Geoelectric Investigation of Groundwater Vulnerability and Radiometric Assessment of Soil Contamination at an Active Mining Site in Jos, Plateau State, North-Central Nigeria

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Abstract: A two-dimensional (2D) electrical resistivity survey and radiometric assessment of soil lithology were conducted in Forest Rayfield to investigate subsurface conditions, groundwater potential, and possible groundwater vulnerability associated with geological formations and mining activities. The electrical resistivity survey was carried out along a single profile using hybrid schlumberger-wenner array configuration. Apparent resistivity data gotten from the field were iteratively converted using RES2DINV to produce 2D resistivity sections for subsurface interpretation. The interpreted resistivity model identified Zone E1 extending from the surface to a depth of approximately 12 m, with resistivity values ranging from 254 to 578 Ωm. Zone E1 therefore represents a transition zone between the weathered layer and fresh basement granite that is suitable for groundwater flow and storage. The most suitable location for groundwater development was identified at a lateral distance of 30–38 m along the profile and at depths greater than 40 m. The radiometric assessment was performed using a sodium iodide [NaI(Tl)] detector to determine the activity concentrations of naturally occurring radionuclides, namely ^40K, ^226Ra, and ^232Th. The mean activity concentrations obtained were 178.3 ± 53.39 Bqkg^{-1} for ^40K, 35.33 ± 10.26 Bqkg^{-1} for ^226Ra, and 32.26 ± 12.23 Bqkg^{-1} for ^232Th. The measured values were generally below the recommended world permissible limits, although ^226Ra showed relatively elevated values in some locations. The estimated radiological hazard parameters, including radium equivalent activity (Raeq), absorbed dose rate (D), annual gonadal equivalent dose (AGED), external hazard index (Hex), internal hazard index (Hin), annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR), were mostly below recommended safety thresholds except for absorbed dose rate, which exceeded the global average in certain areas. The results indicate that the study area is vulnerable but not contaminated, so it is favorable groundwater potential with relatively low radiological health risk to the population.

Keywords: *Radiometric Analysis; Groundwater Potential; ERT; Basement Complex; Contamination Assessment.*

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I. INTRODUCTION

Water in general is one of the most valuable natural resources on Earth, essential for human survival, and socio-economic development. Rapid population growth, and industrialization have significantly increased the global demand for safe and reliable water supplies. In many regions, surface water sources such as rivers are often seasonal and unreliable, especially during prolonged dry periods, thereby increasing dependence on groundwater resources (Macdonald et al., 2002). Groundwater, which occurs within pore spaces and fractures of subsurface geological formations, is widely regarded as a dependable source of potable water due to its relatively stable quality and natural filtration characteristics (Freeze & Cherry, 1979).

In Nigeria, groundwater is the primary source of domestic water supply, particularly in basement complex terrains where surface water cannot be guaranteed all the times. In North-Central Nigeria, including Jos, reliance on groundwater has intensified due to inadequate public water infrastructure and increasing population pressure. Communities in areas such as Rayfield forest depend largely on hand-dug wells and subsurface boreholes for daily water

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needs. Quality and sustainability of these groundwater resources are strongly influenced by degree of weathering, resistivity conductivity and structural features such as fractures, which control groundwater occurrence, movement, and vulnerability to contamination.

Rock and soils systems act as critical parameters in regulating groundwater quality. Soil acts as a natural filter, retaining and transforming organic and inorganic substances, while also serving as a medium for the migration of contaminants into aquifers (Sousa et al., 2008). Naturally occurring radionuclides such as uranium (^{238}U), thorium (^{232}Th), potassium (^{40}K), and radium (^{226}Ra) are commonly present in geological materials and can be mobilized into the soil and groundwater system through weathering and infiltration processes (UNSCEAR, 2000). The concentration and distribution of these radionuclides are largely controlled by the underlying geology and environmental conditions, and their accumulation in soil represents a key indicator of radiological contamination (Taskin et al., 2009).

Anthropogenic activities particularly mining significantly exacerbate environmental degradation more than geogenic activities. Mining is one of the most disruptive land-use practices, involving processing of mineral ores, which generate large volumes of waste materials such as tailings and overburden (Passariello et al., 2002). The Jos area in Plateau is historically known for extensive tin mining, and prolonged mining activities have resulted in widespread environmental disturbances, including altered hydrological pathways, and increased contamination and groundwater vulnerability risk.

Mine waste disposal, particularly through open dumping, enhances the infiltration of leachates into the subsurface environment, thereby posing significant threats to groundwater quality (Tordoff et al., 2000). Contaminants such as lead, cadmium, and zinc are of particular concern due to their toxicity and persistence in the environment. These elements have been associated with severe health effects, including cardiovascular, renal, and neurological disorders (Jarup, 2003). In addition, acid mine drainage and other mining-related effluents can further degrade water quality by increasing acidity and mobilizing harmful substances into aquifers (Banks et al., 1997). The impact of such contamination is often long-lasting and may persist even after mining activities have ceased.

Radiological contamination presents an additional dimension of environmental risk. Naturally occurring radioactive materials (NORMs) released during mining can accumulate in soils and subsequently migrate into groundwater systems. Exposure to elevated radiation levels, either through ingestion of contaminated water or inhalation of radon gas, poses significant health risks, including increased cancer incidence (UNSCEAR, 2000; Onudibia et al., 2023). The complexity of subsurface conditions and contamination processes, geophysical and radiometric integrated approaches are required for effective environmental assessment. Geophysical methods, particularly Electrical Resistivity Tomography (ERT), have proven effective for imaging subsurface structures and identifying aquifer zones, fractures, and potential contaminant pathways (Reynolds, 2011).

Despite the extensive mining history of the Jos Plateau, there is a lack of integrated studies that combine geoelectrical and radiometric techniques to simultaneously assess groundwater vulnerability and subsurface contamination. Most previous research focused either on groundwater exploration or radiological assessment in isolation, thereby limiting understanding of environmental conditions in mining-impacted areas.

This study uses integrated approach by combining Electrical Resistivity Tomography ERT and radiometric analysis to assess groundwater vulnerability and subsurface contamination in Rayfield, Jos, Nigeria.

➢ *Images and Graphs*

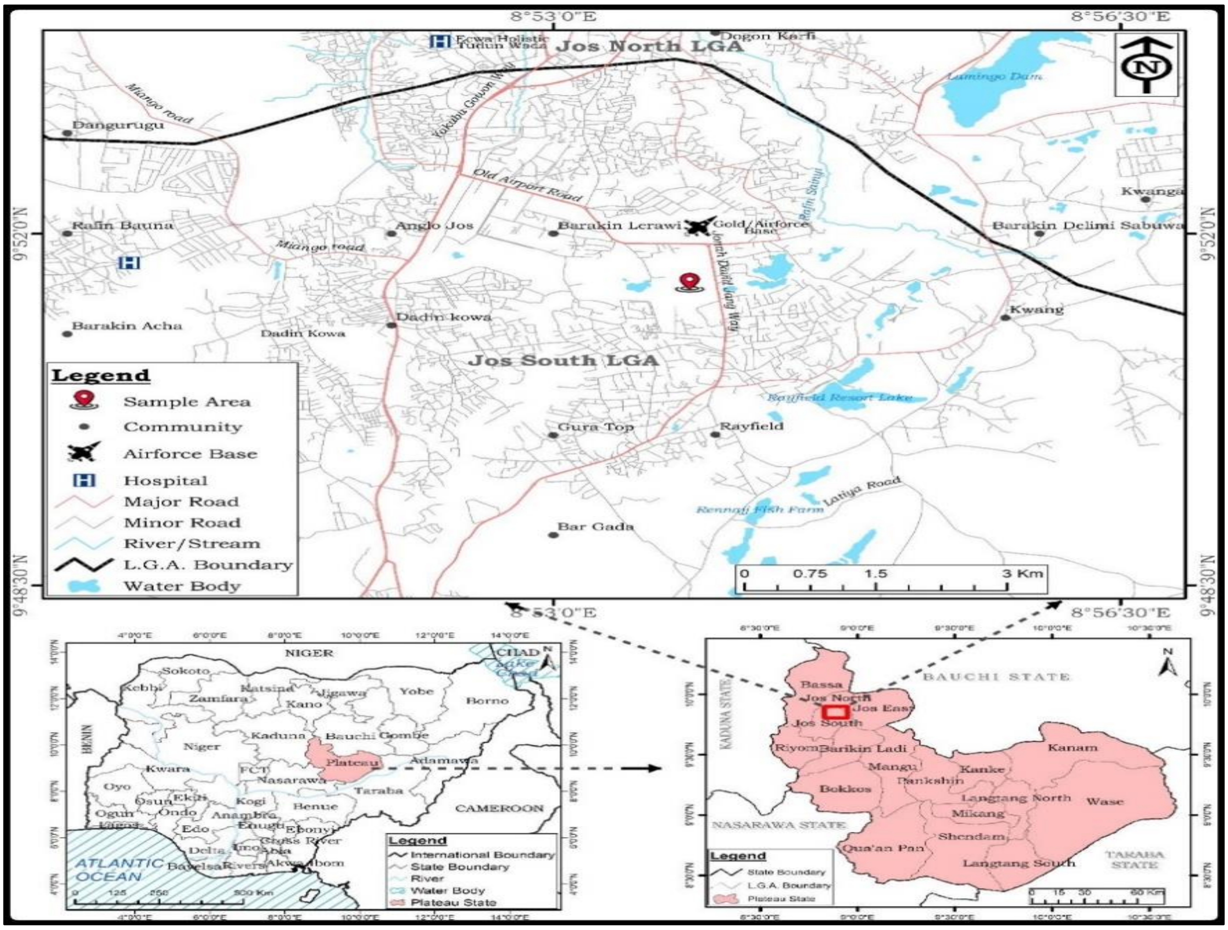

Fig 1 Location Map of Study Area

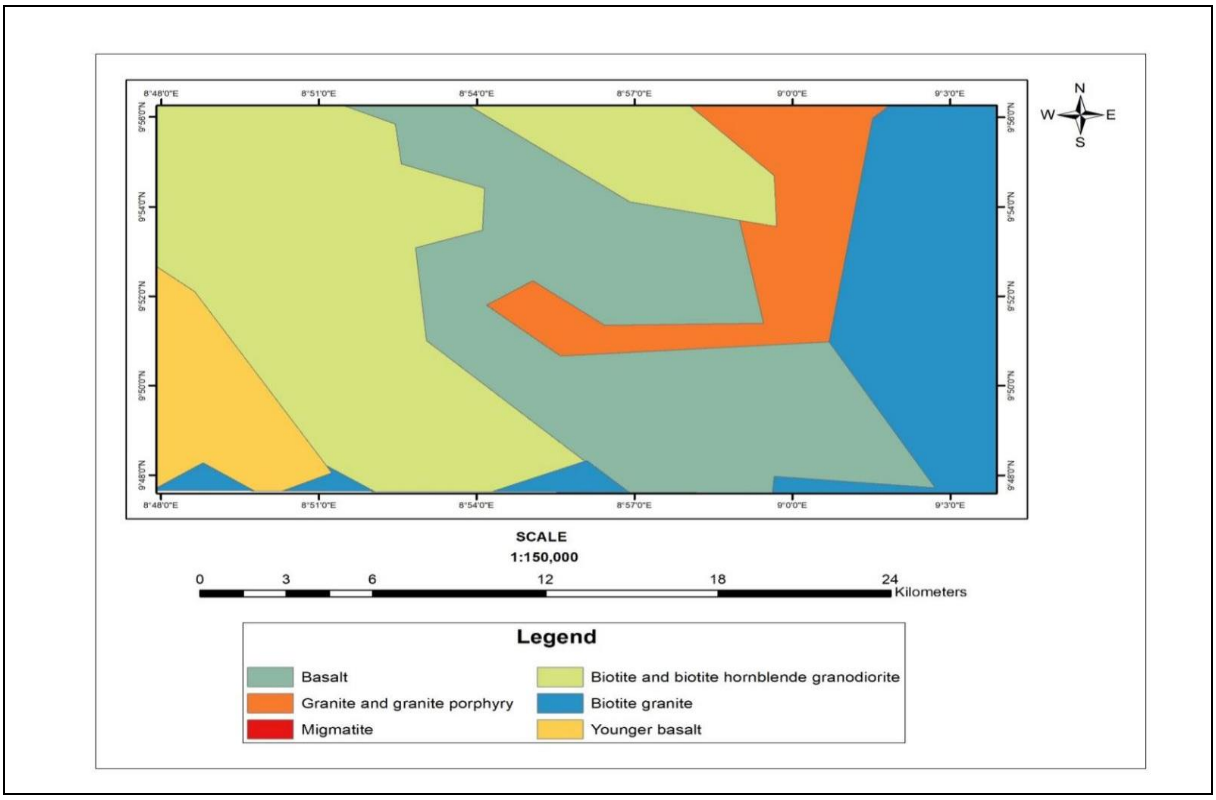

Fig 2 Geological Map of Study Area

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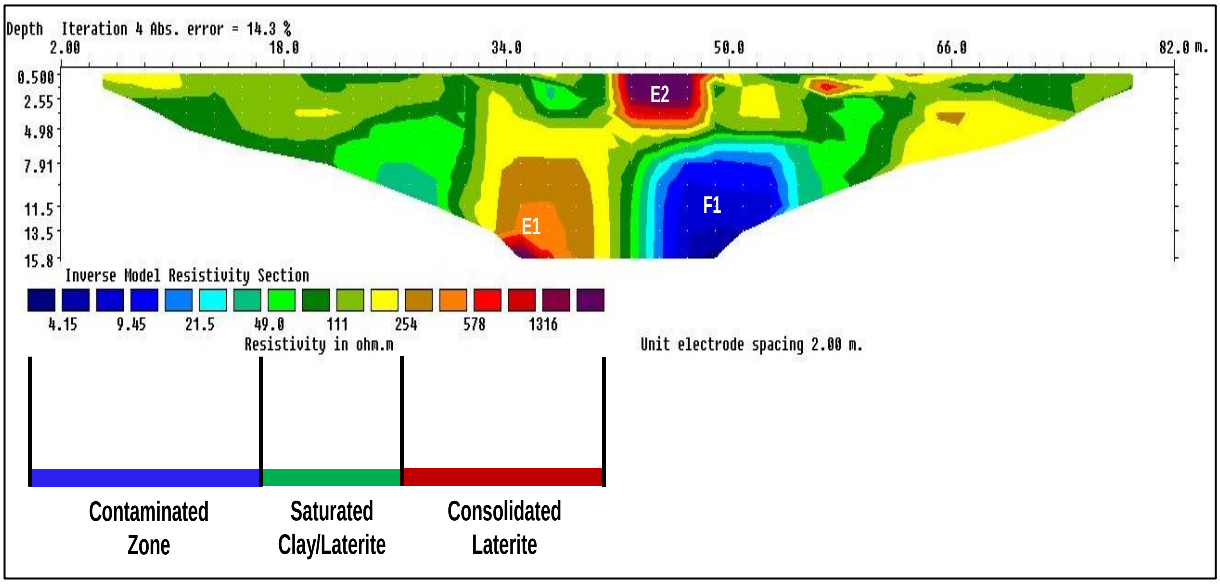

Fig 3 2D Resistivity Section Model for Study Profile

➢ *Graphs*

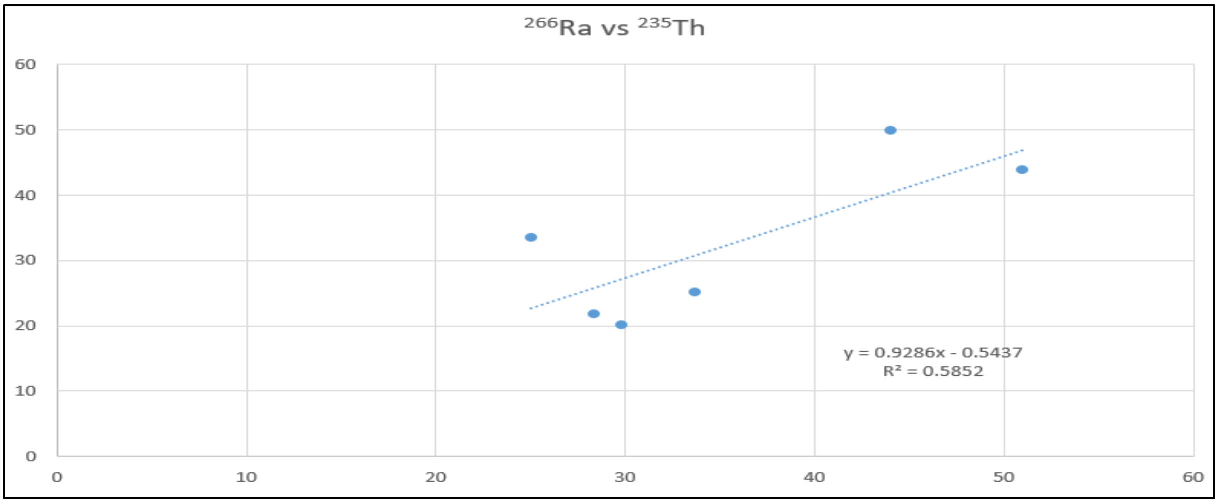

Fig 4 Linear Correlation of ^{266}Ra and ^{235Th}

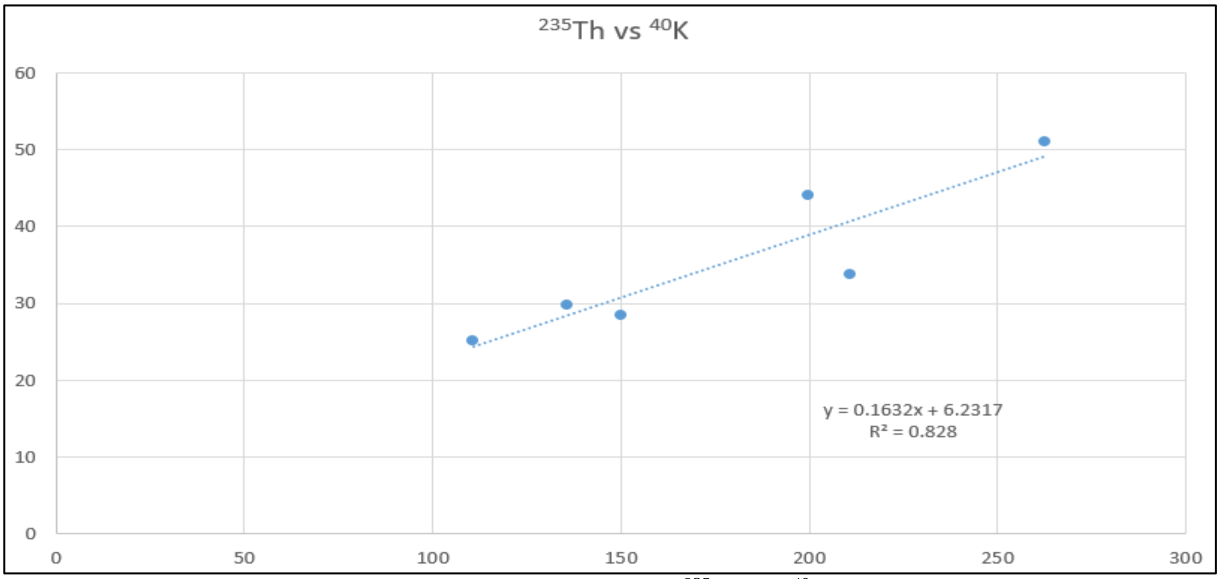

Fig 5 Linear Correlation of ^{235}Th and ^{40}K

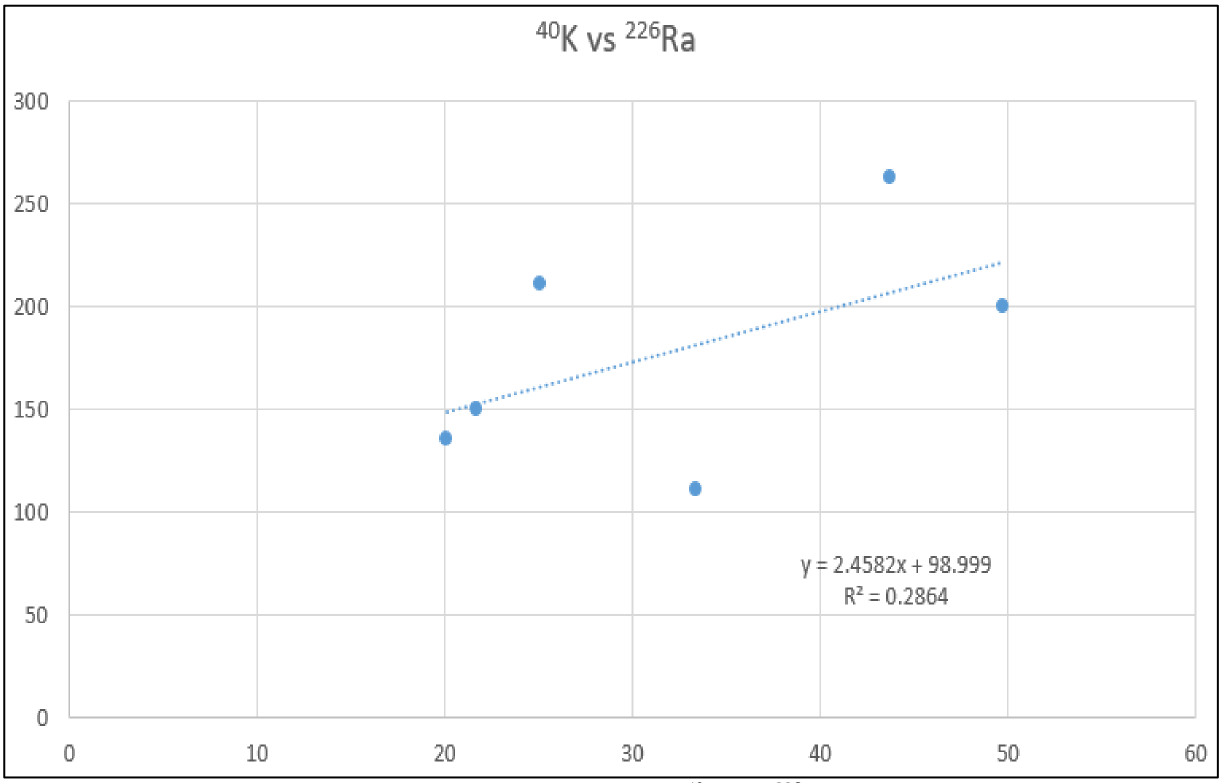

Fig 6 Linear Correlation of ^{40}K and ^{226}Ra

➢ *Study Area*

The study is carried out in Plateau: Jos South. Gold and Base Road Rayfield, Jos Plateau State. Latitude: 9.85^0 Longitude: 8.89^0. The site selection criteria is based on presence of mining activities, presence of plants on the mining sites and duration of the mining activities in the area. The study area lies within a known mineral belt, characterized by active and abandoned mine sites. Accessibility is through major roads and local paths. The mining in this area predates the independence of Nigeria. Gold was primarily the raw mineral sort after by the colonial masters in this region. The reason for the eucalyptus tree over. Figure 1 shows the location of the study area; Rayfield Jos, Nigeria.

Plateau State is renown since pre-independence period not only for the abundance of minerals endowment but also for the exploitation of ore deposits as shown in geological map in figure 2 as shown in geological map in figure 2. Local Government Areas (Bassa, Mangu, Barkin Ladi, Riyom, Bokkos and Jos North and South) are widely known for mining activities and these areas are referred to as Jos-Plateau tin fields. The study area played host to a lot of mining activities. by foreign companies which rendered the area derelict with numerous waste dumps. The numerous mounds of mine dumps and mill tailings resulting from mining activities that were carried out without consideration to the environment has led to soil, water and air pollution and loss of biodiversity. Today, hand methods by a single person or a group of people are used for mining near-surface, high grade deposit in the study area. Hence, the area was described as a “disaster area” by the Plateau State government because of its devastated landscape as a result of indiscriminate mining activities over the years, (Jaiye, 2013).

II. MATERIALS AND METHOD

➢ *2-D Electrical Resistivity Survey*

An electrical resistivity tomography (ERT) survey was carried out (Loke *et al.*, 2013; Eruteya *et al.*, 2021). One profile named ERT (80 m), was acquired over location. The ERT measurements were conducted using the Abem Terrameter resistivity meter. The survey measurements were conducted using four electrodes, two current electrodes, and two potential electrodes using the Schlumberger -Wenner electrode configuration. This configuration involves less cumbersome field procedures. It is sensitive to abrupt vertical changes in subsurface resistivity, has a moderate depth of penetration and good signal strength (Neyamadpour *et al.*, 2010; Okpoli, 2013; Omosanya *et al.*, 2014). The electrodes have fixed spacing (a) and were progressively moved along the traverse during the survey. The electrode spacing was increased sequentially to achieve a 2D measurement. For ERT the minimum and maximum electrode spacing (amax and amin) was and 50 m. Five data levels (n) were acquired for all the profiles. To account and correct for topographic variation in the measurements, the GARMIN 76S GPS was used to measure the elevation and location of each electrode on the ERT profile.

The data obtained were used to generate the resistivity models for the subsurface using the RES2DINV software (Loke, 2003). The software utilizes a forward modelling subroutine to determine the apparent resistivity values, with the inversion scheme performed using the least-squares optimization routine (Loke, 2003). The 2D model is made up of a series of rectangular cells whose size and position are fixed, although the resistivity can vary in the vertical or horizontal directions (Loke, 2011). In the analysis, the model

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width of the cells was set to half the unit electrode spacing (Dahlin *et al.*, 2002) for profiles that showed considerable resistivity variation close to the surface (Loke, 2003). Also, each data set was assessed for bad data points, which are usually characterized by relatively very high or low values of resistivity compared to surrounding data set (Loke, 2003). These points were excluded during the forward modelling. Subsequently, the finite element method (Dey and Morrison, 1979) was adopted for forward modelling to calculate the apparent resistivity. The inversion was performed with at least 5 iterations using a robust data and model inversion method, as this option gives a better model for subsurface with sharp boundaries (Neyamadpour *et al.*, 2010; Omosanya *et al.*, 2012). The inversion process aims to minimize the error between the observed and calculated apparent resistivity, which can be assessed by the root mean square (RMS) value. It is important what is actually measured by an array of current and potential electrodes.

$$\rho = \frac{2\Delta vV}{I}\frac{I}{1\left\{\left(\frac{1}{r_1}-\frac{1}{r_2}\right)-\left(\frac{1}{r_3}-\frac{1}{r_4}\right)\right\}} = \left(\frac{2\pi\Delta V}{I}\right)p \qquad \text{........... (1)}$$

Where p has to do with electrode geometry. By measuring ΔV and I and knowing the electrode configuration, we obtain a resistivity ρ. Over homogeneous isotropic ground this resistivity will be constant for any current and electrode arrangement. If the ground is inhomogeneous, however, and the electrode spacing is varied, or the spacing remains fixed while the whole array is moved, then the ratio will, in general, change. This results in a different value of ρ for each measurement. The magnitude is intimately related to the arrangement of electrodes. This measured quantity is known as the apparent resistivity ρ_a.

Wenner apparent resistivity

$$\rho_a = 2\pi a\frac{V}{I} \qquad \text{..(2)}$$

➢ *Radiometric*

- *Sample Collection*

Soil samples were collected in the same study area using soil auger sampler, digger and spade. Sample soil collected were dug at the depth of 0.3m, 0.6m, 0.9m, 1.2m, 1.5m and 1.8m. The samples were air dried for seven days to attain a constant weight. The samples were lowered into a polythene bag, labelled and transported to the laboratory for analysis. The soil samples was dried in an oven at 110^0 C. The samples was crushed, homogenised and sieved through a mesh. Each of the soil samples collected were dried and crushed to fine powder with the use of pulverizer. Packaging of the samples into radon-impermeable cylindrical plastic containers which were selected based on the space allocation of the detector vessel which measures 7.6cm by 7.6cm in dimension (geometry) was also carried out. To prevent radon-222 escaping, the packaging in each case was triple sealed. The sealing process included smearing of the inner rim of each container lid with Vaseline jelly, filling the lid assembly gap with candle wax to block the gaps between lid and container, and tight-sealing lid-container with masking adhesive tape. Radon and its short-lived progenies were allowed to reach secular radioactive equilibrium by storing the samples for 28-30 days prior to gamma spectroscopy measurements Sample soils at mine sites (Zarie and Al-Mugren 2010; Avwiri et al. 2012; Agbalagba et. al., 2019)

The background spectra measured under the same conditions for both the standard and sample measurements were used to correct the calculated sample activities concentration in accordance with the standard procedures (Nevas et al. 2002b; Arogunjo et al.2005; Avwiri et al. 2012). The activity concentration (*C*) in $Bqkg^{-1}$ of the radionuclides in the samples was calculated after decay correction was made using the expression: where Ac is the sample concentration, Np is the net peak area of a peak at energy, ε_{ff} is the efficiency of the detector for a γ-energy of interest, M_s is the sample mass, Tc is the total counting time, and γ_p is the emission probability of radionuclide of interest.

$$\boldsymbol{A_c} = \frac{\boldsymbol{N_p}}{\boldsymbol{\varepsilon_{ff}\times M_s\times T_c\times\gamma_p}}\ Bqkg^{-1} \qquad \text{... (3)}$$

➢ *Radiological Parameters from Nai(Ti) Gamma Spectrometry Results Obtained and (Compared With Standard Values*

- *Radium Equivalent Activity Index (Ra_{eq})*

Radium equivalent (Ra_{eq}) activity was defined by (UNSCEAR 2000):

$$Ra_{eq} = C_{R_a} + 1.43C_{Th} + 0.077C_K \qquad \text{..........................(4)}$$

- The absorbed dose rates in outdoor (D) was 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)

$$D = 0.462C_{R_a} + 0.621C_{Th} + 0.0417C_K \qquad \text{.....................(5)}$$

- *Hazard Index*

Internal hazard index (H_{in})

The internal exposure to radon and its daughter progenies is quantified by the internal hazard index H_{in}, which is given by the equation:

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} < 1 \qquad \text{...............................(6)}$$

The values of the index (H_{in}) must be less than unity for the radiation hazard to be negligible (Diab et al. 2008; Agbalagba and Onoja 2011)

✓ *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):

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} < 1 \quad (7)$$

- *Annual Gonadal Dose Equivalent (AGDE):*

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):

$$\text{AGDE (mSv/y)} = 0.314k_{At} + 3.09Ra_{At} + 4.18Th_{At} \quad (8)$$

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.

- *Annual Effective Dose Equivalent (AEDE)*

AEDEs were determined using the following expressions:

$$\text{AEDE (outdoor) } (\mu Svy^{-1}) = \text{Absorbed dose } (\eta Gyh^{-1}) \times 8760\text{ h} \times 0.7\text{ SvGy}^{-1} \times 0.2 \quad (9)$$

$$\text{AEDE (indoor) } (\mu Svy^{-1}) = \text{Absorbed dose } (\eta Gyh^{-1}) \times 8760\text{ h} \times 0.7\text{ SvGy}^{-1} \times 0.8 \quad (10)$$

- *Excess Lifetime Cancer Equivalent (ELCR)*

$$\text{ELCR} = \text{AEDE X DL X RF} \quad (11)$$

Where AEDE is the annual effective dose equivalent (out-door), 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).

III. RESULTS

➢ *Interpretation*

- *2D Electrical Resistivity Survey*

The Electrical resistivity survey, ERT is 82 m long, up to a depth of 15.8 m below ground level (Fig.3). The subsurface resistivity distribution on this profile includes three anomaly zones, including high resistivity anomalies designated as E1 and E2, and a low resistivity anomaly designated as F1, respectively. The E1 anomaly extends from a depth of about 6 m bgl to the base of the profile (about 15.8 m), and covers a transverse distance of about 7 m. It was encountered at the distance of 33 m to 40 m along the ground surface. The resistivity values of this anomaly is from 254 Ωm to more than 1316 Ωm. The E2 anomaly extends from the surface to a depth of about 5 m, with resistivity values ranging from 578 Ωm to over 2600 Ωm. The anomaly stretches trnsversely over a distance of about 6 m, from 42 m to 48 m on the ground surface. Below the E2 anomaly, resistivity values decrease from 254 Ωm to 21.5 Ωm. On the other hand, the F1 anomaly is a low resistivity zone that extends from 6 m bgl to the base of the profile (about 15.8 m). The resistivity values of this anomaly ranges from 21.5 Ωm to less than 4.15 Ωm. The anomaly extends laterally over a distance of 9 m, from 45 m to 54 m on the ground surface. The resistivity values of this anomaly is from 21.5 Ωm to less than 4.15 Ωm. The anomaly extends laterally over some distance of about 9 m, from 45 m to 54 m on the ground surface. The observed anomalies in the ERT profile 3 represent three geoelectric layers, including consolidated laterites (254 Ωm to 1316 Ωm), saturated clay/laterite (49.0 Ωm to 254 Ωm), saturated clay-rich layers (< 21.5 Ωm).

The resistivity model for the subsurface beneath ERT (Fig. 3) revealed that resistivity increased with depth. Along the profile, high resistivity were observed on the top soil, at the surface distance of 41 m to 50 m. Another zone of high resistivity was observed between the horizontal distance of 33 m to 40 m along the profile. This high resistivity anomaly extended from a depth of 7.8 m to the base of the profile. It is possible that the anomaly comes from a near-surface intrusive body or a highly resistive consolidated lateritic layer. The reduction in resistivity values observed at the right side of the ERT profile 2, which extended from the approximate depth of 6 m to the base of the model, could be indicative of contaminated groundwater due to mining activities in the area. From the ERT model, it could be observed that higher resistivity ranges of 49 Ωm to 1316 Ωm occurred more frequently than lower resistivity ranges of 4.15 Ωm to 21.5 Ωm. The high resistivity values at the top soil beneath this profile could be due to increased compaction and cementation due to anthropogenic (human) activities in the area.

Zone E2 (Very High Resistivity) with a depth of 1–4 m and Resistivity >1000 Ωm

This might be Fresh is a granitic outcrop**,** Pegmatitic or mineralized intrusion**,** Concentrated mine tailings**.** Granitic rocks often host uranium and thorium bearing minerals or ores.

Zone E1 (Moderate–High Resistivity) with a depth of 12 m, the resistivity is 254–578 Ωm**.** This is a weathered granite core, Structural block or dyke and a reduced permeability compared to surroundings. The Moderate resistivity indicates (Water-filled joints) located below weathered zone. This zone is a very good recharge support. It is a transition between weathered and fresh granite. E1 is in a transition zone ideal for groundwater flow. The Best groundwater development to drill is lateral distance of 30-38 m and depth of 18-20 m.

Zone F1 (Very Low Resistivity), has a depth of 6–14 m and Resistivity of 4–21 Ωm.

This is the most environmentally significant feature. Low resistivity at this depth in granite terrain strongly reflects, Saturated fractured basement, ionic concentration groundwater, Clay alteration products, and possible radionuclide bearing plume. The depth interval (6–14 m) reflects to the main fractured basement aquifer.

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Table 1 Activity Concentration of Study Area

Soil Depth (m)	Activity Concentration (BqKg^{-1}) (±SD)		
	K	Th	Ra
0.3	150.24±1.30	28.40±1.34	21.70±4.30
0.6	262.00±4.30	51.01±2.30	43.71±3.30
0.9	110.71±2.30	25.05±4.40	33.37±4.30
1.2	211.00±2.40	33.70±2.20	25.03±5.30
1.5	135.00±2.50	29.80±5.30	20.07±5.10
1.8	199.00±5.30	44.01±3.30	49.70±5.10
Average	**178.30±10.26**	**35.33±10.26**	**32.26±12.23**
World	**400**	**30**	**35**

Table 2 Radium Equivalent and Summary of Calculated Radiation Hazard Indices.

Lithological Depth (m)	Ra_{eq} (BqKg^{-1})	AGED (mSvy^{-1})	Hazard Indices		D (ηGyh-1)	AEDE (mSvy^{-1})		ELCR X 10^{-3}
			H_{ex}	H_{in}		(Indoor)	(Outdoor)	
0.3	74.500	248.69	0.20	0.24	35.63	0.175	0.044	0.15
0.6	148.71	502.54	0.40	0.47	71.42	0.350	0.088	0.31
0.9	76.290	259.42	0.21	0.26	37.01	0.181	0.045	0.16
1.2	89.700	298.45	0.24	0.29	43.08	0.211	0.053	0.19
1.5	72.350	239.60	0.20	0.23	34.44	0.169	0.042	0.15
1.8	127.46	433.57	0.34	0.41	61.45	0.301	0.075	0.26
Average	**98.17**	**330.38**	**0.27**	**0.32**	**47.17**	**0.231**	**0.058**	**0.20**
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**

IV. DISCUSSION

^{40}K average value of 178.3 BqKg^{-1} is lower than the permissible standard value of 400BqKg^{-1}. This value for K is twice higher than the value for profile 1. K, is depleted in this soil samples compared to the world permissive values, probably as a result of bad rock weathering that occurs in the area. ^{232}Th average value of 35.33 BqKg^{-1} is high than the permissible standard value of 30 BqKg^{-1}. This suggests granitic/mining influence. ^{226}Ra value of 32.26 BqKg^{-1} is lower than the recommended or permissive limit of 35 BqKg^{-1}. The activity concentration of K, Th and Ra values in this area is lower than the values reported by Masok et al (2015). In their finding in same Rayfield area of Jos, Th, Ra and K was reported to have values 351.4±20.1, 132.6±21.4 and 319.6±37.7 respectively. (UNSCEAR 2008)

The average values of (Ra_{eq}), exhibits acceptable values compare with permissible safety standards. Ra_{eq} average values is 98.17 BqKg^{-1} which is well below the

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safety threshold of 370. This value is higher than the mean value of 56.9 $BqKg^{-1}$ reported by Agbalagba et. al (2019) in Geophysical survey of groundwater potential and radioactivity assessment of soil depth lithology for drinking water-quality determination (Agbalagba et. al 2019; OECD 1979; IAEA 2007).

The estimated Absorbed dose rate D(ηGyh^{-1}) values ranging from 34.44 to 71.42 ηGyh^{-1} with a mean value of 47.17 ηGyh^{-1} ; is below the recommended limit of 59 ηGyh^{-1} . (UNSEAR 2008)

All Hazard indice averages; External (H_{ex}) 0.27 and Internal (H_{in}) 0.32 due to the presence of ^{226}Ra, ^{232}Th and ^{40}K is less than unity. (H_{ex}) is 0.27 and Internal (H_{in}) was 0.32; These values are less than 1, which are well below the accepted limit. (OECD 1979; IAEA 2007).

The obtained estimated values for annual gonadal dose equivalent (AGED) ranged from 239.60 to 502.54 $mSvy^{-1}$ with an average value of 330.38 $mSvy^{-1}$; this is above the recommended world permissible value of 300 $mSvy^{-1}$ (Taskin et al. 2009). The values obtained is higher than the average values 189.3 $mSvy^{-1}$ obtained by Agbalagba et. al (2018) in Geophysical survey of groundwater potential and radioactivity assessment of soil depth lithology for drinking water-quality determination, but lower that the values 530 $mSvy^{-1}$ obtained by Onudibia et. al (2023). This elevated values of AGED indicates that the gonadal values may pose some threat to Genetic cells (sperm & ova) even Hereditary mutation risk. The danger might not be immediate but the result indicates increased long-term genetic risk to those living or exploring withing this profile.

The estimated (ELCR) Excess lifetime cancer risk is values ranging from 0.15 x 10^{-3} to 0.26 x 10^{-3} with a mean of 0.20 x 10^{-3} slighly below the recommended permissible safety limit of 0.29 x 10^{-3}. The excess lifetime cancer risk (ELCR) values remain within acceptable radiological limits (Agbalagba 2018; ICRP 2012; WH0 2011)

The computed average annual effective dose rate (AEDE) for indoor is 0.58 $mSvy^{-1}$, the recommended safety limit is 0.41 $mSvy^{-1}$. This source is possibly from radioactive soil or building materials, and may pose moderate radiological health risk over long-term exposure. Outdoor value is 0.231 $mSvy^{-1}$; 0.07 $mSvy^{-1}$ is the recommended safety limit. This elevated values might indicates mining activities. Both indoor and outdoor AEDE values are above recommended limits, This suggests, radiological contamination or enrichment, increased lifetime cancer risk (ELCR). (UNSCEAR 2008; ICRP 2012; Onudibia et al. 2023).

The profile shows non-uniform vertical distribution assessing the result depth by depth, this indicates subsurface radionuclide accumulation likely due to mineralization zone and leaching and migration processes. The total mean values indicate that the study area remains radiologically safe, as almost all hazard indices are below recommended limits, despite localized enrichment. The radiological risk parameters assessed review none of the radiological parameters value is significant to pose any immediate health challenge to the populace within this soil profile nor cause any immediate radiological health-related sickness to those drinking water from the hand-dug well or borehole.

The AGED value slightly exceeds the recommended threshold, but the overall radiological risk remains low. This suggests minimal health risk to the population area. Continuous monitoring is recommended due to possible localized radionuclide accumulation associated with geological formations and mining activities.

- *Regression Analysis*

To identify the extent of dependence and relationship that exist among these 3 natural radioactive nuclides within the soil investigated, correlation analysis were performed between the radionuclides (^{40}K, ^{232}Th), (^{40}K ^{226}Ra) and (^{226}Ra,^{232}Th).

Figure 4 is a linear correlation of ^{235}Th and ^{266}Ra which is y = 0.9286x - 0.5437, with a regression value of R^2 = 0.5852. This indicates a clear relationship exists between the two radionuclides. This reveals a moderately strong correlation between the activities of the two radionuclides. 58% (percent) of the variation in Ra is explained by Th. The two radionuclides might be from same source of materia.

Figure 5 reveals a linear correlation of ^{235}Th and ^{40}K which is y = 0.1632x + 6.2317, with a regression value of R^2 = 0.828. This indicates a good and clear relationship exists between the two radionuclides. This is a very strong correlation between the activities of the two radionuclides. Since R^2 is very close to 1, Th is controlled by K alone. About 83% (percent) of the variation in K is explained by Th. The remaining 17% (percent) is due to other factors. Other contributors might include, Uranium decay series, Soil redistribution processes and Mining disturbances

Figure 6 shows the regression analysis between ^{40}K and ^{226}Ra yielded the equation y = 2.4582x + 98.999, with R^2 = 0.2864, indicating a weak positive linear relationship. 29% (percent) of the variation in radium is explained by potassium, suggesting that potassium has a limited influence on radium distribution in the study area. K has limited influence on Ra distribution. The relationship is weak. Ra is likely controlled by Thorium (Th), Uranium decay series, geological variability and Mining disturbance

The integrated Electrical Resistivity Tomography (ERT) and Radiometric results provide an understanding of the subsurface conditions and environmental status of the study area in Rayfield, Jos. The geophysical section reveal a heterogeneous subsurface characterized by contrasting resistivity zones, which are strongly influenced by lithology, weathering intensity, structural deformation, and anthropogenic activities, particularly mining. The high resistivity (E1 and E2), with values exceeding 254 Ωm and locally reaching over 1300 Ωm, are interpreted as consolidated lateritic cover, fresh basement rock, and possible intrusive or mineralized bodies. The presence of high

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resistivity in Zone E2 suggests relatively fresh or compact geological material, possibly granitic or pegmatitic in nature. Such formations are often associated with low permeability and limited groundwater storage. Their association with mineralized intrusions also raises the possibility of naturally enhanced radiogenic mineral content. Zone E1 represents a moderate to high resistivity transition zone, interpreted as a weathered basement or fractured rock. This zone is particularly relevant hydrogeologically, as it represents a potential aquifer horizon where fractures enhance secondary porosity and groundwater flow. The lateral continuity of this zone points to a structurally controlled pathway favorable for groundwater accumulation and movement. In contrast, the low resistivity Zone F1 is the most hydrogeologically and environmentally significant feature. It is a saturated fractured basement zone, likely enriched with clay alteration products and conductive fluids. The extremely low resistivity suggest high ionic concentration, which may be associated with contaminant migration or leachate/plume infiltration from mining activities. This zone might be a major groundwater pathway and is highly vulnerable to contamination.

The radiometric results indicate moderate variability in radionuclide concentrations across the study area. The mean activity concentrations of ^{40}K, ^{232}Th, and ^{226}Ra remain largely within or slightly above global average values (UNSCEAR, 2008), reflecting the influence of granitic basement rocks and possible mining-related redistribution of radionuclides. The elevated Th, content in particular suggests lithological control and possible enrichment from mineralized zones.

Radiological hazard indices, including radium equivalent activity (Raeq), external hazard index (Hex), and internal hazard index (Hin), are below internationally accepted safety limits, indicating that the area is generally radiologically safe for habitation and groundwater use. However, the elevated Annual Gonadal Dose Equivalent (AGED), which exceeds the permissive threshold, suggests potential long-term genetic and reproductive health risks associated with prolonged exposure to naturally enhanced radiation fields. The evaluated Annual Effective Dose Equivalent (AEDE) values for both indoor and outdoor exposure exceed recommended global limits, indicating that radiation exposure in the area may be influenced by both geological materials and anthropogenic activities, particularly mining and soil disturbance. Although the Excess Lifetime Cancer Risk values remain within acceptable limits, the presence of localized radiological enrichment highlights the need for continued and regular environmental monitoring. Correlation and regression analyses among K, Th, and Ra showed weak to moderate relationships, indicating that radionuclide distribution is controlled by several geological and environmental factors rather than a single source.

V. SUMMARY

This study applied an integrated Electrical Resistivity Tomography and radiometric approach to evaluate groundwater vulnerability and contamination in Rayfield, Jos. The ERT results identified three subsurface units: high resistivity zones interpreted as consolidated laterite and fresh basement rock (E2), moderate resistivity fractured and weathered zones with groundwater potential (E1), and low resistivity saturated fractured zones (F1) interpreted as main aquifer and potential contamination pathway. The integration of ERT and radiometric data clearly demonstrates that subsurface geological structures strongly control both groundwater and radionuclide distribution. Fractured zones not only serve as groundwater pathways but may act as channels for contaminant and radionuclide migration, especially in mining-impacted environments. This reflects the importance of combined geophysical and radiological investigations for comprehensive environmental assessment.

The Radiometric analysis revealed the presence of naturally occurring radionuclides (^{40}K, ^{232}Th, and ^{226}Ra) with generally moderate activity concentrations. Radiological hazard parameters, including Raeq, Hex, Hin, and ELCR, were within permissible limits, indicating overall radiological safety. Although elevated AGED and AEDE values suggest localized radiological enhancement likely influenced by geological formations and mining activities. The integration of geoelectrical and radiometric datasets provided a comprehensive understanding of subsurface conditions than either method alone, revealing both groundwater potential zones and areas of environmental concern.

VI. CONCLUSION

The integrated geophysical and radiometric investigation of Rayfield, Jos, has successfully mapped subsurface geological structures, groundwater potential zones, and radiological conditions associated with mining activities. The work recommends best drill depth for hand dug well to bore holes depth to be more or equal to 40 meters Overall, while the study area remains generally safe from an immediate radiological health perspective, continuous and regular monitoring is recommended due to evidence of localized contamination and elevated dose indices. The findings has provided an important baseline data for groundwater management, environmental protection, and sustainable land use planning in mining-impacted regions.

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