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Assessment of Radiological Risks, Radiogenic Heat and Natural Radioactivity in Kamukuywa River Sediments in Mt. Elgon Bungoma County, Kenya

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Abstract

The activity concentrations of ^{238}U, ^{232}Th and ^{40}K in sediments from the Kamukuywa River in Bungoma County were determined using a NaI(Tl) detector at South Eastern University Kenya, Physics Department in order to obtain the radium equivalent, absorbed dose rate, annual effective dose rate, hazard indices, radioelement concentrations (RC) and radiogenic heat production (RHP). The average activity concentrations for ^{238}U, ^{232}Th and ^{40}K were 31 ± 2 $Bq{\cdot}kg^{-1}$, 51 ± 3 $Bq{\cdot}kg^{-1}$, and 57 ± 3 $Bq{\cdot}kg^{-1}$, respectively. The average activity concentrations of ^{238}U and ^{40}K were less than the global limits of 35 $Bq{\cdot}kg^{-1}$ and 400 $Bq{\cdot}kg^{-1}$. The average activity concentration of ^{232}Th exceeded the international limit of 50 $Bq{\cdot}kg^{-1}$. The activity concentration ranged from 19 ± 1 to 48 ± 2 $Bq{\cdot}kg^{-1}$ for ^{238}U, 17 ± 1 - 89 ± 4 $Bq{\cdot}kg^{-1}$ for ^{232}Th and 35 ± 2 - 90 ± 5 $Bq{\cdot}kg^{-1}$ for ^{40}K. Radioelement concentrations ranged from 1.5 - 3.9 ppm for ^{238}U, 4 - 21 ppm for ^{232}Th and 11 - 28 ppm for ^{40}K, with averages of 2.5 ppm, 12 ± 1 ppm and 18 ± 1 ppm for each. The RHP for ^{238}U, ^{232}Th and ^{40}K was 0.001 $\mu W{\cdot}m^{-3}$ with a range of 0.001 $\mu W{\cdot}m^{-3}$ - 0.002 $\mu W{\cdot}m^{-3}$, 0.009 $\mu W{\cdot}m^{-3}$ with a range of 0.003 $\mu W{\cdot}m^{-3}$ - 0.016 $\mu W{\cdot}m^{-3}$ and 0.013 $\mu W{\cdot}m^{-3}$ with a range of 0.008 $\mu W{\cdot}m^{-3}$ - 0.021 $\mu W{\cdot}m^{-3}$. The average radiogenic heat production (RHP) for all radionuclides was 0.08 $\mu W{\cdot}m^{-3}$, lower than the global average of 4 $\mu W{\cdot}m^{-3}$ and ranging from 0.05 - 0.14 $\mu W{\cdot}m^{-3}$. Radium equivalent averaged 109 ± 6 $Bq{\cdot}kg^{-1}$, with a range of 55 ± 3 to 173 ± 9 $Bq{\cdot}kg^{-1}$. The internal and external hazard indices averaged at 0.2 $mSv{\cdot}y^{-1}$, with a range of 0.1 $mSv{\cdot}y^{-1}$ - 0.4 $mSv{\cdot}y^{-1}$ and 0.3 $mSv{\cdot}y^{-1}$, respectively. The extra lifetime cancer risk averaged 0.5×10^{-4} $mSv{\cdot}y^{-1}$, while the annual gonadal equivalent dosage averaged at 330 ± 17 $mSv{\cdot}y^{-1}$. The

average exposure rate was 47 ± 2 nGy/h, with an annual effective dose rate of 0.1 $mSv \cdot y^{-1}$ for both indoors and outdoors. All samples had radium equivalent, hazard index and annual effective dose rate values that were less than the globally accepted limits of 370 $Bq \cdot kg^{-1}$ and 1 $mSv \cdot y^{-1}$, respectively. As a result, sediment samples collected from Kamukuywa River pose low health risks to the general public. The heat flow (Hf) averaged at 7 $mW \cdot m^{-2}$ and ranged from 4 to 11 ± 1 $mW \cdot m^{-2}$. The Hf and RHP levels indicate that geothermal exploration in Bungoma County's Kamukuywa River is possible.

Subject Areas

Nuclear Physics

Keywords

Sediments, Sand, Activity Concentration Levels, Radiological Hazards and Radiogenic Heat Production

1. Introduction

The presence of radioactive elements in the human environment exposes humans to radiation from a variety of sources. Natural radionuclides in soil, water, air and plants, as well as man-made radioactivity from nuclear testing fallout and medical treatments, are among the sources [1] [2]. While breathing and swallowing radioactive compounds in food and drink may result in internal gamma radiation exposure, natural radionuclides and cosmic rays can cause external exposure [3]. These radionuclides, which decay radioactively in the environment, account for approximately 80% of radiation exposure from naturally occurring radionuclides in subterranean soils [4]. Nuclear activities, medical operations and cosmic rays account for around 20% of the exposure. This study focused on the radiation levels of terrestrial radionuclides such as Uranium-238, Thorium-232 and their decay products, as well as Potassium-40. Natural radionuclides in terrestrial ecosystems include ^{226}Ra, ^{232}Th, ^{40}K and the radioactive gas radon produced by the decay of these naturally occurring isotopes [5] [6].

Natural radioactivity is widely spread throughout the Earth's environment and fluctuates due to geographic and geological factors [7] [8]. [9], reports that the natural radioactivity of soils varies by region. Numerous alluvial and eluvial geological processes deep beneath the Earth's surface generate radionuclides [10] [11]. Many people in developing countries rely on sand harvesting for financial benefits, yet it can expose them to significant quantities of radiation [12]. This exposure can occur in a variety of ways in the mining, manufacturing, and mineral processing industries. These include breathing in dust containing long-lived alpha-emitting radionuclides, being exposed to external gamma radiation from ores, and inhaling radon's short-lived decay products [1] [13]. Inhaling radon decay products from water bodies can result in exposures that exceed the current

radiation threshold limits [14] [15]. Sand harvesters may be more likely to get lung cancer for a period of time as a result of their increased exposure risk [9]. Excavations reveal Naturally Occurring Radioactive Materials (NORMs) on the earth's surface, river sediments and sand tend to have higher radioactivity and background radiation levels [15]. The use of contaminated equipment or sediment waste media without proper controls, as well as drilling, leaching, panning, handling, storing and transporting sand, all pose environmental and health concerns associated with NORMs in sand harvesting locations [8] [16].

Natural radioactivity levels can be used to predict the long-term health effects of exposure to the source on humans, animals and the environment [17]. These isotopes are still present in the Earth's crust as substantial heat generators and their half-lives are roughly equal to the planet's age (1010 years). The average abundances of ^{238}U, ^{232}Th and ^{40}K in the Earth's crust are around 3 ppm, 12 ppm and 120%, respectively [18]. The decay of ^{238}U, ^{232}Th and ^{40}K in the Earth's crust produces energetic particles (α- and β-particles) and γ-rays. Except for the neutrino's energy, all of the energy released during the decay is converted to heat. The decays of ^{238}U and ^{232}Th are currently the most common heat producers, with heat production constants of 2.56×10^{-5} w·kg^{-1} and 9.52×10^{-5} w·kg^{-1} [18]. With a heat production constant of 3.48×10^{-9} w·kg^{-1}, the ^{40}K produces the least heat as compared to the ^{238}U and ^{232}Th [19]. Importantly, the term "Radiogenic Heat Production," or RHP in many parts of the world, has been used to assess geothermal resources because it can quantify heat movement in basement rocks that generate river sediments [20].

River sediments are regarded to be the environmental host of pollutants released by natural or man-made activities in our environment because they store and transmit toxins within the geographic region [20]. The majority of river sediments are formed when organic materials and rock are broken down into little pieces by flowing water, increasing the natural radioactivity levels in river sediments [21] Although it has not yet been done, determining the RHP in sediments is critical for evaluating geothermal potential in the Nzoia River in Bungoma County. To meet people's energy needs, geothermal energy must be developed as an alternative to hydropower and other sources [22]. As a result, in order to estimate the radiation exposure danger and geothermal potential of the area, this study describes the radioelement concentration and RHP findings in Bungoma County's Nzoia River. Kenya's mining department may use the study's findings for geothermal exploration and project development. The County of Bungoma may also use these findings to encourage the development of local geothermal resources as a substitute for traditional energy sources and to raise public awareness of their viability.

Long-term radiation exposure can have either stochastic or deterministic effects, including leukemia, cancer, cataracts, chronic lung diseases and skin damage [23] [24]. Furthermore, ionizing radiation damages human cells and genetic material, potentially resulting in mutations or cell death [16]. The International

Commission on Radiation Protection [25], is one of the international organizations that have implemented stringent safeguards to reduce the health risks associated with NORM exposure and the inhalation of short-lived radon decay products. Numerous nations are actively seeking evaluation and baseline data for naturally occurring radioactivity associated to radiation exposure [15] [16] [26]. Despite previous research investigating radionuclide concentrations in river sediments and sand in Kenya [8] [27]-[29], some river sediments in Kenya have not been subject to radiological regulatory oversight. As a result, the radiological dangers and NORM exposure levels in the Bungoma Rivers are less recognized. This study aimed at determining the activity concentrations of naturally occurring radionuclides in sediment samples collected from the Kamukuywa River in Bungoma County, Kenya. Gamma spectroscopy was used using a sodium iodide thallium doped detector to determine the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in chosen sediment samples. The effective dosage to sand harvesters and the general public from radiation exposure to these sediment samples was also investigated, as were radio ecological danger indicators.

2. Materials and Methods

2.1. Study Area

The Kamukuywa River's coordinates are around 34.97˚ West and 0.7781˚ North. The Kamukuywa River basin in Western Kenya has the following coordinates: latitudes 1˚30'N and 0˚30'S, longitudes 34˚00'E and 35˚45'E. The 120-mile-long Kamukywa River starts in the Mt. Elgon hills before emptying into Nzoia River. The Kamukywa River is formed of intrusive and volcanic rocks. The majority of the River is made up of sedimentary rocks, with limestone, weathering rocks and rare granite intrusion formations adding to its character (See **Figure 1**).

2.2. Sample Preparation

A total of fifteen (15) sediment spots were chosen at random along the river Kamukuywa during the rainy season. At each sampling point, a 1 × 1 m plot with a depth of 1 m was set up, with GPS coordinates recorded. **Figure 1** shows the locations of the sampling sites. One sample was collected at each point along the River Kamukuywa. Each sample, weighing between 0.5 and 1.0 kg, was collected at different points along the river. Following careful mixing, each of these samples was packed in polythene bags and transported to South Eastern University's physics laboratory for additional analysis.

To achieve a constant weight, the fifteen (15) samples were air dried for two weeks before being oven-dried for eight hours at 80˚C. To ensure consistency, dry samples were crushed, ground, and sieved to a particle size of 150 - 200 μm. To ensure secular equilibrium between ^{226}Ra and ^{232}Th and their daughter nuclides for further laboratory analysis, 500 g with a density of 780 kg/m^3 of the homogenized samples were weighed on a weighing balance and stored in a Marinelli container for 30 days [30]. Additionally, an empty Marinelli container filled with de-

ionized water was utilized to assess the lab's background gamma radiation levels under comparable environmental conditions. The activity concentration was then determined by subtracting the resulting background value. In addition to being evaluated alongside the samples, Certified Reference Materials IAEA-447 was used to ensure the correctness of the gamma spectroscopy for the studies.

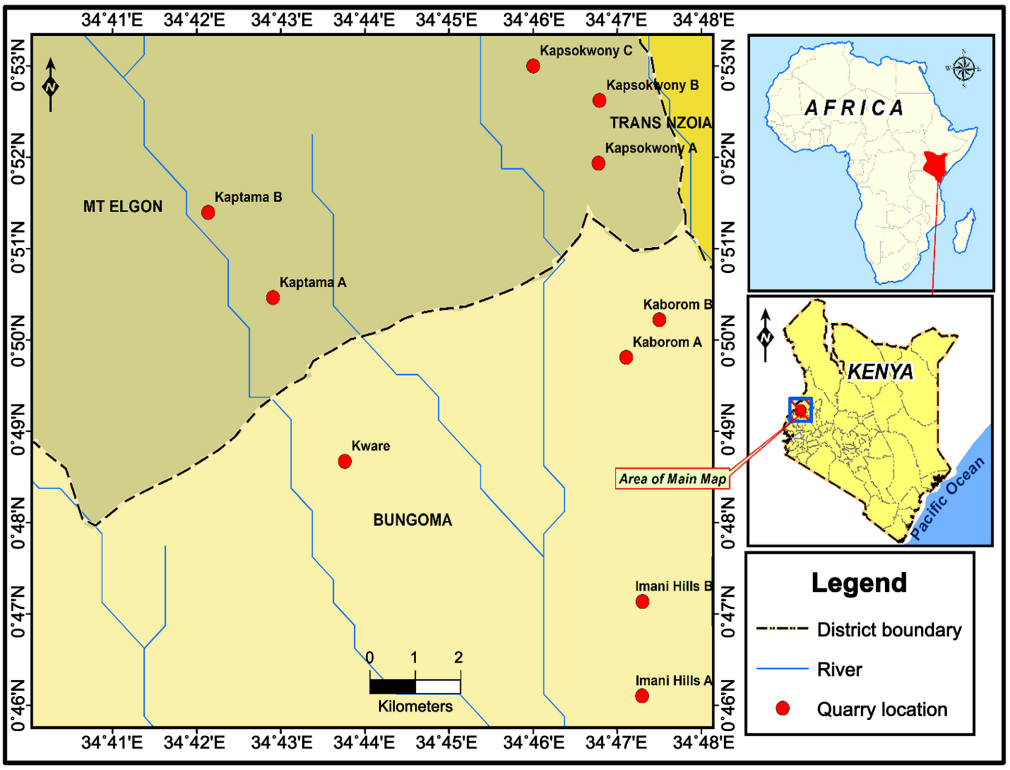

Figure 1. Map of the study area.

2.3. Radioactivity Measurements in Sediment Samples

The levels of ^{226}Ra, ^{232}Th and ^{40}K natural radioactivity were measured using a Gamma-ray Spectrometer equipped with a NaI(Tl) detector. Each sediment sample was placed on a radiation detector and counted for eight to twelve hours after achieving equilibrium. A lead shield and a support table assembly support the spectrometer, which is enclosed within a cylindrical multilayer graded shield. It was operated at a high voltage of 3500 keV, with a 75% relative efficiency and an energy resolution full width at half maximum (FWHM) of 1.91 keV at 1332.5 keV for Co-60. Spectra Line-GP software was used to process the collected data. A Mixed Nuclide BB-3591 gamma reference calibration source operating in the 60 - 3500 keV range was utilized to calibrate energy and efficiency. Elements from this source included Cs-137, Am-241, Co-60, Y-88, Co-57, Sn-113, and Ce-139. The activity concentration of ^{232}Th was calculated using the mean gamma-ray peak energies of ^{212}Pb (238.6 keV) and ^{228}Ac (911.1 keV), while the activity concentration of ^{238}U was calculated using the peak energies of ^{214}Pb (351.9 keV) and ^{214}Bi (609.3 keV). The energy of the 1460.8 keV spectral line was used to calculate the

activity concentration of ^{40}K [8].

3. Data Analysis

3.1. Activity Concentration

Activity concentration Calculations of number of counts per second for the photo peak and activity concentrations of each detected radionuclides was based on the concept secular equilibrium being. The activity concentration in Bq·kg^{-1} (A) in the samples was obtained by using Equation (1) [10]

$$A = \frac{N_s}{\varepsilon \eta m} \tag{1}$$

where, N_s is net counts per second (CPS) = (sample CPS – background CPS), ε is the abundance of the γ-line in a radionuclide, η is the measured efficiency for each gamma-line observed and the mass of the sample in kilograms is denoted by m.

3.2. Radiogenic Heat Production

Regardless of the temperature and pressure *in situ*, the RHP is a scalar petro physical property. According to [22], ^{232}Th and ^{238}U are the two radionuclides that contribute the most to heat production (around 85% each), while ^{40}K contributes less. Daughter radionuclides present in the rocks of the Earth's crust also create RHP; the most geologically significant decay chains in terms of heat production are those of ^{238}U and ^{232}Th. Equation (2) will be used to convert the activity concentrations of the different samples into parts per million (ppm) in order to compute the radiogenic heat production [22].

$$\left.\begin{array}{c} 1\text{ ppm of } {}^{238}\text{U} \equiv 12.35\,\text{Bq/Kg} \\ 1\text{ ppm of } {}^{232}\text{Th} \equiv 4.06\,\text{Bq/Kg} \\ 1\%\text{ of } {}^{40}\text{K} \equiv 313\,\text{Bq/Kg} \end{array}\right\} \tag{2}$$

The heat generation constant (*i.e.*, the quantity of heat released per unit time and per gram of ^{238}U, 2^{32}Th and ^{40}K) and the concentrations of uranium, thorium, and potassium (C_U, C_{Th}, and C_K, respectively) in a sediment will be taken into consideration when calculating the radiogenic heat production of sediments (RHP in μW·m^{-3}) using Equation (3) [19].

$$\text{RHP} = 10^{-5}\rho\left(9.52C_U + 2.56C_{Th} + 3.48C_K\right) \tag{3}$$

where ρ is the density of the sediment sample (kg·m^{-3}) and C_U, C_{Th}, and C_K are the concentrations of uranium (weight ppm), thorium (weight ppm), and potassium (weight %), respectively.

3.3. Determination of Radiological Hazard Indices

A number of radiological risk indices were calculated in order to completely comprehend the radiation hazard posed by ^{226}Ra, ^{232}Th, and ^{40}K in the sediments from River Kamukuywa. These indices were used to assess the level of risk that naturally

occurring radioactive nuclides posed to miners and the public at large.

3.3.1. Radium Equivalent (Ra_{eq})

When determining how natural ionizing radiation from rivers sediments affects radiological health, it is essential to consider the radium equivalent. This guarantees uniformity in the evaluation of radiation exposure and helps to account for the irregular distribution of naturally occurring radionuclides in samples. With a suggested limit of 370 $Bq{\cdot}kg^{-1}$, the radium equivalent is measured in $Bq{\cdot}kg^{-1}$. Equation (4) was used to determine the Ra_{eq} [20].

$$Ra_{eq}\left(Bq\cdot kg^{-1}\right) = A_{Ra} + 1.43A_{Th} + 0.077A_{K} \tag{4}$$

where A_{Ra}, A_{Th} and A_K represent ^{226}Ra, ^{232}Th and ^{40}K specific activity concentration.

3.3.2. External Hazard Index (H_{ex}) and Internal Hazard Index (H_{in})

The values of H_{ex} and H_{in} were determined using Equations (5) and (6), respectively, to evaluate the external and internal exposure to radiation from ^{226}Ra, ^{232}Th and ^{40}K in the samples under examination [31].

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \tag{5}$$

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \tag{6}$$

where A_{Ra}, A_{Th} and A_K represent the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the samples respectively. For the radiation hazards to be considered negligible, the values of H_{ex} and H_{in} must be ≤1, which aligns with the dose equivalent limit of 1 mSv/yr (Mbonu and Ben, 2021).

3.3.3. Absorbed Dose Rate (D)

The absorbed dose rate is the total amount of energy that ionizing radiation deposits per unit mass between two extremes. The specific activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the samples were measured in order to determine the absorbed dose rate from terrestrial gamma radiation sources [9] [24]. Equation (7) was used to determine absorbed dose rate.

$$D\left(\frac{nGy}{h}\right) = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_{K} \tag{7}$$

where; A_{Th}, A_{Ra} and A_K are the activity concentrations of ^{232}Th, ^{226}Ra and ^{40}K, respectively. The global average limit for absorbed dose rate is 60 $nGy{\cdot}h^{-1}$ [32].

3.3.4. Annual Effective Dose (AED)

The yearly effective dose equivalent to the population due to radioactivity in rocks, soils and plants will be calculated using a conversion factor of 0.7 Sv/Gy [33]. For the Kenyan scenario, adult indoor and outdoor dose occupancy factors of 0.4 and 0.6 will be evaluated, respectively. AED for both indoor and outdoor will be computed using Equations (8) and (9), respectively [8].

$$E_{\text{in}}\left(\frac{\text{mSv}}{\text{y}}\right) = D \times T \times 0.4 \times 0.7 \times 10^{-6} \quad (8)$$

$$E_{\text{out}}\left(\frac{\text{mSv}}{\text{y}}\right) = D \times T \times 0.6 \times 0.7 \times 10^{-6} \quad (9)$$

where D represents the absorbed dose rate in air in nGy/h, T is 8760 signifies the total hours in a year, 0.7 $SvGy^{-1}$ is the dose conversion factor and the factor 10^{-6} converts nano scale to mill scale. The AEDE recommended average limit is 1 $mSv{\cdot}y^{-1}$.

3.3.5. Annual Gonadal Equivalent Dose (AGED)

Equation (10) was used to evaluate the Annual Gonadal Equivalent Dose (AGED) sand harvesters and the general population obtained [34]

$$\text{AGED}\left(\frac{\text{mSv}}{\text{y}}\right) = 3.09A_{\text{Ra}} + 4.18A_{\text{Th}} + 0.314A_{\text{K}} \quad (10)$$

where C_{U}, C_{Th}, and C_{K} represent the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively (Wanyama *et al.*, 2020). 300 $\mu Sv{\cdot}y^{-1}$ is the AGED suggested limit.

3.3.6. Excess Lifetime Cancer Risk (ELCR)

Excess Lifetime Cancer Risk (ELCR) is the term used to describe the potential for radiation exposure to cause cancer in the human body when exposure beyond a certain threshold within a certain time frame. Equation (11) was used to calculate the ELCR in order to evaluate the cancer risk among mining workers [15]. This computation is used to determine the probability that a person will get cancer as a result of radiation exposure during their lifetime.

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

where RF is the risk factor, DL is the mean length of life (70 years) representing the fatal cancer risks per Sievert, RF denotes the risk factor of 0.05 Sv^{-1} and AEDE refers to the Annual Effective Dose Equivalent [30].

4. Results and Discussion

4.1. Activity Concentration Levels and RHP in Sediment Samples

Table 1 and Figure 2 display the findings of the radioactivity analysis conducted on sediment samples from River Kamukuywa, Bungoma County. The average activity for ^{238}U, ^{232}Th and ^{40}K was 31 ± 2, 51 ± 3, and 57 ± 3 $Bq{\cdot}kg^{-1}$, respectively. The activity concentrations varied from 19 ± 1 to 48 ± 2, 17 ± 1 to 89 ± 4, and 35 ± 2 to 90 ± 5 $Bq{\cdot}kg^{-1}$. With the exception of ^{232}Th, which surpassed the UNSCEAR, 2000, published average of 45 $Bq{\cdot}kg^{-1}$, the values were below the global averages of 32 $Bq{\cdot}kg^{-1}$ and 400 $Bq{\cdot}kg^{-1}$ for ^{238}U and ^{40}K respectively. The highest activity concentrations for ^{232}Th (89 ± 4 $Bq{\cdot}kg^{-1}$), ^{238}U (48 ± 2 $Bq{\cdot}kg^{-1}$) and ^{40}K (90 ± 5 $Bq{\cdot}kg^{-1}$) were found in sample 9 and 15 respectively. The region's geology, which is linked to granite rocks, is responsible for this high activity. The ^{238}U activity concentrations in about 95% of the sediments were lower than the global mean of

35 Bq·kg^{-1}. The activity concentrations of ^{40}K in all the sediment samples collected were below the global average of 400 Bq·kg^{-1} [35]. Generally, the variability is dependent on local weather circumstances, soil characteristics, geological composition, and geographic considerations.

Table 1. Activity concentration, radioelement concentration and radiogenic heat in the collected samples.

SAMPLES ID	ACTIVITY CONCENTRATION (Bq/kg)			RADIOELEMENT CONCENTRATION			RADIOGENIC HEAT PRODUCTION (μW·m^{-3})		
	^{238}U	^{232}Th	^{40}K	^{238}U (ppm)	^{232}Th (ppm)	^{40}K (%)	^{238}U	^{232}Th	^{40}K
SS1	23 ± 1	29 ± 1	43 ± 2	1.9	7 ± 1	13 ± 1	0.001	0.005	0.01
SS2	31 ± 2	53 ± 3	58 ± 3	2.5	13 ± 1	18 ± 1	0.001	0.009	0.013
SS3	44 ± 2	43 ± 2	81 ± 4	3.5	10 ± 1	26 ± 1	0.002	0.007	0.019
SS4	28 ± 1	53 ± 3	52 ± 3	2.3	13 ± 1	16 ± 1	0.001	0.009	0.012
SS5	28 ± 1	47 ± 2	52 ± 3	2.3	11 ± 1	16 ± 1	0.001	0.008	0.012
SS6	38 ± 2	47 ± 2	70 ± 4	3.0	11 ± 1	22 ± 1	0.002	0.008	0.016
SS7	22 ± 1	21 ± 1	40 ± 2	1.8	5 ± 1	13 ± 1	0.001	0.003	0.009
SS8	22 ± 1	29 ± 1	40 ± 2	1.8	7 ± 1	13 ± 1	0.001	0.005	0.009
SS9	19 ± 1	89 ± 4	35 ± 2	1.5	21 ± 1	11 ± 1	0.001	0.016	0.008
SS10	19 ± 1	78 ± 4	35 ± 2	1.5	19 ± 1	11 ± 1	0.001	0.014	0.008
SS11	20 ± 1	44 ± 2	37 ± 2	1.6	10 ± 1	12 ± 1	0.001	0.008	0.009
SS12	44 ± 2	17 ± 1	81 ± 4	3.5	4 ± 1	26 ± 1	0.002	0.003	0.019
SS13	47 ± 2	78 ± 4	87 ± 4	3.8	19 ± 1	27 ± 1	0.002	0.014	0.02
SS14	28 ± 1	62 ± 3	52 ± 3	2.3	15 ± 1	16 ± 1	0.001	0.011	0.012
SS15	48 ± 2	82 ± 4	90 ± 5	3.9	20 ± 1	28 ± 1	0.002	0.015	0.021
MIN	**19 ± 1**	**17 ± 1**	**35 ± 2**	**1.5**	**4 ± 1**	**11 ± 1**	**0.001**	**0.009**	**0.013**
MAX	**48 ± 2**	**89 ± 4**	**90 ± 5**	**3.9**	**21 ± 1**	**28 ± 1**	**0.001**	**0.003**	**0.008**
AVERAGE	**31 ± 2**	**51 ± 3**	**57 ± 3**	**2.5**	**12 ± 1**	**18 ± 1**	**0.002**	**0.016**	**0.021**

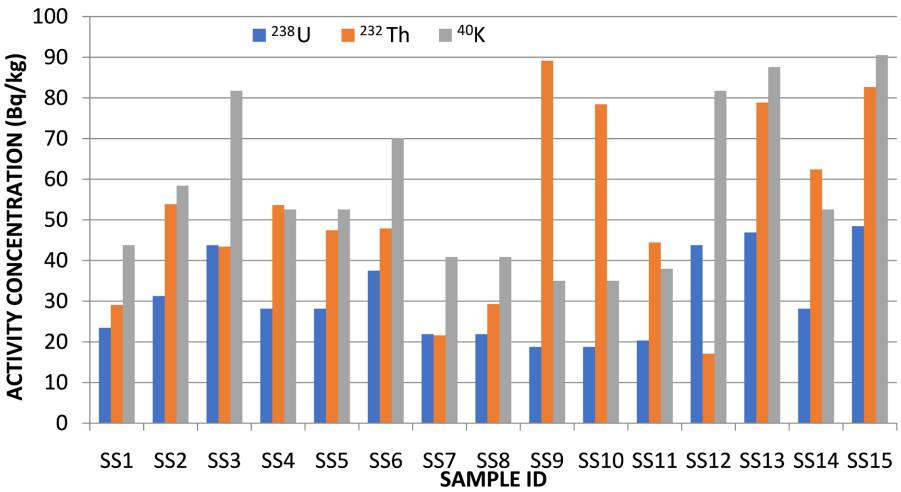

Figure 2. The activity concentration of radionuclides in sediment samples.

A mix of natural geological elements and human activity (excavation and quarrying of rocks) may be responsible for the elevated levels of ^{232}Th radionuclide activity found in sediment samples (Table 1). Due to their geological makeup, some areas naturally have larger concentrations of radioactive materials. Radionuclides may be mobilized and redistributed in water bodies as a result of natural processes like weathering and erosion. Higher levels of pollution may arise from the buildup of radioactive elements in rivers.

It should be noted that determining the precise causes of the elevated radionuclide levels in the area would require a comprehensive scientific examination. A thorough investigation would include a thorough examination of the area geology, soil composition, past land usage near the river, and possible radioactive material sources.

The three radionuclides' activity concentrations (^{238}U, ^{232}Th and ^{40}K) revealed a pattern of regional distribution. The radiation levels of ^{40}K, ^{232}Th and ^{238}U varied from 11% ± 1% to 28%, 4% ± 1% to 21% ± 1%, and 1.5 ppm to 3.9 ppm, respectively (See Figure 3).

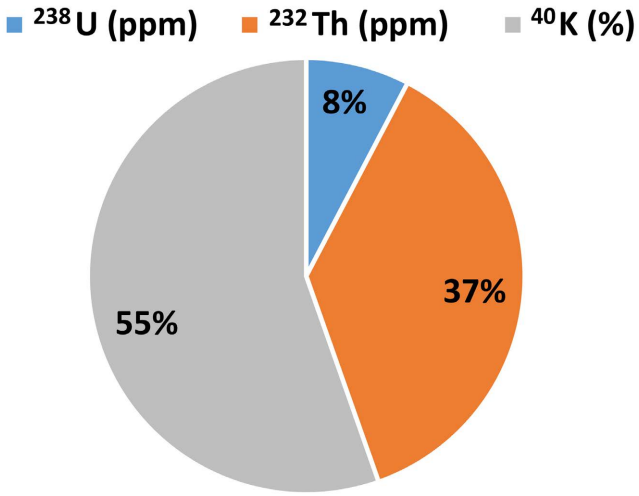

Figure 3. Radioelement concentrations in the collected samples.

The three radionuclides had average concentrations of 2.5 ppm, 12 ± 1 ppm and 18% ± 1% for ^{238}U, ^{232}Th and ^{40}K, respectively (Table 1), which were higher than the global average (UNSCEAR, 2000). The greatest difference from the global average was found in ^{232}Th and ^{40}K. The use of phosphate fertilizers for higher yields and other anthropogenic activities, particularly in agriculture, may be the cause of the higher activity concentrations. Figure 4 displays the individual radioelement radiogenic production from the collected samples.

From Figure 4, ^{238}U, ^{232}Th and ^{40}K corresponding individual RHP values were 0.001 μW/m^3 to 0.002 μW/m^3, 0.003 to 0.016 μW/m^3, and 0.008 μW/m^3 to 0.021 μW/m^3, respectively. For ^{238}U, ^{232}Th and ^{40}K, the average radiogenic heat output was 0.001 μW/m^3, 0.009 μW/m^3 and 0.013 μW/m^3, respectively. The average RHP for the three radionuclides among all samples gathered is displayed in Figure 5.

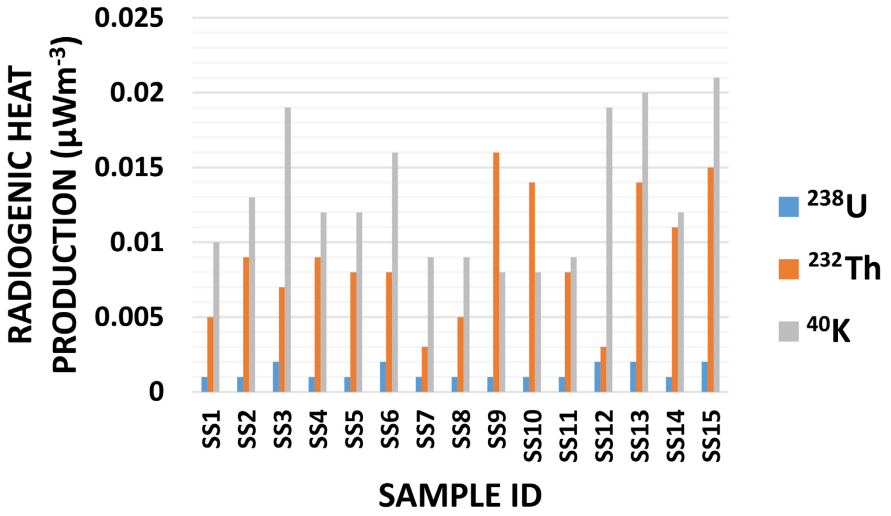

Figure 4. Radiogenic heat production in the collected samples.

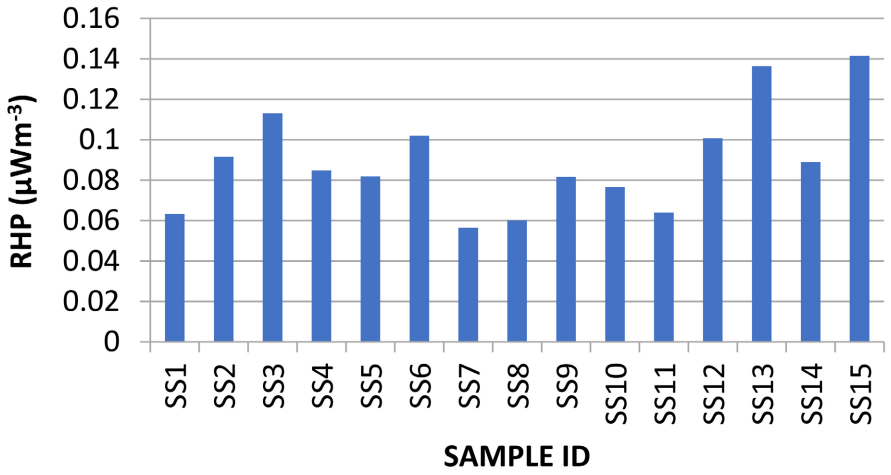

Figure 5. Average radiogenic heat production in the samples.

The total radiogenic heat ranged from 0.056 μW/m³ to 0.14 μW/m³ (**Figure 5**). All the three radionuclides combined provided an average RHP of 0.08 μW/m³. This study's findings are less than those of [20], which found an average of 0.540764 μW/m³. Additionally, the results differ from those of Ahero,s rice field sediments [22], who found an average RHP of 4.5 ± 1.1 μW/m³. The estimated average radiogenic heat production rate was 0.3634 μW/m³ that ranged from 0.2430 to 0.6453 μW/m³ from river Himalayan [36]. Given the varied geological configurations of the study regions and the kinds of rocks that the soils were formed from, the discrepancy in the results can be explained. **Table 2** compares the activity concentrations in River Kamukuywa sediments with data from various countries across the world. The activity concentrations obtained from this study were lower than those obtained from Himalayan river [36]. It is evident that the activity concentrations found in previous research conducted globally are comparable to the findings from the study area.

Table 2. Comparative results for activity concentration levels of radionuclides in various regions.

STUDY AREA/KENYA	ACTIVITY CONCENTRATION (Bq·kg^{-1})			REFERENCES
	^{226}Ra	^{232}Th	^{40}K	
Global average	35	45	400	[9]
Mt. Elgon, Kenya	31 ± 2	51 ± 3	57 ± 3	Current Study
Tamilnadu, India	30.81	85.67	425.72	[6]
Himalayan, Punarbhaba	68.4	85.7	918	[36]
Asa-dam, Nigeria	7.57	8.19	73.48	[37]
Tamilnadu, India	3.8	26.23	328.68	[7]
Orlu, Nigeria	4.15	1.64	134.13	[31]
Eastern, Anatolia, Türkiye	191 ± 0.6	21.9 ± 0.6	437 ± 10.3	[38]
Saryer-Instabul, Türkiye	30.78 ± 2.26	45.57 ± 3.99	863.70 ± 48.7	[30]
Manyoni, Tanzania	107.32 ± 23.1	65.22 ± 3.70	227.43 ± 38.8	[34]
Addis Ababa, Ethiopia	32.8 ± 2.1	62.4 ± 4.4	544 ± 23.3	[32]
North Western-Mediterranean	25.18	11.22	159.16	[16]
Kapchorwa, Uganda	47.8 ± 4.1	61.0 ± 3.8	1339.1 ± 65.3	[15]
Philippi, South Africa	30.71 ± 11.77	31.97 ± 8.90	345.97 ± 98.6	[24]
Northern Jordan, Jordan	42.5	26.7	291.1	[5]
Volta Lake, Ghana	23.1 ± 1.4	34.6 ± 2.9	187.1 ± 13.7	[3]
Osogbo, Nigeria	66.33 ± 41.94	41.35 ± 6.25	533.17 ± 33.0	[39]

Table 3. Summary of the correlation of activity concentration and radiological hazards.

	A_U	A_{Th}	A_K	DOSE	AED_{in}	AED_{out}	Ra_{eq}	H_{in}	H_{ex}	AGED	ELCR	RC_U	RC_{Th}	RC_K	RHP
A_U	1	0.094	1	0.432	0.4321	0.4321	0.428	0.4269	0.626	0.4538	0.4321	1	0.094	1	0.912
A_{Th}	0.094	1	0.094	0.939	0.9386	0.9386	0.94	0.9405	0.836	0.9299	0.9386	0.094	1	0.094	0.495
A_K	1	0.094	1	0.432	0.4321	0.4321	0.428	0.4269	0.626	0.4538	1	1	0.094	1	0.912
DOSE	0.432	0.939	0.432	1	1	1	1	1	0.974	0.9997	1	0.432	0.939	0.432	0.765
AED_{in}	0.432	0.939	0.432	1	1	1	1	1	0.974	0.9997	1	0.432	0.939	0.432	0.765
AED_{out}	0.432	0.939	0.432	1	1	1	1	1	0.974	0.9997	1	0.432	0.939	0.432	0.765
Ra_{eq}	0.428	0.94	0.428	1	1	1	1	1	0.973	0.9996	1	0.428	0.939	0.432	0.762
H_{in}	0.427	0.941	0.427	1	1	1	1	1	0.973	0.9996	1	0.427	0.941	0.761	0.761
H_{ex}	0.626	0.836	0.626	0.974	0.9739	0.9739	0.973	0.9725	1	0.9791	0.9739	0.626	0.836	0.626	0.891
AGED	0.454	0.93	0.454	1	0.9997	0.9997	1	0.9996	0.979	1	0.9997	0.454	0.93	0.454	0.78
ELCR	0.432	0.939	1	1	1	1	1	1	0.974	0.9997	1	0.432	0.939	0.432	0.765
RC_U	1	0.094	1	0.432	0.4321	0.4321	0.428	0.4269	0.626	0.4538	0.4321	1	0.094	1	0.912
RC_{Th}	0.094	1	0.094	0.939	0.9386	0.9386	0.939	0.9405	0.836	0.9299	0.9386	0.094	1	0.094	0.495
RC_K	1	0.094	1	0.432	0.4321	0.4321	0.432	0.761	0.626	0.4538	0.4321	1	0.094	1	0.912
RHP	0.912	0.495	0.912	0.765	0.7648	0.7648	0.762	0.761	0.891	0.7801	0.7648	0.912	0.495	0.912	1

The relationship between naturally occurring radionuclides and radiological features in sediment samples was investigated using a correlation matrix. Table 3 displays the corresponding relationships between naturally occurring radionuclides and radiological properties. According to the findings, there is a stronger association between the chosen pairings when the positive correlation coefficient is large. This implies that each of the three identified radionuclides contributed significantly to radiation exposure. The activity concentrations of uranium, potassium, and thorium mostly affect the changes of the radiological dangers, especially D, AED, H_{in}, H_{ex}, AGED, ELCR, and Ra_{eq} [39].

4.2. Radiological Hazards

The mean values of the radiological hazards specifically Ra_{eq}, H_{ex}, H_{in}, D, AEDE, AGED, and ELCR parameters are displayed in Table 4. Assessing the activity levels of ^{226}Ra, ^{232}Th and ^{40}K is the traditional way of determining the radiological danger related to natural radioactivity in sediments. Ra_{eq} must be less than 370 $Bq{\cdot}kg^{-1}$ in order for sediments or sand to be deemed safe. The average Ra_{eq} value was 109 ± 5 $Bq{\cdot}kg^{-1}$, with a range of 55 ± 3 $Bq{\cdot}kg^{-1}$ to 173 ± 9 $Bq{\cdot}kg^{-1}$. Interestingly, every sediment sample was below the global average of 370 $Bq{\cdot}kg^{-1}$ [40]. The external and internal hazard indices should be kept below a threshold limit of one in order to protect human health from radiation hazards (Figure 6).

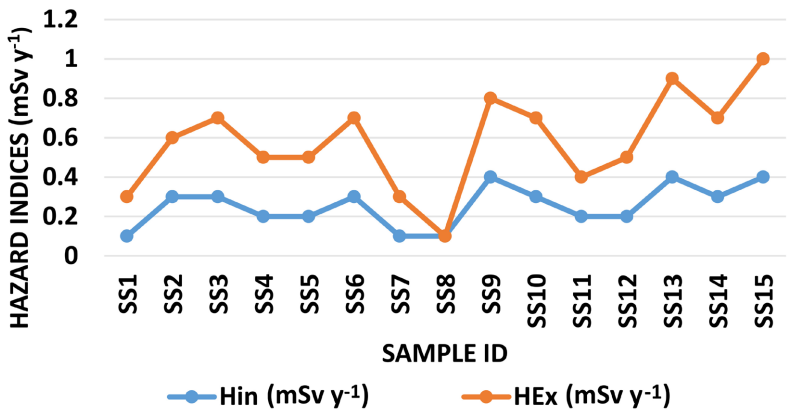

Figure 6. Hazard values calculated from the measured samples.

The H_{ex} values ranged from 0.20 to 0.60 (Figure 6), with an average of 0.30, while the H_{in} values ranged from 0.10 to 0.40 (Figure 6), with an average of 0.40. All these values fall below the global threshold value of 1 [1].

With a range of 24 ± 1 to 76 ± 4 $nGy{\cdot}h^{-1}$, the average absorbed dose rate was 47 ± 2 $nGy{\cdot}h^{-1}$, which was less than the average limit of 60 $nGy{\cdot}h^{-1}$ [35]. Every sediment sample examined for AEDE had AED_{in} values ranging from 0.09 to 0.28 $mSv{\cdot}y^{-1}$ (Figure 7), with an average of 0.18 $mSv{\cdot}y^{-1}$ (Table 4).

From Figure 7, AED_{out} values ranged from 0.06 to 0.19 $mSv{\cdot}y^{-1}$. The average AED_{out} was 0.12 $mSv{\cdot}y^{-1}$ (Table 4). The predicted doses should not surpass 1 $mSv{\cdot}y^{-1}$ for the general population and 100 $mSv{\cdot}y^{-1}$ for occupational workers, ac-

cording to statistics from the (ICRP, 2007) report. There is little chance of radon-related health risks in the area. With a mean value of 330 ± 17 μSv·y^{-1}, the values for the (AGED, μSv·y^{-1}) ranged from 170 ± 9 μSv·y^{-1} to 523 ± 26 μSv·y^{-1}, exceeding the global average of 300 μSv·y^{-1}. Increased AGED values indicate higher amounts of gamma radiation exposure, which could be brought on by nearby geology, substantial industrial or man-made activities and natural background radiation.

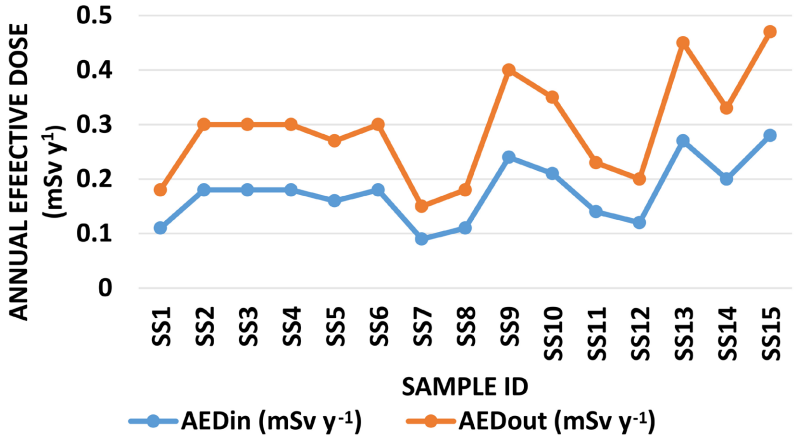

Figure 7. Annual effective dose from the collected samples.

Table 4. Radiological hazards from the sediment samples.

SAMPLE ID	DOSE RATE (nGy·h^{-1})	Ra_{eq} (Bq·kg^{-1})	H_{in} (mSv·y^{-1})	H_{ex} (mSv·y^{-1})	AGED (μSv·y^{-1})	ELCR (×10^{-4} mSv·y^{-1})	AED_{in} (mSv·y^{-1})	AED_{out} (mSv·y^{-1})
SS1	29 ± 1	68 ± 3	0.1	0.2	207 ± 10	0.3	0.11	0.07
SS2	49 ± 2	112 ± 6	0.3	0.3	340 ± 17	0.5	0.18	0.12
SS3	49 ± 2	111 ± 6	0.3	0.4	342 ± 17	0.5	0.18	0.12
SS4	47 ± 2	108 ± 5	0.2	0.3	327 ± 16	0.5	0.18	0.12
SS5	43 ± 2	99 ± 5	0.2	0.3	301 ± 15	0.4	0.16	0.11
SS6	48 ± 2	111 ± 6	0.3	0.4	338 ± 17	0.5	0.18	0.12
SS7	24 ± 1	55 ± 3	0.1	0.2	170 ± 9	0.2	0.09	0.06
SS8	29 ± 1	66 ± 3	0.1	0.	202 ± 10	0.3	0.11	0.07
SS9	64 ± 3	148 ± 7	0.4	0.4	441 ± 22	0.6	0.24	0.16
SS10	58 ± 3	133 ± 7	0.3	0.4	396 ± 20	0.6	0.21	0.14
SS11	37 ± 2	86 ± 4	0.2	0.2	260 ± 13	0.4	0.14	0.09
SS12	32 ± 2	74 ± 4	0.2	0.3	232 ± 12	0.3	0.12	0.08
SS13	72 ± 4	165 ± 8	0.4	0.5	502 ± 25	0.7	0.27	0.18
SS14	53 ± 3	121 ± 6	0.3	0.4	364 ± 18	0.5	0.2	0.13
SS15	76 ± 4	173 ± 9	0.4	0.6	523 ± 26	0.8	0.28	0.19
AVERAGE	**47 ± 2**	**109 ± 5**	**0.2**	**0.3**	**330 ± 17**	**0.5**	**0.18**	**0.12**
MIN	**24 ± 1**	**55 ± 3**	**0.1**	**0.2**	**170 ± 9**	**0.2**	**0.09**	**0.06**
MAX	**76 ± 4**	**173 ± 9**	**0.4**	**0.6**	**523 ± 26**	**0.8**	**0.28**	**0.19**

It is clear from the calculated radiological parameters that every sediment sample hazard was below the recommended average limit. The mean value of the estimated excess lifetime cancer risk (ELCR) for outdoor exposure was 0.50×10^{-4}, with a range of 0.20×10^{-4} to 0.80×10^{-4} mSv·y^{-1} (Table 4). This value is below the threshold limit when compared to the global average of 0.2900×10^{-3} mSv·y^{-1}, which is regarded as the acceptable level [1]. These results imply that ionizing radiation exposure in the investigated area is not linked to a high risk of cancer.

5. Conclusion

The concentrations of radionuclides in sediment samples from River Kamukuywa were measured using NaI(Tl) γ-spectrometry, and the results showed notable differences in activity levels. While ^{232}Th was more concentrated in the sediments, lower amounts of ^{40}K and ^{226}Ra were found in the samples. Radiological parameters were below the suggested safety standards and the activity concentration levels were determined to be lower than global norms. It is recommended to conduct a comprehensive radiometric survey to cover all the areas through which Kamukuywa River passes in Bungoma County. It will help characterize the radiogenic heat produced for each geological area along the river. It is highly advised that radiation levels be regularly monitored due to the possible health and environmental hazards that change due to seasonal variations. According to the correlation study, the main sources of gamma radiation in the sediments were ^{40}K, ^{226}Ra and ^{232}Th. This work provides crucial insights into the dynamics of radionuclide distribution and gamma radiation in the area, highlighting the significance of continuous radiation surveillance and management to reduce potential dangers associated with higher radiation levels.

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Highlights

- The NaI(Tl) detector was used to determine the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in the sediments.
- The radiation indices are comparable to the recommended safety levels.
- To determine the current relationship between radioactive factors, statistical analyses were conducted.
- The average activity of naturally occurring radionuclide for ^{232}Th was observed to be higher in the sediments.
- Regular radiation monitoring and environmental assessment are recommended in the study area.

Conflicts of Interest

The authors declare that they have no competing financial interests, personal relationships nor any other interest that could have influenced the work reported in this research.

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