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Estimation of Radiological Hazard in the Water of Okaba and Okobo Coalfields and their Environs in Ankpa, Kogi State, Nigeria

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This study evaluates the radiological hazard associated with natural radionuclides (238U, 232Th, and 40K) in water samples collected from the Okaba and Okobo coalfields and their environs in Ankpa, Kogi State, Nigeria. Water samples from various sources were analyzed, yielding activity concentrations of 238U from 44.23 to 172.62 Bq L^{-1}, 232Th from 21.66 to 99.20 Bq L^{-1}, and 40K from 101.72 to 987.24 Bq L^{-1}. These values were employed to compute the radium equivalent activity (Raeq), external (Hex) and internal (Hin) hazard indices, as well as the outdoor and indoor gamma dose rates. The mean Raeq value of 573.87 Bq L^{-1} far exceeds the recommended safety threshold of 370 Bq L^{-1}, highlighting a significant radiological risk. Although the Hex values (ranging from 0.421 to 0.987) indicate that external gamma exposure may be within acceptable limits, the elevated indoor absorbed dose rates and annual effective dose equivalents for infants, children, and adults clearly surpass international safety guidelines. These findings suggest that the high radioactivity levels are influenced by geological heterogeneities, mining, and farming activities in the region. The study underscores the urgent need for enhanced regulatory oversight and continuous environmental monitoring to mitigate potential adverse health impacts due to long-term exposure to contaminated drinking water.

Keywords: Radiological hazard; Radionuclides; Drinking water; Environmental monitoring; Nigeria.

1. Introduction

The proliferation of coal mining activities in Nigeria, particularly in the Okaba and Okobo coalfields of Ankpa, Kogi State, has raised significant environmental and public health concerns. Coal mining and its associated activities are known to release naturally occurring radioactive materials (NORMs) into the environment, thereby increasing the risk of radiation exposure to the local population. This issue is particularly pressing in regions where water sources serve as the primary medium for the dispersion of radioactive contaminants. Given

the reliance of local communities on these water bodies for domestic, agricultural, and industrial purposes, assessing the radioactivity levels in water becomes critical.

Radioactivity in water is primarily influenced by the presence of radionuclides such as uranium-238 (^{238}U), thorium-232 (^{232}Th), radium-226 (^{226}Ra), and potassium-40 (^{40}K). These radionuclides can leach into water sources through natural processes such as weathering of rocks and human-induced activities like mining. Studies have shown that prolonged exposure to high levels of radionuclides can lead to severe health risks, including cancer, kidney damage, and developmental issues in children (UNSCEAR, 2000; IAEA, 2018). The need for comprehensive measurements and risk assessment of radioactivity levels in water sources in mining regions is therefore paramount.

The Okaba and Okobo coalfields are among the most active coal mining sites in Nigeria, contributing significantly to the nation's coal production. These coalfields are situated within the Anambra Basin, a geological formation rich in coal deposits and other mineral resources. The mining activities in these regions have led to substantial environmental degradation, including deforestation, soil erosion, and contamination of water bodies. Given the hydrological dynamics of the area, there is a high potential for radionuclides to be transported into nearby rivers, streams, and groundwater systems, thereby posing risks to human health and the ecosystem.

Several studies in Nigeria have addressed the environmental and health implications of mining activities. For instance, Ademola et al. (2014) investigated the radiological hazards of granite quarries in southwestern Nigeria, highlighting the elevated levels of radionuclides in mining areas. Similarly, Farai and Jibiri (2000) assessed the terrestrial gamma radiation in Nigeria, emphasizing the significant contributions of mining activities to environmental radioactivity. However, there is a dearth of research focusing specifically on water sources in coal mining regions like the Okaba and Okobo coalfields. This gap underscores the necessity of targeted studies to evaluate the radioactivity levels and associated health risks in these areas.

Previous research conducted in similar geological settings has demonstrated the potential for high levels of radioactivity in water sources. For example, Jibiri et al. (2011) examined the radioactivity levels in groundwater from mining areas in central Nigeria and reported concentrations exceeding the World Health Organization's (WHO) permissible limits for drinking water. Additionally, studies by Ibrahim et al. (2020) on the environmental impact of coal mining in northern Nigeria have indicated elevated levels of heavy metals and radionuclides in water samples from mining sites. These findings highlight the urgent need for localized studies to provide baseline data for regulatory agencies and policymakers.

This study aims to fill this research gap by conducting a detailed measurement and risk assessment of radioactivity levels in water sources within the Okaba and Okobo coalfields.

The objectives include: (i) determining the concentrations of key radionuclides (238U, 232Th, 226Ra, and 40K) in water samples; (ii) evaluating the potential radiological risks to the local population; and (iii) providing recommendations for mitigating the health and environmental impacts of coal mining activities.

The methodology for this study will involve the collection of water samples from various sources, including rivers, streams, and boreholes, within and around the coalfields. Advanced

analytical techniques such as gamma spectrometry will be employed to quantify the radionuclide concentrations. The collected data will be utilized to assess radiological risk indicators, such as the annual effective dose and excess lifetime cancer risk, following international standards set by the IAEA (2018) and WHO (2011). Furthermore, the results will be compared with national and international standards to assess compliance and identify areas of concern.

By addressing the critical issue of radioactivity in water sources in coal mining regions, this study will contribute to the growing body of knowledge on environmental radioactivity in Nigeria. It will also provide valuable insights for stakeholders, including government agencies, environmental organizations, and local communities, to develop strategies for sustainable mining practices and public health protection.

2. Study Area

Okaba (7°24'28"N, 7°48'06"E) and Okobo (7°22'14"N, 7°37'31"E) are located in the Enjema District in Ankpa Local Government Area in southeastern Kogi State, Nigeria. This region lies within the Middle Benue Trough, a significant geological formation characterized by rift basins extending from the Niger Delta to the Chad Basin. The Benue Trough is notable for its complex stratigraphy, tectonic history, and abundant natural resources (Benkhelil, 1989).

The geology of Okaba and Okobo features sedimentary rocks from the Cretaceous period, forming part of the Anambra Basin within the Middle Benue Trough. This area is rich in bituminous coal, a valuable resource for industrial applications such as power generation and metallurgy (Mbogu & Inoni, 2018). The sedimentary formations in this region also include sandstone, shale, limestone, and coal seams, reflecting depositional environments that alternated between marine and continental settings (Obaje, 2009).

Beyond coal, the sedimentary rocks in Okaba and Okobo may host other economic minerals, such as limestone for cement production and shale, which has applications in construction and as a potential source of shale gas (Ezeigbo & Ozoko, 1987). The region's coal reserves, part of the larger Anambra Coal Basin, have been a focal point of mining activities for decades, making it an area of interest for assessing environmental and health impacts associated with mining.

3. Material and methodology

Collection and preparation of samples

A total of twenty four (24) water samples were collected from Okaba and Okobo coal fields and it's environ between the months of October and December, 2024. Water samples were collected in 1-liter plastic containers with screw caps and pre-cleaned glass bottles from various locations at a coal mining site between 7 AM and 10 AM. Samples were taken in triplicates from upstream, midstream, and downstream points, as well as from five boreholes in each of the two communities. The samples in 1-liter amber bottles were acidified to a pH below 2 using 6 M hydrochloric acid (Adeniji et al., 2019). The natural radioactivity assessment of the water samples was conducted using high – purity germanium.

Table 1: Sampling codes and description

Sample ID	Description
SWA 1, 2, 3	water samples from upper stream in Okaba
SWA 4	water samples from mid stream in Okaba
SWA 5, 6, 7	water samples from downstream in Okaba
SWA 8, 9, 10, 11, 12	Samples from boreholes in Okaba
SWA 13, 14, 15	water samples from upper stream in Okobo
SWA 16	water samples from mid stream in Okobo
SWA 17, 18, 19	water samples from downstream in Okobo
SWA 20, 21, 22, 23, 24	Samples from boreholes in Okobo

HPGe detector

HPGe detector was chosen to analyze the radionuclides of ^{226}C, ^{232}Th and ^{40}K because of its good radiation detection technology that offers adequate information to exactly identify radionuclides, and it is a suitable detector for environmental samples. It is very important to assess the health impact of radionuclides to human population by evaluation of the distribution of radiation dose (Salih 2018b). The specific activities of ^{226}Ra, ^{232}Th, and ^{40} K were detected, and each sample was measured and weighed from 99 to 124 g, as shown in Table 1, by using electronic balance. Before the collection of drinking water samples, the bottles were washed according to the IAEA standard with 15% nitric acid and with double de-ionized water three times (Nisar et al. 2017) and before measurement of natural radioactivity.

Physicochemical parameters of all the water samples such as pH were analyzed by using a pH meter in order to find the impact of these parameters on the concentration of the radionuclides in water (Nisar et al. 2018; Elham et al. 2014).

Each sample was placed in a small empty tube and then stored separately without movement for 1 month to allow radioactive equilibrium stage between ^{226}Ra and ^{232}Th with their respective progenies before performing radioactivity measurements (Salih et al. 2018; Olomo et al. 1994; Tsivou et al. 2010). About 98% equilibrium level was attained for the duration. The natural radioactivity levels of ^{226}Ra, ^{232}Th, and ^{40} K in drinking water samples were measured using a gamma multichannel analyzer equipped with a high-purity germanium coaxial detector (HPGe) system that is agreed with Almayahi et al. (2012). The system has a MCA card with a high power sup- ply that provides a high voltage range of 0–1500 V (Salih et al. 2019) to the detector through an amplifier attached to a windows-operated PC loaded with gamma-W. This detector was shielded by a cylindrical lead shield with a thickness of 5 cm, an inner diameter of 10 cm, and a length of 50 cm in order to achieve the lowest background radiation level. The background radiation was determined using an empty container of dimensions similar to that of the samples.

The analysis was fixed at the duration at of 86,400 s to achieve a statistically viable gamma spectrum, which is consistent with similar reports (Murtadha et al. 2017; Mohammed et al. 2015; Augustine et al. 2015). The sample was placed on the top of the detector and was counted for 86,400 s so as to achieve a minimum counting error (Khandaker et al. 2013). The energy resolution of the detector was 1.99 keV at 1332 keV of ^{60}Co source that has the ability to

differentiate the gamma-ray energies.

The radiometric analysis of radionuclides, including 238U, 232Th, and 40K, was conducted using a high-purity germanium (HPGe) detector coupled with a high-resolution gamma-ray spectroscopic system designed to measure radioactivity in water. This system ensures low background radiation and high accuracy. A p-type HPGe coaxial detector with a vertically closed-end configuration, combined with a compact 8000-series multichannel analyzer for counting and signal processing, was utilized at the nuclear physics laboratory. This advanced setup features a high-performance lead shield, specifically the Kolga Model A340, which has a 10-cm thickness and incorporates a 1-mm tin layer overlaid with a 1.6-mm oxygen-free copper layer. This shielding effectively suppresses lead X-rays and is widely recognized as a reliable tool for environmental and research applications. The Quantum Gold software, used to operate the system, is highly efficient and user-friendly, suitable for both homeland security screenings and ultra-low-activity sample analyses, consistent with Saddon (2016).

Energy and efficiency calibrations

The natural radioactivity levels were measured using the HPGe detector connected to a multichannel analyzer with a high-voltage range of 0–1500 V (Salih et al., 2019). Detector efficiency, defined as the ratio of detected pulses to the number of gamma photons emitted by a source, is a critical characteristic for radionuclide analysis. Precise calibration of the detector's energy and efficiency is essential for accurate measurement. The energy resolution of the HPGe detector was set to 1.99 keV at 1332 keV for a 60Co source, in agreement with Ian (2007).

Energy calibration involved converting channel numbers into corresponding gamma-ray energy values in MeV, while efficiency calibration determined the gamma-ray counting efficiencies across the full energy range of measurement (Darwish et al., 2015).

Standard radioactive sources provided by the International Atomic Energy Agency (IAEA), including 60Co, 137Cs, 22Na, 241Am, and 226Ra, were used for these calibrations (Hossain et al., 2013). The detector demonstrated a relative efficiency of 73.8% at 1.33 MeV for 60Co, with an energy resolution (FWHM) of 1.18 keV at 122 keV for 57Co and 1.97 keV at 1332 keV for 60Co.

The calibration process was conducted for duration of 36,000 seconds (Salih et al., 2020). Efficiency calibration included the use of gamma-ray energies from 226Ra (186.1, 295, 351.9, 609, 665, 1120, and 1764 keV), 60Co (1175.2 and 1332.5 keV), and 137Cs (661.7 keV). A relative efficiency curve was created, covering energy values from 186 keV to 1332.5 keV, consistent with Zakarya et al. (2021). The energy range for calibration extended from 0.026 MeV to 1.332 MeV, with specific gamma-ray energies of 0.0263, 0.0531, 0.1862, 0.6616, 1.1732, 1.2745, and 1.3325 MeV measured over 86,400 seconds. These calibrations ensured reliable and accurate analysis of radionuclides in the samples.

The absolute efficiency of the HPGe detector for the gamma-ray energies was also calculated from Eq. (1) reported by (Fasae and Isinkaye 2018; Njinga et al. 2015);

$$\epsilon = \frac{\text{CPS}}{\text{Ac X I}\gamma} \text{ X } 100\% \quad (1)$$

Where, CPS is count per second, A_c is the activity (Bq) of the standard sources, and I_γ is gamma-ray emission intensity per decay at energy E (Salih 2018a); the efficiency is an important parameter of the HPGe detector (Khandaker 2011).

The radionuclide analysis of drinking water samples were carried out based on the peaks of energies for the progenies, the decay products: ^{214}Pb (abundances 295.224 keV, 18.7%, and 351.932 keV, 35.8%) KeV and ^{214}Bi (609.312 keV, 47%, 1120.287 keV, 14.8%, and 1764.494 keV, 16.75%) KeV were taken to indicate the activity concentrations of ^{226}Ra. The specific activity concentrations of ^{232}Th was calculated from ^{212}Bi (727.33) KeV, ^{212}Pb (238.632 keV, 47.3%) KeV, ^{228}Ac (911.204, 31%, and 968.971 keV, 19.5%) KeV and ^{208}Tl (583.191, 86.5%, 860.564, 13.4%, and 2614.533, 99.0%) KeV, but the activity concentration of ^{40} K was assessed directly from its (1460.83 keV, 11.67%) KeV gamma ray peak which is also in agreement with the study by Salih (2018a, 2022) and Darwish et al. (2015). The specific activity concentration of the radionuclides was calculated from the background subtracted area of prominent gamma-ray energy using Eq. (2) specified by Salih (2018a), Jibiri et al. (2007), and Murtadha et al. (2013).

Calculation of specific activity of radioniclides of (^{238}U, ^{232}Th, and ^{40}K) and hazard indices

The activity concentration of radionuclides (238U, 232Th and 40K) has been calculated using the formula (2) (Fasae and Isinkaye 2018; Nisar 2015; Salih 2018; Salih 2022).

$$\text{Activity concentration, Ac} = \frac{\text{C}-\text{B}}{\varepsilon \text{.I}\gamma \text{.t .m}} \quad (2)$$

Where,

C is the net count under the peak, B is the background count under the peak, ε is the detector efficiency, Iɤ is the gamma emission probability, t is the counting time and m is the mass if water sample.

Assessment of radiological hazard

Radium equivalent (Ra_{eq})

The radium equivalent activity (Ra_{eq}) is a single index used to describe gamma-ray output from different mixtures of radium, thorium, and potassium in the material and was calculated using Eq. 3 (Beretka and Mathew 1985; UNSCEAR 1982; Salih et al. 2018).

$$Ra_{eq}\,(Bqkg^{-1}) = C_U + 1.43C_{Th} + 0.077C_K \quad (3)$$

Where, C_U, C_{Th} and C_k are the respective specific activities of $^{238}C_u$, ^{232}Th, and ^{40}K.

Outdoor hazard index

Gamma index was calculated using Eq. (4) (Angeleska et al. 2017; Alias et al. 2008)

$$I\gamma = C_u/300 + C_{Th}/200 + C_k/3000 \quad (4)$$

The external hazard index was calculated using eq. 5 (Angeleska et al. 2017; Salih

2022).

$$Hex = C_u/370 + C_{Th}/259 + C_k/4810 \quad (5)$$

Where, C_u, C_{Th} and C_k are the activities concentration of ^{238}U, ^{232}Th, and ^{40}K, respectively.

The outdoor external dose was calculated using eq. 6 (Salih 2022)

$$D_{out}\ (nGyh^{-1}) = 0.462C_u + 0.604C_{Th} + 0.0417C_k \quad (6)$$

Indoor hazard index

Alpha index was calculated using eq. 7

$$I\alpha = C_u/200 \quad (7)$$

Internal hazard index, H_{in} was calculated using eq. 8 (Salih 2018b, Salih 2022)

$$H_{in} = C_u/185 + C_{Th}/259 + C_k/4810 \quad (8)$$

Indoor external dose was calculated from eq. 9 (Salih 2018b, Salih 2022)

$$D_{in} = 0.92C_u + 1.1C_{Th} + 0.08C_k \quad (9)$$

Annual effective dose due to ingestion

The total effective dose due to ingestion of 238U, 232Th and 40K in water samples were found for different age groups using eq. 10 (WHO 2018).

$$D = A \times C \times I \quad (10)$$

Where, D is the annual effective dose due to ingestion, A is the activity concentration, C is the consumption rate of drinking water, C is consumption rate of drinking water for relevant age group ($L \cdot year^{-1}$) for a person in 1 year, which is (150, 350, and 500); L for infants, children, and adults, respectively and I = ingestion dose coefficient for relevant age group ($mSv \cdot L^{-1}$), (WHO 2018; Hany et al. 2019).

4. Result and discussion

The purpose of this study is to estimate the radiological hazard of radionuclide (^{238}U, ^{232}Th, and ^{40}K); the specific activity concentration of (^{238}U, ^{232}Th, and ^{40}K), radium equivalent activity, and external hazard and internal indices were calculated for the selected drinking water samples. The activity concentrations of ^{238}U ranged from 44.23 BqL^{-1} in SWA_{11} to 172.62 BqL^{-1} in SWA_{14} with a mean activity concentration value of 104.80 BqL^{-1}. The activity concentrations of ^{232}Th ranged from 21.66 BqL^{-1} in SWA_{20} to 99.20 BqL^{-1} in SWA_{13} with a mean ^{232}Th activity concentration of 51.49 BqL^{-1}.

The activity concentrations of ^{40}K in water ranged from 101.72 BqL^{-1} in SWA_3 to 987.24 BqL^{-1} in SWA_{19} with a mean value of 719.64 BqL^{-1}. The variation in the radioactivity concentration of ^{40}K, ^{238}U, and ^{232}Th, as shown in Table 2 and Figures 1, 2, and 3, may be due to the difference in the nature, of the samples, mining and farming activities.

Table 2: Calculated activity concentration of radionuclides in water samples from Okaba and Okobo

Sample ID	C_u (BqL^{-1})	C_{Th} (BqL^{-1})	C_k (BqL^{-1})
SWA_1	154.11±2.11	61.01±0.81	639.89±4.01
SWA_2	145.14±2.09	68.09±1.10	911.54±5.66
SWA_3	128.09±1.90	59.11±0.59	101.72±0.18
SWA_4	116.24±1.54	44.34±0.66	228.44±1.16
SWA_5	96.63±0.94	22.43±0.29	965.00±4.89
SWA_6	99.12±1.21	26.21±0.11	949.20±4.23
SWA_7	109.13±1.01	28.26±0.18	928.01±4.14
SWA_8	66.34±0.71	44.11±0.34	955.00±4.46
SWA_9	61.56±0.15	45.76±0.52	869.21±3.77
SWA_{10}	58.09±0.52	41.56±0.18	886.45±3.06
SWA_{11}	44.24±0.33	43.66±0.78	943.22±4.64
SWA_{12}	69.48±0.79	47.07±1.12	699.26±2.98
SWA_{13}	167.16±2.07	99.20±0.91	732.04±2.91
SWA_{14}	172.67±2.39	59.32±0.23	625.21±2.31
SWA_{15}	157.27±2.01	84.13±0.10	682.02±2.11
SWA_{16}	121.03±1.88	58.14±0.14	443.02±1.98
SWA_{17}	89.45±0.12	36.12±0,09	190.11±0.89
SWA_{18}	95.23±0.86	44.24±0.01	121.02±0.06
SWA_{19}	98.12±0.93	41.06±0.06	987.24±4.32
SWA_{20}	122.32±1.63	21.66±0.03	812.01±3.53
SWA_{21}	96.68±0.97	60.24±0.24	902.43±4.24
SWA_{22}	84.54±0.72	89.77±0.82	804.03±3.92
SWA_{23}	73.33±0.64	48.01±0.46	900.11±4.23
SWA_{24}	89.21±0.61	62.22±1.14	996.23±4.08
Mean	104.80	51.49	719.64
Maximum	172.67±2.39	99.20±0.91	987.24±4.32
Minimum	44.24±0.33	21.66±0.03	101.72±0.18
Range	44.24±2.39 – 172.67±2.39	21.66±0.03 – 99.20±0.91	101.72±0.18 – 987.24±4.32

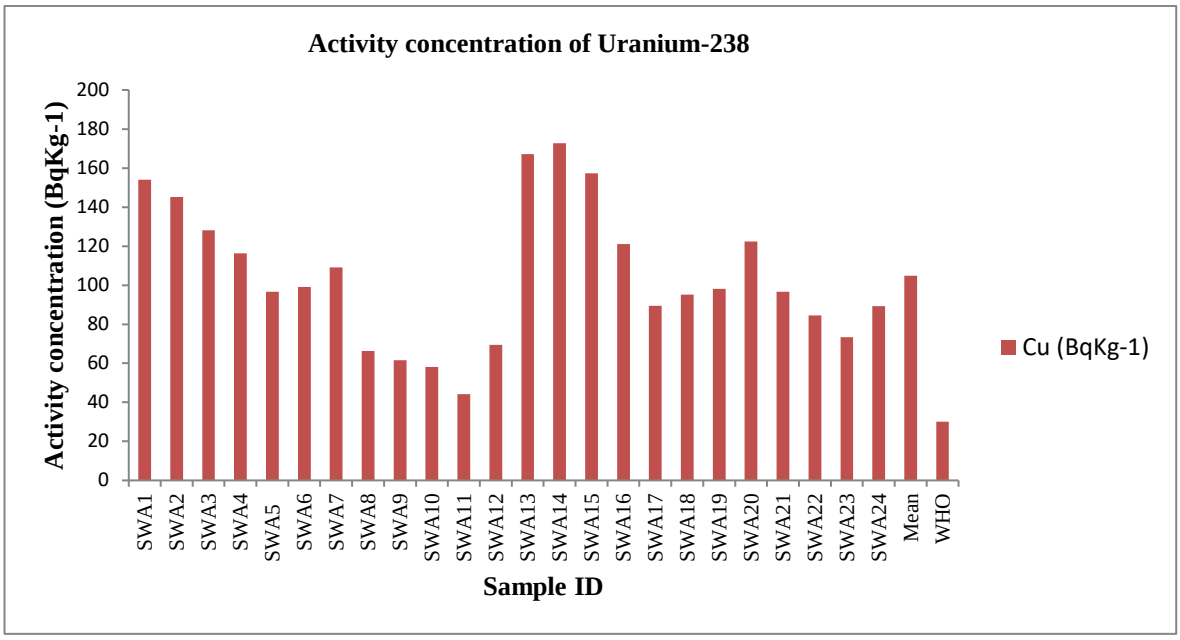

Figure 1: Activity concentration of Uranium-238 in water samples of Okaba and Okobo

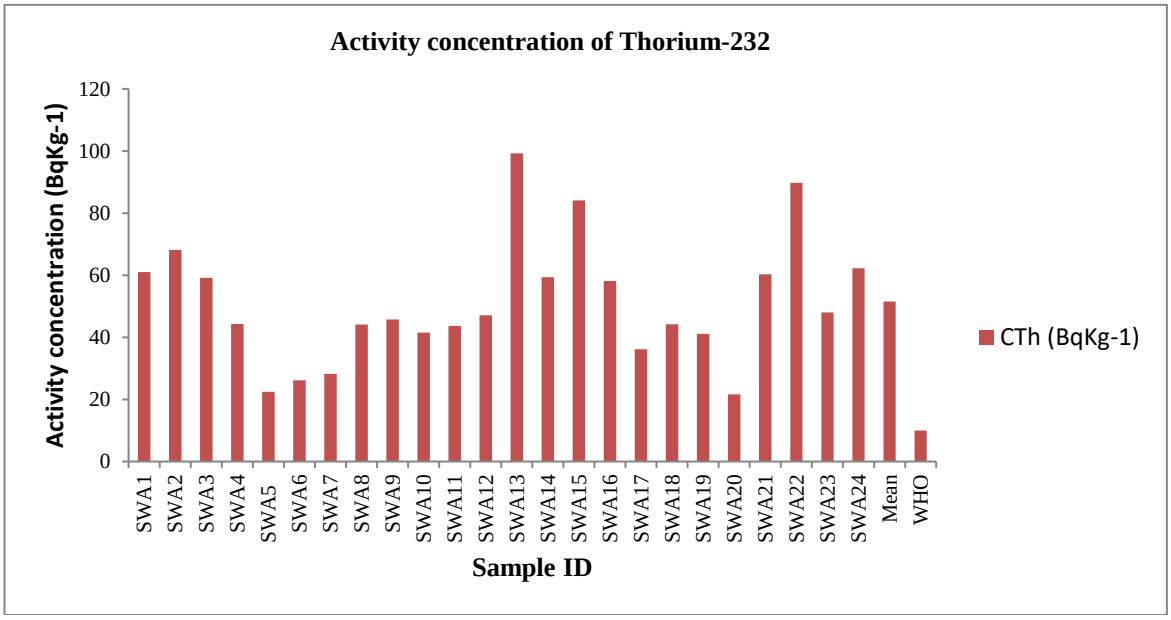

Figure 2: Activity concentration of Thorium- 232 in water samples of Okaba and Okobo

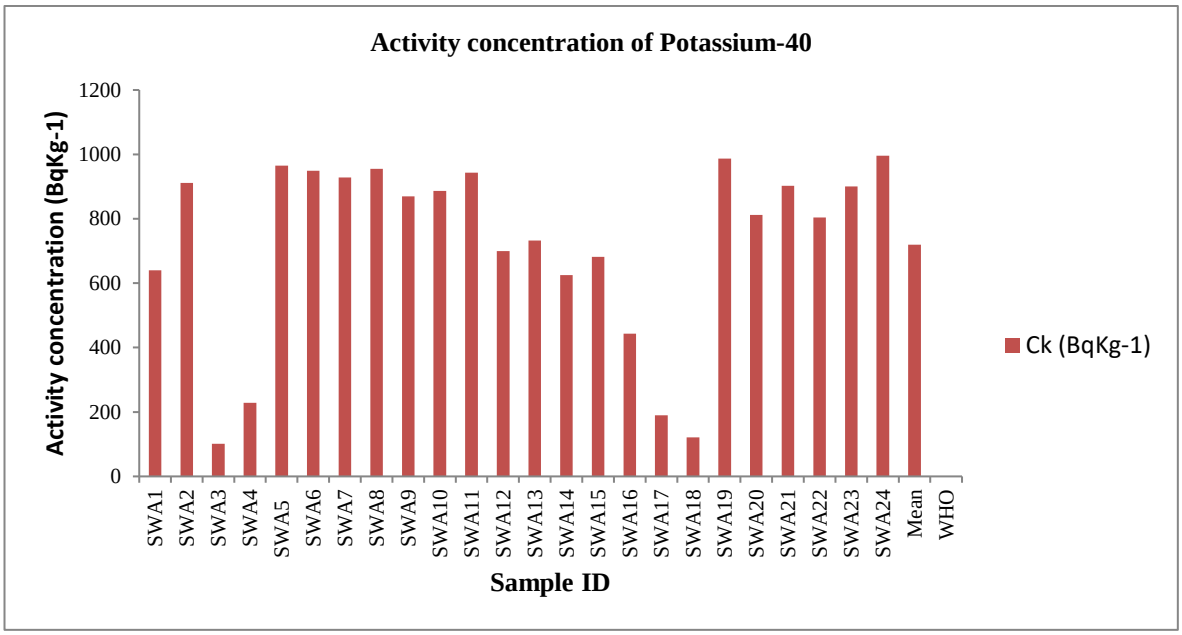

Figure 3: Activity concentration of Potassium-40 in water of Okaba and Okobo

The radium equivalent activity (Ra_{eq}) of ^{238}U, ^{232}Th, and ^{40}K was found to be irregular. The maximum value of Ra_{eq} is more than 370 $Bq \cdot L^{-1}$, which is well above the safe level recommended by the UNSCEAR 2000. The radium equivalent activity (Ra_{eq}) in the water samples varies from 341.69 BqL^{-1} in SWA_6 to 884.73 BqL^{-1} in SWA_1 with a mean value of 573.87 BqL^{-1}, as shown in Table 3, all samples are above the maximum allowable value of 370 BqL^{-1} except for SWA_6 and SWA_7 that are below the permissible value of 370 BqL-1. In addition, the maximum concentration of ^{226}Ra (884.73 BqL^{-1}) in the samples is extremely higher than the maximum admissible value of ^{226}Ra (370 BqL^{-1}), as suggested by UNSCEAR, 2000.

Thus, the samples are characterized by totally high radioactivity and are harmful to the members of the society. The maximum value of Ra_{eq} in water samples was found to be higher than the radium equivalent activity (Ra_{eq}) index which provides a guideline for regulating the safety standards of radiation protection for the general public residing in the area under study because these values are far above the allowable limit (370 $Bq \cdot L^{-1}$), as recommended by the International Atomic Energy Agency (IAEA 1989; Salih 2021; Salih 2022).

The gamma outdoor hazard index and gamma indoor hazard index of the radionuclides for each sample were calculated. The values of external hazard index (H_{ex}) ranged from 0.421 to 0.987 with a mean value of 0.633, while the values of the internal hazard index (H_{in}) ranged from 0.604 to 1.439 with a mean value of 0.908. The outdoor external dose (D_{out}) ranged from 71.069 to 167.670 nGy h^{-1}, while the values of indoor absorbed dose (D_{in}) ranged from 137.235 to 291.793 nGy h^{-1}. The mean values of outdoor external dose (D_{out}) and indoor absorbed dose (D_{in}) were found to be 109.531 nGy h^{-1} and 210.627 nGy h^{-1}, respectively.

The results are shown in Table 3. Given that the maximum value of H_{ex} was less than one (<

1); therefore, the study location is considered safe (UNSCEAR 2000). However, the average value of D_{in} (210.627 nGy h^{-1}) is higher than the recommended value of 70 $nGyh^{-1}$ (UNSCEAR 2000; Salih 2022; Nisar 2015). In addition, the minimum and maximum values of the external gamma (I_γ) were found to be 0.542 and 1.172, while the minimum and maximum values of the internal alpha index (I_α) were found to be 0.221 and 0.863.

The maximum values of I_γ and I_α are less than or equal to one (≤ 1) the maximum permissible value ≤ 1, indicating that water in the study area is safe and poses negligible radiological risk (Bashir et al. 2012; Ababneh et al. 2010) because to keep the radiation hazard in check the value of (Hex) should be less than one. The main objective of this index is to limit the radiation dose to the accepted dose limit of $1.5mSvy^{-1}$that is corresponding to the maximum value of the radium equivalent activity of 370 $BqKg^{-1}$ (UNSCEAR, 2000, Salih, 2022).

Table 3: Radiation hazard indices gamma ray in domestic water of Okaba and Okobo

Sample ID	Raeq (BqL^{-1})	I_γ (BqL^{-1})	H_{ex}	D_{out} ($nGyh^{-1}$)	I_α	H_{in}	D_{in} ($nGyh^{-1}$)
SWA_1	884.73±1.24	1.032 ± 0.028	0.785 ± 0.021	134.732 ± 0.359	0.771 ± 0.013	1.202 ± 0.028	260.083 ± 0.681
SWA_2	617.76±1.03	1.128 ± 0.036	0.845 ± 0.027	146.192± 0.471	0.726 ± 0.018	1.237 ± 0.038	281.351 ± 0.896
SWA_3	510.32±0.98	0.756 ± 0.022	0.596 ± 0.016	99.102± 0.283	0.640 ± 0.010	0.942 ± 0.022	191.001 ± 0.539
SWA_4	496.09±0.67	0.685 ± 0.030	0.533 ± 0.023	98.431± 0.389	0.581 ± 0.016	0.847 ± 0.031	173.990 ± 0.743
SWA_5	437.17±0.46	0.756 ± 0.037	0.547 ± 0.028	101.206± 0.479	0.483 ± 0.018	0.810 ± 0.038	190.773 ± 0.913
SWA_6	341.69±0.11	0.778 ± 0.042	0.566 ± 0.032	106.185± 0.536	0.496 ± 0.021	0.834 ± 0.043	195.957 ± 1.019
SWA_7	345.87±0.17	0.814 ± 0.031	0.597 ± 0.023	97.115± 0.398	0.546 ± 0.015	0.892 ± 0.031	205.726 ± 0.759
SWA_8	700.69±1.08	0.760 ± 0.034	0.548 ± 0.025	92.326± 0.434	0.332 ± 0.017	0.727 ± 0.035	185.954 ± 0.826
SWA_9	794.37±0.96	0.724 ± 0.040	0.524 ± 0.030	88.905± 0.515	0.308 ± 0.021	0.690 ± 0.042	176.508 ± 0.979
SWA_{10}	615.15±1.42	0.698 ± 0.043	0.508 ± 0.033	86.142± 0.553	0.290 ± 0.022	0.659 ± 0.045	170.075 ± 1.053
SWA_{11}	635.05±1.38	0.680 ± 0.042	0.484 ± 0.032	89.689± 0.542	0.221 ± 0.022	0.604 ± 0.044	164.184 ± 1.032
SWA_{12}	720.08±1.39	0.700 ± 0.024	0.515 ± 0.017	167.670± 0.308	0.347 ± 0.011	0.703 ± 0.024	171.639 ± 0.588
SWA_{13}	517.38±0.86	1.297 ± 0.049	0.987 ± 0.037	141.674± 0.636	0.836 ± 0.025	1.439 ± 0.051	321.470 ± 1.210
SWA_{14}	498.05±0.74	1.081 ± 0.045	0. 826± 0.034	151.913± 0.580	0.863 ± 0.023	1.292 ± 0.047	274.125 ± 1.104
SWA_{15}	523.76±1.41	1.172 ± 0.047	0.892 ± 0.035	109.506± 0.604	0.786 ± 0.024	1.317 ± 0.049	291.793 ± 1.149
SWA_{16}	483.19±0.94	0.842 ± 0.028	0.644 ± 0.021	75.763± 0.364	0.605 ± 0.014	0.971 ± 0.028	210.743 ± 0.693
SWA_{17}	429.59±0.89	0.542 ± 0.037	0.421 ± 0.027	111.300± 0.472	0.447 ± 0.018	0.662 ± 0.038	137.235 ± 0.897
SWA_{18}	427.88±0.17	0.579 ± 0.048	0.453 ± 0.036	103.455± 0.618	0.479 ± 0.025	0.711 ± 0.050	145.957 ± 0.932
SWA_{19}	393.64±0.12	0.861±0.032	0.629±0.032	118.682±0.026	0.491± 0.019	0.894± 0.043	214.416 ±0.876
SWA_{20}	557.49±0.79	0.787±0.245	0.583±0.042	126.807±0.024	0.612±0.024	0.745± 0.046	201.321 ±0.795
SWA_{21}	767.63±1.12	0.924±0.024	0.681±0.045	100.411±0.053	0.483±0.018	0.943± 0.035	227.404 ±1.245
SWA_{22}	642.72±2.11	0.999±0.039	0.742±0.028	120.339±0.051	0.423±0.026	0.971± 0.028	240.846 ±1.034
SWA_{23}	801.48±1.42	0.785±0.042	0.601±0.025	90.102±0.0041	0.367±0.027	0.769± 0.041	192.283 ±1.018
SWA_{24}	631.21±1.01	0.940±0.037	0.688±0.031	71.069±0.053	0.446±0.023	0.930± 0.032	230.214 ±0.954

Mean	573.87	0.847	0.633	109.531	0.524	0.908	210.627
Max.	884.73±1.24	1.172 ± 0.047	0.987 ± 0.037	167.670± 0.308	0.863 ± 0.023	1.439 ± 0.051	291.793 ± 1.149
Min.	341.69±0.11	0.542 ± 0.037	0.421 ± 0.027	71.069±0.053	0.221 ± 0.022	0.604 ± 0.044	137.235 ± 0.897

Table 4: Ingestion dose coefficients for different ages (WHO, 2018)

Age categories	^{238}U (mSvBq^{-1})	^{232}Th (mSvBq^{-1})	^{40}K (mSvBq^{-1})
Adults	4.5×10^{-5}	2.3×10^{-4}	6.2×10^{-9}
Children	6.8×10^{-5}	2.9×10^{-4}	1.1×10^{-8}
Infants	1.4×10^{-4}	1.6×10^{-3}	2.0×10^{-8}

Table 5: Annual effective dose due to ingestion by radionuclides of Infants in Okaba and Okobo

Sample ID	238U×10^{-1}(mSvy^{-1})	232Th ×10^{-1} (mSvy^{-1})	40K ×10^{-1} (mSvy^{-1})	Total dose×10^{-1}(mSvy^{-1})
SWA_1	3.236	14.642	0.0027	17.881
SWA_2	3.048	16.342	0.0038	19.393
SWA_3	2.689	14.186	0.0043	16.879
SWA_4	2.441	10.642	0.0095	13.092
SWA_5	2.029	5.383	0.0040	7.416
SWA_6	2.082	6.290	0.0039	8.376
SWA_7	2.292	6.782	0.0039	9.078
SWA_8	1.393	10.586	0.0040	11.983
SWA_9	1.293	10.982	0.0037	12.279
SWA_{10}	1.219	9.974	0.0037	11.197
SWA_{11}	0.929	10.478	0.0039	11.410
SWA_{12}	1.459	11.297	0.0029	12.759
SWA_{13}	3.510	23.808	0.0031	27.321
SWA_{14}	3.626	14.237	0.0026	17.866
SWA_{15}	3.303	20.191	0.0029	23.496
SWA_{16}	2.542	13.954	0.0019	16.498
SWA_{17}	1.878	8.669	0.0080	10.554
SWA_{18}	2.000	10.618	0.0051	12.623
SWA_{19}	2.061	9.854	0.0041	11.919
SWA_{20}	2.569	5.198	0.0034	7.770
SWA_{21}	2.030	14.458	0.0038	16.492
SWA_{22}	1.775	21.545	0.0034	23.323
SWA_{23}	1.540	11.522	0.0038	13.066
SWA_{24}	1.873	14.933	0.0042	16.810
Mean	2.201	12.357	0.0040	35.208
Max.	3.626	23.808	0.0096	23.496

Min.	0.929	5.198	0.0019	7.416

Table 6: Annual effective dose due to ingestion by radionuclides of children in Okaba and Okobo

Sample ID	238U×10^{-1}(mSvy^{-1})	232Th ×10^{-1} (mSvy^{-1})	40K ×10^{-1} (mSvy^{-1})	Total dose×10^{-1}(mSvy^{-1})
SWA_1	3.699	6.101	0.0024	9.802
SWA_2	3.483	6.809	0.0035	10.296
SWA_3	3.074	5.911	0.0004	8.985
SWA_4	2.789	4.434	0.0008	7.224
SWA_5	2.319	2.243	0.0037	4.566
SWA_6	2.379	2.621	0.0036	5.004
SWA_7	2.619	2.826	0.0036	5.449
SWA_8	1.592	4.411	0.0038	6.007
SWA_9	1.477	4.576	0.0033	6.056
SWA_{10}	1.394	4.156	0.0034	5.553
SWA_{11}	1.062	4.366	0.0036	5.432
SWA_{12}	1.668	4.707	0.0027	6.378
SWA_{13}	4.011	9.920	0.0028	13.934
SWA_{14}	4.144	5.932	0.0024	10.078
SWA_{15}	3.774	8.413	0.0026	12.189
SWA_{16}	2.905	5.814	0.0017	8.721
SWA_{17}	2.146	3.612	0.0007	5.759
SWA_{18}	2.286	4.424	0.0005	6.711
SWA_{19}	2.355	4.106	0.0038	6.465
SWA_{20}	2.936	2.166	0.0031	5.105
SWA_{21}	2.320	6.024	0.0035	8.348
SWA_{22}	2.029	8.977	0.0031	11.009
SWA_{23}	1.760	4.801	0.0035	6.565
SWA_{24}	2.141	6.222	0.0038	8.367
Mean	2.515	5.149	0.0013	7.667
Max.	3.774	9.920	0.0038	13.934
Min.	1.062	2.166	0.0004	4.566

Table 7: Annual effective dose due to ingestion by radionuclides of adults in Okaba and Okobo

Sample ID	238U×10^{-1}(mSvy^{-1})	232Th ×10^{-1} (mSvy^{-1})	40K ×10^{-1} (mSvy^{-1})	Total dose×10^{-1}(mSvy^{-1})
SWA_1	3.545	7.321	0.0020	10.868
SWA_2	3.338	8.171	0.0028	11.512
SWA_3	2.946	7.093	0.0003	10.039

SWA_4	2.674	5.321	0.0007	7.996
SWA_5	2.222	2.692	0.0030	4.917
SWA_6	2.280	3.145	0.0029	5.428
SWA_7	2.501	3.391	0.0029	5.895
SWA_8	1.526	5.293	0.0031	6.822
SWA_9	1.416	5.491	0.0027	6.910
SWA_{10}	1.336	4.987	0.0027	6.326
SWA_{11}	1.018	5.239	0.0029	6.260
SWA_{12}	1.598	5.648	0.0022	7.248
SWA_{13}	3.845	11.904	0.0023	5.751
SWA_{14}	3.971	7.118	0.0019	11.091
SWA_{15}	3.617	10.096	0.0019	13.715
SWA_{16}	2.784	6.697	0.0014	9.482
SWA_{17}	2.057	4.334	0.0006	6.392
SWA_{18}	2.190	5.309	0.0004	7.499
SWA_{19}	2.257	4.927	0.0031	7.187
SWA_{20}	2.813	2.599	0.0025	5.415
SWA_{21}	2.224	7.229	0.0028	9.456
SWA_{22}	1.944	10.772	0.0025	12.719
SWA_{23}	1.687	5.761	0.0028	7.451
SWA_{24}	2.052	7.466	0.0031	9.521
Mean	2.410	6.167	0.0022	8.579
Max.	3.974	11.904	0.0031	15.751
Min.	1.010	2.599	0.0003	4.917

The annual effective dose equivalent (AEDE) due to ingestion of ^{238}U, ^{232}Th, and ^{40}K in water samples was measured depending on each individual population group, and were well above the recommended reference value of 0.1 $mSvy^{-1}$ intake of drinking water, in accordance with the recommendations from (WHO, 2018).

It is clear from the results in Tables (5, 6, and 7), that the range estimated values of annual ingestion dose of natural radionuclides of ^{238}U, ^{232}Th, and ^{40}K in water samples (surface and borehole water) were ranged from (7.416 to 23.496) x 10^{-1} $mSvy^{-1}$ for infants, from (4.566 to 13.934) x 10^{-1} $mSvy^{-1}$ for children, and from (4.917 to 15.751) x 10^{-1} $mSvy^{-1}$ for adults, these values are far above the recommended safe level of 0.1 $mSvy^{-1}$ established by the (WHO, 2018). Also, the total mean annual effective dose in water samples for infants, children and adults are estimated to be (35.208, 7.667, and 8.579) x 10^{-1} $mSvy^{-1}$, respectively, which are higher than the WHO permissible limit of 0.1 μSvy^{-1}. This individual dose represents a very high level of risk that is expected to give rise to detectable adverse health effect. Therefore, the studied samples are considered not safe and pose radiological health risk.

5. Conclusion

This study assessed the radiological hazards in the water of the Okaba and Okobo coalfields and their environs in Ankpa, Kogi State, Nigeria, using gamma-ray spectroscopy. The results revealed significant activity concentrations of uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K), with mean values of 104.8 Bq/L, 51.49 Bq/L, and 719.64 Bq/L, respectively. The radium equivalent activity had a mean of 573.87 Bq/L, indicating potential risks from radium exposure.

The calculated radiological hazard indices, including radon equivalent, external hazard index (Hex), internal hazard index (Hin), indoor and outdoor dose rates (Din and Dout), and the alpha index, provide insights into the potential health risks associated with the water in these coalfield areas. The mean values of Hex (0.633) and Hin (0.908) suggest that while external radiation exposure is within safe limits (Hex < 1), internal exposure due to radium and uranium ingestion may pose some health risks (Hin > 1 in certain locations). Additionally, the mean dose rates (Dout: 109.531 nGy/h, Din: 210.627 nGy/h) exceed the global average recommended by UNSCEAR, highlighting potential long-term radiological risks for local populations consuming or using this water.

The estimated annual effective dose for different age groups shows that infants (mean: 0.3521 mSv/year), children (mean: 0.7667 mSv/year), and adults (mean: 0.8579 mSv/year) may be at varying levels of radiological risk, with infants being the most vulnerable. The alpha index, with a mean of 0.524, suggests moderate alpha radiation exposure, which could contribute to long-term health effects.

The findings emphasize the need for continuous radiological monitoring and the implementation of mitigation measures to ensure water safety in the region. Further studies should include biological assessments to evaluate the long-term health implications of radiation exposure and propose appropriate remediation strategies.

Conflicts of Interest: The authors declare no conflict of interest.

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