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Radionuclide Contamination in Water Sources in Kaabong District, Uganda

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Radionuclide Contamination in Water Sources in Kaabong District, Uganda.

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Abstract

This study assessed the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in water samples from selected boreholes in the Kaabong District. The study sampled boreholes from the sub-counties of Loyoro, Sidok, Kaabong Central, Kaabong East, and Kasile. The radioactivity concentration of the radionuclides was determined using gamma-ray spectrometry. We assessed radiological health risks by calculating the annual effective dose (AED) for infants, children, and adults, and the excess lifetime cancer risk (ELCR). The AED and ELCR were compared with the World Health Organization (WHO) safety limits. Results indicated the presence of gamma radiation from ^{226}Ra, ^{232}Th, and ^{40}K in the water samples. The overall average activity concentration in the sub-counties for the radiation was: 1.19 Bq/L for ^{226}Ra, 2.10 Bq/L for ^{232}Th, and 0.62Bq/L for ^{40}K. These levels of activity concentration are above the safety limits of 1.0 Bq/L for ^{226}Ra and ^{232}Th. The activity concentration for ^{40}K, was below the WHO recommended limit of 10.0 Bq/L. The AED averages were above the safety limits of 100 μSv/y for adults. For children, the communities in Loyoro, Sidok, and Kaabong East ingested more than 100 μSv/y of gamma radiation associated with ^{226}Ra. For Kaabong Central and Kasile, the ingestion rate is below the 100 μSv/y safety limit. Overall, the results indicated radiological risks associated with the sampled borehole water.

Keywords: Kaabong, Natural radiation, Annual effective dose, excess life cancer risk.

1 Introduction

A large number of naturally occurring radionuclides are present in the environment [1]. These are referred to as Naturally Occurring Radioactive Materials (NORMs) [2, 3]. The NORMs are emitted as alpha, beta, and gamma rays, predominantly by radionuclides such as uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K) [4, 5]. The sources of the radionuclides have been traced to radioactive decay, nuclear reactions, interaction of cosmic radiation with the Earth's atmosphere, and geological minerals [1].

According to the literature, low levels of exposure to natural radiation have been reported to be harmless [1]. However, many studies have associated prolonged inhalation of NORMs with carcinogenic risks and health effects [3, 5]. For these reasons, regulatory organizations have quantified and established exposure limits to mitigate the effects of radiation exposure [6]. These organizations include the International Commission on Radiological Protection (ICRP), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the World Health Organization (WHO). These organizations recommend: indoor radon levels below 200 $Bqkg^{-1}$, radium equivalent concentration below 370 $Bqkg^{-1}$, annual gamma dose rates not exceeding 1.5 $mSvyear^{-1}$, and internal and external hazard indices below 1 [7]. Additionally, the annual effective does limits by ingestion are: 1Bq/L for ^{226}Ra, and ^{232}Th, and 10Bq/L for ^{40}K. Thus, to ensure that radiation exposures remain within regulatory limits, it is important to assess environmental radioactivity levels to verify compliance [5]. To this end, many studies have been conducted to assess the levels of radioactivity in the environment.

Thabayneh et al [6]evaluated natural radioactivity in soil samples east of Jerusalem, in the West Bank. In particular, the concentrations of ^{222}Rn , radium content, radon exhalation rate, and annual effective dose in the soil samples were determined. Outside the walls, an average radon concentration of 194.4 $\pm$131.9Bqm^{-3} was reported. Inside the walls, the average value was 234$\pm$135.1 $Bqm^{-3.}$ The average total annual effective dose was 6.7 $\pm$ 4.5 $mSvy^{-1}$, outside the wall, and 8.1$\pm$ 4.6$mSvy^{-1}$ inside the walls. The radon concentration levels and annual effective dose in most samples were found to fall within the limits recommended by ICRP and UNSCEAR. Kidane et al assessed the concentration of natural radionuclides in soil samples from Bambasi district in Ethiopia's Benishangul Gumu region [7]. The average concentration of ^{238}U and ^{232}Th was found to exceed the recommended worldwide population-weighted average of 32.0 and 45.0Bg/kg. The mean absorbed dose was reported as 91.6 $\pm$5.1 nGy/h, which is above the recommended limit of 59nGy/h. The AED equivalent for indoor and outdoor exposures was reported as 2.65 $\pm$0.14 mSv/y and 0.66 $\pm$ 0.1 mSv/y, respectively. The calculated mean values of the internal hazard index, external hazard index, and gamma index across all the soil samples were found to be below the recommended thresholds.

Uosif et al[4] evaluated radioactivity in the newly reclaimed soils in Qena, Egypt using natural radioactivity measurements (^{226}Ra, ^{232}Th, ^{40}K). Samples were collected from the surface and subsurface. Bivariate and multivariate statistical studies indicated that the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were within the range: 5 ± 0.20 to 14 ± 0.7, 3 ± 0.20 to 14 ± 0.70, and 11 ± 0.50 to 72 ± 3.60 Bq kg-1, respectively. These values fall below the global average according to the report. Almaoud et al [5] assessed radioactivity levels of groundwater samples from the bedrocks found in the northern region of Saudi Arabia. Gross alpha/beta and ^{228}Ra radioactivity in water samples were determined using a liquid scintillation counting technique. Alpha spectrometry was used to determine the concentration of $^{234,238}U$ and ^{226}Ra. Results indicated that the water samples contained higher levels of gross alpha and beta radioactivity, exceeding the limits recommended by the WHO. Uzorka et al assessed the radiological quality of borehole water in Arua City, Northern Uganda [8]. The aim was to determine the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, the associated Annual Effective Dose (AED), and Excess Lifetime Cancer Risk (ELCR). It was determined that the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, ranged from 0.191–0.971 BqL^{-1}, 0.025–0.244 BqL^{-1}, respectively, which is below the world-recommended limit of 4.36 BqL^{-1}. Further analysis revealed that AED values were between 47.3 and 234.9 μSvy^{-1}, with all boreholes in Arua City Central exceeding the WHO guidance level of 100 μSvy^{-1}. ELCR values ranged from 1.89×10^{-4} to 9.39×10^{-4}, with the highest risks recorded in BH4-. In another study, Tukahirwe et al evaluated the radiological quality and the associated health risks of water from Lake Edward, located in Rukungiri District, Uganda [9]. Radiological water quality was evaluated by measuring gross alpha and beta activities. The activity concentration

of NORMs was also determined using gamma-ray spectroscopy. Annual effective dose (AED) for water consumed by children and adults, excess lifetime cancer risk (ELCR), and radiological hazard index (HI) were also assessed. The mean gross alpha activity ranged from 0.16±0.07 Bq L^{-1} in the fishing zone to 0.66±0.05 Bq L^{-1} in the farming zone, while gross beta activity ranged from 0.22±0.03 to 0.75±0.05 Bq L^{-1}. The activity concentrations of the NORMs, ^{226}Ra, ^{228}Ra, and ^{40}K were 0.28±0.03 Bq L^{-1} , 0.21±0.03 Bq L^{-1} , and 0.44±0.06 Bq L^{-1} , respectively. AED values ranged from 0.022 to 0.128 mSv y^{-1} for adults and from 0.010 to 0.065 mSv y^{-1} for children, with some regions exceeding WHO-recommended levels. ELCR values were within the recommended limits.

In Uganda, limited studies [7, 8, 9] have been done to assess the levels of NORMs in drinking water. In the present study, the presence and activity concentration of naturally occurring radionuclides (^{226}Ra, ^{232}Th, ^{40}K) in borehole groundwater in selected sub-counties of Kaabong District, Uganda, have been assessed, together with the associated radiological health risks.

2 Materials and Methods

2.1 Study area

The study area, Kaabong District, is located between longitudes 33˚ 30’ 31’’ to 34° 31’ 28’’ and latitudes 3° 45’ 11’’ to 3° 6’ 44’’ east of the Green Witch Meridian, and covers an area of approximately 7300 km sq. This region is in the North Eastern part of Uganda. It shares a border with the Republic of South Sudan to the North, the Republic of Kenya to the East, Moroto District to the South East, Kotido District to the South, and Karenga District to the West. Figure 1 is a map extract of the area.

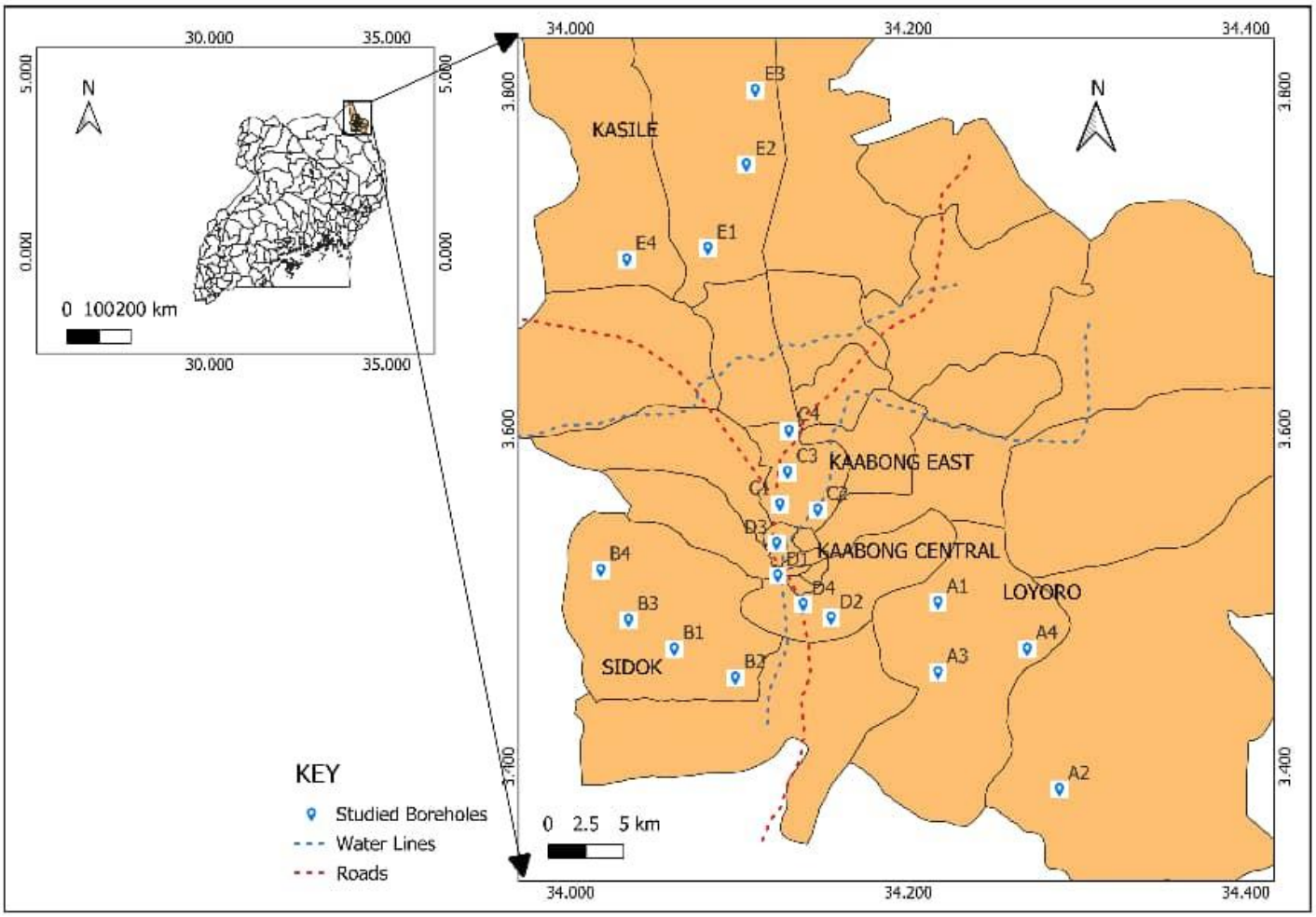


Figure 1: Map of Kaabong District showing locations of boreholes from where water samples were collected

The coordinates of the boreholes are presented in Table 1.

Table 1: Coordinates of boreholes from which samples were collected

SN	Code	Name	Latitude	Longitude
1	A1	Loyoro	3.4976º	34.2175º
2	A3	Loyoro	3.4561º	34.2175º
3	A4	Loyoro	3.4699º	34.2703º
4	A2	Loyoro	3.3868º	34.2894º
5	B2	Sidok	3.4528º	34.0975º
6	B1	Sidok	3.4699º	34.0613º
7	B3	Sidok	3.4871º	34.0342º
8	B4	Sidok	3.5167º	34.0178º
9	C1	Kaabong East	3.5556º	34.1239º
10	C2	Kaabong East	3.5523º	34.1463º
11	C3	Kaabong East	3.5747º	34.1285º

12	C4	Kaabong East	3.5991°	34.1292°
13	D2	Kabong central	3.4884°	34.1542°
14	D4	Kabong central	3.4963°	34.1377°
15	D1	Kabong central	3.5134°	34.1226°
16	D3	Kabong central	3.5325°	34.1219°
17	E4	Kasile	3.7006°	34.0332°
18	E1	Kasile	3.7074°	34.0812°
19	E2	Kasile	3.7569°	34.104°
20	E3	Kasile	3.801°	34.1093°

Geologically, the stratum comprises mainly the Pre-Cambrian system; the Mesozoic and Cenozoic groups of Kaabong District extend from Karamoja Sub-region. The Mesozoic and Cenozoic rocks are associated with volcanic eruptions in the eastern parts of the region.

The soil types in the area include; ferallic, vertigos and ferruginous tropical soils. Additionally, in some areas, there are also litho soils. The rocks in the area are enriched with radioactive minerals, and there is no major water body in the area. Five sub-counties of Kasile, Loyoro, Sidok, Kaabong East, and Kaabong Central were selected due to their geology and borehole density.

2.2 Sample collection and preparation

Water samples were collected from both mineralized and non-mineralized regions within the study area, ensuring representation of varying geological settings. Specifically, four (4) water sources were sampled from each of the five selected sub-counties, with sampling locations chosen to reflect both areas with known mineral deposits and those without significant mineralization. To reduce spatial correlation and ensure independent sampling, water sources were selected such that they were at least 500 meters apart [8]. In total, twenty (20) water samples were collected directly into clean, half-litre (0.5 L) mineral water bottles and clearly labeled with the corresponding sub-county and whether the source was from a mineralized or non-mineralized area. The samples were taken to Makerere University Radiation Laboratory, and each sample was transferred into a standard polyethylene Marinelli beaker for gamma spectroscopy analysis.

The samples were stored at room temperature on numbered shelves within a controlled sample processing area designed to minimize contamination, cross-contamination, and damage to containers. To preserve the integrity of the samples, nitric acid was added to adjust the pH to 2.0. This acidification halts biological activity, stabilizes dissolved radionuclides, and prevents adsorption onto the container walls [10]. The samples were then left for at least 21 days in order to attain secular equilibrium between uranium and thorium decay daughter elements.

The water samples were later analyzed to determine the existence of gamma-ray-emitting radionuclides and the activity concentrations of the radionuclides using a sodium iodide detector that was thallium-activated.

Before measurements, the NaI detector, linked to a computer with a multichannel analyzer (MCA) (Figure 2) was first calibrated. The NaI (Tl) detector system and its photomultiplier tube (PMT) were mounted in a box and surrounded by lead blocks in order to shield the contents from background radiation. The lead shield contained an inner layer of copper (0.3 mm) thick to absorb characteristic X-rays generated in the lead shield. The detector was connected to the computer with.

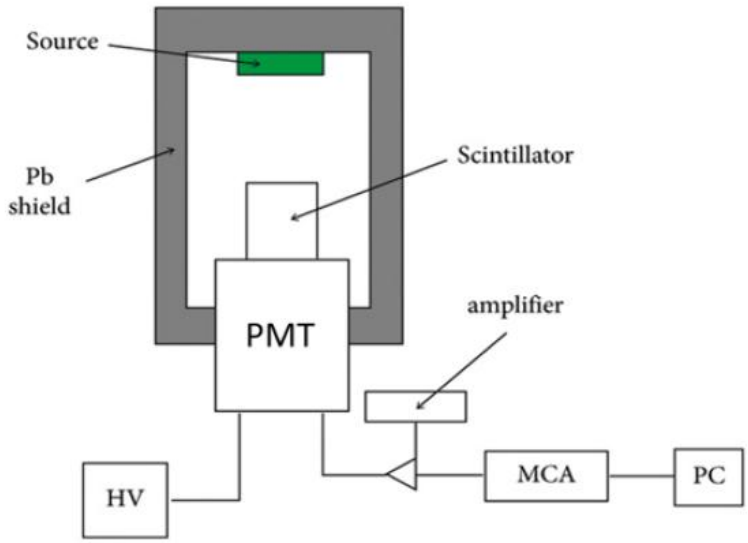


Figure 2: Sodium Iodide scintillator detector system

3 Results and Discussion

3.1 Activity concentration

The activity concentration of each of the radionuclides present was calculated following Equation (1) [8, 9];

$$A = \frac{N}{\varepsilon \times P_\gamma \times t \times V} \qquad (1)$$

Where: A is the activity count (Bq/L), N denotes the peak counts, ε represents the full energy peak efficiency of the detector at the specific gamma energy, P_γ represents the probability of emission of the gamma line, t ,

measured in seconds, stands for the live counting time, and V indicates the volume of the sample, measured in liters.

The calculated values of activity concentration for ^{226}Ra, ^{232}Th, and ^{40}K for the five sub-counties are presented in Table 1

Table 2: Activity *c*oncentration (Bq/L) of *r*adionuclides in *b*orehole *w*ater *s*amples. A = Loyoro; B = Sidok; C = Kaabong East; D = Kaabong Central; E = Kasile; BH = Borehole. Activity concentrations are expressed in Bq/L.

BH	**^{226}Ra**					**^{232}Th**					**^{40}K**				
	A	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
1	0.71	0.66	1.01	0.95	0.88	1.67	1.05	0.78	2.62	2.58	0.28	1.80	0.20	0.92	0.73
2	0.40	0.63	2.15	1.32	2.61	2.46	0.99	2.07	3.14	1.55	0.32	0.68	–	0.82	1.03
3	1.26	1.94	0.92	0.92	0.79	2.67	1.62	0.98	2.00	3.05	0.41	0.33	0.21	–	0.90
4	3.39	1.24	0.22	0.47	1.26	2.46	1.36	0.61	4.15	4.15	–	0.46	–	0.21	0.59
Average	1.44	1.12	1.08	0.92	1.39	2.31	1.26	1.11	2.98	2.83	0.34	0.82	0.14	0.49	0.81

As seen in Table 1, there is significant variation in the radionuclide concentration in all the sub-counties and across all boreholes.

In Loyoro sub-county (A), the radionuclide concentration averages were: 1.44 Bq/L, 2.31Bq/L, and 0.34 Bq/L.

for ^{226}Ra, ^{232}Th, and ^{40}K respectively, with the range of values; 0.40 Bq/L - 3.39 Bq/L for for ^{226}Ra, 1.67 Bq/L - 2.67 Bq/L for ^{232}Th, and 0.28 Bq/L - 0.41Bq/L for ^{40}K .

For Sidkok sub-county, labeled B, the highest values for ^{226}Ra, ^{232}Th, and ^{40}K were: 1.94 Bq/L, 1.62 Bq/L, and 1.80Bq/L respectively. The lowest values were, respectively, 0.63 Bq/L, 0.99 Bq/L, and 0.33 Bq/L. The average values were: 1.12 Bq/L, 1.26 Bq/L, and 0.82 Bq/L. In Kaabong East sub-county labelled C, the range of ^{226}Ra, ^{232}Th, and ^{40}K were, respectively, 1.15 Bq/L – 0.22 Bq/L, 2.07 Bq/L-0.61 Bq/L, and 0.21 Bq/L to 0.20 Bq/L. The average values calculated were, respectively: 1.08 Bq/L, 1.11 Bq/L, and 0.14 Bq/L. In Kaabong Central, labelled D, the range was; 1.32 Bq/L to 0.47 Bq/L, 4.15 Bq/L to 2.62 Bq/L, and 0.92 Bq/L to 0.21 Bq/L for ^{226}Ra, ^{232}TH, and ^{40}K respectively. The average values in the same sub-county were 0.92 Bq/L, 2.98 Bq/L, and 0.49 Bq/L, respectively. In Kasile, labelled E, the range for ^{226}Ra, ^{232}TH, and ^{40}K was 1.26 Bq/L to 0.79 Bq/L, 4.15 Bq/L –

to1.55Bq/L, and 1.03 Bq/L – 0.59 Bq/L , respectively. The average values were; 1.39 Bq/L, 2.83 Bq/L, and 0.81 Bq/L respectively.

The presence of ^{226}Ra and ^{232}Th in the samples suggests the presence of ^{238}U and ^{232}Th in aquifer rocks [11]. This is because ^{226}Ra and ^{232}Th are part of the decay series of the parents: ^{238}U and ^{232}Th. Across the five sub-counties, the concentration level for ^{232}Th was the highest, followed by ^{226}Ra and ^{40}K. The sub-counties with high average values of radioactivity concentration are probably centers at which groundwater dissolves the radionuclides from the mineral-bearing rocks. The radionuclides then find their way into drinking water [8].

The variations in the concentration of the radionuclides in the five sub-counties are shown as a bar graph in *Figure 3* .

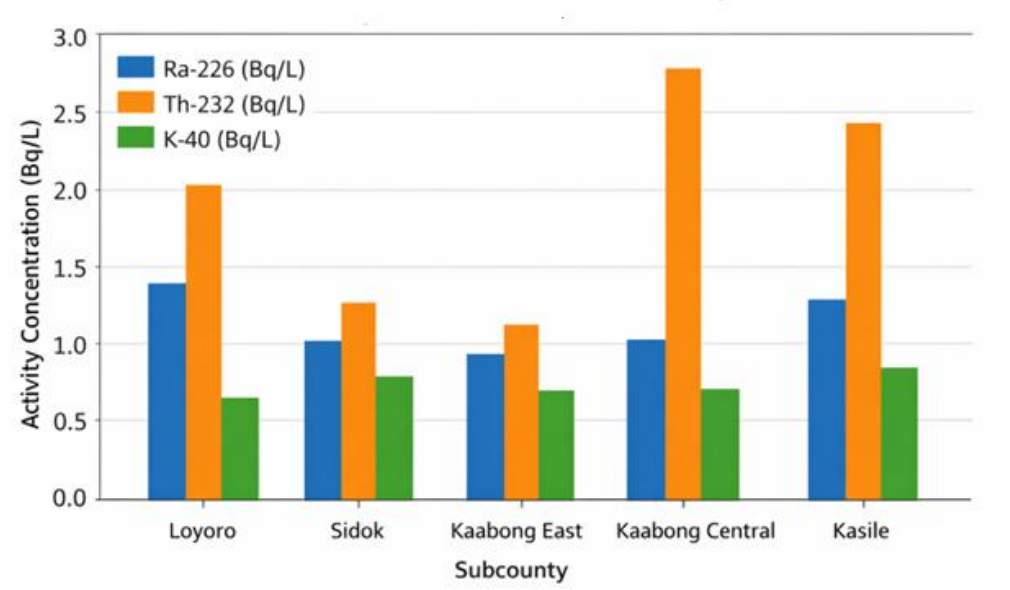


Figure 3: Bar graph showing activity concentration of ^{226}Ra, ^{232}Th and ^{40}K across the five sub counties of Loyoro, Sidok, Kaabong East, Kaabong Central, and Kasile

The WHO safety limits are; 1.0 Bq/L for ^{232}Th and ^{226}Ra, and 10 Bq/L for ^{40}K [12]. Looking at Table 1, the average concentration of ^{40}K in all five sub-counties is below the WHO reference level. The average values of concentration for ^{232}Th and ^{226}Ra are above the WHO reference levels in all sub-counties, except Kaabong Central. The elevated levels of ^{232}Th and ^{226}Ra in the communities therefore pose environmental and health risks to the communities[12]. The descriptive statics for the entire study area of Kaabong is presented in Table 2

Table 3: Descriptive statistics for activity concentration for ^{226}Ra, ^{232}Th, and ^{40}K in water samples

Statistics	**^{226}Ra**	**^{232}Th**	**^{40}K**
Minimum (Bq/L)	0.22	0.61	0.20
Maximum (Bq/L)	3.39	4.15	1.80
Range (Bq/L)	3.17	3.54	1.60
Mean (Bq/L)	1.19	2.10	0.62
Standard deviation (Bq/L)	0.79	1.03	0.42
Skewness	1.51	0.51	1.51
Kurtosis	2.23	-0.35	3.00

From the Table, it is observed that, for ^{226}Ra, the minimum activity concentration was 0.22 Bq/L, and the maximum was 3.39 Bq/L, with a range and mean of 3.17 Bq/L and 1.19 Bq/L respectively. The standard deviation is 0.79 Bq/L, and a kurtosis of 2.23, and skewness 1.51. The small value of the standard deviation signifies that; the data points are spread closer to the mean value, and a kurtosis of 2.23 indicates a platykurtic distribution [13].

Considering ^{232}Th, the range of the activity concentration spanned from 0.61 Bq/L to 4.15 Bq/L, with a range of 3.54 Bq/L. The mean value is 2.10 Bq/L, with a standard deviation of 1.03 Bq/L, which implies that, the data points are spread further way from the mean value. A kurtosis of -0.35 indicates a curve that is flatter than the standard normal curve, and thinner tails [14]. The data is positively skewed with a value 0.51.

The values for the activity concentration for ^{40}K had a range of 1.60 Bq/L, spanning from 0.20 Bq/L to 1.80 Bq/L. The mean and standard deviation were 0.62 Bq/L and 0.42 Bq/L, respectively. The value of the standard deviation is relatively high. This suggests the data points are quite spread away from the mean. The Kurtosis of 3.00 indicates a normal distribution of the data[13].

The WHO recommends safety limits for activity concentration for ^{40}K at 10Bq/ L, and 1.0 Bq/L for ^{226}Ra and ^{232}Th. Thus, in Kabong district, there are elevated gamma radiation attributed to ^{226}Ra and ^{232}Th, which exceed the WHO limits. The activity concentration for ^{40}K, is below the safety limits set by the WHO ().

Studies regarding the activity concentration of naturally occurring radionuclides have been widely studied and documented. In *Table 3* , average values of activity concentration of naturally occurring radiation in water determined in other studies are compared with the results in the present study.

Table 4: Comparison of activity concentration of natural radiation with present study

Place	**Water type**	**Activity concentration (Bq/L)**			
		^{226}Ra	**^{232}Th**	**^{40}K**	
Kampala, Uganda	Bottled water	4.45 ± 0.20	1.32 ± 0.27	46.33 ± 0.24	[10]
Kampala, Uganda	Tap water	4.00 ± 0.10	1.40 ± 0.19	47.05 ± 0.21	
Dhaka city and Savar, Bangladesh	Ground water	1.61 ± 0.51		57.42 ± 3.16	[11]
South West, Nigeria	Ground water		17.42 ± 3.92	220.35 ± 64.43	[15]
Carlsbad, New Mexico	Ground water	5.88 Bq/L			[16]
Kaabong, Uganda	Ground water	1.19	2.10	0.62	Present work

From Table 3,The values of the activity concentration are comparable to those reported elsewhere.

Place	**Water type**	**ELCR**		
		^{226}Ra	**^{40}K**	
Kampala, Uganda	Bottled water	0.00177	0.001	[10]
Kampala, Uganda	Tap water			
Dhaka city and Savar, Bangladesh	Ground water	36.97×10^{-4}		[11]
South West Nigeria	Ground water	7.1×10^{-3}		[15]

3.2 Radiological hazards associated with radionuclide contamination in the water samples

3.2.1 Absorbed Dose due to Ingestion Dose

When water is contaminated with active radionuclides and consumed in the human digestive system, the radionuclides are said to have been ingested. The absorbed active radionuclides are quantified through annual effective dose (AED). The AED was calculated following the Equation [17];

$$AED = A \times CF \times CR \times 10^{6}$$

Where: A stands for activity concentration in Bq/L, CF denotes the dose coefficient, which is 2.8×10^{-7}Sv/Bq for ^{226}Ra, and 6.2×10^{-9}Sv/Bq for ^{40}K, and CR the rate of consumption of water at 250,

350, and 730 L/year for infants, children, and adults, respectively [18]. Table 2, Table 3, and Table 4, indicate the calculated annual effective dose for infants, children, and adults is presented in respectively.

Table 5: Annual effective dose (AED) from ingestion (Infants). A = Loyoro; B = Sidok; C = Kaabong East; D = Kaabong Central; E = Kasile; BH = Borehole.

	AED (μSv/y) for ^{226}Ra					AED (μSv/y) for ^{40}K				
BH	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
1	49.70	46.20	70.70	66.50	61.60	0.43	2.79	1.55	1.43	1.13
2	28.00	44.10	150.50	92.40	182.70	0.50	1.05	-	1.27	1.60
3	88.20	135.80	64.40	64.40	55.30	0.64	0.51	1.55	-	1.40
4	237.30	86.80	15.40	32.90	88.20	-	0.71	-	0.33	0.91
Average	**41.48**	**56.53**	**71.40**	**55.83**	**74.90**	**0.52**	**1.09**	**1.55**	**0.90**	**1.03**

For infants, Table 5, In Loyoro subcounty, the AED for ^{226}Ra in infants averaged 41.48 μSv/y, with values spanning from 28.00 to 237.30 μSv/y. For ^{40}K, the range was 0.43 to 0.64 μSv/y. The average AED for 40K was 0.52 μSv/y. In Sidok, labelled B, the mean value calculated was 56.53 μSv/y for ^{226}Ra, with values ranging from 44.10 to 135.80 μSv/y. In the same subcounty,the range for 40K, was 0.51 to 2.79 μSv/y, with a mean value of 1.09 μSv/y. In Kaabong, C East, AED for ^{226}Ra, ranged from 15.40 to 150.50 μSv/y, with an average value of 71.40 μSv/y. Two samples were registered in respect of ^{40}K, each with AED of 1.55 μSv/y . In Kaabong Central, labelled D, the calculated AED (^{226}Ra) averaged 55.83 μSv/y in infants, with a range from 32.90 to 92.40 μSv/y. For ^{40}K, the mean value registered was 0.90 1.43 μSv/y, and the range was from 0.33 to 1.43 μSv/y. In Kasile, labelled E, AED for ^{226}Ra had an average 74.90 μSv/y, with a range of values spanning from 55.30 to 182.70 μSv/y. For ^{40}K, the AED spanned from 0.91 – 1.13 μSv/ with a mean value of 1.03 μSv/y.

Table 6: Annual effective dose (AED) from ingestion (Children). A :Loyoro; B : Sidok; C :Kaabong East; D:Kaabong Central; E :Kasile; BH:Borehole.

	AED (μSv/y) for ^{226}Ra					AED (μSv/y) for ^{40}K				
BH	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
1	69.58	64.68	98.98	93.10	86.24	0.61	3.91	2.17	2.00	1.58
2	39.20	61.74	210.70	129.36	255.78	0.69	1.48		1.78	2.24
3	123.48	190.12	90.16	90.16	77.42	0.89	0.72	2.17		1.95
4	332.22	121.52	21.56	46.06	123.48		1.00		0.46	1.28
Average	**141.12**	**109.52**	**105.35**	**89.67**	**135.73**	**0.73**	**1.77**	**2.17**	**1.41**	**1.76**

Considering AED for children in Table 6, AED values are significantly larger than those of in Table 5. This is because the Equation used to compute the AED assumes that children consume more water than infants.

In Loyoro sub-county, labelled A, the AED had a mean value of 141.12 μSv/y for ^{226}Ra . The range spanned from 39.2 to 332.22 μSv/y. For ^{40}K , the mean value of AED was 0.73 μSv/y, and the range was from 0.61 to 0.89 μSv/y. In Sidok, the AED values for ^{226}Ra averaged 109.52 μSv/y with a range of values from 61.74 to 192.12. Concurrently, the range recorded for 40K in the sub-county was 1.00 to 3.91 μSv/y, with an average AED of 1.77 μSv/y. In Kaabong East, labelled C, the range for AED was 21.56 to 210.70 μSv/y; the average AED was 105.35 μSv/y in the sub-county. For 40K in the same sub-county, a value of 2.17 μSv/y was recorded at two boreholes. For Kaabong Central, AED values ranged from 46.06 to 129.36 μSv/y, with an average value of 89.67μSv/y. For ^{40}K in the same sub-county, the average was 1.41 μSv/y, with a range from 0.46 to 2.00 μSv/y . In Kasile sub-county, labelled E, the calculated AED averaged 135.67, spanning a range of 77.42 to 255.78 μSv/y for ^{226}Ra. In Sidok, a mean value of 109.52 μSv/y was registered for ^{226}Ra as the AED, with a range of values from 61.74 to 192.12 μSv/y. At the same time, the mean values of AED for ^{40}K were 1.76 μSv/y, with the range 1.28 to 2.54 μSv/y.

Table 7: Annual effective dose (AED) from ingestion (Adults). A : Loyoro; B : Sidok; C :Kaabong East; D :Kaabong Central; E : Kasile; BH :Borehole.

	AED (μSv/y) for ^{226}Ra					AED (μSv/y) for ^{40}K				
BH	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
1	145.12	134.90	206.44	194.18	179.87	1.27	8.15	4.53	4.16	3.30
2	81.76	128.77	439.46	269.81	533.48	1.45	3.08		3.71	4.66
3	257.54	396.54	188.05	188.05	161.48	1.86	1.49	4.53		4.07
4	692.92	253.46	44.97	96.07	257.54		2.08		0.95	2.67
Average	**294.34**	**228.42**	**219.73**	**187.03**	**283.09**	**1.14**	**3.70**	**2.26**	**2.21**	**3.68**

Table 4 presents the calculated values for the annual effective dose by ingestion for adults.

In Loyoro subcounty, labeled A, the annual effective dose for ^{226}Ra averaged 294.34 μSv/y, spanning 81.76 to 692.92 μSv/y. In the same subcounty, the AED for ^{40}K spanned 1.27 to 1.86 μSv/y, with an average value of 1.14 μSv/y. Similarly, the range for AED for ^{226}Ra in Sidok subcounty was 128.77 to 396.54 μSv/y. The average value was 228.42 μSv/y. In Kaabong East, the measured AED for ^{226}Ra averaged 219.73 μSv/y, with a range spanning 44.97 to 439.46 μSv/y. The measured value for ^{40}K in the same subcounty averaged 2.26 μSv/y, with only two values obtained as 4.53μSv/y. In Kaabong Central, the range for AED for ^{226}Ra was 96.07 to 269.81 μSv/y The average value for AED was 187.03 μSv/y. For ^{40}K, the mean value was 2.21μSv/y, with a range spanning 0.95 to 4.16 μSv/y. In Kasile sub-county, the AED for ^{226}Ra averaged 283.09 μSv/y, with a range of 161.48 to 533.48μSv/y. The mean AED for ^{40}K in the same sub-county was 3.68μSv/y, and the AED ranged from 3.30 to 4.66μSv/y.

Considering the average values, the annual effective dose by ingestion for infants (Table *2*) is all below 100 μSv/y. This falls within the safety limits of 100 μSv/y as set by the WHO. For children (Table *3*), the average AED (for 226Ra) for the sub counties: Loyoro, Sidok, and Kaabong East are above the 100 μSv/y limit. These sub counties are at risk of dangers associated with ingestion of gamma radiation. The rest of the sub counties

have average falls that fall below the 100 μSv/y safety limit set by the WHO, both for ^{226}Ra, and ^{40}K. The children in these sub-counties are therefore potentially safe.

The average AED for adults, (Table 4) for ^{226}Ra, are all above the 100 μSv/y limit, for all five sub-counties. For 40K, the average AEDs are all below 10 μSv/y. These communities are therefore not safe, according to the WHO guidelines [18].

3.3 Radiological Risks

3.3.1 Excess Lifetime Cancer Risk (ELCR)

The prolonged consumption of gamma radiation beyond certain levels has the possibility of causing cancer at a later stage in life. The parameter that enables the evaluation of whether cancer will manifest at a later stage in life is the excess lifetime cancer risk (ELCR), as defined through Equation (5).

$$ELCR = A \times CR \times LT \times CRT \quad (5)$$

Where: A stand for the activity concentration in Bq/L, CR is the consumption rate of drinking water, LT is the average lifetime, taken to be 72.4 years, and CRC denotes the cancer mortality risk coefficient for ingestion of radionuclides. The values for CRC are; 7.17×10^{-9}, 2.00×10^{-8}, and 4.30×10^{-10}/Bq for ^{226}Ra, ^{228}Ra, and ^{40}K respectively.

The ELCR due to consumption of ^{226}Ra was evaluated based on values of activity concentration from each sub-county. The consumption rate of drinking water was assumed to be 730L/y. The estimated ELCR values are presented in *Table 5*.

Table 8: ELCR caused by ingestion of ^{226}Ra from each of the sub-counties. A: Loyoro; B: Sidok; C: Kaabong East; D: Kaabong Central, and E: Kasile sub-counties

Borehole	A	B	C	D	E
1	1.02×10^{-3}	7.80×10^{-4}	6.50×10^{-4}	1.40×10^{-3}	1.35×10^{-3}
2	1.35×10^{-3}	7.40×10^{-4}	1.32×10^{-3}	1.38×10^{-3}	1.25×10^{-3}
3	1.70×10^{-3}	1.10×10^{-3}	6.60×10^{-4}	7.60×10^{-4}	1.30×10^{-3}
4	2.00×10^{-3}	9.50×10^{-4}	3.00×10^{-4}	1.20×10^{-3}	1.00×10^{-3}
Average	$\mathbf{1.52 \times 10^{-3}}$	$\mathbf{9.00 \times 10^{-4}}$	$\mathbf{6.95 \times 10^{-4}}$	$\mathbf{1.09 \times 10^{-3}}$	$\mathbf{1.23 \times 10^{-3}}$

As seen in *Table 8* the values of ELCR vary in the order of 10^{-3} – 10^{-4}, across all the sub-counties. In Loyoro sub-county, range of ELCR was from 1.02×10^{-3} to 2.00×10^{-3}, with an average value of 1.52×10^{-3}. Sidok sub-county ristered a range spanning from 7.4×10^{-4} to 1.10×10^{-3} , with an average of 9.00×10^{-4}, .

In Kaabong East, the measurements averaged 6.95×10^{-4} with a range spanning from $30 \times$ed a range from 7.60×10^{-4} to 1.40×10^{-3}, with an average value of 1.09×10^{-3}. In Kasile subcounty, the smallest value of ELCR was 1.00×10^{-3}, and the largest was 1.35×10^{-3}. The calculated mean value was 1.22×10^{-3}. The mean ELCR values for all the sub-counties are above the safety limit value of 0.29×10^{-3} [18]. *Table 9* indicates the descriptive statistics for the ELCR for Kaabong district.

Table 9: Descriptive statistics for the excess lifetime cancer risk for Kaabong District

Statistics	**ELCR**
Minimum	0.30×10^{-3}
Maximum	2.00×10^{-3}
Range	1.70×10^{-3}
Mean	1.11×10^{-3}
Standard deviation	0.40×10^{-3}
Skewness	0.13×10^{-3}
Kurtosis	0.32×10^{-3}

The descriptive statistics indicate a minimum value for excess lifetime cancer risk of 0.30×10^{-3} and a maximum value 2.30×10^{-3}, giving a range of 1.70×10^{-3}. The calculated mean value is 1.11×10^{-3}, with a standard deviation of 0.40×10^{-3}. This standard deviation indicates the data is spread closer about the mean value, but positively skewed. The kurtosis of 0.0032 indicates a platykurtic kind of distribution, that is, flatter than the standard bell curve. The data points are closer to the mean.

Table 9 compares the values mean value of ECLR with values reported in literature.

Table 10: Comparison of values of ECLR obtained in previous studies with the current work

Place	**Water type**	**ELCR**		
		^{226}Ra	**^{40}K**	
Kampala, Uganda	Bottled water	0.00177	0.001	[10]
Kampala, Uganda	Tap water			
Dhaka city and Savar, Bangladesh	Ground water	36.97×10^{-4}		[11]
South West Nigeria	Ground water	7.1×10^{-3}		[15]
Kaabong	Ground water	1.11×10^{-3}		Present work

As can be seen, the average value of ELCR is consistent with values that have been reported in literature.

4 Conclusion.

In Kaabong district, water sampled from selected boreholes in Loyoro, Sidok, Kaabong East, Kaabong Central, and Kasile sub-counties contains gamma radiation from ^{226}Ra, ^{232}Th, and ^{40}K. The overall average activity concentration for the radiation was: 1.19 Bq/L for ^{226}Ra, 2.10 Bq/L for ^{232}Th, and 0.62Bq/L for ^{40}K. These levels of activity concentration are above the safety limits of 1.0 Bq/L for ^{226}Ra, and ^{232}Th. The activity concentration for 40K, falls within the safety limit of 10.0 Bq/L. Analysis of the annual effective dose by ingestion for ^{226}Ra indicated mean values above the safety limit for 100 μSv/y for adults. For children, the communities in Loyoro, Sidok, and Kaabong East ingest more than 100 μSv/y of gamma radiation associated with ^{226}Ra, which is above the limit set by the WHO. For Kaabong Central and Kasile, the ingestion rate is below 100 μSv/y safety limit. The consumption rate by infants is within the safety limits. The calculated excess lifetime cancer risk is above the world safety limit set by the WHO.

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