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Radiological contamination in drinking water of resource extraction regions in Southern Nigeria: Public health implications in the framework of SDG 6

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Abstract

Extraction of natural resources increases radiological stressors in the environment, resulting in human exposure to various health risks. This study was carried out to monitor radiological contaminants in drinking water from crude oil and mining environments in Southern Nigeria. It evaluated radiological indices, including the annual effective dose for different age groups and the excess lifetime cancer risk (ELCR). The assessment was carried out using gamma spectroscopy with a sodium iodide NaI(Tl) detector to measure radionuclides such as ^{40}K, ^{238}U and ^{232}Th. The excess lifetime cancer risk found evaluated surpassed the International Committee on Radiological Protection's cancer risk threshold of 1.0×10^{-3}. This suggests that consumption of water by residents in this region of southern Nigeria may be associated with an increased likelihood of developing long-term carcinogenic risk. The elevated ELCR indicate potential risks to drinking water safety and public health. This finding directly aligns with Sustainable Development Goal (SDG 6) particularly target 6.1, which seeks universal and equitable access to safe and affordable drinking water for all. This underscores the critical need for continuous monitoring of drinking water to protect public health.

Keywords: Radioactivity, Natural resources, Drinking water, public health, Cancer risk, SDG 6

1. Introduction

Exposure to radiological stressors is a significant pathway for water contamination, particularly in mining environments (Akpanowo et al., 2021; Wang et al., 2025; Zhang et al., 2014). Surface water may be contaminated by groundwater or rainwater runoff through the transport or leaching of contaminants from mining environments, drilling sites, waste deposits, soil weathering, and farming practices (Tran et al., 2019). When water bodies are not monitored or managed, this may lead to different health challenges to humans (Boelee et al., 2019). The Sustainable Development Goals (SDG 6) campaign, set by the United Nations, has focused on health promotion by mandating the provision of and access to potable and safe water in developing countries. In Nigeria, it has been reported that over 66 million residents are deprived access to drinking water from safe sources such as piped water or protected dug wells and instead source their water through streams or rainwater (Ayandiran et al., 2018). According to, Nigeria's National Oil Spill Detection and Response Agency (NOSDRA) recorded in every single year, at least a total of 822 oil spills, releasing 28,003 barrels of oil into the environment, which directly and indirectly impacted water bodies in the southwest region of Nigeria (Omokaro et al., 2025).

Access to clean and safe water is a major menace battling most developing countries especially with various health concerns associated by polluted water in resource extraction region (Nwinyi et al., 2020). Clean and safe water utilised for drinking has become a major Sustainable Development Goal of the United Nation for the 2030 agenda. However, unregulated and unmonitored depletion and exploration of natural resources in Southern Nigeria may hinder this goal if groundwater and surface water are not adequately monitored (Akindipe et al., 2025). In Southern Nigeria, the major sources of drinking water are wells, boreholes/tap, and streams. These water sources are frequently polluted due to resource extraction and nearby mining activities in the region, which threaten local ecosystems and public health (Ayandiran et al., 2018).

Monitoring of radiological activity level in drinking water provides an initial assessment of risk of contamination and provides a comprehensive picture of radioactivity contaminants that may affect water quality. In Nigeria, the main sources of drinking water are through groundwater and surface water. Although studies have investigated the radionuclides concentration in drinking water around resources extraction environment in Nigeria such as mining site involving tin, cassiterite, gemstone and gold environment and their potential health risk to public health (Bello et al., 2020; Isinkaye, Fasanmi, Khandaker, et al., 2025; Michael et al., 2022; Muhammad et al., 2022; Owoade et al., 2019), however, despite the growing numbers of artisanal and illegal mining operation, few research outputs are recorded for the monitoring of radiological levels in crude oil resource extraction environment in Southern Nigeria. Moreso, there is currently no evidence of regulated monitoring in place within our study area. Researchers have revealed that residents who are exposed to elevated concentrations of radionuclides and heavy metals in drinking water have demonstrated a significantly increased likelihood of developing severe health conditions such as cancer (Hamlat et al., 2018; Ren et al., 2023).

Based on the known health impacts of radionuclides in drinking water, a critical gap exists in the literature, as the study region lacks documented reports. Extensive historical focus is placed on exposure to radionuclides in water sources because of crude oil extraction and mining activities in Southern Nigeria; however, radiologically associated risk to drinking water remained critically under-examined. Given the extensive mining activities in Southern Nigeria, this study aims to assess radiological stressors in local drinking water sources and their associated adverse health effects on the resident population. This study is necessary at this period due to the escalating frequency of various reported health concerns in Southern Nigeria.

The main objective of this study is to assess the radiological and human health risks for safe drinking water in Southern Nigeria. This study further contributes to strategic plans for ensuring water safety regarding radiological stressors in support of achieving UN SDG 6. To achieve this, we collected samples from the most frequently used water sources in resource extraction areas of Southern Nigeria, including tap, well, and stream water. We then evaluated key radiological indices, including the annual effective dose for different age groups and the excess lifetime cancer risk. Ultimately, this research provides a robust scientific foundation, including data and recommendations, to support the formulation of UN SDG 6 strategies for achieving safe drinking water and environmental security in Southern Nigeria, particularly in areas impacted by crude oil extraction, mining, and other resource extraction activities.

2. Methodology

2.1 Geology and hydrology of study area

Study was carried out in Southern Nigeria, where resource extraction activities such as petroleum mining (Rivers State), bitumen deposits (Agbabu, Ondo State) and coal mining (Enugu State) are prevalent (Figure 1). Rivers State is delineated between Latitude 4º 30' and 4º 55'N and longitudes 6º 55' and 7º 00'E within the Niger Delta region of Nigeria (Figure 2). As a result of the level terrain and moderately dense vegetation, runoff and other water losses are virtually nonexistent, and most water is collected in storage. The aquifers receive consistent replenishment primarily through direct precipitation and incipient flows from rivers in the surrounding area (Ehirim et al., 2018). In general, groundwater flows in a northwest-southeast direction toward the coast, which is consistent with the general pattern observed throughout the Niger Delta (Ehirim et al., 2018).

The Ondo State bitumen deposit is located within the Nigerian basement complex, situated approximately between latitudes 6° 35' N and longitude 4° 54' E (Figure 3), in Africa's equatorial rainforest region. Springs originate from both crystalline basement and sedimentary topography throughout the region. The area is part of the Dahomey Basin in southwestern Nigeria, located on the Atlantic coast; the Dahomey Basin contains a 3,000-meter-thick Mesozoic-Cenozoic sedimentary sequence. The rocks are composed of granites and gneisses limestone that are separated by barren conglomerates comprising sand and pebbles. To varying degrees, the sand and shale are impregnated with bitumen, a heavy oil (Ishola et al., 2026). Enugu coal is found in Udi, Okpara village, Onyeama, which is located between the latitudes 6° 29' N, 7° 31' E (Figure 4). The geological sequence in the Enugu coal mine area consists of three conformable geologic formations: the Enugu shale formation (Campanian), the Mamu formation (Lower Maastrichtian), and the Ajali Sandstone formation (Upper Maastrichtian) (Ezeigbo, 1993).

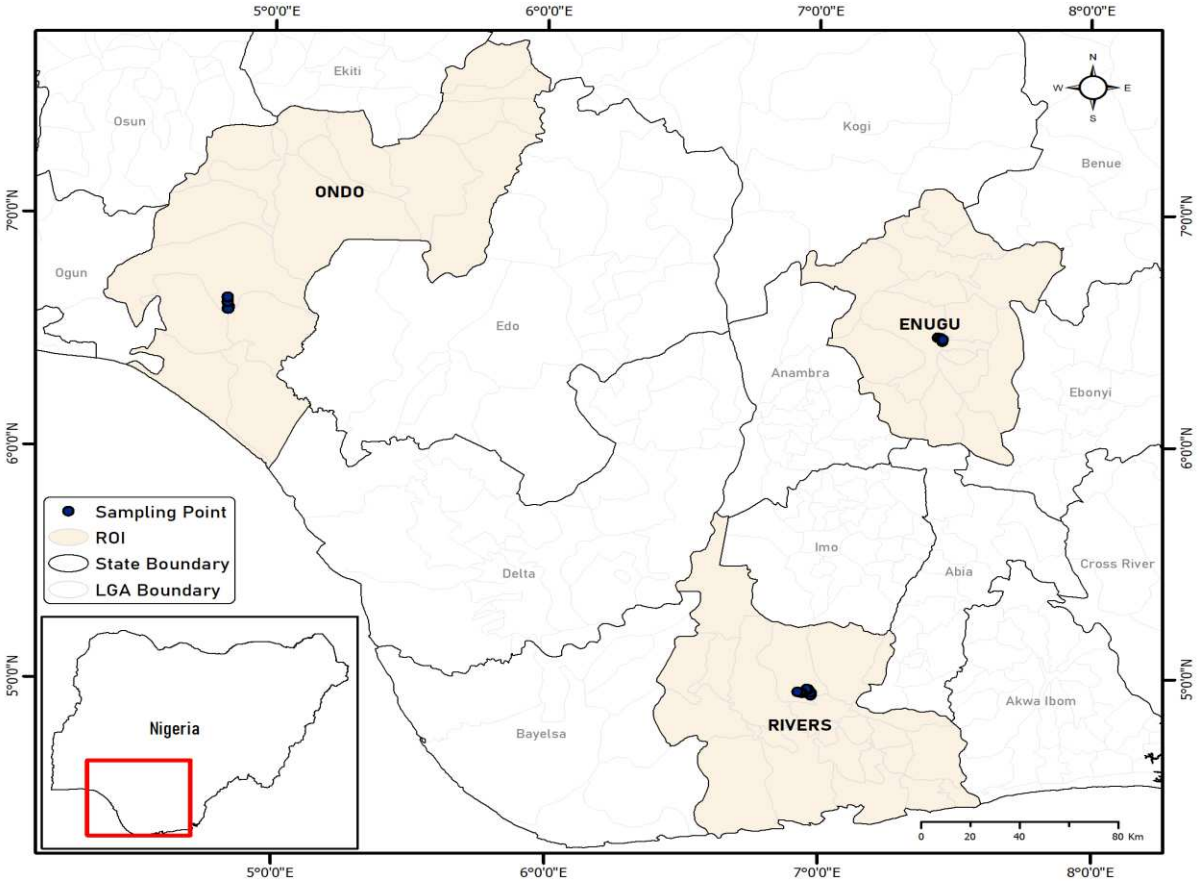


Figure 1: Map of study area showing river state (petroleum drilling area), Ondo State (bitumen deposit area and Enugu State (abandoned coal mining area).

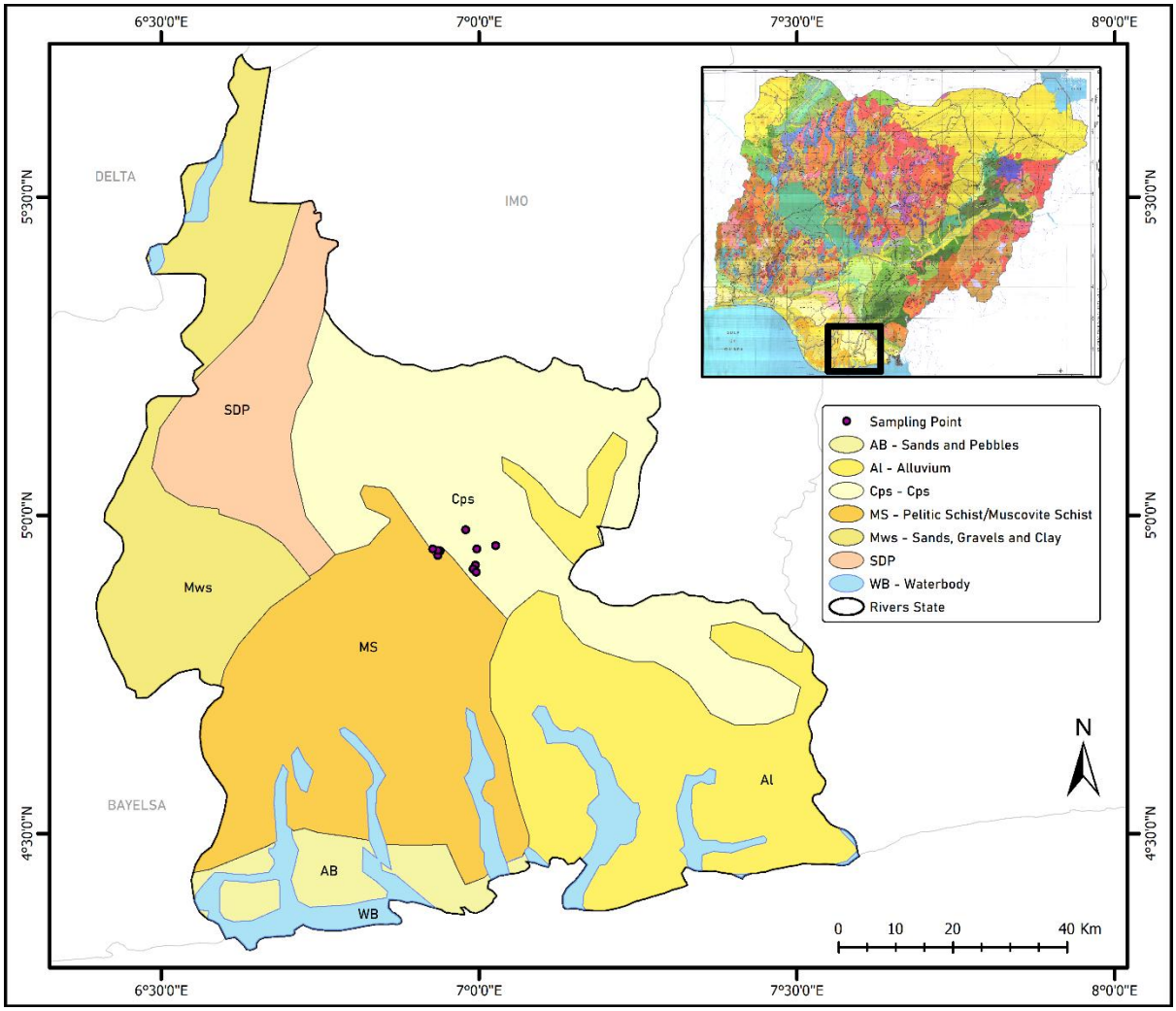


Figure 2: Geology map of petroleum drilling study area, Rivers State Nigeria.

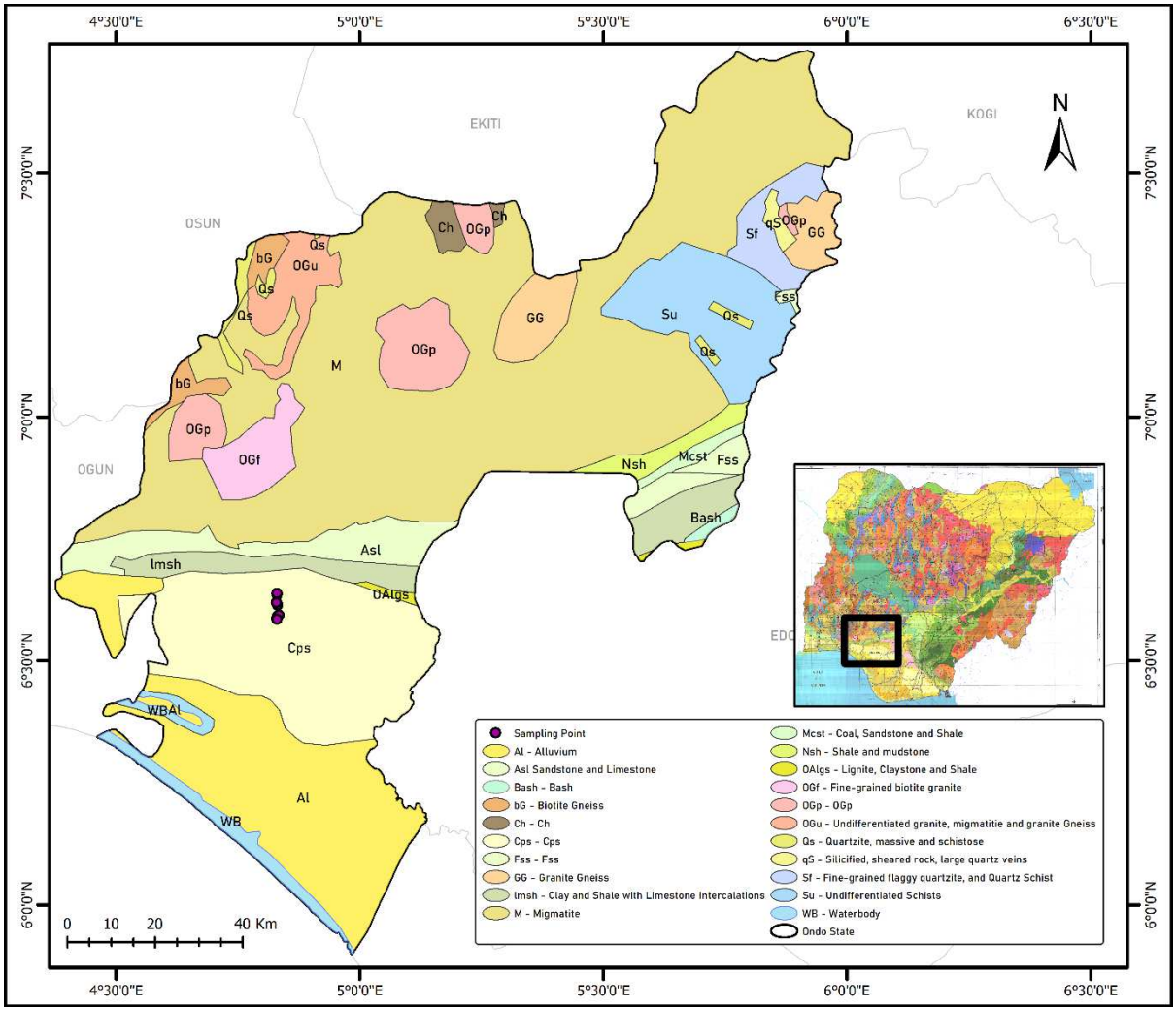


Figure 3: Geology map of bitumen deposit area, Agbabu, Ondo State, Nigeria.

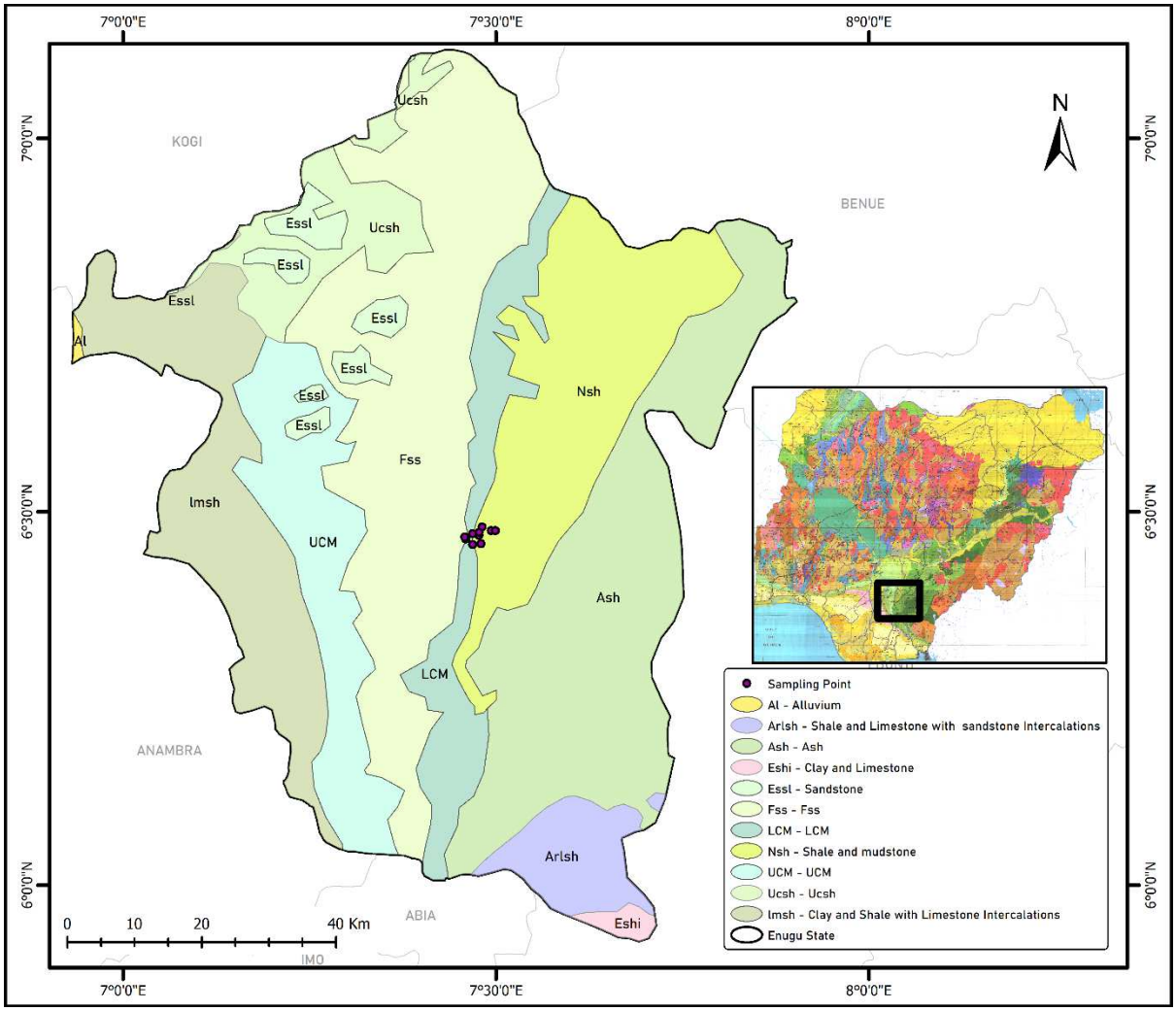


Figure 4: Geology map of coal mining study area, Enugu, Nigeria.

2.2 Sampling

A total of thirty water samples were collected, with ten samples from each of the petroleum, bitumen, and coal mining study locations. Two-litre pre-sterilized polyethylene bottles, which had been previously washed and dried with distilled water, were used to collect water from taps, wells, and streams (Table 1). This was done to prevent any form of contamination from bottles. These water sources serve as drinking water supplies in the study region. The collected water samples were acidified by adding 50 mL of concentrated HNO_3 to bring it to pH of 2 and were then preserved in a laboratory refrigerator at a temperature of 4 °C until the time of the experiment (USEPA, 2011). For the tap water sample collection, the tap was allowed to run for 2-3 minutes to ensure collection of representative samples. For well water sample collection, water was fetched from the well for 5-10 minutes, and the representative samples were collected from each well point. For the stream water collection, flow-weighted composite sampling was adopted. Discrete subsamples were collected at the mid-channel stream point at a depth of 0.5-1.0 m at a standardised 2-hour interval. Following collection, water handling, acidification, and storage procedures were adopted in accordance with the (USEPA, 2011) guidelines. All water samples collected from different sources were sieved with 2 µm filter to remove any solid particles. The samples were then kept for 28 days before gamma-spectroscopy analysis to allow radon to escape and to establish secular equilibrium. This method was previously used by Muhammad et al., (2022).

Table 1: Sampling point, water type and nearest distance to mining site in petroleum, bitumen and coal mining location.

S/N	Longitude	Latitude	location	Type	Nearest distance (m) to mining site
1	6° 59.783’ N	4° 56.826’ E	PPT1	well	1567
2	6° 59.658’ N	4° 55.301’ E	PPT2	tap	1301
3	6° 59.445’ N	4° 54.908’ E	PPT3	well	1173
4	6° 59.725’ N	4° 54.632’ E	PPT4	tap	1470
5	7° 1.575’ N	4° 57.116’ E	PPT5	stream	2394
6	6° 58.726’ N	4° 58.635’ E	PPT6	stream	2763
7	6° 56.323’ N	4° 56.635’ E	PPT7	stream	2607
8	6° 56.088’ N	4° 56.203’ E	PPT8	tap	2615
9	6° 56.098’ N	4° 56.693’ E	PPT9	tap	3195
10	6° 55.633’ N	4° 56.819’ E	PPT10	well	4418
11	4° 49.866’ N	6° 35.488’ E	BPT1	stream	444
12	4° 49.903’ N	6° 35.428’ E	BPT2	tap	489
13	4° 49.906’ N	6° 35.369’ E	BPT3	well	512
14	4° 49.789’ N	6° 35.254’ E	BPT4	stream	791
15	4° 50.033’ N	6° 35.615’ E	BPT5	stream	406
16	4° 49.811’ N	6° 35.094’ E	BPT6	stream	980
17	4° 49.891’ N	6° 36.851’ E	BPT7	stream	2235
18	4° 49.755’ N	6° 37.159’ E	BPT8	stream	2294
19	4° 49.804’ N	6° 38.14’ E	BPT9	stream	4408
20	4° 49.79’ N	6° 38.309’ E	BPT10	well	4745
21	7° 27.548’ N	6° 27.812’ E	CPT1	well	1170
22	7° 28.619’ N	6° 28.109’ E	CPT2	tap	200
23	7° 28.122’ N	6° 28.233’ E	CPT3	Well	232
24	7° 28.777’ N	6° 27.429’ E	CPT4	well	638
25	7° 29.603’ N	6° 28.473’ E	CPT5	well	714
26	7° 28.872’ N	6° 28.773’ E	CPT6	well	709
27	7° 28.623’ N	6° 28.356’ E	CPT7	well	744
28	7° 29.954’ N	6° 28.473’ E	CPT8	well	1885
29	7° 28.101’ N	6° 27.366’ E	CPT9	stream	514
30	7° 27.489’ N	6° 27.968’ E	CPT10	stream	375

2.3 Radionuclides measurement

The gamma ray spectroscopy system equipped with a 7.6 ×7.6 cm^2 NaI (Tl) detector (manufactured by Bicron) was used for radionuclide measurement. Although NaI(Tl) detectors provide high counting efficiency, their lower energy resolution compared with HPGe systems may introduce uncertainties in radionuclide identification and quantification. The detector was shielded from background radiation by a cylindrical lead shield of thickness ~5 cm, with a fixed bottom and a movable cover. The spectroscopy system was energy calibrated using certified reference gamma sources by International Atomic Energy Agency, Vienna. The channel number, being proportional to energy, allows conversion from channel scale to energy scale via energy calibration. The spectrometer was tested for linearity and then calibrated

for energy using sample reference standard sources (ENV94084-200g) by Analytic Inc. Atlanta, GA, USA of ^{137}Cs (662.3 keV), ^{22}Na (511.0 keV and 1274.5 Kev), and ^{60}Co (1173.2 and 1332.5keV), supplied by the International Atomic Energy Agency, Vienna. Gamma ray energy emissions from ^{137}Cs and ^{60}Co were measured, yielding values of 662 keV, 1170 keV, and 1330 keV, respectively, for energy calibration. The system then automatically calculates the slope and the intercept (Figure 5), a method previously adopted by Adesina & Alausa (2025), Ndoma et al., (2025), and Orosun et al., (2022). All system settings and modifications were performed before efficiency evaluation and maintained until a fresh calibration. The absolute efficiency for any gamma-ray energy and activity calibration source was calculated using the Equation 1 and Equation 2 for the activity calibration source and efficiency. For this study, the results of the NaI (Tl) spectrometer efficiency, and minimum detectable amount are shown in Table 2.

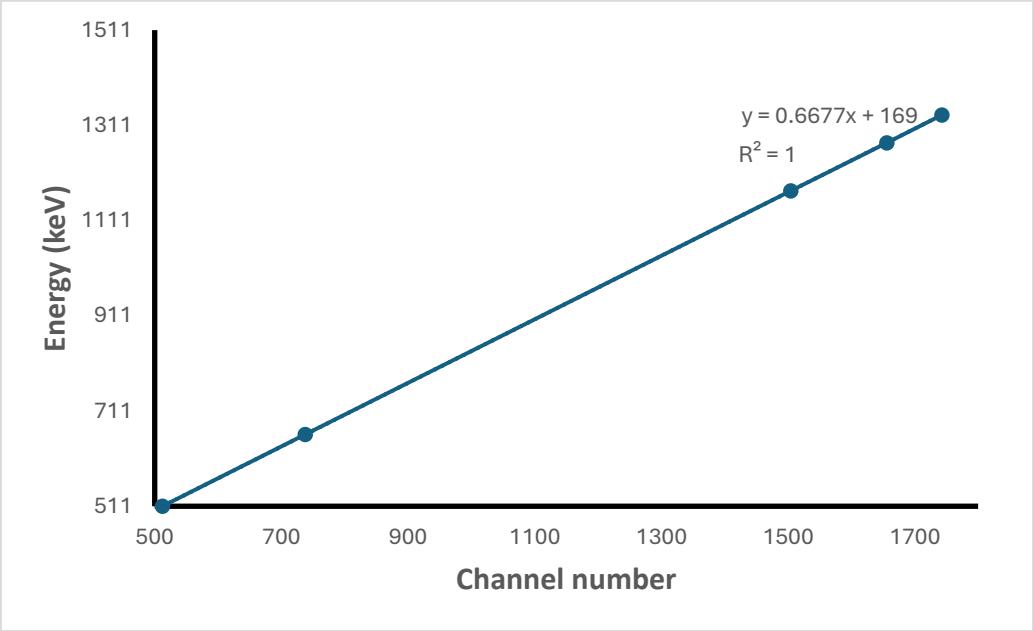


Figure 5: Energy calibration curve

Equation 1: The absolute efficiency was calculated using.

$$\mathcal{E} = \frac{C_{net}}{A \times \gamma \times T} \qquad 1$$

where C_{net} represents the net peak count of the radionuclides, A represents the source of radionuclides activity, γ represents the absolute gamma emission probability of radionuclide, T represents the counting acquisition time and Ɛ represents the efficiency.

Equation 2: Activity calibration source

$$A_{BOC} = A_{DOC} \times Exp(-\lambda \times (BOC \times DOC) \qquad 2$$

where A_{DOC} is the activity (Bq) of the standard source at date of calibration *DOC*, and $\lambda(s^{-1})$ is the decay constant.

Table 2: Energy-dependent full-energy peak efficiency calibration parameters of the NaI(TI) gamma-ray spectroscopy system using certified ^{133}Ba, ^{137}Cs, and ^{60}Co reference sources.

S/N	Energy (keV)	Radionuclides	Efficiency	LLD	MDA±Uncertainty
1	302	Ba(133)	0.033	32.84	0.0096±0.17
2	356	Ba (133)	0.026	34.26	0.0127±0.18
3	383	Ba (133)	0.015	36.60	0.0236±0.15
4	662.5	Cs (137)	0.007	27.66	0.0336±0.19
5	1173.2	Co (60)	0.002	36.93	0.1231±0.16
6	1332	Co (60)	0.001	37.24	0.2790±0.18

For determination of radionuclides and natural occurring radioactive materials, background radiation measurement was counted using empty container identical in same geometry and dimensions like the one used for the samples. Background measurement was counted for 18,000s with the same measurement time for samples to achieved consistency in counting geometry and detector response. The background count was then subtracted from the gross sample count to obtain the activity concentration of radionuclides. Background counting was done at regular interval throughout the sample measurement and stability was observed in the detector by comparing the successive background spectra suggesting that stability in the laboratory condition and detector performance. To reduce uncertainty and improve precision of radionuclides concentration, both samples measurement and background were counted for 18,000s which is relevant for photopeak of the gamma spectroscopy measurement (Gbenu et al., 2021). The spectra were thereafter analysed, and the activity concentrations of the radionuclides were computed using equation 3, previously used by Gbenu et al. (2021), Olaniyi et al. (2025) Tchokossa et al. (2011) and Tzortzis et al. (2003).

Equation 3. Specific activity concentration of radionuclides

$$A_i = \frac{NC_i}{\varepsilon \times yi \times V \times T} \qquad 3$$

Where Ai= activity concentration of radionuclides$\pm combined\ uncertainity$ in Bq/L, NCi= net peak area of samples, Ɛ= efficiency of the detector, y_i= emission probability of radionuclides, V= volume of water sample and T= counting time. Given the non-parametric data of the activity concentration, Kruskal-Walli's test was therefore utilised to determine comparison of radionuclides among the water types samples. All statistical analyses were performed at a 95% confidence interval using SPSS 30.

2.4 Radiological derived doses

2.4.1 Annual effective dose

To facilitate the determination of the impact of partial irradiation based on the knowledge of the irradiated locations, the ICRP has allocated sensitivity factors to specific tissues and organs. The annual effective dose was calculated using equation 4, as previously used by Muhammad et al. (2022).

$$AEDE\ \left(\frac{mSv}{y}\right) = \Sigma l_i \times 365 \times D_i \qquad 4$$

I_i = The daily intakes of radionuclide = concentration of radionuclide in water in Bq/L) × (consumption rate of water L/day), D_i = The ingestion dose coefficient or index (Di) for adults for ^{40}K, ^{232}Th and ^{238}U is 6.2×10^{-9}, 2.3×10^{-7} and 4.5×10^{-8} Sv/Bq, respectively (ICRP, 2011).

The annual effective dose resulting from the ingestion of water was estimated based on the assumption of standard daily water intake of 2 L/day for adults and 1 L/day for lower ages and 0.5 l/day for infants (Hodolli et al., 2025). These consumption level was utilised to facilitate comparison with other studies published and international acceptable radiological indices evaluation. Dose Conversion Factors for

ingestion of radionuclides by members of the public for all ages, provided by ICRP (2011) is given in (Table 3).

Table 3: Dose Conversion Factors for ingestion of radionuclides via drinking of water for different age group (ICRP, 2011.)

Radionuclide	Dose Conversion Factors (Sv/y)					
	Infants	1 year	5 years	10 years	15 years	Adults
^{40}K	5.2×10^{-8}	4.2×10^{-8}	2.2×10^{-8}	1.3×10^{-8}	7.6×10^{-9}	6.2×10^{-9}
^{232}Th	1.6×10^{-6}	4.5×10^{-5}	3.5×10^{-7}	2.9×10^{-7}	2.5×10^{-7}	2.3×10^{-7}
^{238}U	1.4×10^{-7}	1.2×10^{-7}	8.0×10^{-8}	6.8×10^{-8}	6.7×10^{-8}	4.5×10^{-8}

2.4.2 Excess lifetime cancer risk (ELCR)

The ELCR is used to determine the potential for developing cancer following low-dose radiation exposure. It was calculated using formula previously used by (Lee et al. (2026).

$$ELCR = AEDE \times DL \times R_f \qquad 5$$

Where AEDE is the annual effective dose, DL is duration of life 70 years, and RF is risk factor (Sv^{-1}) fatal cancer risk per Sievert. For stochastic effects, ICRP 60 uses values of (RF = 0.05) for the public

3. Results and Discussion

3.1 Radionuclide concentrations in water samples

The mean activity concentration of ^{40}K (259.74, 217.67 and 245.02 Bq/L), ^{238}U (7.70, 6.38 and 7.28 Bq/L) and ^{232}Th (1.76, 1.67 and 1.83 Bq/L) at the petroleum, bitumen, and coal sites, respectively, are presented in Table 4. The distribution of radionuclides was positively skewed across all locations except for ^{40}K and ^{238}U at the petroleum site, which is negatively skewed, suggesting the presence of a longer right tail with occasional higher activity concentration values. The negative kurtosis observed for ^{40}K in bitumen and coal sites, as well as for ^{238}U at the bitumen site, describes a platykurtic distribution, indicating that the data are distributed across locations. In contrast, the positive kurtosis observed illustrates that the concentration at that location was not normally distributed across sampling points.

Additionally, the concentration of ^{40}K was highest at the petroleum site, followed by the coal and bitumen sites. Conversely, ^{238}U displayed the highest value at the coal site, while ^{232}Th followed a trend like ^{40}K, with the highest value at the petroleum site. The higher ^{238}U in the coal site correlate with the lithological composition of the coal-bearing strata from the geology of the coal site. Interaction that exists between the groundwater and host rocks combined with the physical disruption during coal extraction may enhances the leaching of radionuclides in the environment (Obiadi et al., 2016).

It is noteworthy that water samples from this study were sourced from wells, taps, and streams, all of which are utilised for human consumption in our study area. Due to the scarcity of and limited access to potable water, residents in this region rely on these sources as primary drinking water (Ewuzie et al., 2021). The observed radionuclides may originate from both geological formations and anthropogenic resource extraction activities (Muhammad et al., 2022).

Table 4: Radioactivity concentrations of ^{40}K,^{238}U and ^{232}Th in drinking water (Bq/L) collected from petroleum, bitumen and coal sampling sites

^{40}K (Bq/L)	^{238}U (Bq/L)	^{232}Th (Bq/L)

Points	Petroleum	Bitumen	Coal	Petro-leum	Bitumen	Coal	Petro-leum	Bitumen	Coal
1	285.62±5.03	216.21±4.38	277.28±4.96	7.38±0.05	3.47±0.05	8.69±0.05	1.74±0.05	1.37±0.05	1.69±0.05
2	254.20±4.75	232.9±4.55	216.21±4.38	8.31±0.05	6.65±0.05	6.58±0.05	1.90±0.05	1.68±0.05	1.68±0.05
3	267.42±4.87	188.43±4.09	277.28±4.96	6.87±0.05	6.18±0.05	6.53±0.05	1.72±0.05	1.72±0.05	1.68±0.05
4	293.61±5.1	225.97±4.48	281.71±5.0	9.39±0.07	4.4±0.05	10.32±0.06	2.84±0.07	1.85±0.05	2.67±0.06
5	257.22±4.78	208.4±4.30	220.56±4.42	8.27±0.05	5.93±0.05	7.09±0.05	1.89±0.05	1.89±0.05	1.89±0.05
6	189.05±4.1	188.7±4.09	209.47±4.31	7.85±0.04	9.40±0.04	6.52±0.05	1.19±0.04	1.16±0.04	1.57±0.05
7	208.22±4.3	224.82±4.47	279.14±4.98	7.82±0.04	6.28±0.06	6.53±0.06	1.21±0.04	2.09±0.06	2.03±0.06
8	285.62±5.03	194.47±4.15	205.92±4.28	8.07±0.05	8.5±0.05	7.66±0.04	1.89±0.05	1.50±0.05	1.15±0.04
9	277.63±4.96	247.36±4.69	254.11±4.75	7.40±0.05	7.92±0.04	7.40±0.06	1.56±0.05	0.84±0.04	2.28±0.06
10	278.78±4.97	249.41±4.71	228.55±4.50	5.61±0.05	5.07±0.06	5.50±0.05	1.70±0.05	2.63±0.06	1.61±0.05
Min	189.05	188.43	205.92	5.61	3.47	5.50	1.19	0.84	1.15
Max	293.61	249.41	281.71	9.39	9.40	10.32	2.84	2.63	2.67
Mean	259.74	217.67	245.02	7.70	6.38	7.28	1.76	1.67	1.83
STD	34.83	22.51	31.91	1.00	1.84	1.37	0.46	0.50	0.42
SKEW	-1.33	0.00	0.04	-0.61	0.13	1.29	1.27	0.24	0.68
KURT	0.77	-1.29	-2.15	1.79	-0.54	1.96	3.29	0.67	1.01

A Kruskal Wallis test was conducted to determine the differences among the selected drinking water types collected in this study (Table 5 and 6). The highest mean rank concentration for ^{40}K was displayed in tap water (21.0), followed by the stream water (14.96), while the well water displayed the lowest mean concentration (13.29). The tap water (19.75) displayed the highest mean rank ^{238}U concentration, followed by stream water (18.17), while well water (10.71) showed the lowest medium concentration. Similarly, the highest mean rank concentration of ^{232}Th was observed in tap water (17.92), followed by stream water (15.58), while well water (14.21) had the lowest mean rank concentration. Tap water exhibited the highest mean rank content in ^{40}K, ^{238}U and ^{232}Th, may be associated with treatment methods, blending of water sources, or residual minerals from piping infrastructure (Al-Shomali et al., 2025).

Concentration of ^{238}U in stream water suggests interactions with surface water, erosion, and runoff from uranium-rich deposits or anthropogenic influences (Waseem et al., 2015). Unlike ^{232}Th, which remains strongly particle-bound, ^{238}U is relatively mobile under oxidizing conditions, which enhances its aqueous transport (Ram et al., 2021). In contrast, ^{40}K primarily reflects mineral weathering inputs and exhibits weaker hydrological coupling than ^{238}U in stream systems (Smedley & Kinniburgh, 2023).

Although the presence of ^{40}K in drinking water is typically regarded as posing a minimal radiological risk (Ehsanpour et al., 2014). Additionally, Kruskal-Wallis test also reveals a statistically significant difference ($p = 0.048$) for ^{238}U across water types, while ^{40}K and ^{232}Th show no significant difference suggesting uranium's high chemical mobility and solubility in oxidizing surface waters compared to thorium, which remains highly particle-bound and immobile (Porto et al., 2026).

Table 5: Kruskal-Walli's test showing rank means of different water types (well, tap and stream) across sampling location

Radionuclides	Water type	N	Mean Rank
^{40}K	Well water	12	13.29
	Tap water	6	21.00
	Stream water	12	14.96
	Total	30	
^{238}U	Well water	12	10.71
	Tap water	6	19.75
	Stream water	12	18.17
	Total	30	
^{232}Th	Well water	12	14.21
	Tap water	6	17.92
	Stream water	12	15.58
	Total	30	

Table 6: Kruskal-Wallis test comparison among the water types collected in all sampling locations showing statistically significant difference for the ^{238}U in all the water types (well, tap and stream) (p-value<0.05), while ^{40}K and ^{232}Th show no significant difference among the water types collected in all the sampling locations (p-value>0.05).

Test Statistics [a,b]

	^{40}K	^{238}U	^{232}Th
Kruska-Wallis H	3.145	6.057	0.714
Df	2	2	2
Asymp. Sig	0.208	0.048	0.700

a. Kruskal-Wallis Test
b. Grouping variable: Water type (Well, tap and stream water)

Activity concentrations of the radionuclides ^{238}U, ^{232}Th, and ^{40}K (Bq/L) in drinking water from the present study were compared with those reported elsewhere in mining environments, as illustrated in Table 7. The activity concentration reported for drinking water in the gold mining sites in Ghana, Nigeria, Egypt, China, India, South Africa, and Turkey are significantly lower compared to the present study (Awudu et al., 2010; Dizman, 2023; Kamunda, 2021; Lenka et al., 2013; Liu et al., 2021; Orosun et al., 2022). Conversely, the concentrations of ^{238}U, ^{232}Th, and ^{40}K are higher in Iraq and Saudi Arabia compared to this study, suggesting elevated radionuclide contamination due to industrial activities on Iraq drinking water (Alotaibi et al., 2024; Salih, 2022).

This comparison suggests that regions characterised by extensive resource extraction, such as gold, tin, and crude oil extraction, consistently exhibit higher activity concentration of radionuclides compared to baseline levels and non-extraction sites (Mphaga & Rathebe, 2026). Resource extraction activities serve as indicators of the radiological profile of any given environmental medium, which underscores the need for continuous monitoring in a mining and resource extraction region(Alotaibi et al., 2024).

Table 7: Activity concentrations of radionuclides ^{238}U, ^{232}Th and ^{40}K (Bq/L) in water (drinking water) in the present study with comparison with other study conducted in mining environments elsewhere.

Locations	**^{238}U**	**^{232}Th**	**^{40}K**	**Water purpose/source**	**Ref**
Present work	6.5	1.79	245	well and tap	
Nigeria	7.5	1.75	240	stream	

Nigeria, tin mining	3.53 5.88	4.03 4.35	7.61 6.15	Surface water Groundwater	(Muhammad et al., 2022)
Nigeria gold mining site	9.72	16.44	217.04	Drinking water	(Isinkaye, Fasanmi, Osman, et al., 2025)
Ghana gold mining site	0.14 0.12	0.65 0.50	0.64 0.68	borehole river	(Awudu et al., 2010)
Nigeria gold mining	1.0	1.3	29.86	Drinking water	(Orosun et al., 2022)
Algeria	1.9	0.09	131.43	Drinking water from Dam	Hamed et al. (2024)
China near tailings reservoir	4.73	0.44	2.17	Drinking	(Liu et al., 2021)
India	5.3	0.9	5.5	Well	(Lenka et al., 2013)
Almohamadia Saudi Arabia	11.00	9.00	63.00	drinking water	(Alotaibi et al., 2024)
Iraqi	75.6	66.6	447.05	tap water	(Salih, 2022)
South Africa mining site	0.66	0.56	7.36	Surface water	(Kamunda, 2021)
Turkey	1.74	1.39	5.32	Tap water	(Dizman, 2023)

3.2 Radiological indices

The evaluated radiological indices for water are presented in Table 8. The mean value for the annual effective dose (0.30, 0.28 and 0.31 mSv/y), and the excess lifetime cancer risk (1.04, 0.99 and 1.08×10^{-3}) at the petroleum, bitumen, and coal sites, respectively, are shown (Salih, 2022). However, the estimated excess lifetime cancer risk showed higher value in all the sampling sites compared to the international standard threshold recommendation of 1.0×10^{-3} ICRP 60 (ICRP, 1990). This suggests that the consumption of water by residents in this may be associated with an elevated estimated excess lifetime cancer risk above the internationally recommended threshold.

The annual effective dose for various age groups in water samples is illustrated in Figure 6. Infants exhibited the highest annual effective dose. This is due to infant having greater water intake per unit of body mass and exhibiting heightened sensitivity to radiation impacts (Hodolli et al., 2025) The annual effective dose values likewise demonstrate a decline with age, suggesting that as metabolic rates and hydration habits change, the exposure decreases. The annual effective dose received by adults and children of different age groups are within the average planned exposure established by UNSCEAR (2000). UNSCEAR (2000) reported the world average of annual effective dose to be within 0.3-0.6 $mSvy^{-1}$, with a global average of 0.5 $mSvy^{-1}$, while the ICRP recommends a safe limit of 1 $mSvy^{-1}$ (Senthilkumar et al., 2010).

To align a region with a consistent crude oil extraction with the SDG 6 aspiration, a diverse stakeholder framework is needed to manage the radiological health risk in drinking water sources. Sustainable intervention must be prioritized in drinking water monitoring, environmental safety regulation, and compliance to neutralize the threats of resource extraction on drinking water, so that public health may be protected in vulnerable regions.

Table 8: Radiological indices such as annual effective dose and excess lifetime cancer risk in petroleum, bitumen and coal sites.

Points	E(mSv/y)			ELCR×10^{-3}		
	Petroleum Site	Bitumen Site	Coal Site	Petroleum Site	Bitumen Site	Coal Site
1	0.294	0.231	0.285	1.028	0.809	0.999

2	0.320	0.283	0.283	1.122	0.992	0.991
3	0.290	0.290	0.284	1.016	1.014	0.992
4	0.478	0.312	0.450	1.675	1.091	1.575
5	0.319	0.318	0.319	1.116	1.115	1.115
6	0.201	0.196	0.265	0.703	0.686	0.927
7	0.204	0.352	0.342	0.715	1.232	1.198
8	0.319	0.253	0.194	1.116	0.886	0.680
9	0.263	0.142	0.384	0.922	0.498	1.345
10	0.287	0.443	0.272	1.004	1.550	0.950
Min	0.20	0.14	0.19	0.70	0.50	0.68
Max	0.48	0.44	0.45	1.68	1.55	1.58
Mean	0.30	0.28	0.31	1.04	0.99	1.08
STD	0.08	0.08	0.07	0.27	0.29	0.25

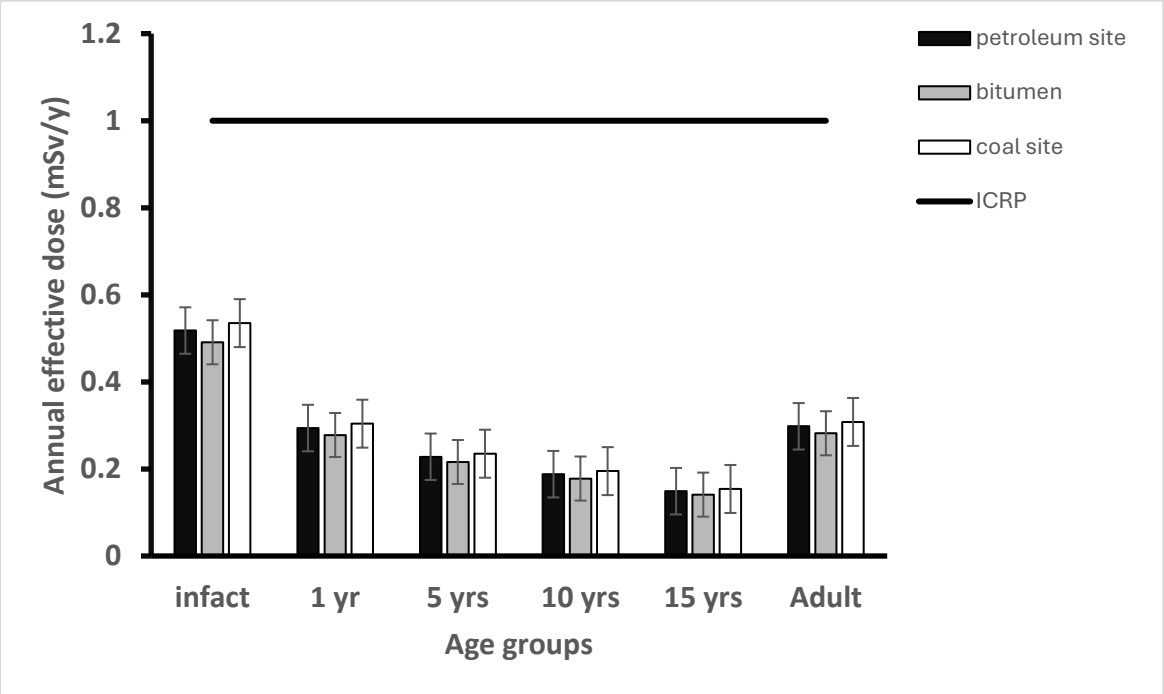


Figure 6: Mean values for annual effective dose (mSv/yr) via drinking water for different age groups (infants, 1, 5, 10, 15 years, and adults) at the petroleum, bitumen, and coal sites. Bars represent mean dose values, error bars indicate standard deviation, and horizontal line shows the dose limit recommended by the International Commission on Radiological Protection (ICRP)

Based on our findings, we propose the following recommendations for residents, occupational workers in mining areas, regulators, and policymakers to facilitate the achievement of SDG 6 in resource extraction regions. (i). Community awareness needs should be prioritised regarding water safety practices, such as the proper construction of wells or tap water near drilling and exploration sites. Educating the residents about the risks of unclean water would promote safe practices, reduce health risks, and lower the incidence of waterborne diseases. (ii). Regulatory bodies and compliance agencies should institutionalise long-term, systematic monitoring of radionuclide concentrations in drinking water to mitigate cumulative impacts of resource extraction. Given the projected increase in both population and crude oil production, such an approach is essential for establishing baseline data for public health and for tracking remediation strategies in areas contaminated by radionuclides. (iii). Immediate attention to

these recommendations is important to achieve safe and healthy standards of residents in resource extraction regions such as Southern Nigeria. This will contribute to the framework of Sustainable Development Goal 6, which aims to ensure clean and safe water for all.

4. Conclusion

Radiological assessment in resource extraction regions of Southern Nigeria was investigated to monitor the safety of drinking water for residents and to assess compliance with international standards for drinking water regarding public health risks. The activity concentrations of ^{238}U and ^{232}Th in drinking water samples from Southern Nigeria suggest that the observed radionuclide levels may be associated with geological and anthropogenic activities in the vicinity of the sampling sites. Radiological indices, such as effective dose, were within the world average recommended by UNSCEAR (2000). However, the higher excess lifetime cancer risk reported in this study suggests that long-term consumption of water by the residents in this region may pose a likelihood of health risks, including cancer, due to compound effects over time.

Our study has demonstrated the need to achieve SDG 6 through monitoring of drinking water and reducing threats from mining to promote water safety. This approach is important for ensuring safe and clean drinking water for residents in Southern Nigeria, thereby improving public health and contributing to the global pursuit of sustainable and clean water enhancement. Furthermore, this study provides insight into the radionuclide levels in drinking water in a resource extraction region and will serve as a baseline for regulatory monitoring and as reference data for future radiation protection efforts.

5. Recommendation

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