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Paper

Radiological impact assessment of natural radioactivity in soil and water in Cape Coast North, Central Region of Ghana

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Abstract

The objective of the study is to evaluate natural radioactivity and its radiological impact on the health of the populace within Cape Coast North. Soil and water samples were taken and analysed using a high purity germanium (HPGe) detector. Results for the average activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soil samples range from 15.0 to 60.8 Bq/kg with a mean of 20.9 ± 7.2 Bq/kg, 16.3 to 97.2 Bq/kg with a mean of 43.8 ± 2.4 Bq/kg, and 4.7 to 411.4 Bq/kg with an average of 140.6 ± 4.2 Bq/kg, respectively. The absorbed dose rate in air and outdoor annual effective dose to the public were estimated to be 46.6 nGyh^{-1} and 0.1 mSv, respectively, which fell below the recommended average. The average activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in water samples were 1.4, 0.4, and 1.2 Bq/L, respectively. The annual effective dose is 0.4 mSv, which is greater than the WHO recommended level of 0.1 mSv/y.

Introduction

Environmental media, including the human body, contain naturally occurring radionuclides, causing external and internal exposure due to gamma-emitting radionuclides found in trace levels in rock and soil, particularly ^{238}U, ^{232}Th, and ^{40}K [1]. The main source of internal radiation exposure is due to ingested of food and water and inhalation of air. These constitute the natural ionizing radiation contributing to the total exposure to humans [2, 3]. For the past 30 y, the United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR) has been comparing data on ionizing radiation and its effects on the environment and human health. Due to the growing interest in its radiological effects, several national surveys had been carried out throughout the world to ascertain their influence on the populace [4]. Radionuclide levels are influenced by the kinds of rock that the soils are made of in different regions. Rocks classified as sedimentary rocks have lower levels, whereas igneous rocks, such as granite, have greater levels [5]. In order to lessen the negative impacts of radionuclides, especially ^{222}radon, research had to be conducted to identify natural background levels of these radionuclides in the environment, especially soils, which can be linked to the rates of absorption of airborne doses [3, 6].

Despite extensive research in several nations, Ghana has limited data on natural background radioactivity levels. Most of the studies on naturally occurring radionuclides in the country have been carried out in mining areas to ascertain the level of radioactivity in communities closed to the mining sites [7–9]. Additionally, studies had been conducted in soil and sediments used for building construction in the Greater Accra region and along the coast of Ghana to determine their radioactive levels [10–12]. Faanu *et al.* conducted a study in hand-dug wells in some selected communities

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in Cape Coast, Central Region of Ghana, to determine the radioactive levels in the water used by the residents [13]. Based on a review of the literature, there is data on radioactive levels in some selected towns in other regions of Ghana; however, there is relatively little information available for the Central region. In order to determine the background levels of natural radioactivity in the Central region and other locations where granite predominates, radionuclide study is crucial [14, 15]. The main goal of the current study is to measure the levels of radionuclides in the environment and assess the exposure rate in selected towns in Cape Coast North municipalities in the Central region of Ghana.

Methodology

Description of the study area

The Central Region is one of Ghana's sixteen administrative regions, with its capital being Cape Coast. It is bounded to the north by the Ashanti and Eastern regions, to the west by the western region, to the east by the Greater Accra region, and to the south by the Gulf of Guinea. Cape Coast Metropolitan Assembly (CCMA) is divided into two sub-metropolis (north and south) [16]. It is situated at latitude 5° 06′N and longitude 1° 15′W. According to the 2021 population and housing census, the Metropolis has a population of 189 925, including 92 790 males and 97 135 females [17]. The average temperature during the period of study ranged between 26.7°C and 30.1°C [18]. The study was conducted in Cape Coast North in these three communities [Kwaprow (KP), Amamoma (AMM), and University of Cape Coast (UCC) residential area], as shown in Fig. 1.

The geology of the study area

The Central Region of Ghana is part of a Phanerozoic sedimentary unit of the West African craton that includes the Sekondian Formation, the Tarkwaian System, and the Birimian System [14, 15]. Granites and granite gneisses cover one-fifth of Ghana and believed to be post-Birimian and pre-Tarkwaian in age. Granitoids, found in Ghana's northern, western, southwestern, and southern regions, include Winneba, Cape Coast, Dixcove, and Bongo types. The Cape Coast granite complex (Fig. 2), which is connected to the metasedimentary rocks of the Birimian in Ghana, is one of the two main types of Eburnean granitoids that outcrop in portions of southern and northern Ghana [14, 15]. The research area is dominated by the Cape Coast granitoid complex and is composed of rocks, such as gneiss, granite, and granodiorites, covering ∼90% of the basin [22, 38].

Soil and water sample collection and preparation

Soil sample collection and preparation

Soil samples were collected from the UCC residential areas, KP, and AMM township. Sample locations were randomly chosen and closed to dwellings to cover a wide area in order to ensure that they were representative of the place under investigation [19]. Based on these criteria, 46 samples were collected in these three areas, where the samples were placed in a Ziploc bag that weighed 1 kg and were transported to the laboratory for analysis. The soil samples were air-dried in the laboratory for some days before being dried in an oven at 150°C to totally remove all moisture and then ground into a fine powder using a ball mill (model LC-91) manufactured by Gilson Company Inc. in the US. The grounded soil was sieved through a mesh with a pore size of 0.2 mm to ensure that the soil sample was homogeneous. Each ground sample was then put into a 1-L Marinelli beaker and sealed for 4 weeks to allow the short-lived progeny of ^{226}Ra in the uranium and thorium decay series to reach secular equilibrium with their long-lived parent radionuclides before counting.

Water sample collection and preparation

The water samples were collected from 12 hand-dug wells available in KP and AMM. Two samples were collected from each sampling point for replication and placed in 1-L plastic bottles. Bottles were acid cleaned with concentrated HNO_3 to prevent radionuclides sticking to the bottle walls before being filled with water samples, and these were transported to the laboratory for analysis. To avoid gas being trapped, the bottles were completely filled and sealed for 4 weeks for secular equilibrium to be reached.

Analysis of samples using gamma spectrometry

Radioactivity counting was done using a PC-based gamma ray spectrometry, featuring an n-type high purity germanium (HPGe) detector (ORTEC GEM-C5970) coupled to a computer-based multi-channel analyser. The detector's efficiency was 40%, with a 2.0 keV energy resolution of 1.332 keV of ^{60}Co. The radionuclides were identified using ORTEC MAESTRO-32 software. The energy calibration involved counting standard radionuclides with IAEA reference materials [IAEA-RGU-1 (U-ore), IAEA-RGTh-1 (Th-ore), and IAEA-RGK-1] with defined energies ranging from 60 to ∼2000 keV for 36 000 s. The system's gain was adjusted to align the 662 keV of ^{137}Cs with the multichannel analyser's channel number, and results were plotted against gamma ray energy on a linear graph. Background radiation dispersion in the

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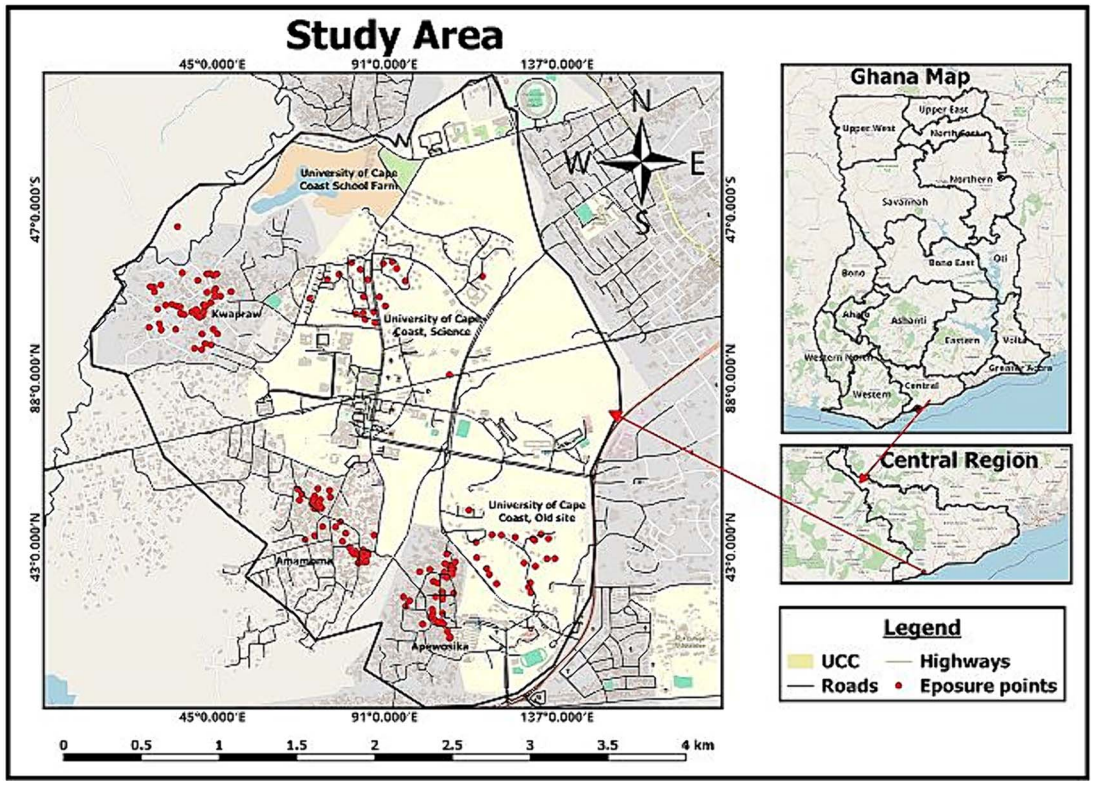

Figure 1. Map of the study area.

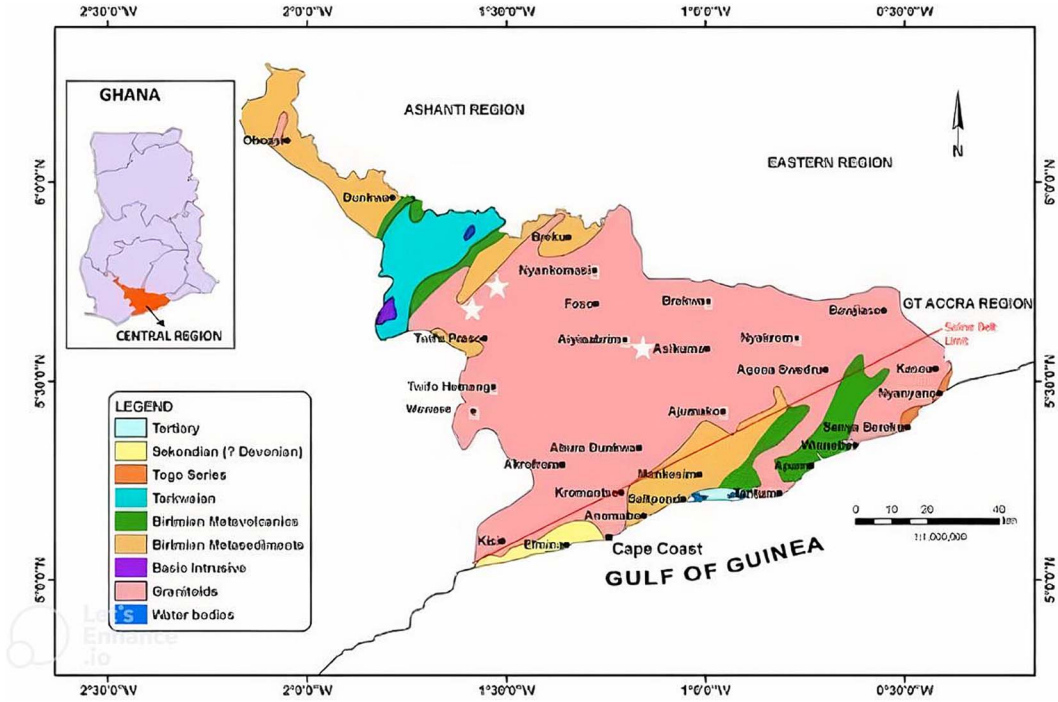

Figure 2. Geological map of central region, Ghana [38].

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area surrounding the detector was determined using a Marinelli beaker filled with distilled water, counted for 36 000 s in the same geometry as the samples, and subtracted from the sample count.

Activity concentration of radionuclides

The following energies were used to identify the radionuclides of interest: 351.9 keV (^{214}Pb) and 609.3 keV (^{214}Bi) for ^{226}Ra; 911.02 keV (^{228}Ac), 238.63 keV (^{212}Pb), and 583.2 keV (^{208}Tl) for ^{232}Th; the line at 1460.8 keV was directly used to determine the ^{40}K concentration. The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soil and water were determined using (1). The activity concentration for a nuclide with multiple peaks in its spectrum was calculated as the weighted average at each peak [11]

$$A_c = \frac{N_{\text{sam}} \times \exp\left(-\lambda T_d\right)}{P(E) \times \eta(E) \times T_c \times M_{\text{sam}}} \quad (1)$$

where N_{sam} is the net counts of the radionuclide in the samples, T_c is the counting time in seconds, $P(E)$ is the gamma emission probability (gamma yield), $\eta(E)$ is the absolute counting efficiency of the detector system, M_{sam} is the mass of the sample (kg), T_d is the delay time between sampling and counting, λ is the decay constant, and $\exp(-\lambda T_d)$ is the correction factor between sampling and counting.

Assessment of radiological risk

Radium equivalent activity (Ra_{eq})

The radium equivalent activity index assesses the total gamma output from the combination of the radionuclides (^{226}Ra, ^{232}Th, and ^{40}K). By assuming that 370 Bq/kg of ^{226}Ra, 259 Bq/kg of ^{232}Th, and 4810 Bq/kg of ^{40}K generate an equal amount of gamma dose, the expression Ra_{eq} can be obtained using (2) [9, 20]

$$\text{Ra}_{\text{eq}} = A_{\text{Ra}} + 1.43A_{\text{Th}} + 0.077A_K \quad (2)$$

where A_{Ra}, A_{Th}, and A_{K} are the activity concentrations of ^{226}R, ^{232}Th, and ^{40}K, respectively.

Hazard indices

The external and internal hazard indices (3) and (4) are used to evaluate the radiological hazards associated with building materials due to external and internal exposure to gamma radiation. Radiation must be less than one for it to be deemed insignificant [9]

$$H_{\text{ex}} = \frac{A_{\text{Ra}}}{370} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810} \leq 1 \quad (3)$$

$$H_{\text{in}} = \frac{A_{\text{Ra}}}{185} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810} \leq 1. \quad (4)$$

Estimation of radiation dose to the public

Adsorbed dose rate in air (D_R)

To determine the absorbed dose rate in air (5) at 1 m above ground level, the dose conversion factors of 0.462 $\text{nGyh}^{-1}\text{Bq}^{-1}\text{kg}^{-1}$, 0.604 $\text{nGyh}^{-1}\text{Bq}^{-1}\text{kg}^{-1}$, and 0.0417 $\text{nGyh}^{-1}\text{Bq}^{-1}\text{kg}^{-1}$ for ^{238}U, ^{232}Th, and ^{40}K respectively were used to transformed activity concentration into doses [1, 21]. However, in this calculation radium (^{226}Ra) activity concentration was used instead of ^{238}U.

$$D_R(nGyh^{-1}) = 0.462A_{\text{Ra}} + 0.604A_{\text{Th}} + 0.0417A_{\text{K}} \quad (5)$$

where A_{Ra}, A_{Th}, and A_{K} are the activity concentrations of uranium, thorium, and potassium, respectively.

Annual effective dose equivalent (AEDE)

The annual effective dose equivalent is calculated by considering an outdoor occupancy factor of 0.2 and a conversion factor of 0.7 SvGy^{-1}. The estimated average effective dose equivalent received by the public annually [3, 21] is then computed using equations (6) as follows.

$$\text{AEDE}_{\text{Out}}(mSv) = DR(nGyh^{-1}) \times 8760h \times 0.2 \times 0.7(SvGy^{-1}) \times 10^{-6} \quad (6)$$

where DR is the absorbed dose rate in air and the annual time in hours is 8760.

Annual committed effective dose in water, H_{ing} (W)

The annual committed effective dose from radioactive ingestion in water was calculated (7) using the estimated annual consumption of water and the radionuclide activity concentration in water. According to WHO recommendations, the daily water consumption rate for all ages is 2.0 L/d, with an annual intake of 730 L [36]. The dose conversion factor for adults for the ingestion of radionuclides was estimated to be 2.8×10^{-4} mSv/Bq for ^{226}Ra, 2.3×10^{-4} mSv/Bq for ^{232}Th and 6.2×10^{-6} mSv/Bq for ^{40}K

$$H_{\text{ing}}(W) = \sum_{i=i}^{N} \text{DCF}\left(\text{Ra}, \text{Th}, \text{K}\right) \times A_{\text{sp}} \times I \quad (7)$$

where DCF (Ra, Th, K) is the dose conversion coefficients of the radionuclides in Sv/Bq, A_{sp} is the specific

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Table 1. Activity concentration of radionuclides and radium equivalent (Ra_{eq}) index in soil samples at University of Cape Coast (UCC) residential area.

Sample code	Activity concentration (Bq/kg)			
	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}
U1	23.6 ± 0.1	40.0 ± 0.2	70.4 ± 8.1	86.2
U2	57.4 ± 0.3	70.7 ± 0.1	277.0 ± 3.0	179.8
U3	27.5 ± 0.0	34.9 ± 0.4	140.7 ± 2.4	88.2
U4	60.8 ± 0.0	97.2 ± 0.8	188.3 ± 2.3	214.3
U5	33.6 ± 0.1	95.7 ± 1.2	180.5 ± 2.2	184.4
U6	20.8 ± 0.2	30.1 ± 0.5	47.1 ± 5.1	67.5
U7	30.1 ± 0.1	47.5 ± 0.3	53.8 ± 7.0	102.2
U8	44.9 ± 0.1	80.7 ± 0.2	156.0 ± 2.2	172.3
U9	28.2 ± 0.0	50.5 ± 0.3	64.3 ± 7.9	105.4
U10	60.0 ± 0.0	74.2 ± 0.0	310.7 ± 3.1	190.0
U11	31.4 ± 0.2	40.9 ± 0.6	153.2 ± 2.8	101.7
U12	54.5 ± 0.1	91.4 ± 0.9	191.6 ± 2.6	200.0
U13	38.1 ± 0.2	85.4 ± 0.5	173.2 ± 2.9	173.6
U14	16.5 ± 0.1	22.8 ± 0.4	30.5 ± 4.2	51.5
U15	31.9 ± 0.1	50.7 ± 0.2	59.9 ± 7.0	109.0
U16	46.9 ± 0.5	71.8 ± 0.2	162.2 ± 2.5	162.1
Mean	38.0	61.5	141.2	139.1
SD	14.5	24.7	82.3	53.5
Range	16.5–60.8	22.8–97.2	30.5–310.7	51.5–214.3

Table 2. Average activity concentration of radionuclides and radium equivalent (Ra_{eq}) index in soil samples at AMM township.

Sample code	Activity concentration (Bq/kg)			
	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}
AM1	20.6 ± 0.1	23.2 ± 0.5	90.4 ± 1.0	60.7
AM2	29.9 ± 0.1	51.0 ± 0.2	101.7 ± 1.6	110.7
AM3	20.3 ± 0.2	29.0 ± 1.1	116.5 ± 1.8	70.7
AM4	23.7 ± 0.1	49.1 ± 0.3	132.9 ± 1.8	104.2
AM5	25.1 ± 0.0	37.6 ± 0.3	4.7 ± 2.7	79.2
AM6	15.0 ± 0.1	17.3 ± 0.4	67.0 ± 7.6	44.9
AM7	23.0 ± 0.1	34.7 ± 0.4	94.0 ± 1.7	79.9
AM8	27.9 ± 0.2	33.5 ± 0.4	129.0 ± 1.4	85.7
AM9	29.0 ± 0.1	54.0 ± 0.2	140.9 ± 2.4	117.1
AM10	21.4 ± 0.2	28.4 ± 0.6	93.8 ± 1.8	69.2
Mean	22.6	35.5	96.4	82.2
SD	4.7	12.6	39.6	22.8
Range	15.0–29.9	17.3–54.0	4.7–140.9	44.9–117.1

activity concentrations of radionuclides in the water samples in Bq/L, *I* is the water intake in litres per year, assuming 2 L average water intake per day for 365 d/y (730 L/y) [13].

Results and discussion

Natural radioactivity in soil

The activity concentrations of natural radioactivity in soil samples taken from UCC, KP, and AMM residential areas had been determined as shown in Tables 1–3. The results of the average activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K for the study were compared to the UNSCEAR (2008) recommended values, which are 32 Bq/kg, 45 Bq/kg, and 412 Bq/kg [1], respectively, as presented in Fig. 3. From the Tables 1–3, the average activity concentrations of ^{226}Ra in soil recorded at UCC, KP, and AMM were found to be 38.0 ± 1.5 Bq/kg, 30.4 ± 1.3 Bq/kg, and 22.6 ± 4.7 Bq/kg, respectively. With the exception of UCC, which reported a level that was greater than the world average, the two towns had lower levels.

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Table 3. Average activity concentration of radionuclides and radium equivalent (Ra_{eq}) index in soil samples at KP township.

Sample code	Activity concentration (Bq/kg)			
	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}
KP1	32.9 ± 0.0	48.5 ± 0.1	82.3 ± 9.5	108.6
KP2	19.2 ± 0.0	27.6 ± 0.6	102.8 ± 1.5	66.6
KP3	50.9 ± 0.1	40.4 ± 0.6	344.5 ± 4.6	133.0
KP4	42.0 ± 0.0	38.0 ± 0.6	278.1 ± 4.9	117.8
KP5	15.4 ± 0.1	16.3 ± 0.5	49.1 ± 6.0	42.5
KP6	35.0 ± 0.1	44.8 ± 0.3	74.4 ± 9.0	104.8
KP7	45.4 ± 0.3	40.7 ± 0.7	372.3 ± 4.4	132.3
KP8	25.6 ± 0.2	25.4 ± 0.8	276.5 ± 3.4	83.0
KP9	21.3 ± 0.1	32.4 ± 0.6	130.8 ± 1.5	77.7
KP10	20.0 ± 0.2	26.1 ± 0.6	104.0 ± 1.7	65.3
KP11	37.1 ± 0.2	50.7 ± 0.3	85.9 ± 1.3	116.2
KP12	16.0 ± 0.1	18.3 ± 0.6	83.4 ± 9.5	48.6
KP13	43.6 ± 0.1	35.3 ± 0.6	308.2 ± 3.7	117.8
KP14	45.6 ± 0.0	41.3 ± 0.6	411.4 ± 4.4	136.3
KP15	18.3 ± 0.1	20.8 ± 0.6	61.6 ± 7.5	52.8
KP16	36.1 ± 0.3	49.3 ± 0.3	80.5 ± 9.5	112.8
KP17	42.8 ± 0.1	38.5 ± 0.5	342.3 ± 4.2	124.2
KP18	21.9 ± 0.4	23.8 ± 0.6	252.2 ± 3.7	75.4
KP19	29.6 ± 0.0	34.1 ± 0.3	114.2 ± 1.6	78.2
KP20	23.1 ± 0.2	26.4 ± 0.6	117.1 ± 1.8	69.9
Mean	30.4	33.7	184.1	93.2
SD	11.3	10.2	122.6	30.4
Range (Min–Max)	15.4–49.7	16.3–50.7	49.1–411. 4	42.5–136.3

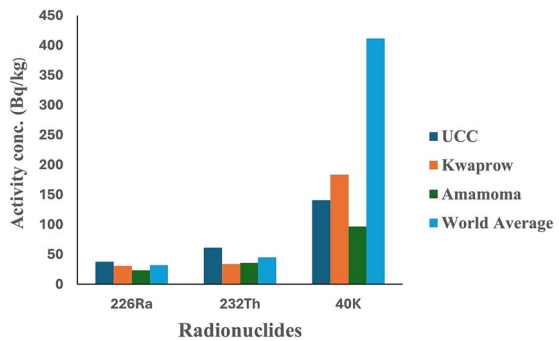

Figure 3. Comparison of natural radionuclides in soil for the three communities to the world average.

Nonetheless, few sample locations at UCC (Table 1) and KP (Table 3) had levels above 40 Bq/kg. The average activity concentration of ^{232}Th in soil samples observed at UCC was 61.5 ± 2.7 Bq/kg, which was higher than the global average, whereas KP and AMM (Table 2) reported values below the recommended average with some of the sample locations recording levels above the world average of 45 Bq/kg. The average activity concentration of ^{40}K was found to be below the world recommended level of 412 Bq/kg, but higher than that of ^{226}Ra and ^{232}Th in all the study areas, possibly as a result of abundant background radiation. Since ^{40}K undergoes a homeostatic mechanism in the body, most of it comes out of the body during extracellular processes. Hence, higher quantities could not have a significant radioactive impact on the body [23].

A comparison was made between the current mean activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K, and other studies conducted in other regions of Ghana. For instance, to ascertain the natural radioactivity levels and their exposure to the people, Yeboah *et al.* [24] studied soil and rock samples in some selected locations in the Greater Accra region. In comparison to other data published across the nation, they concluded that the values obtained for the radionuclides (^{238}U, ^{232}Th, and ^{40}K) were highly significant, which necessitated the monitoring of indoor radon in that region. Again, Otoo *et al.* evaluated natural radioactivity levels in Quarry Towns in the Greater Accra region, and the value obtained for ^{226}Ra (27.0 Bq/kg) was higher than this study, although ^{232}Th and ^{40}K values were lower [25]. Amable *et al.* results for ^{40}K (187.0 Bq/kg) and ^{226}Ra (23.1 Bq/kg) in the Volta region were greater than those found in this work, with the exception of ^{232}Th (34.6 Bq/kg), which is lower [26]. Also, Doyi *et al.* values obtained for ^{238}U (8.65 Bq/kg) and ^{232}Th (12.5 Bq/kg) in Tano Basin in

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Table 4. Comparison of average activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K in soil with similar studies in some selected countries.

Country	Area/region	Activity concentration (Bq/kg)			Reference
		^{226}Ra	^{232}Th	^{40}K	
Ghana	Cape Coast	30.9	43.8	140.6	Present study
Burkina Faso	Ouagadougou		29.4	206.9	[35]
Cameroon	Douala	25.0	66.3	33.7	[28]
Ethiopia	Metekel	64.0	70.0	330.0	[30]
Nigeria	Pindiga	40.8	31.3	156.0	[32]
Botswana	–	34.8	41.8	432.7	[31]
Egypt	Yemen	30.4	36.3	358.1	[29]
Gabon	Mounana	2811.0	63.0	355.0	[34]
India	Sijua Dhanbad	60.3	64.5	481.0	[33]

the Brong Ahafo region were very low compared to this study; however, the ^{40}K (214.0 Bq/kg) level was higher than this study [27]. Also, the study was compared with other research carried out in a few selected countries worldwide (Table 4). The mean concentration of ^{226}Ra found in this study was lower than the global average, as well as those reported by Ndontchueng *et al.* [28] and Harb *et al.* [29]. Nonetheless, levels recorded by Abate [30], Murty and Karunakara [31], Hassan *et al.* [32], and Zubiar [33] were above the recommended average, with Mouandza *et al.* [34] reporting the highest level. Similarly, the mean activity concentration of ^{232}Th observed in this study, as well as those reported by these authors [28–29, 31] was lower than the world average. With the exception of Murty and Karunakara [31] and Zubiar [33], which reported levels of ^{40}K higher than the world average, all other authors had levels below the global average of 412 Bq/kg.

The presence of granite in the studied areas may explain the increased level of ^{226}Ra and ^{232}Th concentrations in soil samples from the UCC residential area as compared with the world average as shown in Fig. 3. According to Yendaw [14], granitoids from the Sekondi Series and the sedimentary basin make up the Cape Coast's geology, which confirms the results obtained. The sedimentary rocks in the studied areas provide geological evidence supporting the claim that greater radiation levels are connected with igneous rocks followed by sedimentary rocks [35, 28].

Figures 4–6 show the spatial distribution of radioactivity measured in the studied areas. The distribution shows a slight variation in radioactivity concentration from one location to another. In comparison to KP and AMM, which have light red coloration, UCC exhibits the widest spatial distribution of ^{226}Ra and ^{232}Th in terms of concentration in the studied areas, as shown by the deep red colour (Figs 4 and 5). These variations may originate from the nonuniform distribution of radioactive content existing in the bedrock or soil, as published by other authors [35, 28].

Natural radioactivity in water

Table 5 shows the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in water samples from AMM and KP, with the estimated annual effective dose. The maximum allowed guidance level recommended by WHO on intake of primordial radionuclides in water is 1.0 Bq/L [36]. Since some of the activity concentrations of ^{40}K were below the minimum detectable activity (MDA), it was reported as the detection limit (DL). From the Table 5, the average activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K recorded in AMM were 1.8 ± 0.9 Bq/L, 0.4 ± 0.2 Bq/L, and 0.7 ± 0.7 Bq/L, whiles KP reported 1.0 ± 0.8 Bq/L, 0.4 ± 0.2 Bq/L, and 1.7 ± 1.2 Bq/L, respectively. Apart from the activity concentration of ^{226}Ra in AMM, which exceeded the recommended level of 1.0 Bq/L, the rest of the radionuclides were below the guidance level. This study was compared with a similar study conducted by Faanu *et al.* at the same locations where activity concentrations of ^{238}U and ^{232}Th obtained by these authors were also below the recommended guidance level. However, ^{40}K values were greater than the world recommended level and this study [13].

Radiological risk assessment of natural radioactivity

The assessment of natural radioactivity in soil and water to public exposure is critical for the determination of internal and external ionizing radiation exposure. Since the people in the communities used the soil in constructing their buildings, the radium equivalent activity and hazard index were evaluated. From Table 6, the average radium equivalent activity (Ra_{eq}) concentration in these three communities (UCC, KP, and AMM) were all below the world recommended level of 370 Bq/kg [3]. This demonstrates that the soils in these communities are safe for use in building construction. The calculated values of external hazard (H_{ex}) index for UCC, KP, and AMM were 0.4 ± 0.1,

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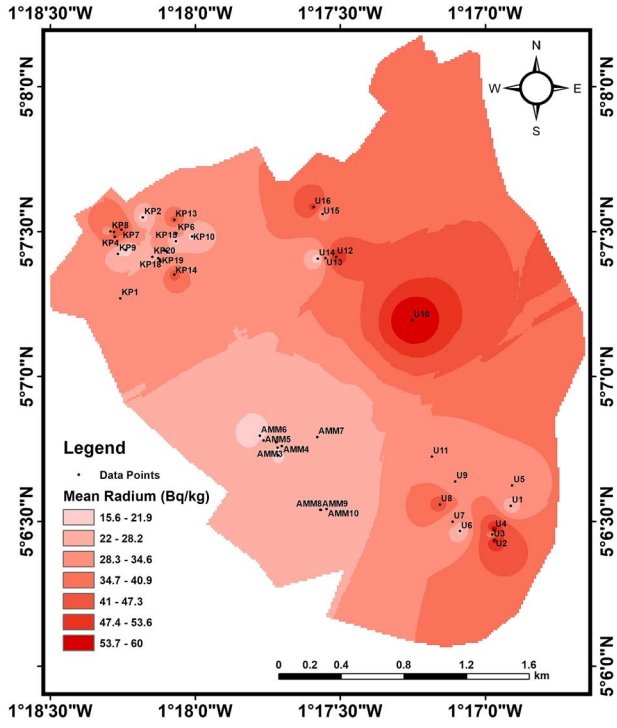

Figure 4. Spatial distribution of ^{226}Ra in the studied area.

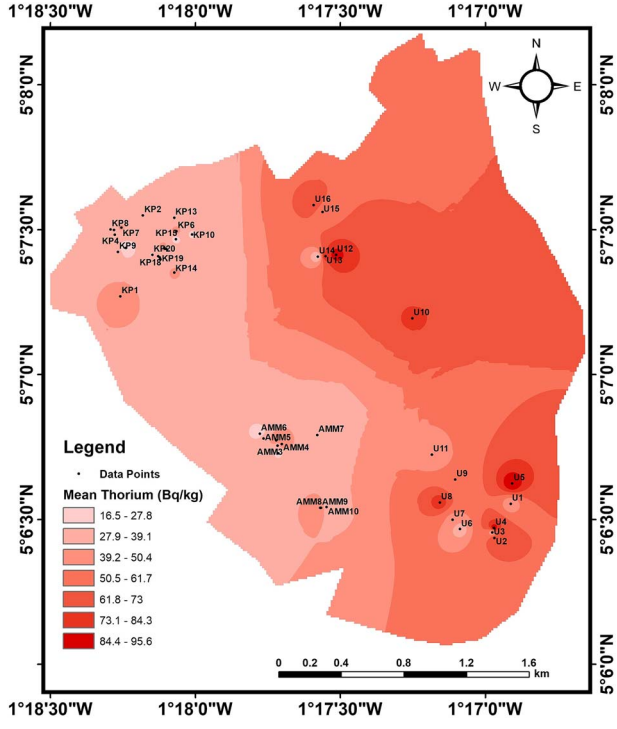

Figure 5. Spatial distribution of ^{232}Th in the studied area.

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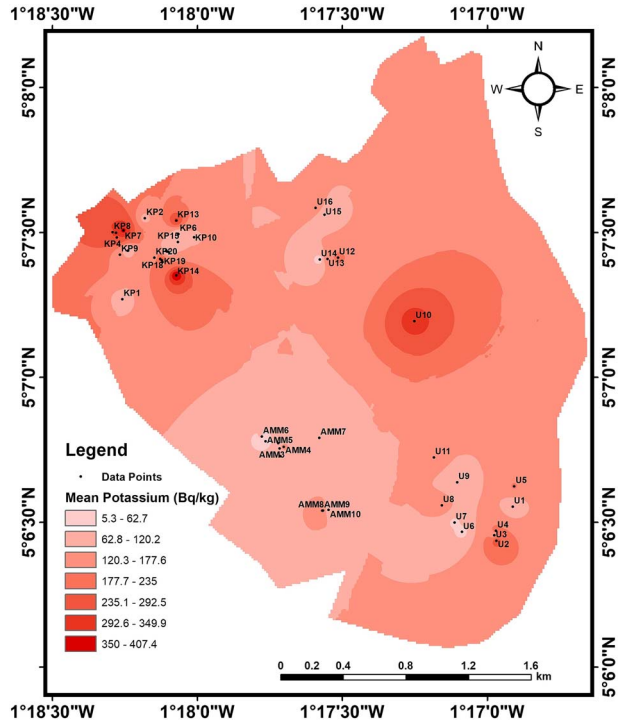

Figure 6. Spatial distribution of ^{40}K in the studied area.

Table 5. Activity concentration and annual effective dose of radionuclides in water from hand dug wells at AMM and KP.

Sample location	Activity concentration (Bq/L)			H_{ing} (mSv/y)
	^{226}Ra	^{232}Th	^{40}K	
AMB1	2.0 ± 0.1	0.2 ± 0.1	1.1 ± 0.4	0.4
AMB2	0.8 ± 0.2	0.3 ± 0.0	DL	0.2
AMB3	1.0 ± 0.4	0.8 ± 0.1	DL	0.3
AMB4	2.3 ± 0.3	0.3 ± 0.0	1.1 ± 0.4	0.5
AMB5	3.1 ± 0.4	0.2 ± 0.0	1.4 ± 0.6	0.7
Mean ± SD	1.8 ± 0.9	0.4 ± 0.2	0.7 ± 0.7	0.4 ± 0.2
KPB1	1.2 ± 0.7	0.6 ± 0.0	2.5 ± 0.5	0.4
KPB2	0.5 ± 0.1	0.2 ± 0.0	3.0 ± 0.5	0.2
KPB3	0.8 ± 0.1	0.4 ± 0.0	2.3 ± 0.5	0.2
KPB4	0.8 ± 0.1	0.5 ± 0.0	2.3 ± 0.5	0.3
KPB5	0.3 ± 0.1	0.3 ± 0.1	DL	0.1
KPB6	2.5 ± 0.6	0.7 ± 0.0	DL	0.6
KPB7	0.7 ± 0.1	0.4 ± 0.0	2.0 ± 0.4	0.2
Mean ± SD	1.0 ± 0.8	0.4 ± 0.2	1.7 ± 1.2	0.3 ± 0.2
Overall Mean	1.4	0.4	1.2	0.4

0.3 ± 0.1, and 0.2 ± 0.1, respectively, with an overall mean of 0.3. Similarly, the internal hazard (H_{in}) index for UCC, KP, and AMM were 0.5 ± 0.2, 0.3 ± 0.1, and 0.3 ± 0.1, respectively, with a total average of 0.4. The overall mean for both external and internal hazard indexes for the three communities was 0.3, which was <1. Per the results obtained for the hazard indices, it can be concluded that the soils in the studied areas are safe for habitation and are suitable for use in building construction in accordance with radiation protection requirements [9].

The assessment of the absorbed dose rate helps in determining the dosage received outdoors from radiation released by radionuclides in the environment

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Table 6. Average and range (min-max) of the radiological risks for the three communities.

Radiological risks	UCC	Kwaprow	Amamoma	Average
Ra_{eq} (Bq/kg)	136.9 ± 5.6	93.4 ± 3.4	78.8 ± 2.7	103.0
Range (Min–Max)	(51.5–214.3)	(42.5–136.3)	(42.5–112.2)	–
D_R (nGy/h)	60.6 ± 23.4	42.5 ± 14.1	36.6 ± 9.9	46.6
Range (Min–Max)	(22.7–94.7)	(19.0–63.2)	(20.6–51.9)	–
External hazard index (H_{ex})	0.4 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.3
Range (Min–Max)	(0.1–0.6)	(0.1–0.4)	(0.1–0.3)	–
Internal hazard index (H_{in})	0.5 ± 0.2	0.3 ± 0.1	0.3 ± 0.1	0.4
Range (Min–Max)	(0.2–0.7)	(0.2–0.5)	(0.2–0.4)	–
AEDE (mSv/y)	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1
Range (Min–Max)	(0.0–0.1)	(0.0–0.1)	(0.1–0.1)	–

in order to assess the health risk by the public [37]. The recommended global average concentration for absorbed dose rate varies from 18 to 93 $nGyh^{-1}$, and the population-weighted concentration resulted in an outdoor average of 60 $nGyh^{-1}$ from terrestrial gamma radiation [3]. The average absorbed dose rate in air at UCC, KP, and AMM were 60.6 ± 2.4 $nGyh^{-1}$, 42.5 ± 1.1 $nGyh^{-1}$, and 36.6 ± 9.9 $nGyh^{-1}$, respectively. The overall average value across the three communities was 46.6 $nGyh^{-1}$, which is below the global recommended level of 60 $nGyh^{-1}$. Even though the UCC value was slightly above the recommended level.

According to UNSCEAR, the global recommended average for the annual effective dose equivalent (both indoor and outdoor) is 0.48 $mSvy^{-1}$, with an indoor dose of 0.41 $mSvy^{-1}$ and an outdoor exposure of 0.07 $mSvy^{-1}$. Individual country results range from 0.3 to 0.6 $mSvy^{-1}$ [3]. As presented in Table 6, the average outdoor annual effective dose equivalent for UCC, KP, and AMM were 0.07, 0.05, and 0.05 mSv/y, respectively, and the overall average was 0.06 mSv/y for the three communities, which was below the recommended level of 0.07 mSv/y. The average adult annual effective dose per year from ingesting radionuclides in groundwater from AMM was 0.4 ± 0.2 mSv/y, while that from KP was 0.3 ± 0.2 mSv/y. WHO recommends that a yearly dose comparable to any one organ or tissue of these radionuclides in water should not be >0.1 mSv/y [36]. However, the annual effective dose for the two communities exceeded the 0.1 $mSvy^{-1}$ global guidance level. Similarly, the annual effective dose obtained by Faanu *et al.* for both communities was higher than the WHO guidance level [13].

Conclusion

A study on background natural radioactivity had been conducted at the UCC and its nearby towns to assess the risk of exposure of these radionuclides to the general public. Soil and water samples analysed show elevated levels of ^{226}Ra and ^{232}Th in soil at UCC residential areas and ^{226}Ra in water at AMM township. The parameters (D_R, Ra_{eq}, AEDE, Hex, Hin) used to assess radiological risk in soil calculated for the three communities (UCC, KP, AMM) were below the world average, with UCC having equivalent levels of D_R and AEDE. The disparity in the activity concentration of the radionuclides in these communities indicates some variation in geological formations in the area. Also, the higher activity concentration in underground water may be caused by the extended contact period of groundwater with soil and bedrock, during which minerals dissolve in the groundwater. Even though, the Ra_{eq}, hazard indices and outdoor annual effective dose were below the recommended level, further studies of indoor radon levels in dwellings are recommended to ascertain the cancer risk of these radionuclides to the populace.

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Conflict of interest

The authors declare no conflicts of interest and that none of the work presented in this study may have been influenced by any known conflicting financial interests or personal relationships.

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