



Radiological assessment of ^{40}K , ^{238}U and ^{232}Th from soil and groundwater in Port Harcourt Metropolis, Rivers State, Nigeria

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Abstract

Environmental contamination by naturally occurring radionuclides is a growing concern in urban-industrial regions, where both geological processes and human activities can increase radiation exposure risks. Port Harcourt Metropolis, Nigeria, a major petroleum hub, faces potential contamination challenges in soil and groundwater, but comprehensive assessments remain limited. This study investigated the concentrations of ^{40}K , ^{232}Th , and ^{238}U in soil and groundwater samples collected from residential, industrial, and natural zones. High-resolution NaI(Tl) gamma-ray spectrometry was employed to determine activity concentrations and assess radiological health risks. Soil concentrations ranged from 153.98 - 434.53 Bq/kg (^{40}K), 16.01 - 38.84 Bq/kg (^{232}Th), and 6.01 - 15.07 Bq/kg (^{238}U), while groundwater values ranged from 15.09 - 46.72 Bq/L (^{40}K), 1.71 - 5.20 Bq/L (^{232}Th), and 1.26 - 5.94 Bq/L (^{238}U), respectively. Several groundwater samples exceeded World Health Organization (WHO) guideline limits, indicating possible chronic exposure risks. Radiological hazard indices showed spatial variability, with Rukpawurushi New Area consistently recording higher values. The results suggest both geogenic and anthropogenic contributions, particularly from petroleum-related activities. Elevated radionuclide levels highlight potential risks through ingestion, inhalation, and external exposure, with implications for public health and aquatic food chains. The findings of this study are expected to inform environmental monitoring, guide policy interventions, and support sustainable public health management in Nigeria's oil-producing regions.

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1.0 Introduction

Naturally occurring radioactive materials (NORMs), including uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K), are present in soils, rocks, and groundwater worldwide, contributing to background radiation (Agbo et al., 2023; Ndoma et al., 2024). While largely geogenic in origin, their concentrations can be elevated by human activities such as oil and gas production, mining, and waste disposal (Adesina et al., 2025; Ndoma et al., 2023; Ndoma et al., 2025). Chronic exposure to ionizing radiation, whether through ingestion, inhalation, or external contact, is associated with cancer, hereditary disorders, and organ damage (Ndoma et al., 2024, 2025; Okon et al., 2025). To protect human health, the International Commission on Radiological Protection (ICRP, 1991) recommends that public exposure should not exceed 1 mSv/year above the natural background. In many developing regions, including Nigeria, inadequate monitoring of radionuclide levels has raised concerns about potential risks that remain poorly characterized.

Port Harcourt Metropolis, the capital of Rivers State in Nigeria's Niger Delta, represents one such high-risk setting. The area hosts extensive petroleum exploration, refining, and associated industrial activity, alongside rapid urbanization and population growth. These processes contribute to multiple pathways for radionuclide contamination, particularly given the city's reliance on shallow groundwater for drinking and domestic uses. Previous studies in the Niger Delta (Akinfolarin et al., 2018; Avwiri et al., 2007, 2014; Farai et al., 2008) have reported radionuclide enrichment in either soils or water bodies. However, most investigations were medium-specific and did not incorporate radiological hazard indices, leaving a knowledge gap in assessing cumulative exposure risks across environmental compartments. This study

addresses this gap by providing an integrated assessment of radionuclide concentrations in both soil and groundwater within Port Harcourt Metropolis. Specifically, the activity concentrations of ^{40}K , ^{232}Th , and ^{238}U were determined using high-resolution NaI(Tl) gamma-ray spectrometry. From these values, key radiological hazard indices, including the external hazard index (H_I), radium equivalent activity (R_{eq}), absorbed dose rate (D_{out}), annual effective dose (AED), annual gonadal equivalent dose (AGED), and excess lifetime cancer risk (ELCR), were calculated to evaluate human health risks. Results were benchmarked against international guidelines from (ICRP, 1991; UNSCEAR, 2010) and WHO (2004) to assess the level of compliance with recommended exposure limits.

Port Harcourt, the study lies on the Bonny River within the Niger Delta sedimentary basin and is characterized by low-lying terrain, coastal plain sands, and a tropical monsoonal climate that enhances radionuclide mobility through runoff and groundwater recharge. These environmental conditions, combined with the city's dependence on groundwater and proximity to industrial discharges, increase the likelihood of population exposure. By linking environmental radioactivity data with hazard assessment, this research provides one of the first comprehensive evaluations of multi-pathway radionuclide risks in Port Harcourt Metropolis. The findings are expected to inform environmental monitoring, guide policy interventions, and support sustainable public health management in Nigeria's oil-producing regions.

2.0 Materials and Methods**2.1 Sampling Materials and Equipment**

The following materials were employed for sampling, preparation, and analysis: clean plastic containers were employed for soil

samples; pre-rinsed 750 mL and 1 L plastic bottles for water samples; shovels and hand trowels for soil sample collection; a ruler for depth measurements; masking tape for sample labelling; a 0.45 μm mesh filter for removing suspended solids; and a GPS-enabled smartphone for recording sampling locations.

2.2 Study Area

The Trans-Amadi Industrial area in Port Harcourt, including the Mini-Okoro/Oginigba Creek, formed the primary study area. Port Harcourt is situated on the Bonny River in the Niger Delta region, approximately 468 m above sea level, between latitudes 4.698° N and 4.836° N, and longitudes 6.912° E and 7.074° E. The terrain features gentle NW–SE slopes (3–5°) contributing to poor drainage, low relief, and slow river flow. The coastal plain belongs to the Niger Delta sedimentary formation (Adegoke et al., 2017). The geographic location of Port Harcourt Metropolis within Nigeria, its position in Rivers State, and the specific boundaries of the study area are illustrated in Figure 1.

The climate is tropical monsoonal, characterized by a short dry season, a pronounced wet season, and average monthly temperatures above 18 °C (Onyekwelu et al., 2023). Vegetation types include mangrove forests and coastal vegetation (dominant), freshwater swamps, and lowland rainforest (Igu, 2016). The area is underlain by Niger Delta sedimentary formations consisting mainly of fluvial sediments from the Niger River and other regional waterways. These deposits transition from freshwater to brackish conditions, influencing both soil fertility and settlement patterns. Over 60% of the city's topsoil is low in fertility (Folorunsho & Awosika, 2014). The Trans-Amadi area hosts sawmills, the Shell Petroleum Development Company, Pabod Breweries, Nigerian Bottling Company, Schlumberger, and various oil service firms. Discharges from breweries and the now-inactive Michelin Tyre company have contributed to creek pollution. Other activities include boat building, welding, metallurgy,

abattoirs, block moulding (using stream sand), fuel stations, electrical substations, and direct disposal of household waste into waterways (Akinfolarin et al., 2018).

2.3 Sampling Strategy

Ten locations across the Local Government Areas (LGAs) of Port Harcourt Metropolis were purposively selected based on three criteria, namely: residential areas, flowing rivers, which could directly affect local communities and Industrial zones with high activity levels. A total of 20 samples were collected (10 soil samples and 10 groundwater samples). The exact GPS coordinates of all soil and groundwater sampling points are presented in Figure 1, providing a spatial reference for subsequent analysis. The soil samples were taken from industrial, residential, and natural zones, while groundwater was obtained from wells, boreholes, and surface water sources.

2.4 Sample collection and preparation

2.4.1 Soil Samples

Soil sampling sites were selected to represent the industrial, residential, and natural zones of Port Harcourt Metropolis, while deliberately avoiding contamination sources such as highways, commercial facilities, and known oil spill sites. Samples were collected at depths of 0–5 cm, 10–15 cm, and 15–20 cm to assess the vertical distribution of radioactivity. Stainless steel augers were employed to avoid contamination from sampling tools. At each site, triplicate samples were collected to ensure quality assurance. The samples were air-dried at room temperature, sieved to a grain size of ≤ 2 mm to remove debris, and homogenized before being sealed in labelled polyethene containers. Samples were stored for 28 days to allow for radon equilibrium, following IAEA recommendations.

2.4.2 Groundwater Samples

Groundwater sampling sites were chosen to represent variations in geology, industrial impact, and depth. Groundwater sources

employed in this study included wells, boreholes, and surface water. Boreholes were flushed by pumping for 15 minutes before sampling to ensure fresh groundwater collection. Glass bottles were employed for sample storage, filled slowly to prevent radon degassing, and checked to ensure airtight sealing. Samples were

filtered to remove organic matter and suspended particles, then mixed with hydrochloric acid (HCl) immediately to acidify the water and prevent radionuclides from sticking to the walls of the containers. Samples were kept in cold, dark conditions during transport to minimize chemical changes.

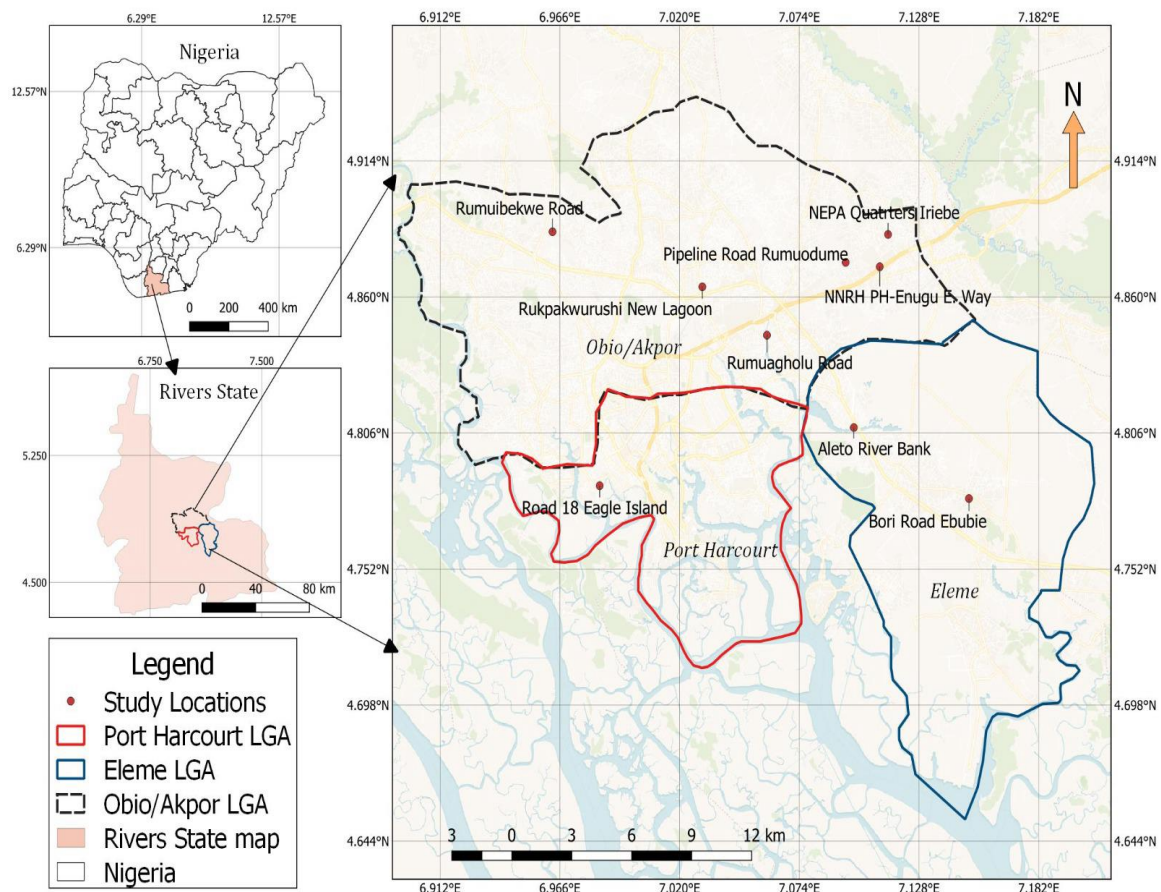


Figure 1: Location maps showing (a) Nigeria, (b) Rivers State, and (c) the study area/sampling points within Port Harcourt Metropolis

2.5 Measurement and instrumentation

2.5.1 Gamma-Ray Spectrometry

Gamma-ray spectrometry was employed due to its high sensitivity, non-destructive analysis, and suitability for quantifying gamma-emitting radionuclides in environmental samples. This method allows the identification and quantification of ^{40}K , ^{232}Th (via ^{228}Ac , ^{212}Pb , ^{208}Tl), and ^{238}U (via ^{226}Ra , ^{214}Pb , ^{214}Bi). A sodium iodide detector doped with thallium [NaI(Tl)] was employed due to its high detection efficiency for medium–high energy gamma rays, lower cost compared to HPGe detectors, and

faster data acquisition; advantages that make it ideal for environmental monitoring. The arrangement of the gamma spectrometry set-up, including detector shielding, sample positioning, and counting system, is shown in Figure 2. Before measurements, an empty container was counted for 36,000 s to determine the background gamma-ray distribution. Sealed samples, after reaching secular equilibrium, were placed on the detector and counted for the same duration as the background measurement. The photo-peaks used for analysis were: 1460.0 keV (^{40}K), 295.3 keV (^{214}Pb) and 1764.5 keV

(^{214}Bi) for ^{238}U and 238.6 keV (^{212}Pb), 911.1 keV (^{228}Ac), and 2614.7 keV (^{208}Tl) for ^{232}Th .

2.5.2 Activity Concentration Calculation

The activity concentration A of each radionuclide was calculated using equation 1:

$$A = \frac{C_{\text{net}}}{P_{\gamma} \times \epsilon \times m \times t} \quad (1)$$

where: A = activity concentration of the radionuclide (Bq/L, Bq/kg); C_{net} = net count rate (counts per second), P_{γ} = gamma ray emission probability of the identified radionuclide, ϵ = detector efficiency (fraction of emitted gamma photons detected), m = mass of the sample (kg), t = measurement time (seconds).



Figure 2: Gamma spectrometry set-up

3.0 Radiological Hazards Indices

Radiological hazard indices are essential for evaluating and quantifying radiation risks to human health and the environment. In this study, six indices were calculated from the measured activity concentrations of ^{40}K , ^{232}Th , and ^{238}U in soil and groundwater samples. These indices provide an integrated assessment of external, internal, and long-term radiation hazards.

3.1 External Hazard Index

The external hazard index (H_{ext}) estimates the potential gamma radiation hazard to the public from natural radionuclides in soil. It is calculated using Equation 2, adapted from UNSCEAR (2000):

$$H_{\text{ext}} = \frac{A_U}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (2)$$

where A_U , A_{th} , and A_K are the activity concentrations of ^{238}U , ^{232}Th , and ^{40}K (Bq/kg), respectively. The denominators represent the activity levels producing a gamma dose of 1

mSv/year. For radiological safety $H_{\text{ext}} \leq 1$ (UNSCEAR 2000).

3.2 Radium Equivalent Activity Index

The radium equivalent activity index (Ra_{eq}) combines the activity concentrations of ^{238}U , ^{232}Th , and ^{40}K into a single value representing the gamma output from each radionuclide (Banik et al., 2021). It is calculated using Equation 3:

$$Ra_{\text{eq}} = A_U + 1.43A_{Th} + 0.077A_K \quad (3)$$

For safety, $Ra_{\text{eq}} \leq 370$ Bq/kg, corresponding to an external gamma dose rate of approximately 1.5 mSv/year (UNSCEAR, 2000).

3.3 Annual Effective Dose (AED)

The AED estimates the annual radiation dose to an individual from gamma radiation in the environment (UNSCEAR, 2000). It is calculated using Equation 4:

$$AED = Ra_{\text{eq}} \times 0.7 \times 10^{-6} \times 8760 \times 0.7 \quad (4)$$

where 0.7 Sv/Gy = dose conversion factor; 10^{-6} = unit conversion from nGy to mSv; 8760 = hours per year and 0.7 = occupancy factor (70% indoors).

3.4 Outdoor Absorbed Dose Rate (D_{out})

The outdoor absorbed dose rate (D_{out}) measures the gamma radiation dose absorbed in air at 1 m above the ground. It is calculated using Equation 5:

$$D_{out} = 0.462A_U + 0.604A_{Th} + 0.0417A_K \quad (5)$$

The global average outdoor dose rate is about 55 nGy/h (UNSCEAR, 2010).

3.5 Annual Gonadal Equivalent Dose (AGED)

The AGED estimates the annual radiation dose to reproductive organs, bone marrow, and bone surfaces from natural gamma radiation (Ndoma et al., 2025; Satyanarayana et al., 2023). It is calculated using Equation 6:

$$AGED = 3.09A_U + 4.18A_{Th} + 0.314A_K \quad (6)$$

Values of AGED above the safety limit of 300 $\mu\text{Sv/year}$ may cause genetic mutations and increase leukemia risk (Senthilkumar et al., 2010).

3.6 Excess Lifetime Cancer Risk (ELCR)

The ELCR estimates the probability of developing cancer over a lifetime due to exposure to ionizing radiation (Isinkaye et al., 2018). It is estimated by using Equation 7.

$$ELCR = AED_{out} \times DL \times RF \quad (7)$$

where AED_{out} = Outdoor annual effective dose; DL = Duration of Life (70 years); RF = Risk Factor (0.05 Sv^{-1}). An ELCR value greater than 0.0001 (1 in 10,000) may be considered significant (Mohammed & Ahmed, 2017). The ELCR is crucial in health risk evaluations for populations living in areas with high background radiation.

4.0 Results

4.1 Radioactivity Measurement of Soil and Groundwater

4.1.1 Soil Samples

The measured activity concentrations of ^{40}K , ^{238}U , and ^{232}Th in soil samples from the ten selected sites are summarized in Table 1. The corresponding radiological hazard indices calculated from these concentrations are provided in Table 2.

Table 1: Measured activity concentrations of ^{40}K , ^{238}U , and ^{232}Th in soil samples from Port Harcourt Metropolis

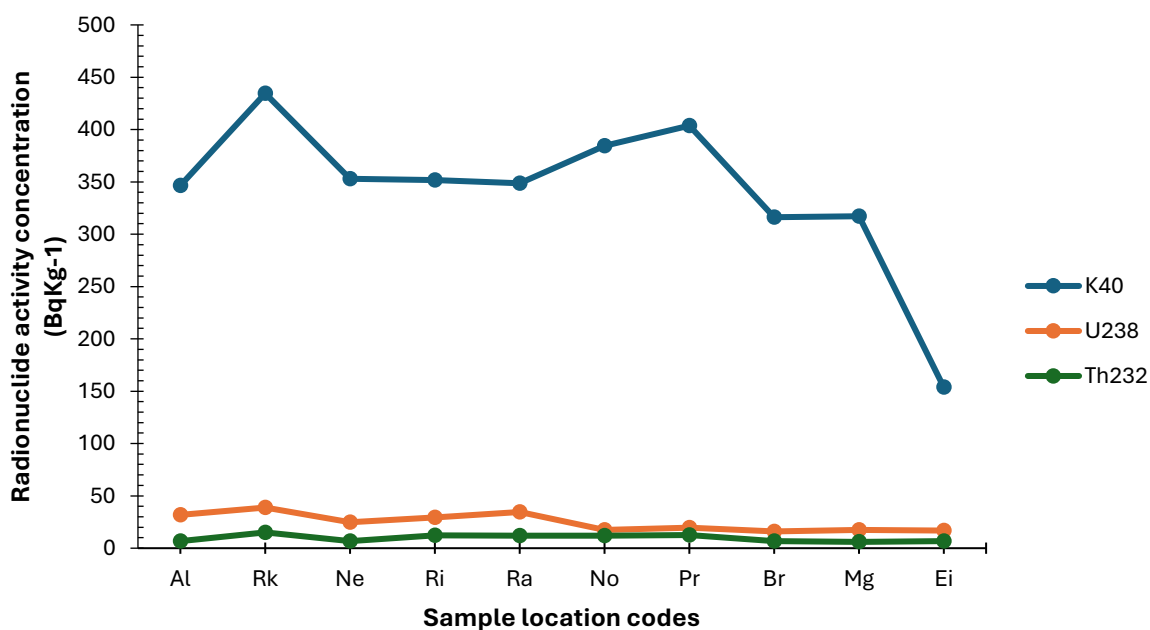
Sample Locations	Sample Codes	^{40}K (Bqkg $^{-1}$)	^{238}U (Bqkg $^{-1}$)	^{232}Th (Bqkg $^{-1}$)
Aleto River Bank	Al	346.63 ± 5.90	31.91 ± 2.17	6.78 ± 1.05
Rukpakwurushi New Area	Rk	434.53 ± 14.35	38.84 ± 0.65	15.07 ± 0.95
NEPA Quarters Iriebe	Ne	352.86 ± 6.40	24.64 ± 2.41	6.82 ± 1.05
Rumuibekwe Road	Ri	351.65 ± 12.18	29.28 ± 0.56	12.18 ± 0.85
Rumuaghorlu Road	Ra	348.70 ± 12.44	34.50 ± 0.51	11.94 ± 0.84
NNRA Office PH-Enugu Exp way	No	384.59 ± 11.15	17.33 ± 0.65	12.08 ± 0.95
Pipeline Road Rumuodume Obio/Akpor	Pr	403.61 ± 9.88	19.46 ± 0.68	12.51 ± 0.97
Bori Road Ebubie Eleme	Br	316.35 ± 7.81	16.01 ± 0.42	6.74 ± 0.71
Change Ogun Street, Mgbuodhia	Mg	317.28 ± 5.23	17.31 ± 0.44	6.01 ± 0.67
Road 18 Eagle Island	Ei	153.98 ± 4.95	16.79 ± 0.43	6.65 ± 0.70

Table 2: Calculated radiological hazard indices for soil samples from Port Harcourt Metropolis

Sample Locations	H_{ext}	D_{out} $nGyh^{-1}$	AED $mSvy^{-1}$	AGED $mSvy^{-1}$	ELCR $\times 10^{-3}$	Ra_{eq} $Bqkg^{-1}$
Aleto River Bank	0.18	33.29	0.04	0.24	0.14	68.30
Rukpakwurushi New Area	0.25	45.17	0.06	0.32	0.19	93.85
NEPA Quarters Iriebe	0.17	30.22	0.04	0.22	0.13	61.56
Rumuibekwe Road	0.20	35.55	0.04	0.25	0.15	73.77
Rumuaghorlu Road	0.21	37.69	0.05	0.27	0.16	78.42
NNRA Office PH-Enugu Exp way	0.17	31.34	0.04	0.22	0.13	64.22
Pipeline Road Rumuodume Obio/Akpor	0.18	33.38	0.04	0.24	0.14	68.43
Bori Road Ebubie Eleme	0.14	24.66	0.03	0.18	0.11	50.01
Change Ogun Street, Mgbuodhia	0.14	24.86	0.03	0.18	0.11	50.33
Road 18 Eagle Island	0.10	18.19	0.02	0.13	0.08	38.16

To visualize the spatial variations in the measured activity concentrations, the distribution of radionuclide concentrations across the ten soil sampling locations is shown in Figure 3. This figure facilitates comparison of relative radionuclide enrichment at each site. The results indicate that ^{40}K concentrations were highest at Rukpakwurushi New Area (434.53

Bq/kg) and lowest at Eagle Island (153.98 Bq/kg). ^{238}U concentrations peaked at Rukpakwurushi New Area (38.84 Bq/kg) and were lowest at Bori Road Ebubie Eleme (16.01 Bq/kg). ^{232}Th concentrations were highest at Rukpakwurushi New Area (15.07 Bq/kg) and lowest at Mgbuodhia (6.01 Bq/kg).

**Figure 3:** Activity concentrations of ^{40}K , ^{238}U , and ^{232}Th in soil samples from different locations within Port Harcourt Metropolis

4.2.2 Groundwater Samples

The measured activity concentrations of ^{40}K , ^{238}U , and ^{232}Th in groundwater are summarized in Table 3, with the calculated hazard indices

shown in Table 4. The Spatial differences are illustrated in Figure 4, which compares radionuclide concentrations across the ten water sampling points.

Table 3: Measured activity concentrations of ^{40}K , ^{238}U , and ^{232}Th in groundwater samples from Port Harcourt Metropolis

Sample Location	Sample Codes	^{40}K (Bq/l)	^{238}U (Bq/l)	^{232}Th (Bq/l)
Aleto River	Ar	28.95 ± 1.73	3.66 ± 0.12	1.68 ± 0.04
Rukpakwurushi New Area	Rk	46.72 ± 2.49	5.20 ± 0.11	1.26 ± 0.15
NEPA Quatres Iriebe	Ne	32.70 ± 2.73	3.75 ± 0.12	5.74 ± 0.12
Woji River Rumuibekwe	Wr	38.26 ± 1.99	1.99 ± 0.05	2.98 ± 0.09
Rumuaghorlu Road	Ra	15.09 ± 0.64	3.97 ± 0.11	3.98 ± 0.08
NNRA Office PH-Enugu Exp way	No	28.46 ± 1.66	2.64 ± 0.19	2.45 ± 0.11
Pipeline Road	Pr	23.91 ± 1.21	3.29 ± 0.09	5.94 ± 0.09
Rumuodume Obio/Akpor	Br	30.62 ± 1.84	5.20 ± 0.13	2.46 ± 0.08
Abuluoma Road Alode Eleme	Mg	19.99 ± 1.30	4.64 ± 0.12	3.88 ± 0.04
Mgbuodohia River Iwofe PH	Ei	32.07 ± 1.65	1.71 ± 0.04	1.95 ± 0.07

Table 4: Calculated radiological hazard indices for groundwater samples from Port Harcourt Metropolis

Sample Locations	H_{ext}	D_{out} $n\text{Gy}\text{h}^{-1}$	AED mSvy^{-1}	$AGED$ mSvy^{-1}	$ELCR$ $\times 10^{-3}$	Ra_{eq} Bq/l
Aleto River	0.02	3.91	0.00	0.03	0.02	8.29
Rukpakwurushi New Area	0.03	5.11	0.01	0.04	0.02	10.60
NEPA Quatres Iriebe	0.04	6.56	0.01	0.05	0.03	14.48
Woji River	0.02	4.31	0.01	0.03	0.02	9.20
Rumuibekwe	0.03	4.87	0.01	0.03	0.02	10.82
Rumuaghorlu Road	0.02	3.89	0.00	0.03	0.02	8.33
NNRA Office PH-Enugu Exp way	0.04	6.10	0.01	0.04	0.03	13.63
Pipeline Road	0.03	5.17	0.01	0.04	0.02	11.08
Rumuodume	0.03	5.32	0.01	0.04	0.02	11.73
Obio/Akpor	0.02	3.31	0.00	0.02	0.01	6.97
Abuluoma Road Alode Eleme						
Mgbuodohia River						
Iwofe PH						
Eagle Island River						

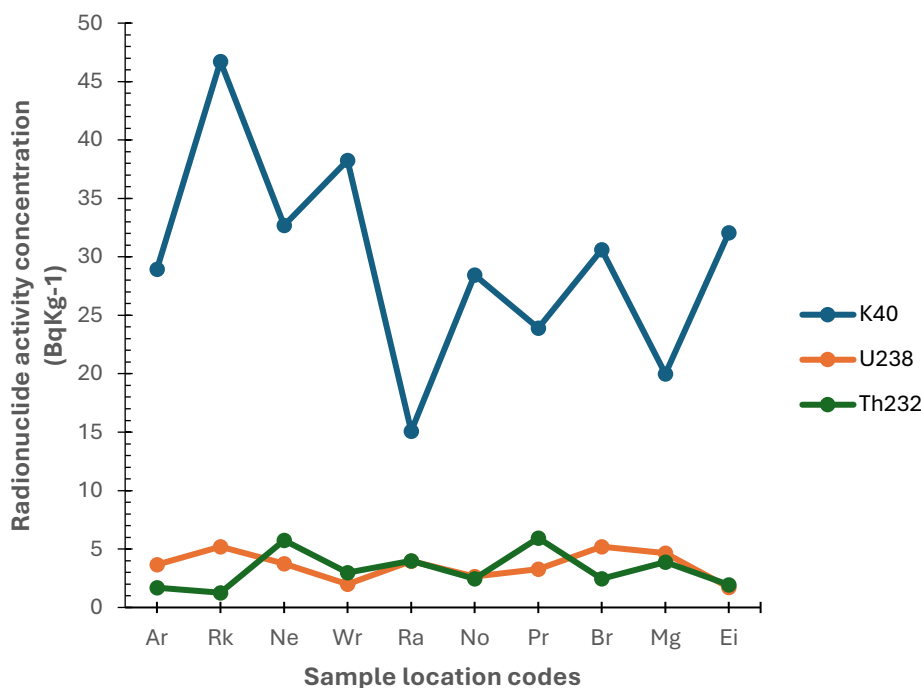


Figure 4: Activity concentrations of ^{40}K , ^{238}U , and ^{232}Th in groundwater samples from different locations within Port Harcourt Metropolis

Similarly, ^{40}K concentrations were observed to be highest in Rukpakwurushi New Area (46.72 Bq/L) and lowest in Rumuaghorlu Road (15.09 Bq/L). ^{238}U concentrations recorded maximum concentrations of 5.20 Bq/L in Rukpakwurushi New Area and Abuluoma Road Alode Eleme, with the lowest in Eagle Island River (1.71 Bq/L). ^{232}Th concentrations were highest in Pipeline Road Rumuodume Obio/Akpor (5.94 Bq/L) and lowest in Rukpakwurushi New Area (1.26 Bq/L).

4.3 Statistical Summary of Results

Summary statistics for the activity concentrations of natural radionuclides in soil and groundwater are presented in Tables 5 and 6, respectively. These tables show minimum, maximum, range, mean, standard deviation, and coefficient of variation (CV) values, allowing an assessment of spatial variability.

5.0 Discussion

5.1 Soil Radionuclide Concentration

The concentrations of ^{40}K , ^{232}Th , and ^{238}U in soil samples (Table 1, Figure 3) show noticeable spatial variability across Port Harcourt Metropolis. ^{40}K concentrations ranged from

153.98 to 434.53 Bq/kg, with a mean value of 341.02 Bq/kg, slightly below the UNSCEAR (2010) global average of 400 Bq/kg, but still elevated in certain hotspots. The coefficient of variation (CV) for ^{40}K was 21%, suggesting moderate variability, possibly influenced by agricultural practices and industrial discharges. Comparable values have been reported by Manisa et al. (2021) and Mbonu et al. (2021). ^{232}Th concentrations (16.01–38.84 Bq/kg, mean = 24.61 Bq/kg) were within the range observed in previous Niger Delta studies (Agbalagba et al., 2012; Avwiri *et al.*, 2014; Mbonu *et al.*, 2021) but with a relatively high CV of 32.6%, pointing to both geological influences and anthropogenic inputs. Similar spatial heterogeneity was noted by Ekong et al. (2021) and Farai et al. (2008). ^{238}U concentrations (6.01–15.07 Bq/kg, mean = 9.68 Bq/kg) were below the UNSCEAR (2010) global average of 35 Bq/kg. However, the high CV (33%) indicates localized uranium enrichment, likely related to oil exploration activities that mobilize deep geological materials. Avwiri *et al.* (2014) recorded comparable values in similar environments.

Table 5: Statistical summary of measured activity concentrations of ^{40}K , ^{238}U , and ^{232}Th in soil samples from Port Harcourt Metropolis

Measures	^{40}K (Bqkg ⁻¹)	^{238}U (Bqkg ⁻¹)	^{232}Th (Bqkg ⁻¹)
Min.	153.98	16.01	6.01
Max.	434.53	38.84	15.07
Range	280.55	22.83	9.06
Sum	3410.18	246.07	96.78
Mean	341.02	24.61	9.678
SD	71.46	8.02	3.19
CV	20.95	32.60	33.01

Table 6: Statistical summary of measured activity concentrations of ^{40}K , ^{238}U , and ^{232}Th in groundwater samples from Port Harcourt Metropolis

Measures	^{40}K (Bq/l)	^{238}U (Bq/l)	^{232}Th (Bq/l)
Min.	15.09	1.71	1.26
Max.	46.72	5.2	5.94
Range	31.63	3.49	4.68
Sum	296.77	36.05	32.32
Mean	29.68	3.605	3.232
SD	8.50	1.16	1.54
CV	28.63	32.29	47.75

5.2 Groundwater Radionuclide Concentrations

Groundwater radionuclide concentrations (Table 3, Figure 4) exceeded WHO guideline values for ^{232}Th and ^{238}U in all locations, and for ^{40}K in several locations. ^{40}K concentrations ranged from 15.09 to 46.72 Bq/L (mean: 29.68 Bq/L), exceeding typical safe limits and indicating significant contamination sources, possibly linked to industrial effluent and leaching from fertilised soils. ^{232}Th concentrations ranged from 1.71 to 5.20 Bq/L (mean: 3.61 Bq/L), far above the WHO limit of 0.1 Bq/L. This pattern suggests leaching from both natural mineral deposits and industrial waste sites, consistent with findings by Purnama and Damayanti (2020). ^{238}U concentrations ranged from 1.26 to 5.94 Bq/L (mean: 3.23 Bq/L), significantly exceeding the WHO limit of 0.1 Bq/L. The highest levels were observed near petroleum and

industrial zones, in agreement with Esan *et al.* (2022).

5.3 Radiological Hazard Assessment

The calculated hazard indices for soil (Table 2) show that most values fall within international safety limits, although Rukpakwurushi New Area recorded elevated readings that deserve closer attention. The external hazard index (Hext) ranged from 0.10 to 0.25, which is below the recommended safe limit of 1, though the highest values were observed at industrial hotspots. Similarly, the radium equivalent activity (Raeq) remained below the safety threshold of 370 Bq/kg, but its spatial distribution followed the same trend as Hext, reflecting common contamination drivers. The outdoor absorbed dose rate (Dout) ranged between 18.19 and 45.17 nGy/h, which falls within the (UNSCEAR 2010) reference range of

18 - 93 nGy/h. However, the annual gonadal equivalent dose (AGED) exceeded the global average of 0.30 mSv/year at some locations, especially in Rukpakwurushi New Area, highlighting potential hereditary risks. The excess lifetime cancer risk (ELCR) for soil ranged from 0.08% to 0.19%, values that are close to the upper acceptable limit recommended by UNSCEAR (2010).

For groundwater (Table 4), most hazard indices also remained within safety limits, but elevated values were observed in NEPA Quarters Iriebe. This suggests localized contamination that could contribute to long-term health risks if exposure persists. Continuous monitoring and detailed source-tracing are therefore necessary to better understand and mitigate the risks associated with groundwater in the affected areas.

5.4 Statistical Variability and Hotspot Analysis

Statistical summaries (Tables 5 and 6) confirm greater variability in groundwater radionuclide levels than in soils, with CV values up to 47.7% for ^{238}U in water. This suggests highly localized contamination sources, likely linked to industrial discharges and poor waste management. Identified hotspots include Rukpakwurushi New Area (both soil and groundwater), Pipeline Road Rumuodume (water), and NEPA Quarters Iriebe (water), which should be prioritized for monitoring and remediation.

5.5 Environmental and Health Implications

Elevated radionuclide concentrations in soil can disrupt nutrient cycling, including reducing soil fertility, and increase the likelihood of radionuclide uptake by crops, leading to food-chain contamination. Leafy vegetables and root crops are particularly susceptible (Avwiri et al., 2007). In groundwater, chronic ingestion of ^{238}U and ^{232}Th can cause kidney damage and skeletal problems before cancer risks manifest (Arcones et al., 2017). Given that many residents rely on untreated groundwater, this poses an immediate public health concern. Bioaccumulation in

aquatic species can also impact fisheries, reducing the availability of safe food in the region.

5.6 Integrated Risk Considerations

The simultaneous presence of radionuclides in soil and water increases exposure through ingestion, inhalation of contaminated dust, and dermal contact. This multi-pathway exposure necessitates integrated risk assessments rather than evaluating each medium in isolation. Spatial patterns also highlight environmental justice concerns: if hotspots coincide with low-income residential areas, these communities may face higher exposure with fewer mitigation options.

6.0 Conclusion

This study presented an integrated soil and groundwater assessment of naturally occurring radionuclides (^{40}K , ^{232}Th , and ^{238}U) in Port Harcourt Metropolis, Nigeria's oil hub, using gamma-ray spectrometry. While soil concentrations were mostly below UNSCEAR (2010) global averages, groundwater frequently exceeded WHO (2004) limits for ^{232}Th and ^{238}U , with elevated ^{40}K suggesting industrial and petroleum-related inputs. Although hazard indices were generally within safe ranges, exceedances of AGED and ELCR in some areas indicate potential long-term health risks. The integrated approach highlights the need for routine monitoring, safe water interventions in hotspot zones, and stricter industrial compliance to mitigate radiological exposure.

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