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Application of 2-D Electrical Resistivity Tomography and Radiometric Techniques in Assessing Groundwater Vulnerability and Soil Contamination in Jos Mining Area, Nigeria

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ABSTRACT

Groundwater resources within mining environments are increasingly threatened by contaminant infiltration and radionuclide migration resulting from intensive mineral exploitation. This study integrates Vertical Electrical Sounding (VES), Two-Dimensional Electrical Resistivity Tomography (ERT), and radiometric techniques to assess groundwater vulnerability and soil contamination in the Rayfield mining area of Jos Plateau, North-Central Nigeria. Geoelectrical investigations were conducted to delineate subsurface lithology, identify aquifer units, and evaluate groundwater vulnerability, while radiometric analyses were performed to determine the distribution and potential hazards of naturally occurring radionuclides. The VES results revealed a seven-layer geoelectric succession characterized by an HQ-type curve, with resistivity values ranging from 20.5 to 509 Ωm. A thick fractured basement aquifer with a resistivity of 271 Ωm and thickness of approximately 36.2 m constitutes the principal groundwater reservoir. ERT imaging delineated three distinct subsurface zones comprising a conductive contaminated zone, saturated weathered materials, and consolidated lateritic-basement formations. A prominent low-resistivity anomaly (<36.5 Ωm) was interpreted as a contaminant plume associated with mining-derived leachates and radionuclide-enriched pore fluids, indicating active contaminant migration through weathered and fractured pathways. Radiometric assessment showed mean values of 88.91 Bq kg^{-1}, 279.4 μSv y^{-1}, 0.24, 0.33, and 0.17×10^{-3} for Raeq, AGED, Hex, Hin, and ELCR, respectively, all below internationally recommended limits. However, localized radionuclide enrichment was observed at specific lithological horizons. The integrated interpretation indicates moderate to high groundwater vulnerability despite favourable groundwater potential. The study demonstrates that combining geoelectrical and radiometric methods provides an effective framework for identifying contaminant migration pathways, evaluating environmental risks, and supporting sustainable groundwater management in mining environments.

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INTRODUCTION

Groundwater is one of the most important natural resources supporting domestic, agricultural, and industrial activities worldwide. It represents the largest accessible source of freshwater and plays a crucial role in sustaining human health, food production, ecosystem stability, and economic development. In many developing countries, including Nigeria, groundwater constitutes the principal source of potable water because of its generally superior microbiological quality and relatively stable availability compared with surface water resources. Water availability has historically influenced patterns of human settlement, and communities have often developed around reliable water sources. Although rivers, streams, lakes, and ponds provide significant freshwater resources, groundwater remains one of the most dependable sources due to its natural filtration through soil and rock formations (MacDonald et al., 2002). The growing global population, rapid urbanization, industrialization, and agricultural expansion have significantly increased the demand for freshwater resources. Consequently, groundwater exploitation has intensified in many regions of the world. In developing countries where surface water sources are often seasonal and unreliable, groundwater serves as a critical alternative for domestic, agricultural, and industrial uses. Alabi et al. (2010) reported that a substantial proportion of the population depends on groundwater for drinking water supply. In Jos and its surrounding communities, wells and boreholes constitute the major sources of potable water, making groundwater quality and sustainability issues of considerable importance. The quantity and quality of groundwater are strongly influenced by geological formations, hydrogeological conditions, and anthropogenic activities occurring at the surface. While groundwater is naturally protected from direct contamination compared with surface water, it remains vulnerable to pollutants introduced through land-use activities, industrial operations, agricultural practices, and mining activities. Mining activities are among the most significant anthropogenic factors capable of degrading groundwater quality. The Jos Plateau of north-central Nigeria has experienced extensive tin and columbite mining for several decades. These mining operations have generated numerous spoil heaps, mine tailings, abandoned mine ponds, and disturbed geological formations that continue to influence the environmental quality of the region. Weathering and leaching of mining residues release contaminants into surrounding soils and groundwater systems. Mining wastes often contain elevated concentrations of heavy metals and naturally occurring radioactive materials (NORMs), which can migrate through weathered and fractured geological formations into groundwater resources. Such processes increase groundwater vulnerability and pose potential environmental and public health concerns. Contamination of soils and sediments within mining environments can significantly affect groundwater quality because contaminants retained within soils may eventually migrate downward through infiltration processes. The mobility of contaminants depends on several factors, including soil mineralogy, pH, moisture content, hydraulic conductivity, and geochemical conditions. Heavy metals and radionuclides associated with mining residues can be transported through groundwater flow systems, potentially affecting drinking water supplies and ecological receptors. Naturally occurring radionuclides such as uranium (^238U), thorium (^232Th), potassium (^40K), and radium (^226Ra) are common constituents of rocks and soils. These radionuclides originate from geological materials and contribute significantly to natural background radiation. Through weathering, dissolution, erosion, and groundwater recharge processes, radionuclides may be released into soils, sediments, and aquifer systems. Soil serves as both a reservoir and a transport medium for radionuclides and therefore represents an important indicator of environmental contamination. According to Taskin et al. (2009), radionuclides are continuously redistributed through natural weathering processes and transported by rainwater and surface runoff. The concentration of radionuclides in soils depends largely on geological and geographical conditions, resulting in considerable spatial variations in environmental radioactivity (UNSCEAR, 2000). Although natural radioactivity forms part of the Earth's background radiation, elevated radionuclide concentrations can increase radiation exposure and present potential health risks to exposed populations. Radionuclides may enter the human body through ingestion, inhalation, or direct external exposure. Long-term exposure to elevated radiation levels has been associated with various adverse health effects, including increased cancer risk. Furthermore, groundwater interacting with radionuclide-bearing formations may contain measurable levels of natural radioactivity, thereby creating additional pathways for human exposure. Agbalagba et al. (2019) emphasized that radionuclides derived from geological materials and anthropogenic disturbances can constitute important sources of environmental pollution when present in elevated concentrations. The assessment of groundwater vulnerability is therefore essential for identifying areas susceptible to contaminant infiltration and for developing effective groundwater protection strategies. Geophysical techniques have become valuable tools for groundwater exploration and vulnerability assessment because they provide rapid, non-invasive, and cost-effective information on subsurface conditions. Among these techniques, Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) have been widely applied in groundwater investigations, aquifer characterization, contamination studies, and environmental monitoring. Electrical resistivity methods are particularly effective in delineating lithological variations, identifying weathered and fractured zones, mapping contaminant plumes, and evaluating aquifer protective capacity. Previous hydrogeophysical investigations have focused primarily on groundwater potential assessment, aquifer characterization, and vulnerability mapping using resistivity-derived parameters. Studies by George (2021), Khan et al. (2024), Akintorinwa et al. (2020), and Oguama (2019) successfully delineated aquifer systems and groundwater potential zones using geoelectrical parameters such as resistivity, transmissivity, hydraulic conductivity, and Dar Zarrouk indices. However, these studies largely excluded radiometric indicators and their implications for groundwater contamination and human health. Consequently, the role of naturally occurring radionuclides in groundwater vulnerability assessments remains inadequately understood. Similarly, radiometric investigations conducted by Onudibia et al. (2023), Ini et al. (2022), and Atipo et al. (2020) focused mainly on radionuclide activity concentrations, radiological hazard indices, and associated health risks. While these studies provided important information regarding environmental radioactivity, they did not evaluate the hydrogeological controls governing contaminant migration, aquifer protective capacity, or groundwater vulnerability. As a result, limited information exists regarding the relationship between subsurface geological structures, groundwater flow pathways, and radionuclide transport within mining environments. The integration of geoelectrical and radiometric techniques provides an opportunity to bridge this knowledge gap by simultaneously characterizing aquifer vulnerability and radionuclide contamination. Geoelectrical methods can identify lithological units, fracture systems, contaminant migration pathways, and aquifer protective characteristics, whereas radiometric techniques provide quantitative information on radionuclide distribution and radiological hazards. The combined application of these methods offers a more comprehensive understanding of groundwater contamination processes than either approach alone. Therefore, this study integrates Vertical Electrical Sounding (VES), Two-Dimensional Electrical Resistivity Tomography (ERT), and radiometric techniques to assess groundwater vulnerability and soil contamination within the Rayfield mining area of Jos Plateau, Nigeria. The specific objectives are to delineate subsurface lithological units and aquifer systems, identify contaminant migration pathways, evaluate groundwater vulnerability, determine radionuclide activity concentrations and radiological hazard parameters, and establish the relationship between subsurface geoelectrical characteristics and radionuclide distribution. The findings are expected to contribute to sustainable groundwater resource management and environmental protection in mining-impacted regions

MATERIALS AND METHODS

Study Area

The study was conducted in Rayfield, Jos South Local Government Area, Plateau State, Nigeria. The area lies within the Younger Granite Province of the Jos Plateau and has experienced extensive tin mining activities. Geologically, the area comprises granitic rocks, weathered overburden, fractured basement formations, and mining-derived sediments. Groundwater occurrence is controlled primarily by weathered and fractured basement aquifers.

Electrical Resistivity Tomography (ERT)

The measured resistance data collected in the field was converted to apparent resistivity values using

$$\rho a = \pi\left(\frac{\frac{AB}{2}-\frac{MN}{2}}{MN}\right)\frac{\Delta V}{I} \quad (1)$$

$$k = \pi\left(\frac{\frac{AB}{2}-\frac{MN}{2}}{MN}\right) \quad (2)$$

Where $\frac{\Delta V}{I}$ is the measured resistance and k is the geometric factor.

Two-dimensional resistivity imaging was carried out along selected traverses crossing active mining zones. Data acquisition employed a multi-electrode Schlumberger-Wenner hybrid array, using Abem Terrameter Resistivity meter (SAS 4000). The datasets were processed using RES2DINV software to generate resistivity sections showing subsurface lithological variations and potential contaminant migration pathways.

Vertical Electrical Sounding (VES)

VES surveys were conducted using the Schlumberger electrode configuration. Apparent resistivity measurements were obtained and interpreted using one-dimensional inversion techniques made possible by using IPI2WIN software. Layer resistivities, thicknesses, and depths were derived from the inversion models.

Dar Zarrouk Parameters

Computed using these relationships. Longitudinal Conductance:

$S = \Sigma(h_i/\rho_i)$ (3)

Transverse Resistance:

$T = \Sigma(h_i\rho_i)$ (4)

where:

S = longitudinal conductance (mhos)
T = transverse resistance (Ωm²)
h = layer thickness (m)
ρ = layer resistivity (Ωm)

Longitudinal conductance was used to evaluate aquifer protective capacity, while transverse resistance was used as an indicator of groundwater transmissivity.

Radiometric Survey

Soil samples were collected from locations corresponding to geoelectrically identified aquifer zones. Activity concentrations of 40K, 232Th, and 226Ra were measured using a NaI(Tl) gamma-ray spectrometer at Ahmadu Bello University Energu Centre Zaria, after appropriate sample preparation and secular equilibrium. These radiological equations were used to evaluate radiological parameters.

i. Radium Equivalent Activity Index (Ra_{eq}) : To represent the activity levels of ^{226}Ra, ^{232}Th and ^{40}K by a single quantity, which takes into account the radiation hazards associated with them, a common radiological index has been introduced (Diab et al. 2008). This index is called radium equivalent (Ra_{eq}) activity and is mathematically defined by (UNSCEAR 2000):

$$Ra_{eq} = C_{R_a} + 1.43C_{Th} + 0.077C_K \quad (5)$$

ii. The absorbed dose rates in outdoor (D) due to gamma radiations in air at 1 m above the ground surface for uniform distribution of the naturally occurring radionuclides (^{226}Ra, ^{232}Th and ^{40}K) were calculated based on guidelines provided by UNSCEAR (2000). The conversion factors used to compute absorbed ƛ-dose rate (D) in air per unit activity concentration in Bqkg^{-1} (dry weight) correspond to 0.462 ɳGh^{-1} for ^{226}Ra (of U-series), 0.621 ɳGh^{-1} for ^{232}Th and 0.0417 ɳGh^{-1} for ^{40}K (UNSCEAR 2000; Ashraf et al. 2010).

$$D = 0.462C_{R_a} + 0.621C_{Th} + 0.0417C_K \quad (6)$$

iii. Hazard Index:

Internal hazard index (H_{in}): In addition to external hazard index, radon and its short-lived products are also hazardous to the respiratory organs. The internal exposure to radon and its daughter progenies is quantified by the internal hazard index H_{in}, which is given by the equation:

$$H_{in} = \frac{C_{R_a}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} < 1 \quad (7)$$

The values of the index (H_{in}) must be less than unity for the radiation hazard to be negligible

External hazard index (H_{ex}): Another widely used hazard index (reflecting the external exposure) called the external hazard index H_{ex} is defined as follows (UNSCEAR 2000):

$$H_{ex} = \frac{C_{R_a}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} < 1 \quad (8)$$

iv. Annual Gonadal Dose Equivalent (AGDE):

The gonads, the bone marrow and the bone surface cells are considered as organs of interest by UNSCEAR (2000, 2008) and ICRP (2012) because of their sensitivity to radiation. An increase in AGDE has been known to affect the bone marrow, causing destruction of the red blood cells that are then replaced by white blood cells. This situation results in a blood cancer caused Leukamia which is fatal (Avwiri et al., 2014).

Therefore, the AGDE due to the activities of ^{226}Ra, ^{232}Th and ^{40}K in the soil of residents in a community using this environmental material (soil) is evaluated using this equation (Avwiri et al. al., 2012; UNSCEAR, 2008):

AGDE (mSv/y)= $0.314k_{At} + 3.09Ra_{At} + 4.18Th_{At}$ (9)

Where k_{At}, Ra_{At}, and Th_{At} are respectively the activity concentrations of ^{40}K, ^{226}Ra and ^{232}Th in Bq/kg for the soil samples.

v. Annual effective dose equivalent (AEDE): The annual effective dose equivalent received outdoor by the populace was estimated from the absorbed dose rate by applying dose conversion factor of 0.7 SvGy^{-1}, and the occupancy factor for outdoor as 0.2 (5/24) and indoor as 0.8 (19/24) (Veiga et al. 2006 and Ravisankar et al. 2014). The AEDEs were determined using the following expressions:

AEDE (outdoor) (µSvy^{-1}) = Absorbed dose (ηGyh^{-1}) x 8760 h x 0.7 SvGy^{-1} x 0.2 (10)

AEDE (indoor) (µSvy^{-1}) = Absorbed dose (ηGyh^{-1}) x 8760 h x 0.7 SvGy^{-1} x 0.8 (11)

vi. Excess lifetime cancer equivalent (ELCR):

ELCR = AEDE X DL X RF (12)

Where AEDE is the annual effective dose equivalent (outdoor), DL is average life span of man in Africa (estimated to be 70 years), and RF is a risk factor (Sv^{-1}), i.e., fatal cancer risk per Sievert. For stochastic effects, ICRP uses RF value of 0.05 for the public (Taskin et al. 2009).

RESULTS AND DISCUSSION

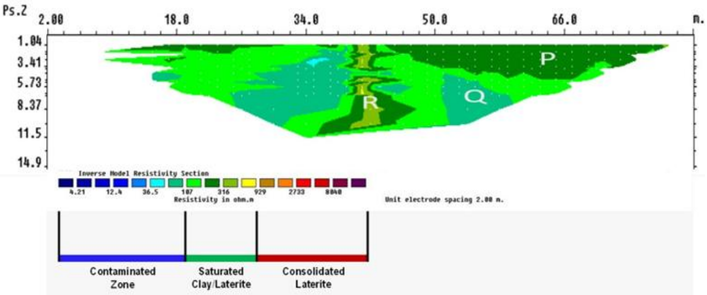

Figure 1: ERT Inverse Resistivity Section of the Rayfield Mining Area

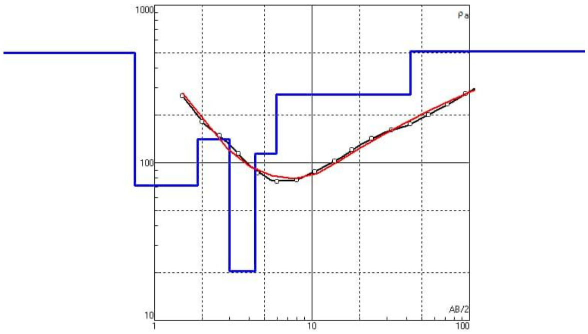

Figure 2: VES Interpretation Curve for Point P1

Table 1: Geoelectric Layer Parameters from VES Interpretation

N	ρ (Ωm)	h (m)	d (m)	Alt (m)
1	501	0.75	0.75	-0.7499
2	71.7	1.12	1.87	-1.875
3	141	1.12	2.99	-2.992
4	20.5	1.37	4.36	-4.359
5	114	1.58	5.94	-5.944
6	271	36.2	42.2	-42.17
7	509	—	—	—

Table 2: Summary of VES Geoelectrical Characteristics

Ves Point	Layer resistivity (Ωm)	Layer Depth (m)
	Curve type No. of layers	
	ρ1 ρ2 ρ3 ρ4 ρ5 ρ6 ρ7	d1 d2 d3 d4 d5 d6 d7
P1	501 71.7 141 20.5 114 271 509	0.75 1.12 1.87 2.99 4.36 5.94 42.2
HQ	7	

Table 3: Geoelectrical and Dar Zarrouk Parameters for VES Point P1

Resistivity (Ωm)	Thickness (m)	Longitudinal Conductance, S (mhos)	Transverse Resistance, T (Ωm²)
501	0.75	0.00150	375.75
71.7	1.12	0.01562	80.30
141	1.12	0.00794	157.92
20.5	1.37	0.06683	28.09
114	1.58	0.01386	180.12
271	36.20	0.13358	9810.20

Table 4: Aquifer Protective Capacity Classification

S (mhos)	Protective Capacity
>10	Excellent
5 – 10	Very Good
0.7 – 4.9	Good
0.2 – 0.69	Moderate
0.1 – 0.19	Weak
< 0.1	Poor

The cumulative longitudinal conductance of 0.23933 mhos falls within the weak to moderate protective capacity class according to the classification of aquifer protective capacity proposed by Henriet (1976):

The value of 0.23933 mhos indicates moderate aquifer protective capacity, suggesting that although some clay-rich horizons are present, the overburden is insufficiently thick to provide strong protection against contaminant infiltration.

Table 5: Depth Distribution of Natural Radionuclide Activity Concentrations in Soil

Soil Depth (m)	Activity Concentration (BqKg-1)		
	K	Th	Ra
0	161.31±2.5	21.3±5.1	22.3±2.5
1	153.45±1.4	26.3±2.3	31.4±5.3
2	103.1±5.1	29.1±2.2	41.2±4.5
3	114.6±6.2	30.1 ± 2.4	31.0±4.5
4	179.5 ±2.3	51.3±4.3	41.3± 2.3

Soil Depth (m)	Activity Concentration (BqKg-1)		
	K	Th	Ra
5	112.3±4.2	32.2±5.2	29.9±9.2
Average	137.38±32.56	31.72±10.37	32.85±7.16
World background levels	400	30	35

Table 6: Radiological Hazard Parameters

Lithological Depth (m)	Ra_{eq} ($BqKg^{-1}$)	AGED ($mSvy^{-1}$)	Hazard Indices		D (ηGyh-1)	AEDE ($mSvy^{-1}$)	ELCR X 10^{-3}	
			Hex	Hin			(Indoor)	(Outdoor)
0	65.71	203.60	0.18	0.24	29.73	0.146	0.036	0.13
1	80.59	253.80	0.22	0.29	36.66	0.180	0.045	0.16
2	90.60	285.31	0.24	0.33	41.02	0.201	0.050	0.18
3	82.90	262.38	0.22	0.30	37.59	0.184	0.046	0.16
4	128.87	403.75	0.35	0.48	58.36	0.286	0.076	0.25
5	84.81	267.54	0.23	0.31	38.36	0.188	0.047	0.16
Average	88.91	279.4	0. 24	0.33	0.29	0.198	0.049	0.17
UNSCEAR (2008), WHO (2011); IAEA (2007), OECD (1979); ICRP (2012). Taskin et. al. (2009)	≤ 370	300	≤ 1	≤ 1	59	0.41	0.07	0.29

Discussions

Interpretation and Discussion of the 2-D Electrical Resistivity Tomography (ERT) Result

The inverse resistivity model (Figure X) reveals significant lateral and vertical variations in subsurface resistivity, indicating heterogeneous geological conditions beneath the study area. The resistivity values range approximately from 4.21 Ωm to over 8840 Ωm, reflecting variations in lithology, moisture content, degree of weathering, and possible contaminant distribution.

Three major geoelectrical zones were delineated and classified as P, Q, and R based on their resistivity characteristics and hydrogeological significance.

Zone R: Contaminated Conductive Zone

Zone R occupies the central portion of the profile and is characterized by very low resistivity values ranging approximately between 4.21 and 36.5 Ωm. The conductive nature of this zone suggests the presence of highly saturated materials enriched with dissolved ions. Such low resistivity values are commonly associated with Leachate-contaminated soils, Clay-rich materials, Mine waste infiltration, Radionuclide-bearing pore fluids and Elevated concentrations of dissolved heavy metals.

The location of this conductive anomaly directly beneath the surface suggests active infiltration of contaminants from mining activities. The conductive plume extends vertically downward, indicating possible migration pathways through fractures and weathered materials. Similar conductive anomalies have been reported in contaminated mining environments where groundwater and soil have been affected by weathering of mine tailings and waste materials.

The occurrence of this low-resistivity zone strongly suggests contaminant accumulation and represents the most vulnerable section of the profile. The anomaly may also serve as a preferential pathway for the downward transport of radionuclides and other contaminants into underlying aquifer systems.

Zone Q: Saturated Clay/Lateritic Weathered Layer

Zone Q surrounds the conductive anomaly and is characterized by intermediate resistivity values approximately between 36.5 and 187 Ωm. These resistivity values are typical of Saturated clay, Clayey sand, Weathered laterite and Weathered basement materials.

The moderate resistivity indicates increased moisture content relative to the surrounding resistive materials. This zone likely represents the weathered overburden that functions as the primary groundwater storage medium in the area. This zone performs acts as a groundwater reservoir due to its relatively high porosity it also provides partial attenuation of contaminants through adsorption and ion exchange processes within clay minerals. Though prolonged exposure to contaminants originating from mining activities may gradually reduce its protective efficiency and facilitate contaminant migration toward deeper groundwater-bearing formations.

Zone P: Consolidated Lateritic and Basement Materials

Zone P occupies the upper and lateral portions of the profile and exhibits relatively high resistivity values ranging approximately between 187 and 929 Ωm, with some localized values exceeding this range. These high resistivity values indicate Consolidated lateritic materials, Competent basement rocks, Dry unsaturated formations, Relatively uncontaminated zones.

The high resistivity suggests limited pore water content and reduced ionic concentration. Consequently, these materials are less susceptible to contaminant accumulation and provide a degree of natural protection against vertical contaminant migration.

The extensive occurrence of Zone P along both flanks of the profile indicates that contamination is localized rather than regionally distributed across the entire site. The conductive anomaly (Zone R) indicates a possible contaminant plume migrating through the weathered profile. The downward extension of this anomaly suggests that contaminants may eventually reach deeper groundwater-bearing units if attenuation mechanisms become ineffective.

The surrounding weathered layer (Zone Q) likely represents the main infiltration and groundwater storage zone. Its moderate resistivity values indicate partial saturation and relatively favourable groundwater conditions. However, because this layer surrounds the contaminant plume, groundwater quality within this zone may be compromised.

The resistive basement and lateritic units (Zone P) provide some protection against contaminant migration. Nevertheless, localized fractures may still permit vertical transport of contaminants into deeper horizons.
The two-dimensional resistivity model delineated three distinct geoelectrical zones corresponding to contaminated conductive materials, saturated weathered formations, and consolidated lateritic-basement units. The central conductive anomaly, characterized by resistivity values below 36.5 Ωm, is interpreted as a contaminant plume associated with mining-derived leachates and radionuclide-enriched pore fluids. The anomaly extends vertically through the weathered profile, suggesting active contaminant migration and increased groundwater vulnerability. Intermediate resistivity zones represent saturated weathered materials that constitute the principal groundwater-bearing horizon, while the high-resistivity zones correspond to consolidated lateritic and basement formations that provide limited natural protection.
Vertical Electrical Survey (VES)

Analysis and Discussion of VES Results

The VES P1 results revealed a seven-layer subsurface sequence characterized by an HQ-type curve, indicating a heterogeneous basement complex environment influenced by weathering and fracturing processes. The subsurface consists of lateritic topsoil, clayey weathered materials, saturated clay horizons, weathered basement, fractured basement, and fresh basement. Resistivity values ranged from 20.5 Ωm to 509 Ωm, with the fresh basement occurring below 42.2 m depth.
The principal aquifer is represented by a thick fractured basement layer with a resistivity of 271 Ωm and a thickness of approximately 36.26 m, suggesting moderate to high groundwater potential. A highly conductive layer (20.5 Ωm) occurring above the aquifer is interpreted as saturated clay-rich material capable of retaining dissolved ions, radionuclides, and other mining-derived contaminants. Although the clay horizons provide some natural protection against contaminant migration, the relatively thin overburden thickness of about 5.94 m indicates only moderate aquifer protection. The ERT results, when integrated with VES and radiometric data, demonstrate that groundwater contamination within the study area is structurally controlled by weathered and fractured zones that facilitate the transport of dissolved contaminants. The findings therefore indicate moderate to high groundwater vulnerability in the mining environment and highlight the need for continuous groundwater quality monitoring and environmental remediation measures
The presence of fractures within the basement aquifer may facilitate the downward movement of contaminants from the surface. Consequently, the aquifer system is considered productive but moderately vulnerable to contamination. Integration with radiometric data suggests that radionuclides released from mining activities may migrate through the conductive weathered zone into the groundwater system, posing potential risks to groundwater quality. These findings highlight the need for continuous groundwater monitoring and sustainable management practices within the Rayfield mining area.

Dar Zarrouk Parameters and Hydrogeological Implications

The interpreted geoelectrical parameters and corresponding Dar Zarrouk parameters for VES Point P1 are presented in Table X. The calculated longitudinal conductance (S) and transverse resistance (T) provide valuable information regarding aquifer protective capacity and groundwater potential within the study area.

Radiological/Radiometrics

Radiological Hazard Assessment

The radiological hazard parameters calculated from the activity concentrations of naturally occurring radionuclides are presented in Table 6. The parameters include radium equivalent activity (Raeq), annual gonadal equivalent dose (AGED), external hazard index (Hex), internal hazard index (Hin), absorbed dose rate (D), annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR).
The calculated Raeq values ranged from 65.71 to 128.87 Bq kg^{-1}, with a mean value of 88.91 Bq kg^{-1}. These values are considerably lower than the recommended safety limit of 370 Bq kg^{-1} proposed by UNSCEAR (2008), indicating that the radionuclide content of the soils does not pose significant radiological hazards. The highest Raeq value was observed at a depth of 4 m, suggesting localized enrichment of radionuclides within that lithological horizon, possibly due to the concentration of radioactive minerals associated with mining activities.
The annual gonadal equivalent dose (AGED) varied between 203.60 and 403.75 μSv y^{-1}, with an average of 279.4 μSv y^{-1}. Although the mean value is below the recommended limit of 300 μSv y^{-1}, the value recorded at 4 m depth exceeded this threshold, indicating localized radiological enhancement. Elevated AGED values may increase radiation exposure to sensitive organs such as bone marrow and reproductive tissues if exposure is prolonged.
The calculated external hazard index (Hex) ranged from 0.18 to 0.35, with an average value of 0.24, while the internal hazard index (Hin) ranged from 0.24 to 0.48, with a mean value of 0.33. Both indices are significantly below the recommended safety limit of unity (≤1), indicating that the soils do not present appreciable external or internal radiation hazards to the public. The low Hex values suggest minimal gamma radiation exposure from the soil, whereas the low Hin values indicate negligible risk from radon inhalation and its progeny.
The absorbed dose rate (D) ranged from 29.73 to 58.36 nGy h^{-1}, with a mean value of approximately 40.29 nGy h^{-1}. This average is lower than the global average value of 59 nGy h^{-1} reported by UNSCEAR (2008), indicating relatively low environmental gamma radiation levels within the study area. The maximum dose rate recorded at 4 m depth approached the global average, further supporting the existence of localized radionuclide accumulation.
The annual effective dose equivalent (AEDE) values ranged from 0.146 to 0.286 mSv y^{-1} for indoor exposure and 0.036 to 0.076 mSv y^{-1} for outdoor exposure. The average indoor and outdoor AEDE values were 0.198 mSv y^{-1} and 0.049 mSv y^{-1}, respectively. These values are below the recommended limits of 0.41 mSv y^{-1} (indoor) and 0.07 mSv y^{-1} (outdoor), suggesting that radiation exposure to residents and mine workers remains within internationally acceptable levels.
The excess lifetime cancer risk (ELCR) values ranged from 0.13×10^{-3} to 0.25×10^{-3}, with a mean value of 0.17×10^{-3}. This average is lower than the world average reference value of 0.29×10^{-3}, indicating a relatively low probability of developing radiation-induced cancer over a lifetime due to exposure to radionuclides in the study area. However, the elevated ELCR observed at 4 m depth reflects localized radiological anomalies that may be linked to the presence of mining-derived radioactive minerals.
Overall, the radiological assessment indicates that the investigated soils are radiologically safe, as all average hazard parameters remain below the internationally recommended limits established by UNSCEAR, IAEA, OECD, WHO, and

ICRP. Nevertheless, the consistently elevated values recorded at the 4m lithological horizon suggest that mining activities have contributed to localized radionuclide enrichment. These zones warrant periodic monitoring because prolonged weathering and groundwater infiltration may facilitate radionuclide migration into underlying aquifers. The integration of these radiological findings with geoelectrical vulnerability assessments provides valuable insight into the potential pathways through which radionuclides may contaminate groundwater resources in the Jos mining environment.

CONCLUSION

The integrated application of VES, ERT, and radiometric techniques successfully characterized groundwater vulnerability and soil contamination within the Jos mining area. Results indicate that weathered and fractured basement aquifers are vulnerable to contaminant infiltration, particularly in zones affected by mining activities. Elevated radionuclide concentrations further highlight potential environmental and health concerns. The study demonstrates that integrating geoelectrical and radiometric methods provides a reliable framework for groundwater vulnerability assessment and environmental management in mining environments.

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