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Natural radionuclides and assessment of radiological hazards in different geological formations in Khammouan province, Laos

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Abstract

The ^{226}Ra, ^{232}Th (^{228}Ra), ^{40}K activity concentrations in soil distributed in 67 points belonging to different geological formations in Khammouan, Laos were measured using HPGe detector. The results showed that the activity concentration varies from (6.0 ± 0.61) Bq/kg to (68.5 ± 8.0) Bq/kg, (8.7 ± 1.0) Bq/kg to (78.9 ± 8.3) Bq/kg, (32.1 ± 3.1) Bq/kg to (812 ± 63) Bq/kg with the mean values of (32.2 ± 1.7) Bq/kg, (41.6 ± 2.2) Bq/kg, (279 ± 24) Bq/kg for ^{226}Ra, ^{232}Th (^{228}Ra), ^{40}K respectively. The highest and lowest average activities were found at cPz2 (Middle Paleozoic) and Mz1 (Lower Mesozoic) formations respectively. With regard to radiation hazards, the ^{232}Th (^{228}Ra) concentration has a major contribution to the Ra_{eq}. In general, in the study area, the activity concentration of natural radionuclides has an insignificant effect on human health.

Keywords Natural radionuclides · Radiation hazards · Geological formation · Khammouan province

Introduction

Assessment of natural radionuclides and related radiation hazards play an important role in radioactivity research regarding human health and have been received much attention from worldwide researchers. In which, the distribution of natural radionuclides in different types of soil and rock and assessment of their radiological hazards have been also widely investigated. For urban soils in Armenia, Belyaeva et al. [1] indicated that in the Kapan area, although the natural radioactivity (^{238}U, ^{232}Th, ^{40}K) levels in soil were enhanced by mining activities, they did not significantly

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affect human health. By contrast, these authors showed that the level of radioactivity in the soil at some locations was higher than the background values, but it did not come from the mining activities. In Egypt, for some rocks such as marble, granite, serpentine, Shohda et al. [2] presented that the measured activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K in these rock samples was within the safety limits and had also no significant radiation hazards to human health. According to the research results of Birami et al. [3], the high radioactivity levels and radiation hazards were observed in Arud granitic rock and Ramsar's soil in Northern Iran. These authors indicated that the main contributors to the high level of radiation in the study area are ^{40}K-bearing feldspars and ^{226}Ra-rich carbonates. In general, as reported in the literature, the level of natural radioactivity in soil and rock significantly depends on the feature of geological formation. Thus, the distribution of natural radionuclides in soil, rock which comes from different geological formations in different areas needs to be further investigated with aiming to evaluate the natural radiation hazards to human health as well as providing special information for different economic policies of the local authority.

The Khammouan province, a high population density which is one of the key economic areas of Laos. This province borders Bolikhamxay province to the north, Xavanakhet province to the South, Ha Tinh, Quang Binh provinces (Vietnam) to the east, and Thailand to the west (Fig. 1). In Laos, the mining activities in Khammouan province are not significant. However, the copper and gold mining activities in Bolikhamxay and Xavanakhet provinces are the most significant mining interest [4, 5]. Thus, investigation of the natural radionuclide concentration in soil samples in the Khammouan area will provide baseline data for further research on TENORM. Recently, the assessment of natural radionuclide in soil samples and building materials distributed in different areas of Laos also attracted many researchers [4–8].

From the geological point of view, the geological formations of Khammoun province include Mz1 (Lower Mesozoic), Mz2 (Middle Mesozoic), N2Q (Upper Neogene-Quaternary), PR (Proterozoic), Pz2 (Middle Paleozoic), Pz3 (Upper Paleozoic), cPz2 (Middle Paleozoic), cPz3 (Upper Paleozoic), gPz2 (Middle Paleozoic), gPz3 (Upper Paleozoic), vPz3 (Upper Paleozoic) and can be divided into two main groups of geological formations in the direction from the North East to the South West strike: sedimentary and magmatic—volcanic formations. In the spatial distribution, in the Northeastern, there are intrusive magmatic rocks, basalt rocks, and volcanoes (magmatic—volcanic) whose composition is granitoid gneiss, granite, gneiss micas, marble, and mafic volcanic rocks. While the Southwestern part is the sedimentary formation which contains red arenite, gravel, sandstone, clay, limestone, coal, and conglomerate. In this study, the activity of natural radionuclides in soil samples of different geological formations in the centre province of Laos will be measured and analyzed. The 67 points for soil and rock sampling were chosen in densely populated areas, agricultural zones, tourist resorts, and schools. The samples were collected in an undisturbed area, away from trees, buildings, roads, and other structures, and followed the trending from the North East to the South West at different geological formations to observe the alteration—related formations (Fig. 1). The results of radioactivity measurement were also used to calculate the radiological hazards.

Sample preparation and methods

Sample preparation

In this study, the samples were taken at Khammouan province of Laos in the dry season in 2020 (Fig. 1). The soil samples after taking were removed from gravel, rock fragments, and tree roots. These soil samples were dried at 105 °C temperature for 10 to 24 h and then milled less than 0.2 mm in size. Each fine soil sample was weighed, then packed into a cylindrical plastic box. Each soil sample box was sealed for 30 days to reach a secular equilibrium between the radium and its daughter radionuclides.

Methods

The method for measurement of radionuclide concentration in this study follows the method which was used in previous studies [9–14]. Accordingly, a high-resolution HPGe detector with a low background of Ortec™ was used to measure the radionuclide activities and Gamma Vision software was employed to analyze the spectrum. The detector energy resolution is 1.9 keV at the 1.33 MeV ^{60}Co gamma-ray peak. A 10-cm thick old-lead cylinder with a 1 mm cadmium and 1 mm copper inner lining detector was used to reduce the radiation inside the lead shield. The time for the measurement process was about two days to minimize the statistical counting error. The standard reference materials (reference materials RG produced by IAEA and IAEA-375) were employed for activity calculation and calibration.

The activity concentration of each soil sample was calculated based on its respective gamma lines with the gamma lines of 609.3 keV, 1120.3 keV, and 1764.5 keV for ^{226}Ra, the gamma line of 1460 keV for ^{40}K. The lines of 911.2 keV, 969.0 keV, 2614.5 keV, 583.0 keV were used for ^{232}Th (^{228}Ra). The ^{232}Th was mentioned and measured with the assumption of equilibrium between ^{232}Th and ^{228}Ra (^{228}Th) in soil samples [11, 14–16].

The calculation of activity concentrations of natural radionuclides, radiation hazard indices including the radium

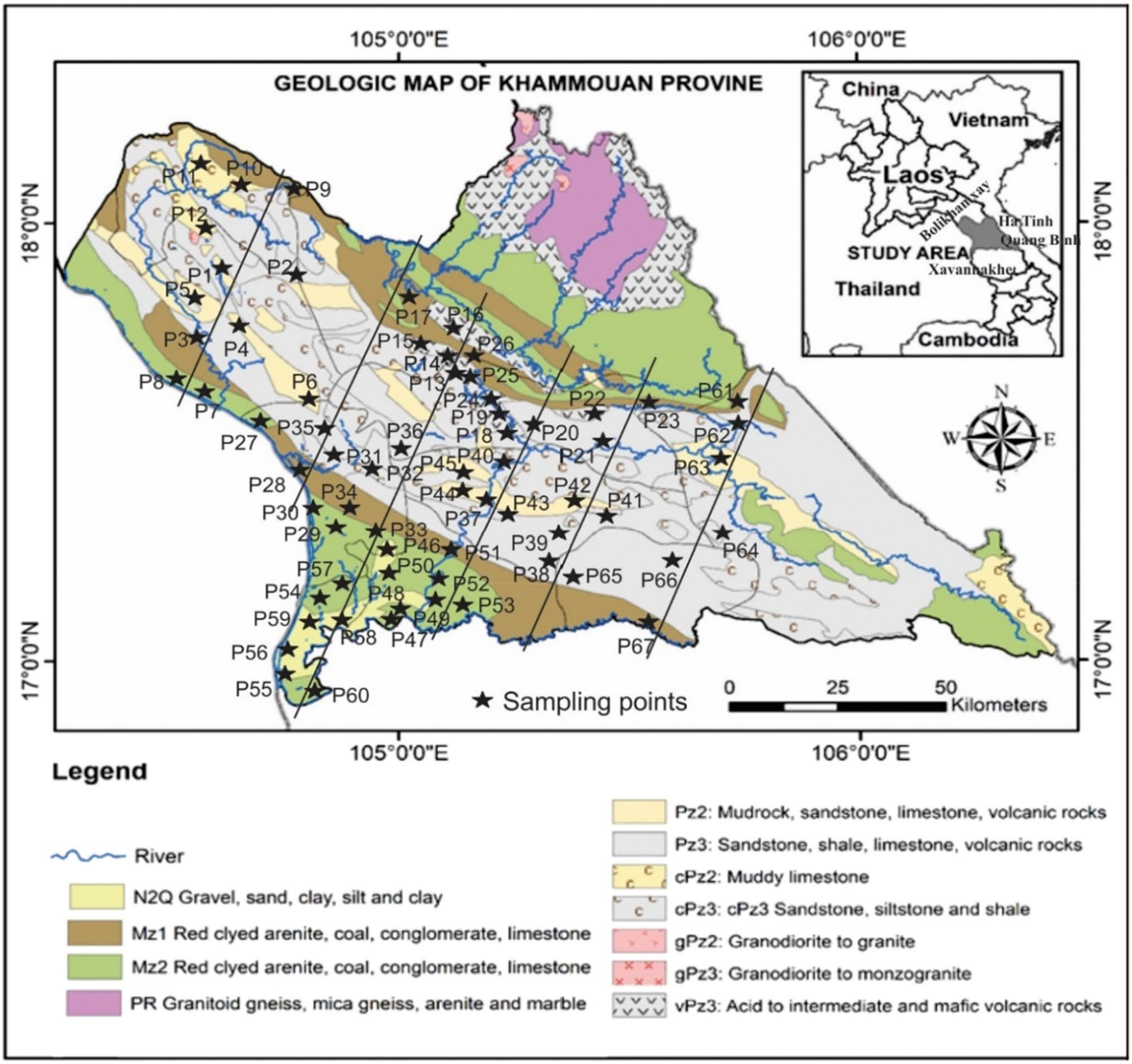

Fig. 1 Geological map and sampling points

equivalent activity concentration (Ra_{eq}), the absorbed gamma dose rate (D), the annual effective dose equivalent (AEDE), and the excess lifetime cancer risk (ELCR) were conducted following the methods shown in Duong et al. (2021) [14]. In this study, the life expectancy of Laos people is 68.9 years [17].

Results and discussions

Activity concentration

The results of measured activity concentration of natural radionuclides are presented in Table 1. As shown, the activity concentrations of ^{226}Ra, ^{232}Th (^{228}Ra), and ^{40}K in the study area range from (6.0 ± 0.61) Bq/kg to (68.5 ± 8.0) Bq/kg, from (8.7 ± 1.0) Bq/kg to (78.9 ± 8.3) Bq/kg, from

Table 1 Activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K

Sampling points	Geological formation	Activity concentration (Bq/kg)		
		^{226}Ra	^{232}Th(^{228}Ra)	^{40}K
P1	Pz2	43.7 ± 2.1	60.5 ± 3.6	356 ± 24
P2	Pz3	25.3 ± 1.6	42.7 ± 2.7	256 ± 13
P3	Pz3	68.5 ± 8.0	47.0 ± 2.2	106 ± 5.5
P4	Pz2	52.9 ± 2.9	63.0 ± 3.6	590 ± 36
P5	Pz2	31.6 ± 1.9	33.7 ± 2.2	58.8 ± 4.6
P6	Pz2	48.7 ± 3.0	56.5 ± 2.7	235 ± 14
P7	Mz2	61.5 ± 3.4	53.2 ± 2.9	146 ± 7.0
P8	Mz2	14.9 ± 0.9	22.9 ± 1.4	181 ± 10
P9	Pz3	64.8 ± 3.7	35.7 ± 2.1	674 ± 31
P10	cPz2	30.1 ± 1.5	52.8 ± 2.8	462 ± 25
P11	cPz2	40.0 ± 2.4	76.9 ± 3.9	675 ± 19
P12	cPz2	52.8 ± 3.2	50.9 ± 3.9	577 ± 30
P13	vPz3	24.1 ± 1.5	43.5 ± 2.7	364 ± 16
P14	vPz3	27.7 ± 1.7	43.0 ± 2.6	475 ± 22
P15	vPz3	25.8 ± 1.6	33.0 ± 2.8	393 ± 16
P16	vPz3	16.1 ± 1.0	31.7 ± 2.1	326 ± 9.0
P17	Mz1	10.5 ± 0.70	24.0 ± 1.0	431 ± 20
P18	vPz3	22.2 ± 1.3	29.1 ± 2.2	86.8 ± 8.6
P19	vPz3	57.7 ± 3.4	76.1 ± 3.6	336 ± 16
P20	Pz3	55.3 ± 3.3	38.9 ± 2.1	40.7 ± 3.2
P21	Pz3	51.4 ± 3.2	48. 9 ± 3.0	67.8 ± 5.6
P22	vPz3	22.2 ± 1.6	39.1 ± 2.0	376 ± 18
P23	Mz1	24.1 ± 1.6	36.2 ± 2.4	353 ± 18
P24	vPz3	43.4 ± 2.6	64.3 ± 4.6	455 ± 21
P25	vPz3	46.0 ± 2.8	72.8 ± 4.6	812 ± 63
P26	Mz1	14.1 ± 1.1	17.3 ± 1.4	140 ± 7.0
P27	Mz2	38.9 ± 2.0	62.6 ± 3.1	560 ± 25
P28	Mz1	30.0 ± 1.8	30.3 ± 1.9	128 ± 7.0
P29	Mz2	44.5 ± 2.1	36.2 ± 2.0	357 ± 16
P30	Mz2	32.4 ± 1.9	29.1 ± 1.7	140 ± 8.0
P31	Pz3	9.1 ± 0.70	19.8 ± 1.6	131 ± 7.1
P32	Pz3	49.0 ± 2.2	34.3 ± 2.4	44.9 ± 3.2
P33	Mz2	37.7 ± 1.7	59.3 ± 3.2	186 ± 6.2
P34	Mz1	28.6 ± 1.4	34.0 ± 1.8	126 ± 5.1
P35	Pz3	31.9 ± 1.6	46.0 ± 2.1	189 ± 6.0
P36	Pz3	35.7 ± 2.2	58.6 ± 2.4	409 ± 19
P37	Pz2	35.0 ± 2.6	66.2 ± 3.6	371 ± 16
P38	Pz3	21.2 ± 1.4	25.9 ± 1.8	210 ± 10
P39	Pz3	30.8 ± 2.0	67.2 ± 3.0	280 ± 12
P40	Pz3	31.2 ± 2.1	36.5 ± 2.1	260 ± 12
P41	Pz3	13.1 ± 1.0	14.0 ± 1.1	65.6 ± 3.8
P42	Pz2	30.0 ± 1.4	32.9 ± 1.7	120 ± 5.2
P43	Pz2	31.1 ± 1.6	45.1 ± 2.1	135 ± 6.1
P44	Pz2	30.6 ± 1.6	38.9 ± 1.9	121 ± 5.1
P45	Pz2	10.6 ± 1.0	10.7 ± 1.0	68.1 ± 4.3
P46	N2Q	37.2 ± 2.2	20.5 ± 1.1	396 ± 16
P47	Mz2	23.8 ± 1.7	29.8 ± 1.7	114 ± 8.3
P48	Mz2	20.7 ± 1.4	12.3 ± 1.1	104 ± 8.2
P49	Mz2	18.0 ± 1.5	24.8 ± 2.1	38.9 ± 4.5
P50	Mz2	14.8 ± 1.4	19.3 ± 1.8	76.7 ± 7.0
P51	Mz1	30.8 ± 1.6	43.8 ± 2.0	185 ± 6.3
P52	Mz2	31.9 ± 1.6	16.3 ± 1.2	56.5 ± 3.6
P53	Mz2	55.2 ± 2.6	78.9 ± 8.3	71.5 ± 3.6
P54	Mz2	33.1 ± 2.0	48.9 ± 2.7	440 ± 18
P55	N2Q	43.4 ± 2.3	70.7 ± 2.7	634 ± 20
P56	N2Q	34.1 ± 2.1	49.9 ± 3.0	382 ± 15
P57	Mz2	27.3 ± 1.8	54.3 ± 3.0	384 ± 15
P58	N2Q	26.8 ± 1.8	41.4 ± 2.1	164 ± 8.1
P59	N2Q	28.6 ± 1.9	45.3 ± 2.6	602 ± 25
P60	Mz2	29.6 ± 2.0	56.4 ± 3.0	304 ± 15
P61	Mz1	30.4 ± 2.9	55.9 ± 2.6	343 ± 11
P62	Pz3	44.2 ± 2.4	64.1 ± 3.0	724 ± 25
P63	Pz2	21.6 ± 1.5	19.8 ± 1.8	117 ± 12
P64	Pz3	27.1 ± 2.4	8.7 ± 1.0	49.0 ± 4.5
P65	Pz3	13.9 ± 1.2	33.9 ± 2.5	489 ± 37
P66	Pz3	14.7 ± 1.2	21.6 ± 2.3	80.9 ± 4.5
P67	Mz1	6.0 ± 0.61	25.1 ± 2.2	32.1 ± 3.1
Average		32.2 ± 1.7	41.6 ± 2.2	279 ± 24
Min		6.0 ± 0.61	8.7 ± 1.0	32.1 ± 3.1
Max		68.5 ± 8.0	78.9 ± 8.3	812 ± 63
Standard deviation		14.2	17.9	200
Median		30.6	39.1	235
Skewness		0.49	0.21	0.72
Kurtosis		-0.15	-0.76	-0.36

(32.1 ± 3.1) Bq/kg to (812 ± 63) Bq/kg with the mean values of (32.2 ± 1.7) Bq/kg, (41.6 ± 2.2) Bq/kg, (279 ± 24) Bq/kg respectively. The highest concentration of ^{226}Ra is found in sampling point P3 which belongs to Pz3 formation while the lowest one is found in P67 (Mz1). For ^{232}Th (^{228}Ra) concentration, the highest value is observed in P53 (Mz2) while the lowest one is in P64 (Pz3). For ^{40}K concentration, the highest value is found in P25 (vPz3) whereas the lowest one is observed in P53 (Mz2). The asymmetric distribution curve of these natural radionuclides is plotted in Fig. 2. As shown in this figure, since the mean and median values of ^{226}Ra, ^{232}Th (^{228}Ra) are almost similar and the Skewness values are 0.49 and 0.21 respectively, the concentrations of ^{226}Ra, ^{232}Th (^{228}Ra) are nearly normal distribution. By contrast, the concentration of ^{40}K is the right-skewed (positive skew) distribution with the Skewness value of 0.72. It can be seen that the highest variation of measured activity concentration is also observed for ^{40}K with the standard deviation, SD of 200 Bq/kg. This phenomenon is due to the high mobility of potassium and it is easily transported by water [18, 19]. The large variation of ^{40}K concentration was also found in

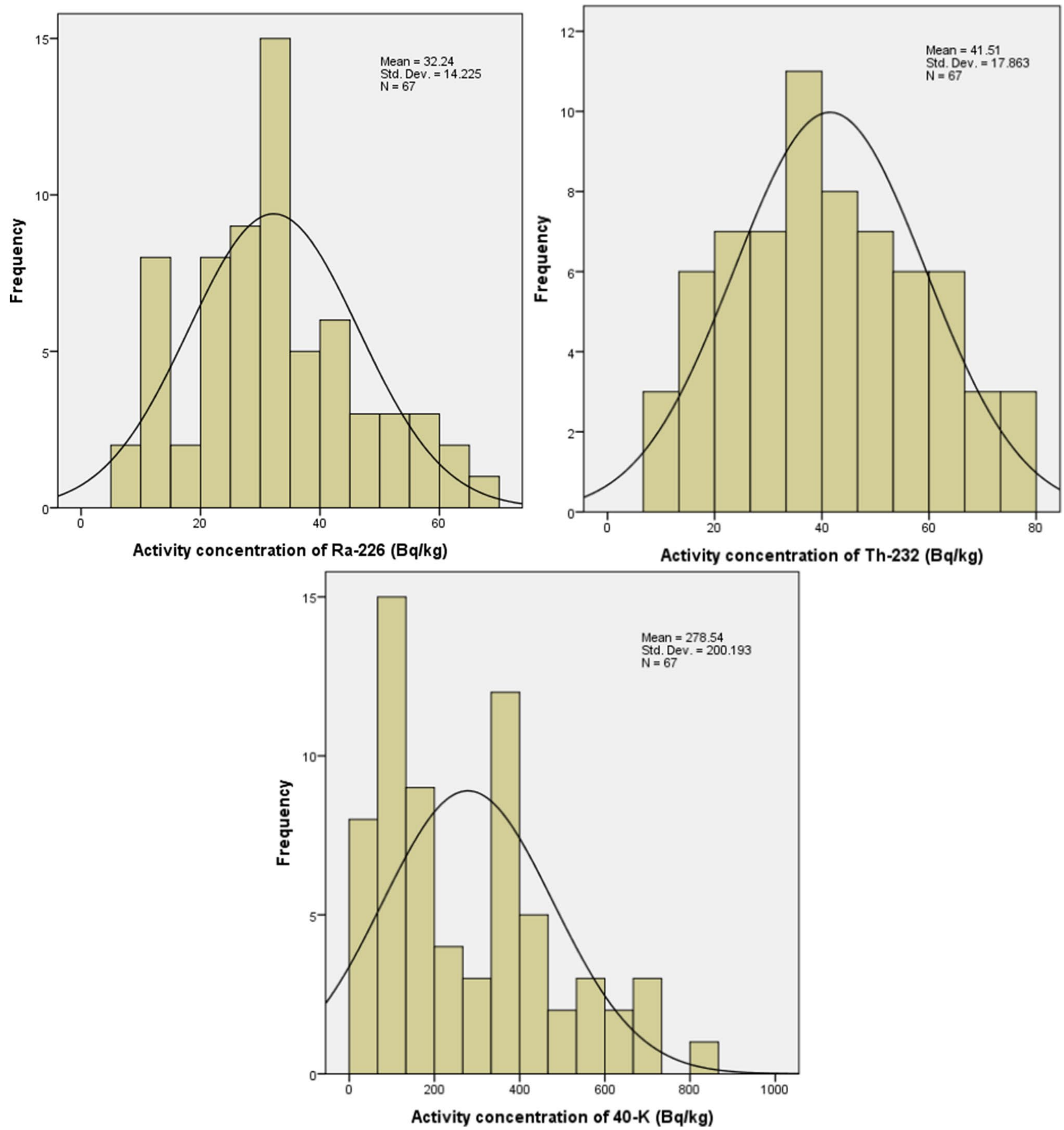

Fig. 2 Distribution curve of ^{226}Ra, ^{232}Th(^{228}Ra), and ^{40}K concentration in the study area

soil sample outside the ore body in Muong Hum, Viet Nam [14]; in surface soil sample in Bolikhamxay, Laos [5]; in soil sample in Savannakhet, Laos [4].

In general, there are about 38.8% (26 points), 41.8% (28 points), and 22.4% (15 points) of total sampling points that has concentrations of ^{226}Ra, ^{232}Th (^{228}Ra), and ^{40}K are higher than the global average values respectively. However, the average concentration of ^{226}Ra is almost close to the global average value (32 Bq/kg) whereas the average concentrations of ^{232}Th (^{228}Ra) and ^{40}K in the study area are lower than the global average values which are 45 and 420 Bq/kg respectively [16]. In comparison to some surrounding areas of the

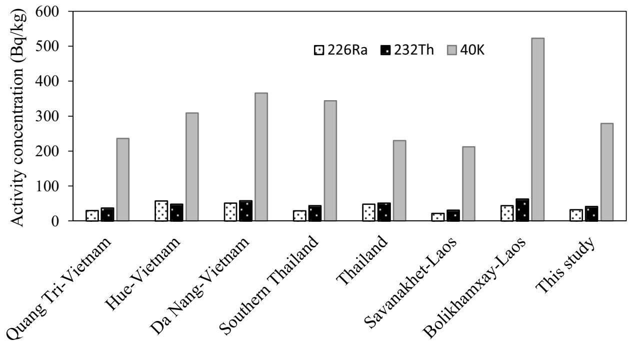

Fig. 3 Variation of natural radionuclides in soil in some surrounding areas

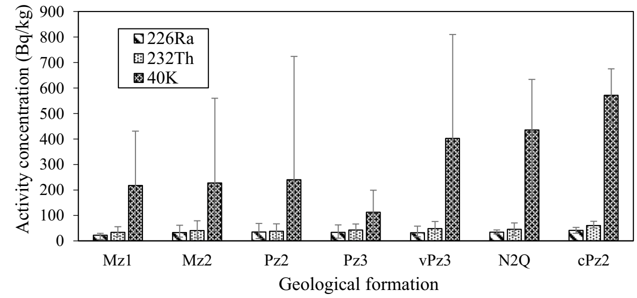

Fig. 5 Natural radionuclide concentration at different geological formations

study area, the variation of average concentrations of ^{226}Ra, ^{232}Th (^{228}Ra), and ^{40}K in these areas are shown in Fig. 3. The values of these radionuclides in these areas are taken from Leuangtakoun et al. 5]. As shown, in Laos, the average concentrations of studied radionuclides in Khammouan province (this study) are slightly higher than those in Savannakhet province [4] but lower than those in Bolikhamxay province [5]. Additionally, the average concentrations of natural radionuclides in the soil in this study are almost similar to those in other areas which are shown in Fig. 3.

The variation of natural radionuclides in terms of geological formations is shown in Figs. 4 and 5. As presented in Fig. 4, the average concentrations of ^{226}Ra and ^{232}Th (^{228}Ra) slightly range from 21.8 Bq/kg (Mz1) to 41.0 Bq/kg (cPz2) Bq/kg and from 33.3 Bq/kg (Mz1) to 60.2 Bq/kg (cPz2) Bq/kg while the average concentration of ^{40}K significantly varies from 112 Bq/kg (Mz1) to 571 Bq/kg (cPz2). This indicates that the radionuclide concentration in soil significantly depends on the geological formations. Some previous studies, such as Birami et al. [3] revealed that the types of rock are the main factor enhancing the radionuclide concentration in soil samples. In this study, it is found that the highest average concentrations of ^{226}Ra, ^{232}Th, and ^{40}K are found in cPz2 formation whereas the lowest average concentrations of these radionuclides are detected in Mz1 formation. The cPz2 formation is mainly composed of muddy limestone, claystone, and shale. Among geological formations, the muddy limestone in the cPz2 formation has the highest dissolution ability and claystone, and shale are easily weathered. These phenomena may lead to a high concentration of natural radionuclides in this geological formation. By contrast, the Mz1 formation is the youngest formation in the study area and is mainly composed of coal, red arenite, and conglomerate which have a low ability of weathering, so it may lead to a low concentration of studied radionuclides in this formation. Additionally, as shown in Fig. 5, for all geological formations, the highest activity concentration is observed for ^{40}K while the lowest one is seen for ^{226}Ra. This phenomenon can be explained based on the mobility of radionuclides. The potassium has the highest mobility while the Ra has the lowest mobility among studied radionuclides [18, 19]

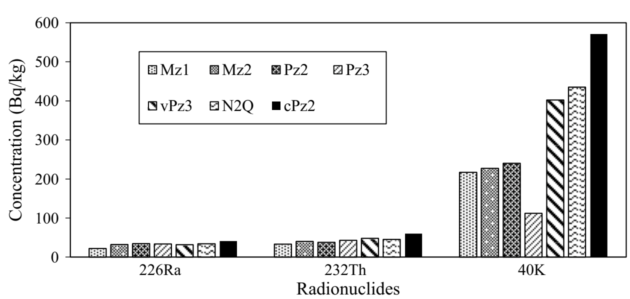

Fig. 4 Variation of natural radionuclide concentration

Radiological hazards

The calculated results of radiological hazard indices for the soil in Khammouan province are presented in Table 2. The world average values are also listed in this table.

As shown in Table 2, the radium equivalent activity (Ra_{eq}) in the soil samples in the study area varies from 31.1 to 213 Bq/kg with a mean value of 113 Bq/kg. As reported in UNSCEAR (2000), the maximum value of Ra_{eq} should be lower than the limit value of 370 Bq/kg to ensure the external dose less than 1.5 mGy/h. It can be seen that the average value of Ra_{eq} in the study area is significantly lower than the recommended value of UNSCEAR (2000) [16]. Additionally, the highest value of Ra_{eq} in the study area observed in sampling point P25 is still lower than the limit value of 370 Bq/kg.

The correlation between Ra_{eq} and studied radionuclide concentrations is plotted in Fig. 6. As shown, the correlation coefficients (R^2) of the Ra_{eq} and ^{226}Ra, ^{232}Th (^{228}Ra), ^{40}K concentrations are 0.56, 0.88, 0.56 respectively. It can be seen that among studied radionuclides, the Ra_{eq} has the strongest correlation with ^{232}Th concentration. This indicates

Table 2 Results of radiological hazard indices

Indices	Average	Maximum	Minimum	SD	Skewness	Kurtosis	World average (UNSCEAR, 2000)
R_{aeq} (Bq/kg)	113	31.1	213	46	0.18	− 0.79	370
D (nGy/h)	52.3	100	14.4	21.6	0.21	− 0.73	57
AEDE (μSv/y)	64.1	123	17.6	26.5	0.21	− 0.73	70
ELCR	0.25×10^{-3}	0.48×10^{-3}	0.07×10^{-3}	0.10×10^{-3}	0.21	− 0.73	0.29×10^{-3}

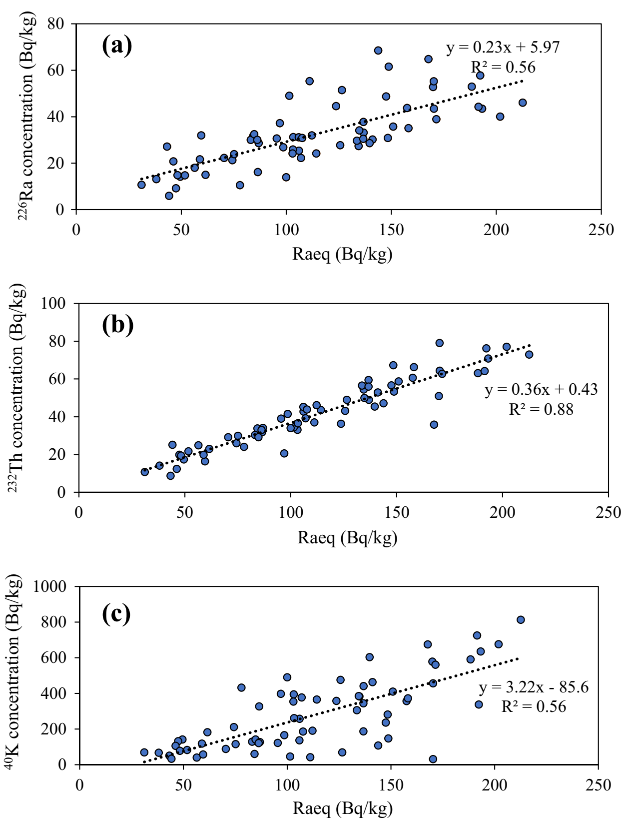

Fig. 6 Correlation between ^{226}Ra, ^{232}Th, ^{40}K and Ra_{eq}

that the concentration of ^{232}Th has a major contribution to the Ra_{eq}. This research result well agrees with the research result reported in Bolikhamxay province, Laos [5].

The variation of absorbed dose rate (D), annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR) values are shown in Figs. 7, 8 and 9. For details as shown in Table 3, the calculated results of (D) range from 14.4 to 100 nGy/h with the mean value of 52.3 nGy/h; the results of the AEDE values vary from 17.6 to 123 μSv/y with the mean value of 64.1 μSv/y, and the ELCR values range from 0.07×10^{-3} to 0.48×10^{-3} and the mean value of ELCR is 0.25×10^{-3}. In general, the values of D, AEDE, and ELCR in some sampling points are higher than the world average values while those in some other points are lower than the world average one. However, the average values of D, AEDE, and ELCR in the study area are still lower than the world average values (Table 2).

Table 3 Calculated results of hazard indices in different sampling points in the study area

Sampling points	Geological formation	Hazard indices		
		D (nGy/h)	AEDE (μSv/y)	ELCR (× 10^{-3})
P1	Pz2	72.6	89.0	0.35
P2	Pz3	48.9	59.9	0.24
P3	Pz3	65.1	79.8	0.31
P4	Pz2	88.2	108	0.42
P5	Pz2	37.9	46.5	0.18
P6	Pz2	67.3	82.5	0.32
P7	Mz2	67.4	82.7	0.32
P8	Mz2	28.7	35.1	0.14
P9	Pz3	80.3	98.4	0.39
P10	cPz2	66.0	80.9	0.32
P11	cPz2	94.4	116	0.45
P12	cPz2	80.1	98.2	0.39
P13	vPz3	53.3	65.4	0.26
P14	vPz3	59.4	72.8	0.29
P15	vPz3	48.8	59.9	0.24
P16	vPz3	40.8	50.0	0.20
P17	Mz1	37.8	46.4	0.18
P18	vPz3	31.9	39.1	0.15
P19	vPz3	87.8	108	0.42
P20	Pz3	50.0	61.4	0.24
P21	Pz3	56.8	69.7	0.27
P22	vPz3	50.2	61.6	0.24
P23	Mz1	48.4	59.3	0.23
P24	vPz3	78.9	96.8	0.38
P25	vPz3	100	123	0.48
P26	Mz1	23.1	28.3	0.11
P27	Mz2	80.2	98.4	0.39
P28	Mz1	38.0	46.6	0.18
P29	Mz2	57.9	71.0	0.28
P30	Mz2	38.8	47.6	0.19
P31	Pz3	22.0	26.9	0.11
P32	Pz3	45.7	56.0	0.22
P33	Mz2	61.9	75.9	0.30
P34	Mz1	39.5	48.5	0.19
P35	Pz3	51.1	62.7	0.25
P36	Pz3	69.9	85.8	0.34
P37	Pz2	72.7	89.2	0.35
P38	Pz3	34.6	42.5	0.17
P39	Pz3	67.6	82.9	0.33
P40	Pz3	47.9	58.7	0.23
P41	Pz3	17.5	21.4	0.08
P42	Pz2	39.2	48.1	0.19
P43	Pz2	47.9	58.8	0.23
P44	Pz2	43.3	53.1	0.21
P45	Pz2	14.4	17.6	0.07
P46	N2Q	46.5	57.0	0.22
P47	Mz2	34.2	42.0	0.16

Table 3 (continued)

Sampling points	Geological formation	Hazard indices		
		D (nGy/h)	AEDE (μSv/y)	ELCR (× 10^{-3})
P48	Mz2	21.5	26.4	0.10
P49	Mz2	25.3	31.0	0.12
P50	Mz2	22.0	27.0	0.11
P51	Mz1	49.1	60.2	0.24
P52	Mz2	27.2	33.3	0.13
P53	Mz2	77.3	94.8	0.37
P54	Mz2	64.0	78.5	0.31
P55	N2Q	90.4	111	0.44
P56	N2Q	62.7	76.9	0.30
P57	Mz2	62.4	76.5	0.30
P58	N2Q	44.9	55.0	0.22
P59	N2Q	66.5	81.6	0.32
P60	Mz2	61.4	75	0.30
P61	Mz1	63.0	77.3	0.30
P62	Pz3	90.5	111	0.44
P63	Pz2	27.1	33.3	0.13
P64	Pz3	19.9	24.4	0.10
P65	Pz3	48.0	58.8	0.23
P66	Pz3	23.6	28.9	0.11
P67	Mz1	19.6	24.1	0.09
Average		52.3	64.1	0.25
Min		14.4	17.6	0.07
Max		100	123	0.48

Conclusions

The concentrations of natural radionuclides (^{226}Ra, ^{232}Th (^{228}Ra), ^{40}K) in 67 soil samples in Khammouan province, Laos have been measured and used to evaluate the radiological hazards in this area. Some main conclusions are drawn as follows:

The study radionuclide concentration in soil significantly depends on the geological formations. The highest average concentration of these radionuclides is found in cPz2 formation while the lowest one is found in Mz1 formation in general. The cPz2 formation is mainly composed of muddy limestone, claystone, and shale while the Mz1 formation is composed of coal, red arenite, and conglomerate. In all studied geological formations, the highest average concentration was found for ^{40}K whereas the lowest one was observed for ^{226}Ra. The average concentration of ^{226}Ra is almost similar to its limit value as reported in UNSCEAR (2000) whereas the average concentrations of ^{232}Th, ^{40}K in the study area are lower than their limit values. Additionally, the average values of studied radionuclide concentration in the study area are almost similar to those in some surrounding areas.

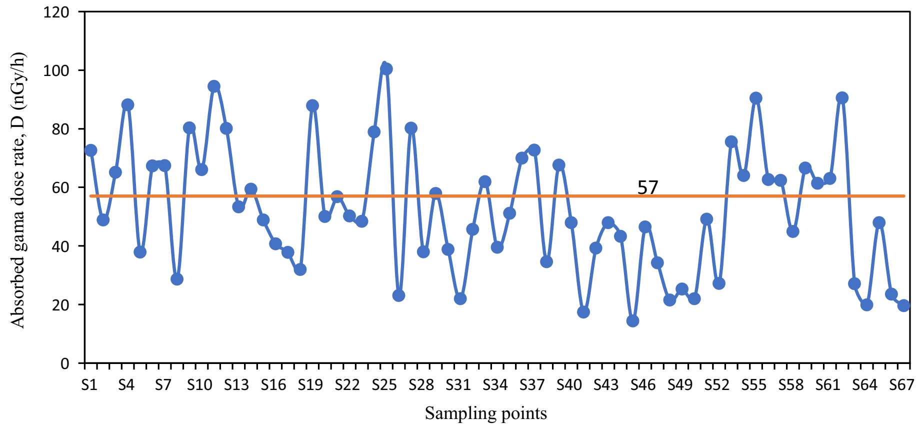

Fig. 7 Variation of absorbed dose rate (D)

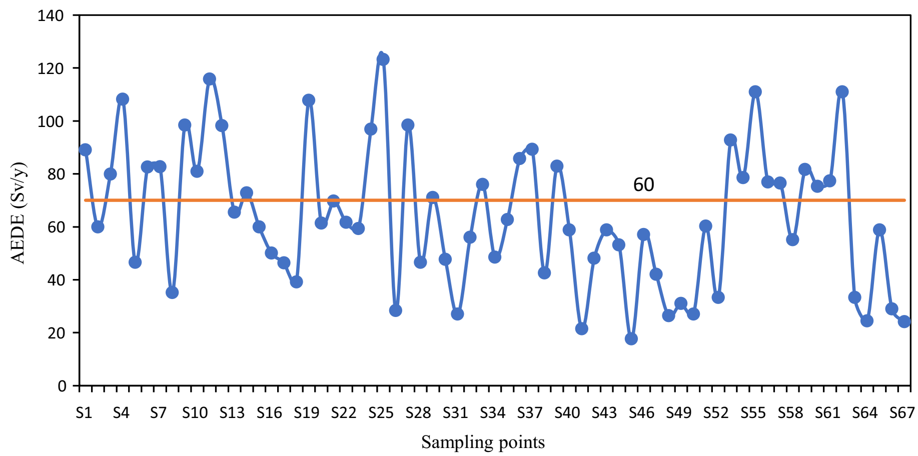

Fig. 8 Variation of annual effective dose equivalent (AEDE)

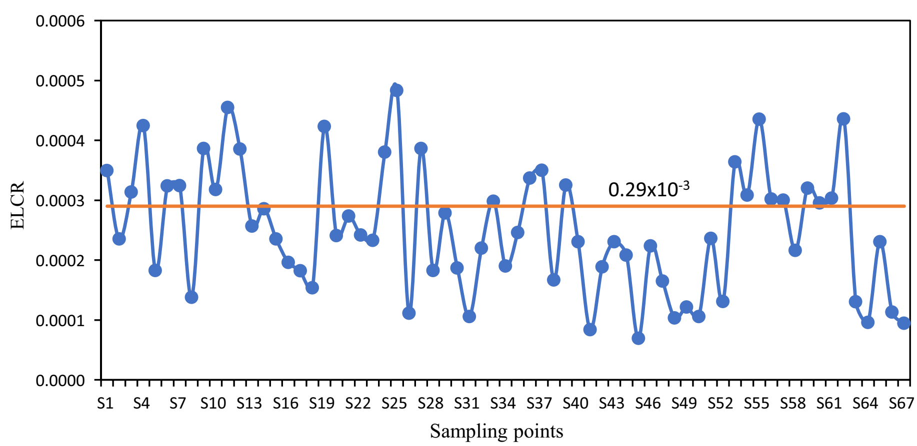

Fig. 9 Variation of excess lifetime cancer risk (ELCR)

Regarding the radiation hazards, the Ra_{eq} has the strongest correlation with ^{232}Th concentration. In general, the radiological hazard indices, including absorbed dose rate (D), annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR) are lower than the world limit values and there is no effect to human health.

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