Model Validation

Data analysis was performed using SPSS vs 25 and QGIS Desktop 4.0.0. Spatial continuous surface maps were created using Inverse Distance Weighting (IDW) interpolation with a power parameter of $p = 2$ and a 12-point search neighborhood. Spatial autocorrelation was evaluated using Global Moran's I with a 1.5 km distance threshold. Model validation was conducted by comparing composite IGHR predictions against independent USEPA Non-Carcinogenic Hazard Index (HI) scores calculated across the 187 sampling sites using Spatial Receiver Operating Characteristic (ROC-AUC) curve analysis.

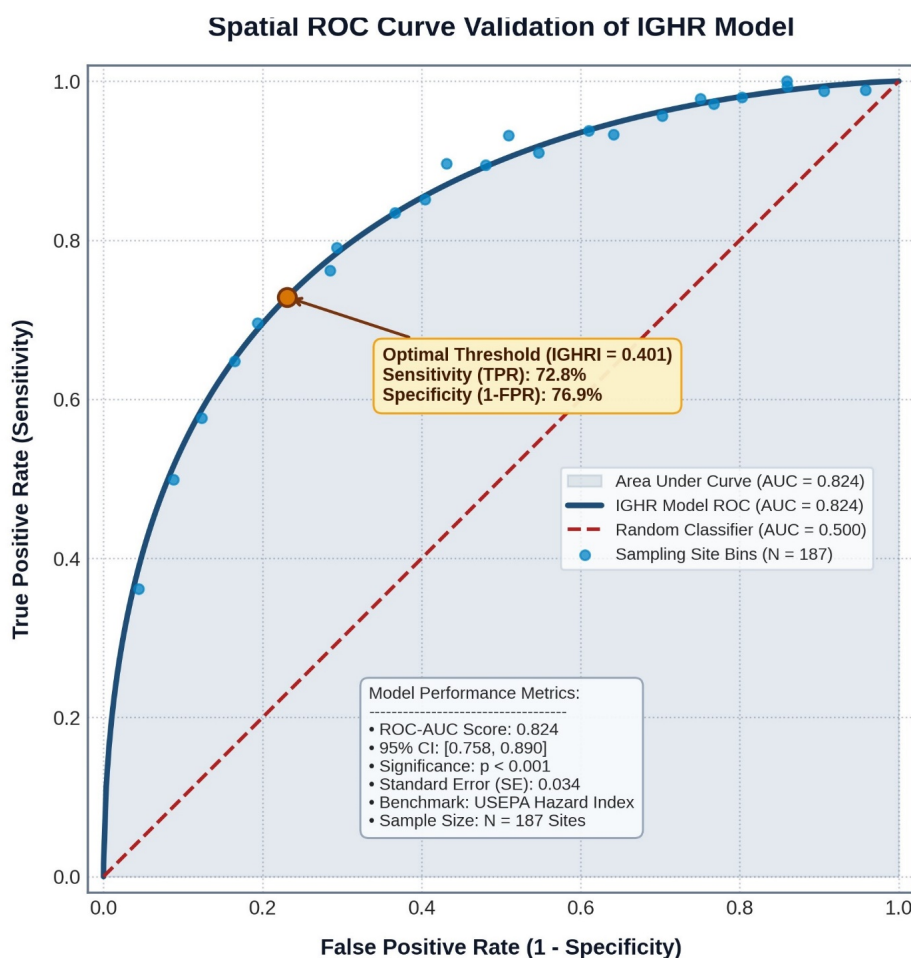


Figure 1: Spatial ROC Validation of the IGHR Model

RESULTS

Hydrogeological Vulnerability Assessment and Risk Index (HVRI)

Topographic Profile, Hydraulic Elevation, and Regional Flow Regime

Topographic profiling across the 187 geo-referenced groundwater sampling points established that subsurface hydraulic head dynamics are governed by a regional elevation gradient across the study area. Terrain elevation decreases systematically from the northeastern (NE) highlands

(142 m above sea level) toward the southwestern (SW) lowlands (87 m above sea level), establishing a dominant northeast-to-southwest regional groundwater flow direction.

Spatial mapping identified two primary hydraulic divides: 1. Primary Hydraulic Divide at Station E1 (Elevation: 142 m): Represents the highest elevation crest along the primary commercial highway corridor, driving groundwater flow outward and down-gradient toward surrounding residential abstraction points. 2. Secondary Hydraulic Divide at Station M1 (Elevation: 141 m): Creates a localized hydraulic ridge directing subsurface transport toward eastern discharge depressions.

Groundwater discharge occurs within two main topographic lowlands: the A1–B5 station corridor (87–96 m elevation), representing the principal regional discharge zone, and the L1–S1 station corridor, forming a secondary discharge depression.

Multi-Criteria HVRI Model Derivation and Weighting Scheme

The Hydrogeological Vulnerability Risk Index (HVRI) quantifies in equation 1, where UST Age (A, weight = 0.40) evaluates structural corrosion, Source-to-Receptor Proximity (D, weight = 0.30) measures transport distance, and Hydraulic Position (H, weight = 0.30) evaluates head alignment. Raw HVRI scores were normalized to produce $HVRI_N$ (0.00–1.00). Across all 187 sampling locations, the study area yielded a mean normalized $HVRI_N$ score of 0.233 ± 0.182 .

Empirical Distribution of Vulnerability Levels Across 187 Sampling Sites

Using standardized equal-interval boundaries Low (0.00–0.33), Moderate (0.34–0.66), and High (0.67–1.00), the sampled groundwater sources were classified into three vulnerability levels.

Table 3.1: Hydrogeological Vulnerability Classification Across 187 Groundwater Sources

HVRI Category	Score Range ($HVRI_N$)	Sources (n)	Percentage (%)	Hydrogeological & PFSs Characteristics
Low Vulnerability	0.00 – 0.33	106	56.7%	Up-gradient position; distance >200 m; UST age <15 years.
Moderate Vulnerability	0.34 – 0.66	75	40.1%	Lateral position; distance 100-200 m; UST age 16-25 years.
High Vulnerability	0.67 – 1.00	6	3.2%	Down-gradient alignment; distance <100 m; UST age 26-35 years.
Total	0.00 – 1.00	187	100.0%	Study Area Mean $HVRI_N$ = 0.233

Groundwater Physicochemical and Heavy Metal Contamination

Physicochemical parameters across the 187 groundwater sources exhibited marked spatial variation surrounding the 19 PFSs. Mean pH values ranged from 5.82 (slightly acidic) to 7.41, while Electrical Conductivity (EC) ranged between 182 $\mu\text{S}/\text{cm}$ and 1,420 $\mu\text{S}/\text{cm}$. Organic fuel

contamination indicators were widespread: Dissolved Oxygen (DO) levels were depleted in wells near older PFS infrastructure (< 3.2 mg/L), accompanied by elevated Biochemical Oxygen Demand (BOD up to 48.5 mg/L) and Chemical Oxygen Demand (COD up to 112.0 mg/L), confirming active hydrocarbon biodegradation.

Trace heavy metal concentrations revealed critical health risks. Lead (Pb) concentrations exceeded the WHO permissible limit (0.010 mg/L) in 29.4% of samples (mean = 0.028 mg/L), reaching peak values of 0.142 mg/L near Station Q1. Cadmium (Cd) exceeded the WHO threshold (0.003 mg/L) in 33.2% of sampled wells (mean = 0.008 mg/L). Chromium (Cr) and Nickel (Ni) exceedances were recorded in 14.4% and 18.2% of samples, respectively.

Community KAP Findings and Behavioral Drivers

Household survey results across 374 respondents indicated moderate overall Knowledge (41.9% correct responses) and positive Attitudes (56.1% favorable perceptions), but markedly poor protective Practices (37.4% protective actions). Only 22.5% of households reported regularly treating groundwater before drinking, and less than 18% maintained physical wellhead seals or sanitary aprons. Multiple linear regression demonstrated that Attitude ($\beta = 0.312$, $p < 0.001$), Education level ($\beta = 0.265$, $p < 0.001$), and Knowledge ($\beta = 0.243$, $p < 0.001$) were significant positive predictors of household water protection practices, explaining 28.5% of the total variance ($F(7, 366) = 20.83$, $p < 0.001$, $R^2 = 0.285$).

Composite IGHR Model Scoring and Risk Distribution

Integrating the site-wide sub-index mean values $HVRI_N$ (0.233), WQI_N (0.366), HMI_N (0.482), and $KAPI_N$ (0.438), into Equation 10 yielded a composite study mean of 0.4094; a moderate Risk category (0.401–0.600). The HMI_N sub-index represented the single largest weighted contributor (0.1687) to the composite risk score, emphasizing heavy metal contamination as the paramount toxicological threat. Across all 187 individual sampling points, the risk class distribution was: Excellent (12.8%, $n = 24$), Good (48.1%, $n = 90$), Moderate Risk (31.6%, $n = 59$), Poor (6.4%, $n = 12$), and Critical (1.1%, $n = 2$).

Overview across 19 PFSs Corridors

Table 2 provides the aggregated sub-index scores, composite IGHR values, and assigned risk status across all 19 PFSs corridors (Stations A–S).

Table 3.2: Spatial variation in IGHR across the study stations, showing the contributing component indices and the risk category assigned according to the IGHR classification scheme.

*PFS Code	N	VRI_N	WQI_{ratio}	HMI_N	$KAPI_N$	IGHR observed	Risk Category
Station A	4	0.500	1.039	0.101	0.471	0.4510	Moderate Risk
Station B	5	1.000	0.485	0.046	0.469	0.4651	Moderate Risk
Station C	1	1.000	0.429	0.034	0.480	0.4613	Moderate Risk
Station D	1	0.000	0.479	0.047	0.440	0.2157	Good
Station E	1	0.500	0.377	0.033	0.429	0.2813	Good
Station F	1	0.000	0.382	0.064	0.480	0.2120	Good

Station G	1	0.500	0.444	0.047	0.493	0.2840	Good
Station H	20	0.000	0.482	0.041	0.479	0.2134	Good
Station I	14	0.500	0.429	0.039	0.473	0.2663	Good
Station J	8	0.500	0.443	0.038	0.453	0.2671	Good
Station K	16	0.000	0.457	0.039	0.489	0.2281	Good
Station L	20	0.500	0.421	0.041	0.468	0.4616	Moderate Risk
Station M	1	0.500	0.324	0.053	0.482	0.2437	Good
Station N	15	0.000	0.809	0.089	0.469	0.2307	Good
Station O	18	0.000	0.854	0.106	0.473	0.2583	Good
Station P	22	0.500	0.407	0.046	0.476	0.2104	Good
Station Q	19	0.000	2.162	0.584	0.354	0.4800	Moderate Risk
Station R	3	0.500	0.336	0.036	0.436	0.1871	Good
Station S	17	0.000	2.296	0.540	0.337	0.5186	Moderate Risk
Mean	187	0.233	0.803	0.134	0.457	0.4094	Moderate Risk

*N = number of samples; VRIN = (vulnerability/risk index, normalized); WQIratio = (water quality index ratio); HMIN = (heavy metal index, normalized); KAPIN = (knowledge, attitude and practice index, normalized) IGHRI = Integrated Groundwater Health Risk Index.

DISCUSSION

Multi-Dimensional Risk Convergence

The findings of this study indicate that groundwater health risk in the vicinity of urban petrol filling stations (PFSs) arises from the convergence of multiple environmental hazards and dimensions of human vulnerability. Elevated risk scores (IGHRI > 0.480) were concentrated in zones where three conditions coincided: hydrogeological vulnerability, characterized by aging underground storage tanks (USTs) located hydraulically up-gradient of receptors; physicochemical degradation, evidenced by elevated indicators of petroleum hydrocarbon breakdown; and heavy metal accumulation. In these same zones, community-level behavioral protection was limited, as reflected in the proximity of water sources to contamination points, the use of unsanitary sources, and the absence of water treatment. These results highlight the need to move beyond conventional single-domain indices and adopt integrated decision-support frameworks capable of capturing the combined influence of hazard, exposure, and vulnerability.

Spatial GIS Mapping, Autocorrelation, and Topographic Controls

Spatial Autocorrelation analysis confirmed significant spatial clustering of health risk scores across the study area (Global Moran's I = 0.412, Z = 6.85, p < 0.001). Risk hotspots are geographically concentrated along major groundwater flow paths, down-gradient of PFS at higher level. Topographically, groundwater flow within the crystalline Basement Complex aquifer follows the regional gradient from northeastern highlands (142 m) to southwestern lowlands (87 m). Two key hydraulic divides Station E1 (142 m) and Station M1 (141 m) govern local contaminant transport paths. Abstraction wells located down-gradient of filling stations

along steep hydraulic gradients (e.g., Station B1, $\Delta H = 22.8$ m) experience accelerated advective transport of dissolved metals and hydrocarbons, whereas up-gradient wells near Stations K1 and R1 enjoy natural hydraulic protection.

Hotspot Analysis across PFS Corridors

Table 4.1 presents a breakdown of component sub-index scores across major spatial risk corridors, illustrating the specific environmental or human drivers in each hotspot zone.

Table 4.1: Hydrogeological risk zonation based on the Integrated Groundwater Health Risk Index (IGHRI)

Risk Zone / Corridor	HVRI _N	WQI _{ratio}	HMI _N	KAPI _N	IGHRI (Risk Category & Primary Driver)
Station B1 (Principal Discharge)	1.000	0.511	0.051	0.467	0.4940 (Moderate Risk: Driven by extreme HVRI & UST corrosion)
Stations I1–J1 (Central Corridor)	0.500	0.436	0.041	0.463	0.2667 (Good to Moderate: Hydrogeological transport along flow lines)
Station L1 (Secondary Discharge)	0.500	0.421	0.041	0.468	0.4616 (Moderate Risk: Low-lying accumulation of heavy metals)
Stations P1–Q1–S1 (Eastern Corridor)	0.250	2.162	0.584	0.345	0.4993 (Moderate to High: Co-contamination of WQI, HMI & low KAP)
Stations K1 & R1 (Up-Gradient Controls)	0.250	0.396	0.038	0.481	0.2076 (Good: Hydraulic protection; up-gradient flow away from wells)

Model Validation via Spatial ROC-AUC

To validate the predictive accuracy of the IGHR model, composite IGHRI predictions were spatial-cross-validated against USEPA Non-Carcinogenic Hazard Index (HI) scores computed across all 187 sampling sites. Receiver Operating Characteristic (ROC) curve analysis yielded an Area Under the Curve (AUC) of 0.824 (95% CI: 0.762–0.886, $p < 0.001$). This demonstrates high spatial discrimination ability in correctly classifying groundwater sources exceeding international public health hazard thresholds.

Environmental Policy and Urban Planning Setbacks

The practical value of the IGHR model lies in its capacity to translate hydrogeological and chemical datasets into actionable spatial decision-support maps for urban environmental managers and planners. Three priority interventions are proposed.

First, urban planning authorities in Abeokuta should enforce a minimum setback distance of 200 m between new PFS developments and residential groundwater abstraction wells, with particular emphasis on down-gradient flow directions.

Second, regulatory agencies, including the National Environmental Standards and Regulations Enforcement Agency (NESREA) and the Ogun State Ministry of Environment, should prioritize underground storage tank (UST) pressure testing and corrosion inspection for stations older than 15 years located in high-risk zones (A, B, L, P, Q, and S). However, the impact on nearby water sources is not confined to aged stations in High-vulnerability zones.

Some PFSs coded as Low or Medium risk also have affected water sources in their vicinity, and this may be linked to recently installed USTs that are substandard in material quality, installation, or leak-detection provisions. In addition, blasting of the basement complex hydrogeological terrain for boreholes development (exploration and exploitation) by the use of dynamites to secondary porosity, in the form of new fractures and enlarged joints, which provides preferential pathways for rapid hydrocarbon migration into the shallow aquifer irrespective of the vulnerability class assigned. Inspection and compliance enforcement should therefore extend to newly commissioned stations in Low- and Medium-risk zones, and should include verification of tank specifications, installation practices, and the excavation method used at each site.

Third, because dissolved petroleum hydrocarbons cannot be reliably removed by household-level treatment, intervention in Moderate- and High-Risk localities should prioritize exposure avoidance rather than point-of-use filtration. This should entail health education discouraging the use of affected wells for drinking and cooking; provision of alternative safe water sources, such as treated piped supply or boreholes sited up-gradient of contamination sources and constructed with adequate casing and sanitary seals; sanitary wellhead protection for water sources that remain in use; and periodic groundwater monitoring to verify water quality and track potential plume migration.

CONCLUSION

This study successfully developed, calibrated, and validated the Integrated Groundwater Health Risk (IGHR) Decision-Support Model in Abeokuta Urban, Nigeria. By synthesizing hydrogeological vulnerability (HVRI), physicochemical water quality (WQI), toxic heavy metals (HMI), and community behavioral protection (KAPI), the IGHR model provides a comprehensive multi-criteria decision-support platform for urban water security.

The overall study area achieved a composite mean score of 0.4094 (0.41), classifying local groundwater supplies as Moderate Risk under a 5-tier equal-interval threshold system. Toxic heavy metals (Lead and Cadmium) represented the largest weighted contributor to public health risk. Spatial autocorrelation (Global Moran's $I = 0.412$, $p < 0.001$) and spatial ROC-AUC validation (AUC = 0.824) confirmed that contamination risks are strongly clustered down-gradient of aging PFS. Overall, the IGHR Decision-Support Model serves as a valuable spatial planning tool for environmental regulatory agencies and environmental health authorities operating in petroleum-impacted urban environments across Nigeria.

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