Journal of Radioanalytical and Nuclear Chemistry (2020) 323:303–315
https://doi.org/10.1007/s10967-019-06965-0

Natural radioactivity and radiological hazards in soil samples in Savannakhet province, Laos

Van Loat Bui[1] · Somsavath Leuangtakoun[1,2] · Thi Hong Bui[1] · Thi Kim Duyen Vu[3] · Thiem Ngoc Le[4] · Thang Duc Duong[4] · Sounthone Singsoupho[2] · Hoai-Nam Tran[5]

Received: 13 August 2019 / Published online: 6 December 2019

Abstract

This paper presents the evaluation of natural radioactivity and radiological hazards of the terrestrial naturally occurring radionuclides of ^{226}Ra, ^{232}Th and ^{40}K in Savannakhet province, Laos. The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K are in the range of 6.6–73.6, 3.8–113.8 and 13.6–906.4 Bq kg^{-1}, with the average values of 22.4 ± 2.1, 30.8 ± 2.9 and 211.6 ± 16.5 Bq kg^{-1}, respectively. The average radium equivalent activity Ra_{eq} is calculated as 82.8 ± 9.7 Bq kg^{-1}, which is smaller than the safety limit of 370 Bq kg^{-1}. Radiological hazard indices have also been evaluated in comparison with the world average values.

Keywords Natural radioactivity · Activity concentration · Radiological hazard · Soil sample

Introduction

Two main sources of the exposure of general public to natural radiation are cosmic ray and radioactive nuclides existing in the earth's crust [1, 2]. The average dose rate of cosmic ray at sea level is about 30 nGy h^{-1}, while the world average dose rate of terrestrial natural occurring radionuclides is about 59 nGy h^{-1} [1, 3]. Natural radioactivity in soils comes mainly from radionuclides in the decay series of uranium (^{238}U), thorium (^{232}Th) and potassium (^{40}K). The levels of natural radioactivity are also dependent on the geological and geographical structure of soils [1, 2]. ^{226}Ra subseries contributes about 98.5% of the total external gamma dose induced by the whole ^{238}U decay series, and therefore, it is usually referred to as ^{226}Ra series instead of ^{238}U series [4]. As reported in UNSCEAR report [1], the world average radionuclide concentrations in soils are 35 Bq kg^{-1} for ^{226}Ra, 30 Bq kg^{-1} for ^{232}Th and 400 Bq kg^{-1} for ^{40}K, respectively [1]. Although the world average values of natural radionuclides in soils are low, the variation between different locations could be up to 1000 Bq kg^{-1} for ^{238}U, 360 Bq kg^{-1} for ^{232}Th and 3200 Bq kg^{-1} for ^{40}K [2]. Several worldwide regions with higher background radiation were notified in China, Iran, India, Italy, France, Switzerland, Australia and Brazil [1]. Therefore, the data of radioactivity concentrations in a specific area should be connected with its population distribution to evaluate the health effect to human livings.

Majority of the external gamma dose rate above typical soils (95%) arises from primordial radionuclides incorporated in soils [1]. The soil layer upper 30 cm contributes predominantly to the natural terrestrial radiation exposure [5]. Soils are also the sources of spreading radionuclides to water, air, sediments and biological systems. Thus, soils are important matrices for evaluating the radiological exposure of the humans and biota, and examining the environmental radiological contamination. It means that measurement of natural radioactivity in soils is necessary to determine the change of the natural background activity with time in case of radioactive release, which is essential for environmental protection [6]. There has been increasing interest in

✉ Hoai-Nam Tran
tranhoainam4@dtu.edu.vn

1 Faculty of Physics, VNU University of Science, 334 Nguyen Trai, Hanoi, Vietnam

2 National University of Laos, P.O. Box 7322, Dongdok, Vientiane, Laos

3 Centre for Technology Environmental Treatment, Military Chemical and Environmental Institute, 282 Lac Long Quan, Hanoi, Vietnam

4 Institute for Nuclear Science and Technology, Vinatom, 179 Hoang Quoc Viet, Hanoi, Vietnam

5 Institute of Fundamental and Applied Sciences, Duy Tan University, Ho Chi Minh City, Vietnam

mapping the natural radioactivity concentrations and radium equivalent activity in soils and establishing baseline data in many countries [4, 6–15]. Consequently, radiological hazard parameters can also be evaluated based on the radioactivity concentrations of natural occurring radioactive materials [1–3]. Therefore, these efforts are considerably important for assessing the public dose rates and the performance of epidemiological studies.

Assessment of the natural radionuclide concentrations in soil samples in Laos for establishing a baseline data is of high important. Several efforts have been made to survey and evaluate the terrestrial natural occurring radioactivity in soils and building materials in Laos. Leuangtakoun et al. [16] assessed the natural radioactivity in surface soils in Bolikhamxay province, Laos. The natural radioactivity and radiological hazards in building materials in Laos were investigated in Ref. [17, 18].

The present work aims at evaluating the natural radionuclide concentrations of ^{232}Th, ^{226}Ra and ^{40}K in soil samples collected widely in Savannakhet province, Laos for establishing a baseline data in this region. The results were then used to analyze radiological hazard indices such as absorbed gamma dose rate in air (D), annual effective dose equivalent ($AEDE$), radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}) and internal hazard index (H_{in}). The radioactivity concentrations of several radionuclides and radiological hazard indices in Savannakhet province have also been evaluated in comparison with neighboring and worldwide regions.

Materials and methods

Sampling area

Laos is a landlocked Southeast Asian country lying between latitude from 14.117° to 23.684° N and longitude from 100.413° to 108.832° E. It shares the borders with Myanmar and China to the northwest, Vietnam to the east, Cambodia to the southwest, and Thailand to the west and southwest.

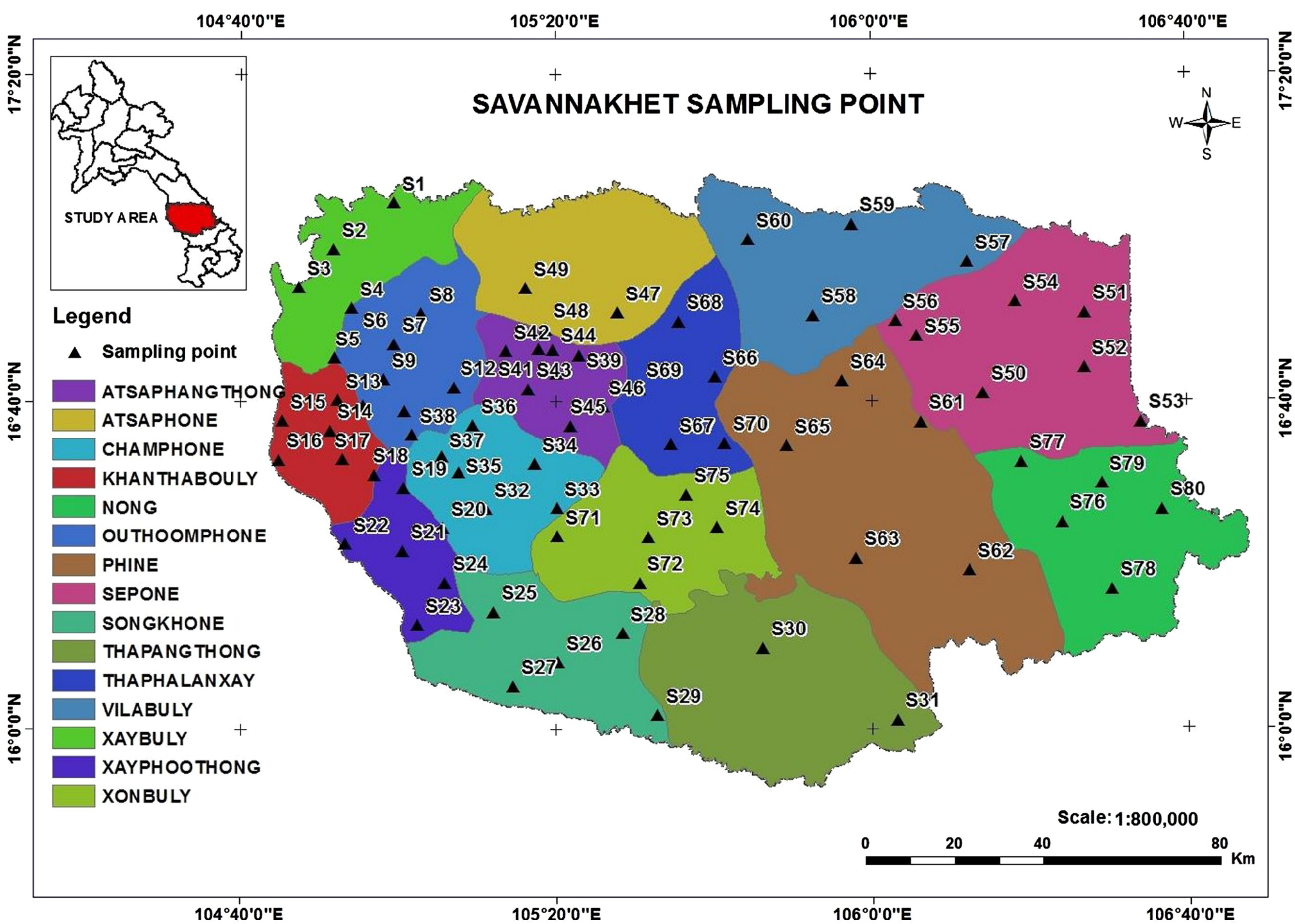

Fig. 1 Map of Savannakhet Province, Laos and the locations of soil samples

Laos has an abundance of natural resources and environmental riches with forest covering half of the country. The climate is tropical and affected by the monsoon pattern. Savannakhet is the largest province located in the southern part of Laos with the area of 21,774 km^2 and the population of 970,000. The province lies on the latitude of 16° 33′ 54.18″ N and the longitude of 104° 45′ 9.83″ E as shown in Fig. 1. It shares the borders with Khammuane province to the north, Quang Tri and Thua Thien-Hue provinces of Vietnam to the east, Salavan province to the south, and Nakhon Phanom and Mukdahan provinces of Thailand to the west. The capital of Savannakhet province, also known as Kaysone Phomvihane or Muang Khanthabouly, is one of the two notable cities of Laos. Savannakhet province is administratively divided into 15 districts as displayed in Fig. 1. Sepone district is the largest mining location of copper and gold, and the most significant mining interest in Laos. Other mining locations include Vilabuly and Champhone districts. The province is also one of the main tobacco producing areas, and is an important trading post between Thailand and Vietnam.

Sample collection and preparation

Soil samples at 80 locations distributed widely in Savannakhet province, Laos were collected during November and December, 2018. This time period was also the dry season in Laos with the outdoor temperature of about 30–40 °C. The sample locations are close to populated agriculture fields and tourist areas. The sampling locations are denoted as S1–S80 as depicted in Fig. 1. At the sampling sites, soil samples were collected from the surface layer with the depth of about 5–30 cm [10, 11, 19]. Five topsoil samples were collected at the four corners and the center of a square with the side of 60 cm. The soils were then mixed up, and the amount of 1–2 kg was taken using a quartile method. After removing organic materials and pieces of stone, the samples

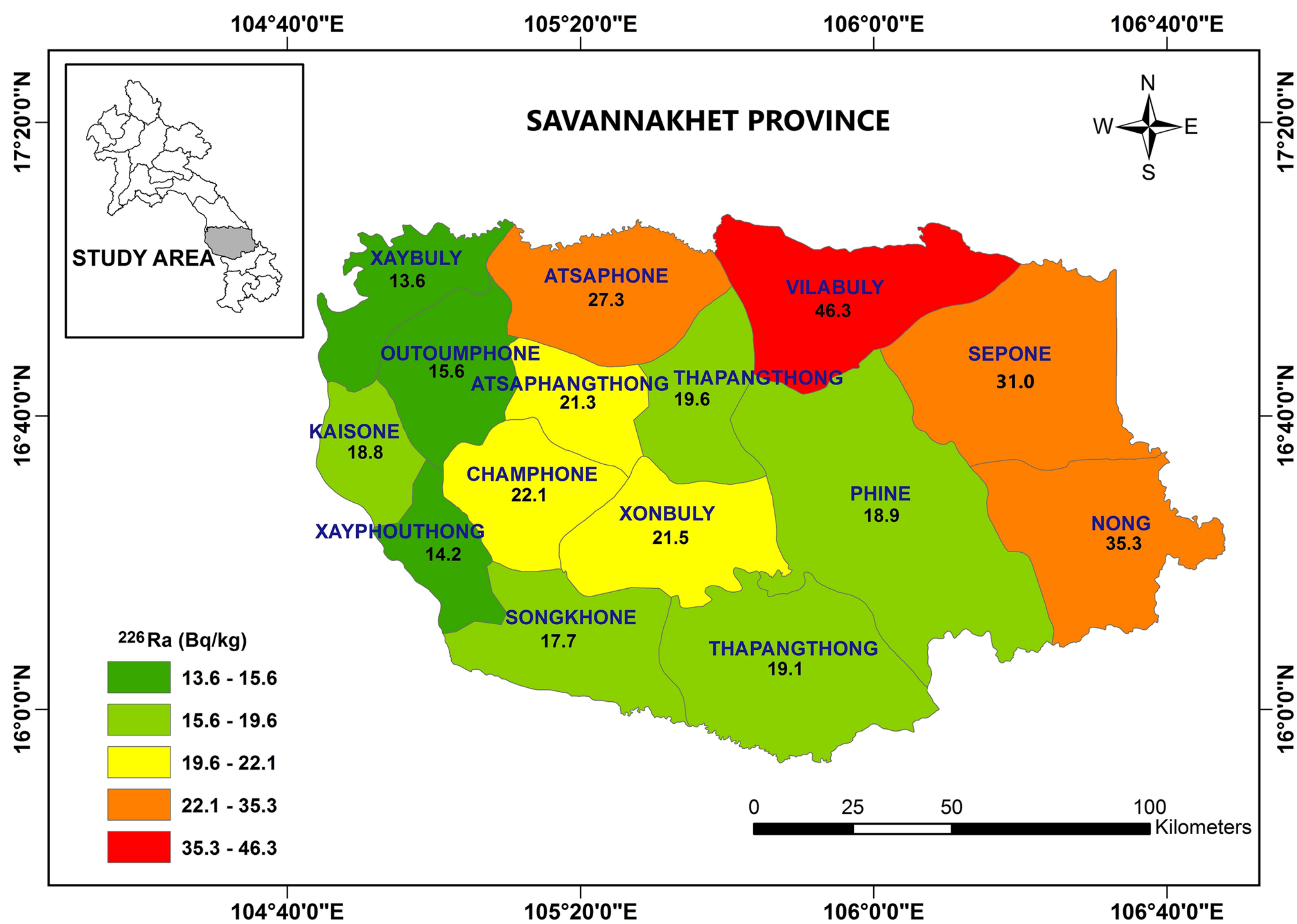

Fig. 2 Average activity concentrations of ^{226}Ra in soil samples in 15 districts of Savannakhet province, Laos

were air dried at room temperature for about 24–48 h at laboratory. Then, the samples were dried in an electric oven at the temperature of 110 °C for about 6 h. In other related works, samples were dried for about 10–12 h at the temperature of 100–110 °C to obtain constant masses [11, 20]. In the present work with relatively dried soil samples, the drying duration of about 6 h is considerably adequate. The samples were crushed and served with a mesh having holes with the diameter of 0.2 mm. The homogenized samples were weighted and placed in a cylindrical polyethylene box having the diameter of 7.5 cm and the height of 3.0 cm. The samples were stored in a period of four weeks for attaining secular equilibrium between ^{226}Ra with ^{214}Bi and ^{214}Pb.

Analysis method

The soil samples were measured using a low background gamma spectroscopy of ORTEC P-type coaxial high purity Germanium (HPGe). The gamma spectroscopy was calibrated using the IAEA RGU–1, RGTh–1 and RGK–1 reference materials to construct the detector efficiency curve as a function of gamma energy [21]. The detector was then used to measure the IAEA–375 soil reference material. The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K were obtained with the deviation less than 3% compared to the reported values. Each soil sample was measured during a period of 60,000–86,400 s to ensure that the 1σ statistic errors of important photopeaks are less than 5%. Similar measurement duration of 60,000 was also applied in Ref. [6]. In particular, to evaluate the activity concentration of ^{226}Ra, it is determined based on the photopeaks of 295.57 keV and 351.9 keV emitted from ^{214}Pb and the photopeaks of 609.3 keV and 1120.3 keV emitted from ^{214}Bi. The activity concentration of ^{232}Th was determined based on the photopeaks of 338.6 keV and 911.1 keV of ^{228}Ac and the peak of 583.19 keV of ^{208}Tl. Whereas, the activity concentration

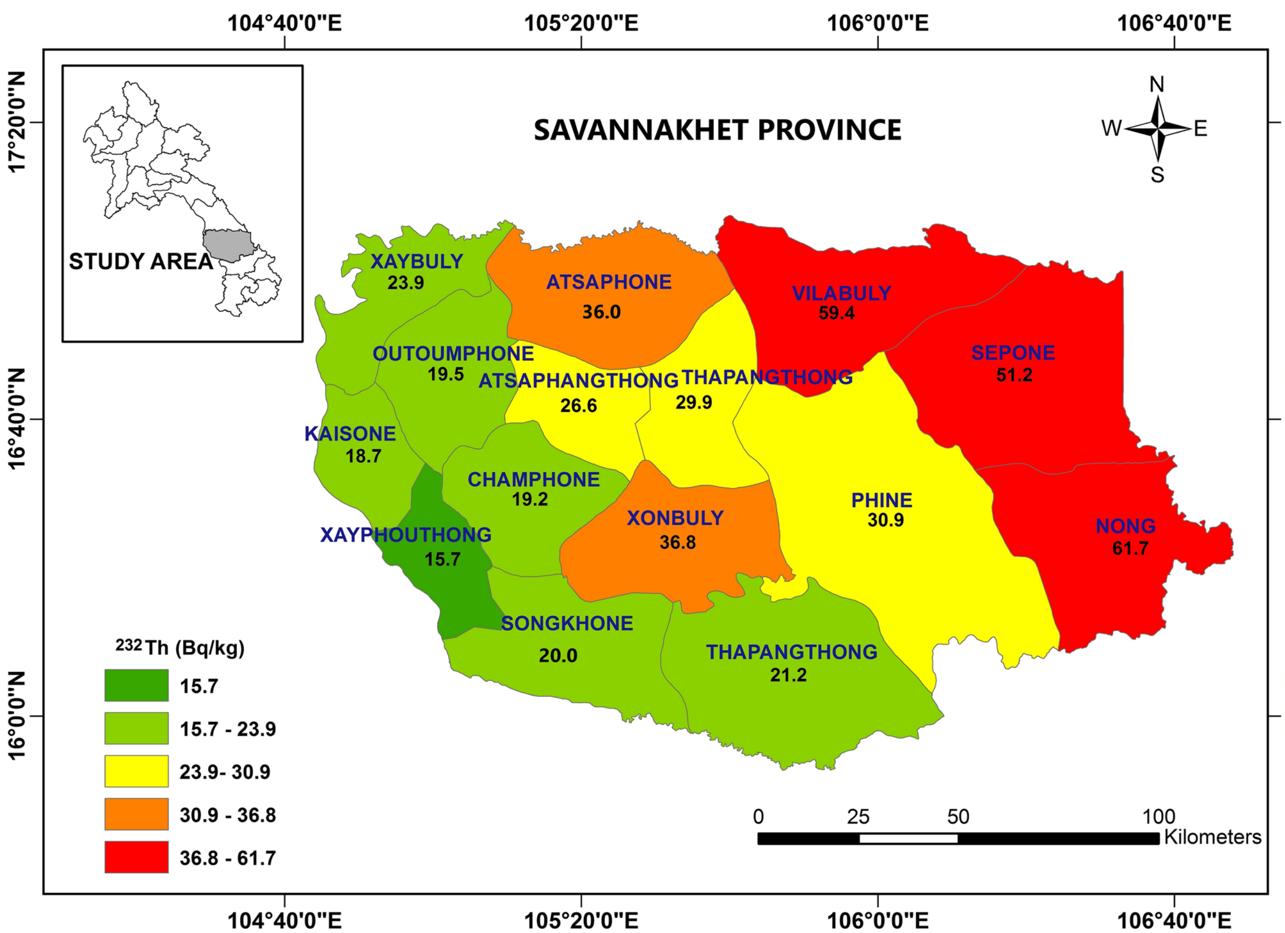

Fig. 3 Average activity concentrations of ^{232}Th in soil samples in 15 districts of Savannakhet province

of ^{40}K was determined directly from its gamma line of 1460 keV. The activity concentration of a certain radionuclide is calculated as follows [13]:

$$A(\mathrm{Bq\,kg^{-1}}) = \frac{n}{\epsilon \times I_{\mathrm{eff}} \times m_{\mathrm{s}}}, \tag{1}$$

where A is the activity concentration of the radionuclide in Bq kg^{-1}; n is the net gamma counting rate (cps) for a peak at a given energy; ϵ is the detector efficiency of a specific gamma-ray, I_{eff} is the emission probability of the photon, and m_{s} is the mass of a soil sample. The 2σ standard deviations of the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K are calculated from the errors of the net gamma counting rates, the detector efficiency, the branching ratios and the mass of soil samples.

In order to assess the radiological hazards associated with natural occurring radioactivity materials, radium equivalent activity Ra_{eq}, absorbed gamma dose rate D, annual effective dose equivalent *AEDE*, external hazard index H_{ex} and internal hazard index H_{in} have been evaluated from the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K. Since the radioactivity levels of ^{226}Ra and ^{232}Th decay series and ^{40}K in soils are non-uniform, the Ra_{eq} is commonly used to determine the total radioactivity of a sample. The Ra_{eq} is evaluated based on an estimation that 10 Bq kg^{-1} of ^{226}Ra, 7 Bq kg^{-1} of ^{232}Th and 130 Bq kg^{-1} of ^{40}K produce the same gamma ray dose rate. Thus, the Ra_{eq} is calculated as follows [22, 23]:

$$Ra_{\mathrm{eq}} = A_{\mathrm{Ra}} + 1.43A_{\mathrm{Th}} + 0.077A_{\mathrm{K}} \tag{2}$$

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

The calculated absorbed gamma dose rate, denoted as D, at about 1 m above the ground surface has been evaluated using the conversion factors of 0.46 nGy h^{-1} for ^{226}Ra, 0.62 nGy h^{-1} for ^{232}Th and 0.042 nGy h^{-1} for ^{40}K. Hence, the absorbed gamma dose rate, D, can be expressed in as follows [24]:

$$D(\mathrm{nGy\,h^{-1}}) = 0.46A_{\mathrm{Ra}} + 0.62A_{\mathrm{Th}} + 0.042A_{\mathrm{K}}. \tag{3}$$

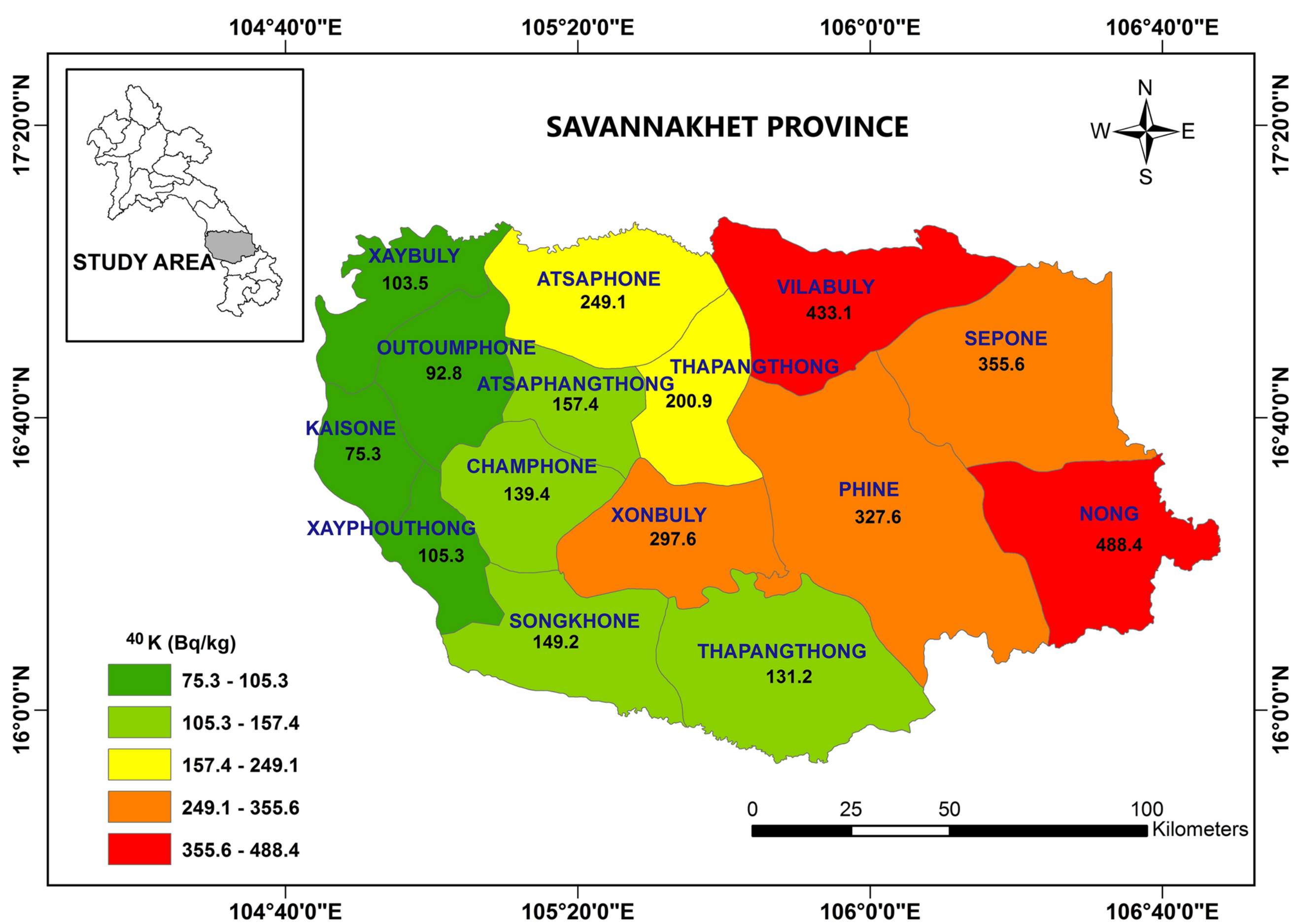

Fig. 4 Average activity concentrations of ^{40}K in soil samples in 15 districts of Savannakhet province

The outdoor annual effective dose equivalent, *AEDE*, was calculated using following equation [1]:

$$AEDE(\mathrm{mSv\,y^{-1}}) = D \times DCF \times OF \times T \quad (4)$$

where D is the absorbed gamma dose rate obtained in Eq. (3); DCF is a dose conversion factor; OF is an outdoor occupancy factor and T is the time factor (8760 h). The values of DCF and OF are 0.7 Sv Gy^{-1} and 0.2, respectively, as taken from UNSCEAR 2000 [1]. The outdoor occupancy factor $OF = 0.2$ is originally from considering people spending about 20% of their time outdoor [25].

The external hazard index, H_{ex}, representing the hazard of natural gamma radiation is calculated as [3, 23, 24]:

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

The internal hazard index, H_{in}, is calculated as [23]:

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810}. \quad (6)$$

The radiation hazard is insignificant when the H_{ex} and H_{in} are less than unity. The value of $H_{ex} = 1$ corresponds to the upper Ra_{eq} limit of 370 Bq kg^{-1}.

Results and discussion

Activity concentrations

Fig. 2 shows the average ^{226}Ra activity concentrations in soil samples in 15 districts of Savannakhet province. The activity concentrations of ^{226}Ra in soils are vary in the range from 6.6 ± 1.5 to 73.6 ± 7.7 Bq kg^{-1}. The smallest activity concentration of 6.7 ± 1.5 Bq kg^{-1} is obtained with sample S7 in Outhoompone district, whereas the highest value of 73.6 ± 7.7 Bq kg^{-1} is obtained with sample S80 at Nong district. The average radioactivity level of ^{226}Ra in Savannakhet province is about 22.4 ± 2.1 Bq kg^{-1}. Comparing to the world average value of 35 Bq kg^{-1}, the average radioactivity concentration of ^{226}Ra is smaller by a factor of 0.64, but the highest value in this region is about two times greater than the world average value [1]. It can also be seen from Fig. 2 that three regions in Savannakhet province having greater radioactivity concentrations of ^{226}Ra than others are Nong, Vilabuly and Sepone districts. The highest average ^{226}Ra activity concentration of 46.3 Bq kg^{-1} is obtained at Nong district.

Figures 3 and 4 display the average ^{232}Th and ^{40}K activity concentrations in soil samples in 15 districts of Savannakhet province. The values of ^{232}Th activity concentrations

Table 1 Activity concentrations of radionuclides ^{226}Ra, ^{232}Th and ^{40}K in soil samples in Savannakhet province, Laos

District name	Samples	Activity concentration (Bq kg^{-1})					
		^{226}Ra		^{232}Th		^{40}K	
		Average	Range	Average	Range	Average	Range
Xaybuly	S1–S5	13.6 ± 1.5	8.0–18.5	23.9 ± 2.2	7.7–44.7	103.5 ± 9.3	48.9–216.7
Outhoomphone	S6–S12	15.6 ± 2.0	6.6–20.2	19.5 ± 2.0	5.4–33.7	92.8 ± 8.3	44.5–161.6
Khanthabouly	S13–S18	18.8 ± 2.3	10.8–24.2	18.7 ± 2.0	7.4–26.4	75.3 ± 6.8	13.6–210.1
Xayphoothong	S19–S24	14.2 ± 2.1	7.4–23.6	15.7 ± 1.7	3.8–24.0	105.3 ± 9.5	39.5–243.3
Songkhone	S25–S28	17.7 ± 2.2	13.6–19.3	20.0 ± 2.2	10.6–29.6	149.2 ± 12.0	84.6–209.1
Thapangthong	S29–S31	19.1 ± 2.3	18.3–24.1	21.2 ± 2.2	16.9–28.1	131.2 ± 11.7	56.7–128.4
Champhone	S32–S38	22.1 ± 2.4	15.1–33.5	19.2 ± 2.1	5.9–38.0	139.4 ± 11.4	85.8–264.8
Atsaphangthong	S39–S46	21.3 ± 2.5	18.1–31.6	26.6 ± 2.6	18.1–41.5	157.4 ± 12.8	86.4–317.4
Atsaphone	S47–S49	27.3 ± 3.1	23.9–32.1	36.0 ± 3.2	29.5–45.0	249.1 ± 18.6	240.8–262.7
Sepone	S50–S55	31.0 ± 3.6	15.9–50.2	51.2 ± 3.8	28.2–80.6	355.6 ± 23.8	242.2–583.8
Vilabuly	S56–S60	46.3 ± 4.4	35.4–69.3	59.4 ± 3.6	38.2–113.8	433.1 ± 32.8	322.5–627.3
Phine	S61–S65	18.9 ± 3.0	15.8–22.6	30.9 ± 3.2	20.6–48.7	327.6 ± 22.2	196.0–463.7
Thaphalanxay	S66–S70	19.6 ± 2.3	13.7–25.4	29.9 ± 2.8	18.8–37.9	200.9 ± 17.4	46.1–359.5
Xonbuly	S71–S75	21.5 ± 2.1	9.7–41.8	36.8 ± 3.2	17.1–51.3	297.6 ± 19.7	92.5–585.8
Nong	S76–S80	35.3 ± 3.9	24.0–73.6	61.7 ± 4.3	41.4–109.4	488.4 ± 34.0	219.7–906.4
Average		22.4 ± 2.1	6.6–73.6	30.8 ± 2.9	3.8–113.8	211.6 ± 16.5	13.6–906.4
World average		35	–	30	–	400	–

in the soil samples vary in the range from 3.8 ± 1.5 to 113.8 ± 3.2 Bq kg^{-1}. The smallest value of 3.8 ± 1.5 Bq kg^{-1} corresponds to sample S24 collected in Xayphoothong district, while the highest value of 113.8 ± 3.2 Bq kg^{-1} is obtained with sample S57 in Vilabuly district. The highest average value of 61.7 Bq kg^{-1} is obtained at Nong district as shown in Fig. 3. It is noticed that the average radioactivity concentration of ^{232}Th in Savannakhet province is about 30.8 ± 2.9 Bq kg^{-1} which is approximate the world average value of 30 Bq kg^{-1} [1]. However, the highest concentration of ^{232}Th in Savannakhet province is greater than the world average value by a factor of 3.8.

The activity concentration of ^{40}K in Savannakhet province is in the range from 13.6 ± 3.3 to 906.4 ± 31.4 Bq kg^{-1}. The lowest value of 13.6 ± 3.3 Bq kg^{-1} is obtained with sample S13 in Khanthabuly district, and the highest value of 906.4 ± 31.4 Bq kg^{-1} is obtained with sample S80 in Nong district. Nong district also corresponds to the highest average value of 488.4 Bq kg^{-1} as shown in Fig. 4. The average ^{40}K activity concentration is 211.6 ± 16.5 Bq kg^{-1}, which is about half of the world average value (400 Bq kg^{-1}) [1]. However, the highest value in Nong district is greater than the world average value by a factor of 2.3.

Table 1 presents the average activity concentrations of radionuclides ^{226}Ra, ^{232}Th and ^{40}K in soil samples in 15 districts of Savannakhet province in comparison with the world average values. It is noticed that the activity concentrations of the radionuclides are higher at Sepone, Vilabuly and Nong districts compared to other regions in Savannakhet province. The three districts are also known as locations of mining interest. From Figs. 2, 3 and 4, one can also see the higher activity concentrations of natural occurring radioactive materials in the three districts than that in the others. The activity concentrations of ^{226}Ra and ^{232}Th in the three

Table 2 Comparison of activity concentrations of radionuclides in Savannakhet province, Laos and other worldwide regions

Region	Activity concentration (Bq kg^{-1})			References
	^{226}Ra	^{232}Th	^{40}K	
Savannakhet, Laos	22[a] (7–74)[b]	31 (4–114)	212 (14–906)	This work
Quang Tri, Vietnam	30	37	236	[11]
Hue, Vietnam	57	48	309	[11]
Da Nang, Vietnam	51	58	366	[11]
Southern Thailand	29 (4–122)	44 (6–170)	344 (5–1422)	[21]
Thailand	48 (11–78)	51 (7–120)	230 (7–712)	[1]
Perak, Malaysia	112 (12–426)	246 (19–1377)	277 (19–2204)	[27]
Johor, Malaysia	162 (12–968)	261 (11–1210)	300 (12–2450)	[20]
Malaysia	67 (38–94)	82 (63–110)	310 (170–430)	[1]
Xi'an, China	36 (28–49)	51 (44–61)	733 (640–992)	[19]
China	32 (2–440)	41 (1–360)	440 (9–1800)	[1]
Japan	33 (6–98)	28 (2–88)	310 (15–990)	[1]
India	29 (7–81)	64 (14–160)	400 (38–760)	[1]
Iran	28 (8–55)	22 (5–42)	640 (250–980)	[1]
Abha, Saudi Arabia	39 (14–142)	23 (10–47)	218 (49–362)	[28]
Turkey	21 (10–44)	25 (9–37)	299 (144–401)	[29]
Denmark	17 (9–29)	19 (8–30)	460 (240–610)	[1]
Switzerland	40(10–900)	25(4–70)	370 (40–1000)	[1]
Poland	26 (5–120)	21 (4–77)	410 (110–970)	[1]
Greece	25 (1–240)	21 (1–190)	360 (12–1570)	[1]
Romania	32 (8–60)	38 (11–75)	490 (250–1100)	[1]
Spain	32 (6–250)	33 (2–210)	470 (25–1650)	[1]
Luxembourg	35 (6–52)	50 (7–70)	620 (80–1800)	[1]
Niger Delta, Nigeria	18 (11–40)	22 (12–46)	210 (69–530)	[30]
World average	35	30	400	[1]

[a]Average activity concentration

[b]Range of activity concentration

districts are greater than the average value by a factor of 1.5–2.1. Whereas, the activity concentration of ^{40}K obtained in the three districts is greater than the average value by a factor of 1.7–2.4.

Table 2 shows the comparison of the average activity concentrations of natural radionuclides obtained in soil samples in Savannakhet province, Laos with other worldwide regions. Comparing with neighboring regions such as Hue and Da Nang provinces of Vietnam, the average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Hue province are 57.0, 47.8 and 309.0 Bq kg^{-1}, while the values in Da Nang province are 51.0, 58.2 and 366.2 Bq kg^{-1}, respectively, which are greater than that obtained in Savannakhet province [11]. Comparing with other worldwide regions as listed in Table 2, one can see that in general, Savannakhet province is among the regions with relatively lower activity concentrations of natural radionuclides in soils than others.

Radium equivalent activity

The maximum value of Ra_{eq} in soils should be less than the limit of 370 Bq kg^{-1} to ensure the external dose less than 1.5 mGy h^{-1} as recommended by UNSCEAR reports [1, 3]. Figure 5 shows the calculated average Ra_{eq} in the soil samples in 15 districts of Savannakhet province. The Ra_{eq} values vary in a wide range from 17.5 to 299.9 Bq kg^{-1} with the average value of 82.3 Bq kg^{-1}. One can see that similar to the radioactivity concentrations, three districts having greater average values of Ra_{eq} than others are Nong, Vilabuly and Sepone. The highest Ra_{eq} value of 299.9 Bq kg^{-1} obtained with sample S80 at Nong district is still smaller than the limit of 370 Bq kg^{-1}, while the average Ra_{eq} is much smaller than the limit value by a factor of 0.22 [1].

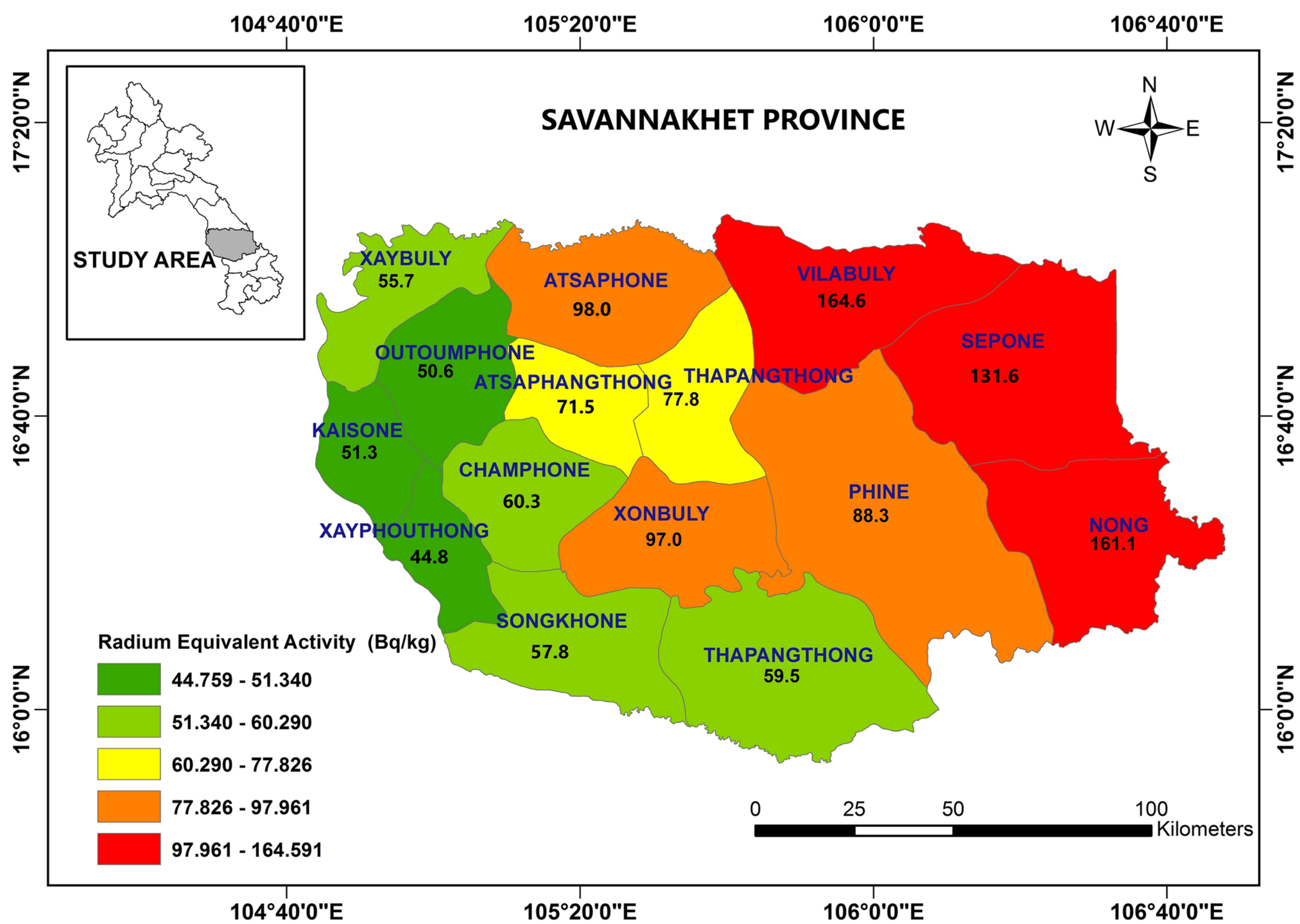

Fig. 5 Average radium equivalent activity Ra_{eq} in 15 districts of Savannakhet province

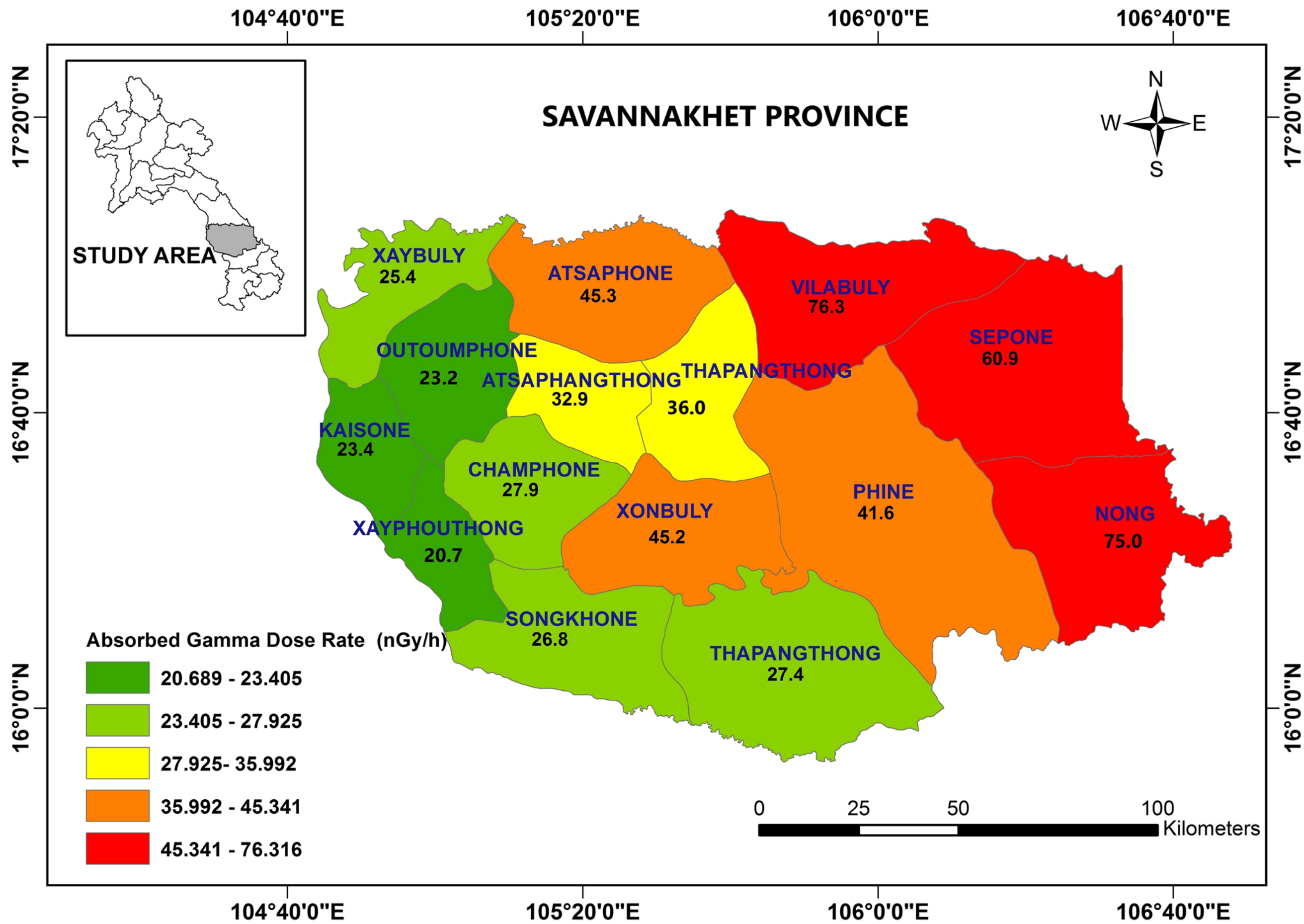

Fig. 6 Calculated average absorbed gamma dose rate D (nGy h^{-1}) in 15 districts of Savannakhet province

Absorbed gamma dose rate

Fig. 6 shows the average D values in 15 districts of Savannakhet province. The calculated values of D due to the terrestrial gamma radiation are obtained in the range of 8.1–137.5 nGy h^{-1} with the highest value of 137.5 nGy h^{-1} occurring at Nong district. The average value of D in Savannakhet province is 37.4 nGy h^{-1}, which is smaller than the world average value of 59 nGy h^{-1}, but the highest value of D is greater than the world average value by a factor of 2.3.

Annual effective dose equivalent

The *AEDE* values are obtained in the range from 0.01 to 0.17 mSv y^{-1}. The highest *AEDE* value corresponds to sample S80 at Nong district, where the highest activity concentrations of radionuclides are obtained. Figure 7 show the average values of *AEDE* in 15 districts of Savannakhet province, which vary in the range of 0.026–0.093. The average value of *AEDE* in total is 0.05 mSv y^{-1} which is lower than the world average value of 0.07 mSv y^{-1} [1]. These values are less than the *AEDE* limit of 1 mSv y^{-1} for an individual and 20 mSv y^{-1} for radiation workers as recommended by International Commission on Radiation Protection [26].

External and internal radiological hazard indices

Figures 8 and 9 show the calculated average H_{ex} and H_{in} obtained from the activity concentrations in soil samples in 15 districts of Savannakhet province. The H_{ex} values in the soil samples are within the range from 0.05 to 0.81. This means that the highest value of H_{ex} is less than unity. The average values of H_{ex} in 15 districts (0.121–0.444) as displayed in Fig. 8 and the average H_{ex} in total of 0.22 ± 0.03 are much less than unity. As shown in Fig. 9, the average H_{in} values in 15 districts and the average H_{in} of 0.28 ± 0.03 in Savannakhet province are much less than unity in most of the area. There are two samples with higher values of H_{in} (0.94 and 1.01) found in Vilabuly and Nong districts, but only one sample (S80 at Nong district) has the H_{in} greater than unity. The results of H_{ex} and H_{in} imply that there is

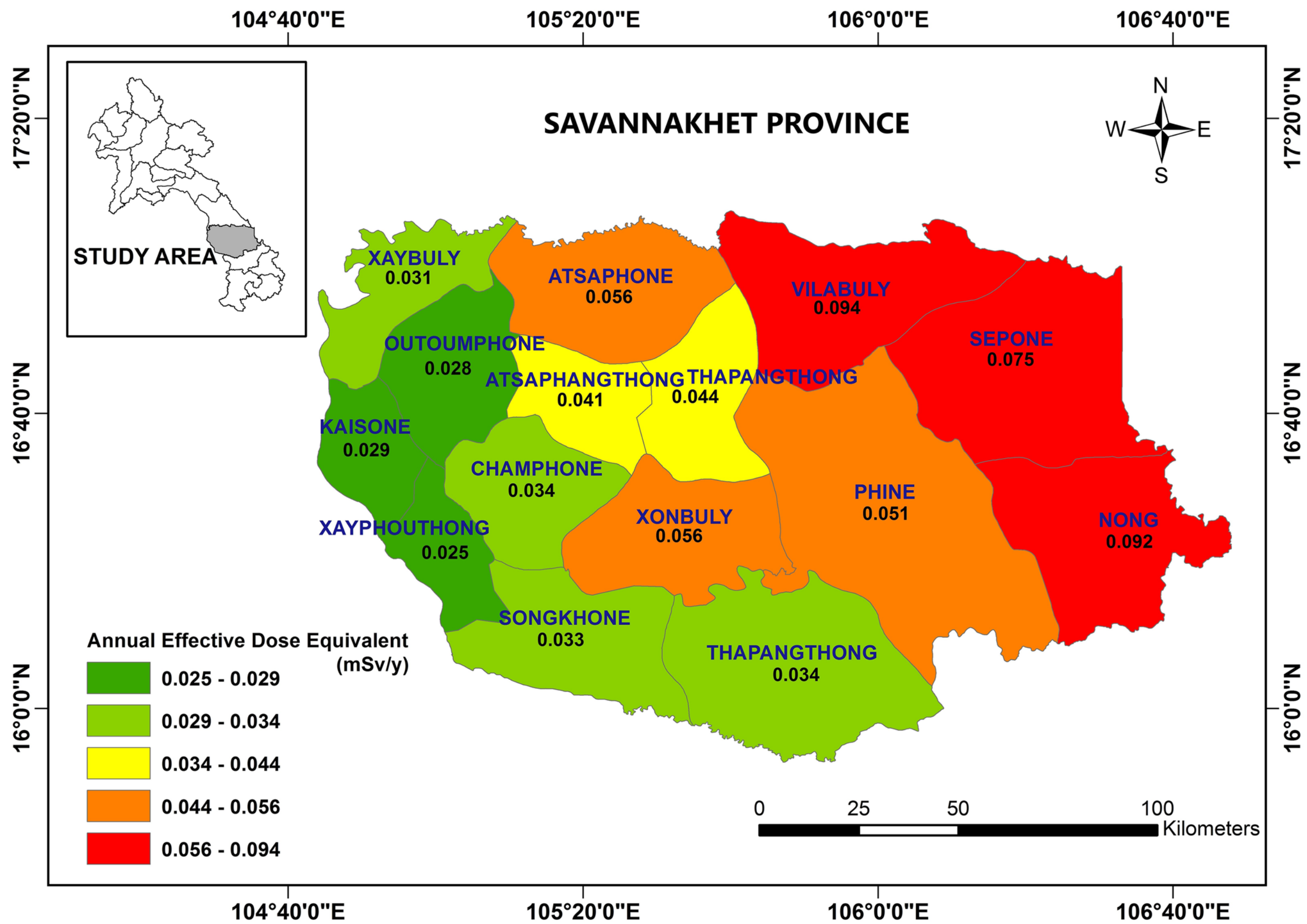

Fig. 7 Calculated average annual external effective dose rate *AEDE* (mSv y^{-1}) in 15 districts of Savannakhet province

no significant radiological hazard to human health in this region.

Table 3 shows comparison of the average radiological hazard indices obtained in Savannakhet province with that reported for worldwide regions. In general, the radiological hazard indices obtained in Savannakhet province are relatively lower than that of other regions in Southeast Asian countries as well as world average values. The average Ra_{eq} values in neighboring regions such as Hue and Da Nang provinces, Vietnam (149 and 162 Bq kg^{-1}, respectively) are comparable with the highest values obtained in Savannakhet province (131 and 160 Bq kg^{-1} in Sepone and Nong districts, respectively) [11].

Conclusions

Measurement of the radioactivity concentrations of 80 soil samples collected widely in Savannakhet province, Laos is conducted using a HPGe gamma spectrometer for evaluating a baseline data of radioactivity concentrations and radiological hazards in the area. The activity concentrations in soil samples are in the range from 6.6 to 73.6 Bq kg^{-1} for of ^{226}Ra, from 3.8 to 113.8 Bq kg^{-1} for ^{232}Th and from 13.6 to 906.4 Bq kg^{-1} for ^{40}K, respectively. The average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K are 22.4 ± 2.1, 30.8 ± 2.9 and 211.6 ± 16.5 Bq kg^{-1}, respectively. The values of activity concentrations are relatively low compared to the

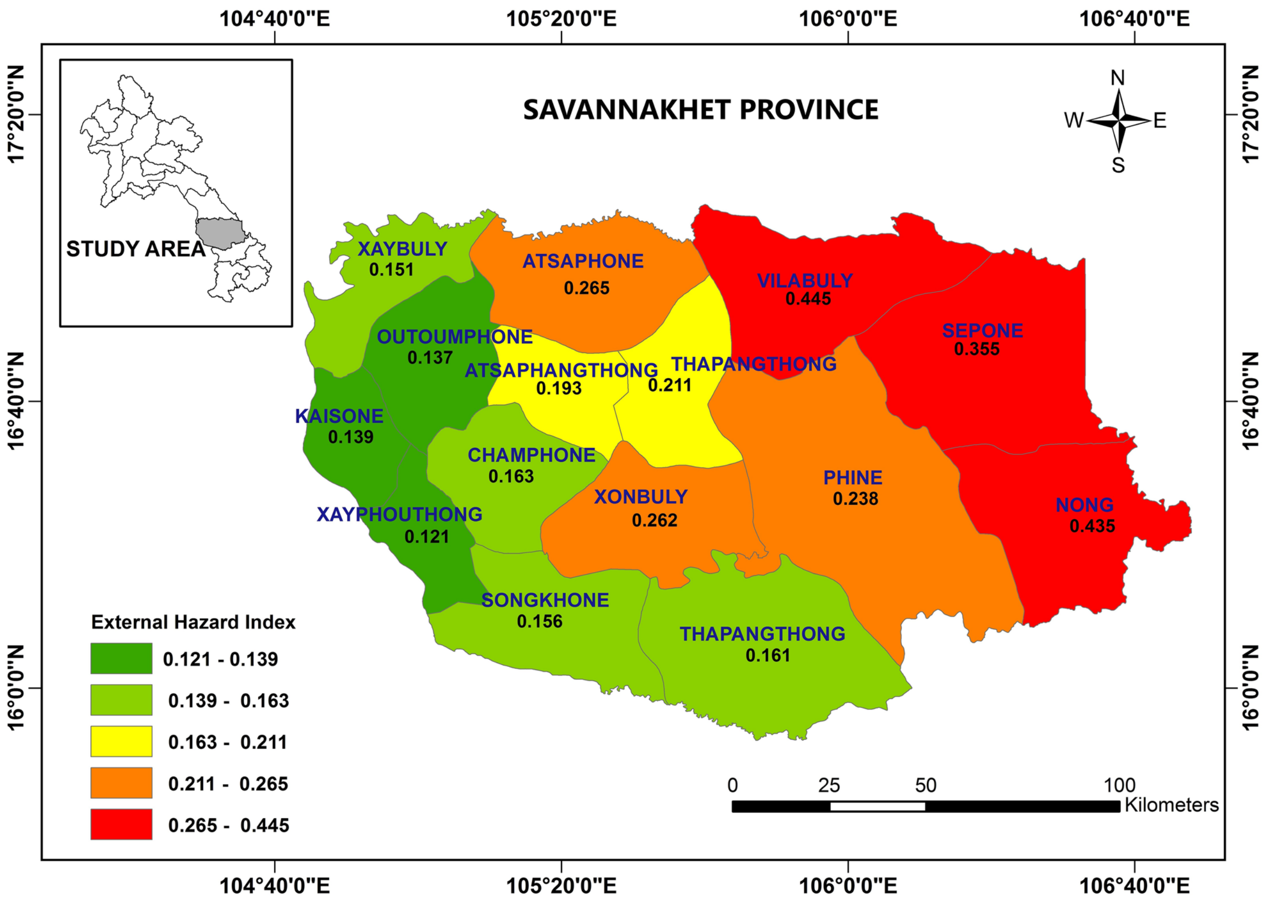

Fig. 8 Calculated average external hazard index H_{ex} in 15 districts of Savannakhet province

world average values and that of other worldwide regions. The average activity concentration of ^{232}Th is approximate the world average value (30 Bq kg^{-1}), but the value of ^{40}K is about half of the world average value (400 Bq kg^{-1}). The average Ra_{eq} is 82.8 ± 9.7 Bq kg^{-1}, which is much less than the safety limit of 370 Bq kg^{-1}. The highest concentrations of all three nuclides were found at Nong district but the highest value of Ra_{eq} (300 Bq kg^{-1}) is still less than the safety limit value. The results of radiological hazard indices such as absorbed gamma dose, annual effective dose equivalent, external and internal radiation hazard indices indicate no significant effect to human health.

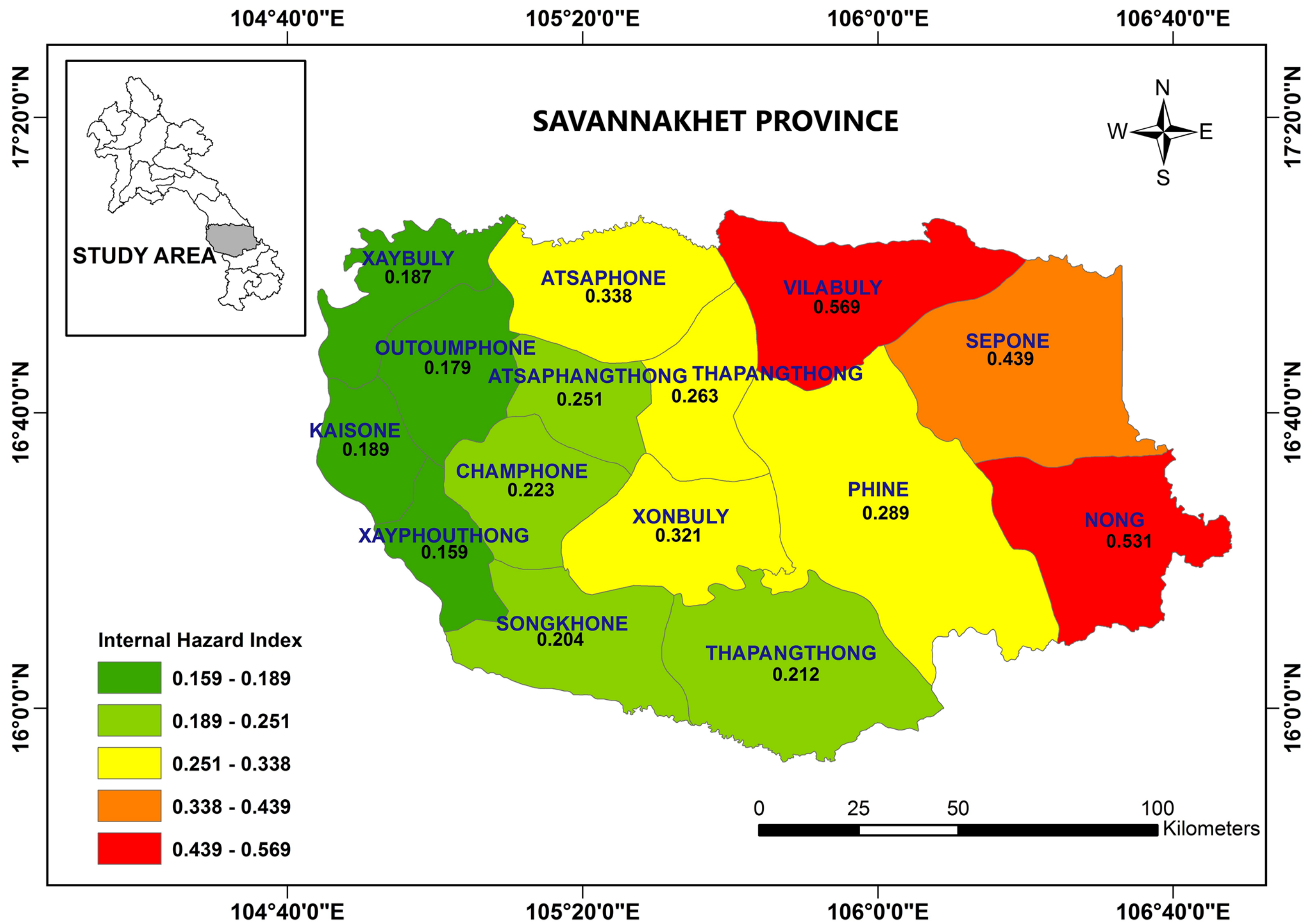

Fig. 9 Calculated average internal hazard index H_{in} in 15 districts of Savannakhet province

Table 3 Radiological hazard indices in soils in Savannaket province, Laos and other worldwide regions

Region	Ra_{eq} (Bq kg^{-1})	D (nGy h^{-1})	$AEDE$ (mSv y^{-1})	H_{ex}	H_{in}	References
Savannakhet, Laos	83[a] (17–300)[b]	37 (8–137)	0.05 (0.01–0.17)	0.22 (0.05–0.81)	0.28 (0.07–1.01)	This work
Quang Tri, Vietnam	100	45	–	0.27	–	[11]
Hue, Vietnam	149	67	–	0.40	–	[11]
Da Nang, Vietnam	162	72	–	0.44	–	[11]
Perak, Malaysia	478 (52–2227)	222 (39–1039)	–	–	–	[27]
Penang, Malaysia	696 (268–1103)	315 (125–496)	–	1.78 (0.72–2.98)	2.9 (1.07–5.08)	[31]
Southern Thailand	126 (14–446)	58 (6–203)	0.07 (0.01–0.25)	0.34 (0.04–1.20)	–	[21]
Xi'an, China	166 (148–199)	79 (71–96)	0.10 (0.09–0.12)	–	–	[19]
China	(230–676)	(86–237)	(0.10–0.29)	(0.60–1.80)	–	[32]
Nigeria	(50–110)	(23–52)	(0.03–0.06)	(0.14–0.29)	(0.18–0.37)	[30]
Jordan	(12–702)	(45–73)	(0.05–0.08)	(0.87–4.0)	–	[8]
Abha, Saudi Arabia	89 (68–184)	41 (16–87)	–	0.24 (0.01–0.50)	0.35 (0.10–0.90)	[28]
World average	89	59	0.07	–	–	[1]
Limit	370	–	1	1	1	[1]

[a]Average value

[b]Range of the values

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest regarding the publication of this paper.

References

1. UNSCEAR (2000) Radiation sources and effects of ionizing radiation. Report of the United Nations Scientific Committee on the effect of atomic radiation to general assembly. Technical report, United Nations, New York
2. UNSCEAR (2008) Sources and effects of ionizing radiation, annex B: exposures of the public and workers from various sources of radiation. Technical report, United Nations, New York
3. UNSCEAR (1988) Sources, effects and risks of ionizing radiation. United Nations Scientific Committee on the effects of atomic radiation. Technical report. United Nations, New York
4. Singh J, Singh H, Singh S, Bajwa BS, Sonkawade RG (2009) Comparative study of natural radioactivity levels in soil samples from the upper Siwaliks and Punjab, India using gamma-ray spectrometry. J Environ Radioact 100:94–98. https://doi.org/10.1016/j.jenvrad.2008.09.011
5. Chikasawa K, Ishii T, Sugiyama H (2001) Terrestrial gamma radiation in Kochi prefecture, Japan. J Health Sci 47:362–372
6. Ribeiro FCA, Silva JIR, Lima ESA, do Amaral Sobrinho NMB, Perez DV, Lauria DC (2018) Natural radioactivity in soils of the state of Rio de Janeiro (Brazil): radiological characterization and relationships to geological formation, soil types and soil properties. J Environ Radioact 182:34–43. https://doi.org/10.1016/j.jenvrad.2017.11.017
7. Ahmad N, Jaafar MS, Bakhash M, Rahim M (2015) An overview on measurements of natural radioactivity in Malaysia. J Radiat Res Appl Sci 8:136–141. https://doi.org/10.1016/j.jrras.2014.12.008
8. Al-Kharouf SJ, Al-Hamarneh IF, Dababneh M (2008) Natural radioactivity, dose assessment and uranium uptake by agricultural crops at Khan Al-Zabeeb, Jordan. J Environ Radioact 99:1192–1199. https://doi.org/10.1016/j.jenvrad.2008.02.001
9. Dabayneh KM, Mashal LA, Hasan FI (2008) Radioactivity concentration in soil samples in the southern part of the West Bank, Palestine. Radiat Prot Dosim 131:265–271. https://doi.org/10.1093/rpd/ncn161
10. Degerlier M, Karahan G, Ozger G (2008) Radioactivity concentrations and dose assessment for soil samples around Adana, Turkey. J Environ Radioact 99:1018–1025. https://doi.org/10.1016/j.jenvrad.2007.12.015
11. Huy NQ, Hien PD, Luyen TV, Hoang DV, Hiep HT, Quang NH, Long NQ, Nhan DD, Binh NT, Hai PS, Ngo NT (2012) Natural radioactivity and external dose assessment of surface soils in Vietnam. Radiat Prot Dosim 151:522–531. https://doi.org/10.1093/rpd/ncs033
12. Huy NQ, Luyen TV (2005) Study on external exposure doses from terrestrial radioactivity in Southern Vietnam. Radiat Prot Dosim 118:331–336. https://doi.org/10.1093/rpd/nci341
13. Ibrahim N (1999) Natural activities of ^{238}U, ^{232}Th and ^{40}K in building materials. J Environ Radioact 43:255–258
14. Singh S, Singh B, Kumar A (2003) Natural radioactivity measurements in soil samples from Hamirpur district, Himachal Pradesh, India. Radiat Meas 36:547–549
15. Sroor A, El-Bahi SM, Ahmed F, Abdel-Haleem AS (2001) Natural radioactivity and radon exhalation rate of soil in southern Egypt. Appl Radiat Isot 55:873–879
16. Leuangtakoun S, Loat BV, Duyen VTK, Khang KN (2017) Natural radioactivity and external dose assessment of surface soils in Bolikhamxay province, Laos. VNU J Sci Math Phys 33:10–16
17. Xayheungsy S, Khiem LH, Nam LD (2018) Assessment of the natural radioactivity and radiological hazards in Lao cement samples. Radiat Prot Dosim 181:208–213. https://doi.org/10.1093/rpd/ncy014
18. Sonexay X, Khiem LH, Nam LD (2018) Assessment of natural radioactivity levels and radiation hazards of building materials of Lao PDR. Int J Mod Eng Res 8:29–35
19. Lu X, Liu W, Zhao C, Chen C (2013) Environmental assessment of heavy metal and natural radioactivity in soil around a coal-fired power plant in China. J Radioanal Nucl Chem 295:1845–1854. https://doi.org/10.1007/s10967-012-2241-9
20. Saleh MA, Ramli AT, Alajerami Y, Aliyu AS (2013) Assessment of environmental ^{226}Ra, ^{232}Th and ^{40}K concentrations in the region of elevated radiation background in Segamat District, Johor, Malaysia. J Environ Radioact 124:130–140
21. Kritsananuwat R, Arae H, Fukushi M, Sahoo SK, Chanyotha S (2015) Natural radioactivity survey on soils originated from southern part of thailand as potential sites for nuclear power plants from radiological viewpoint and risk assessment. J Radioanal Nucl Chem 305:487–499. https://doi.org/10.1007/s10967-015-3994-8
22. Krieger R (1981) Radioactivity of construction materials. Betonw Fertigtl Tech 47:468–475
23. Beretka J, Mathew PJ (1985) Natural radioactivity of Australian building materials, industrial wastes and by-products. Health Phys 48:87–95
24. NEA-OECD (1979) Exposure to radiation from natural radioactivity in building materials. Report by NEA group of experts. Technical report, OECD, Paris, France
25. Debertin K, Helmer RG (1988) Gamma- and X-ray spectrometry with semiconductor detectors. North-Holland, Amsterdam, Netherlands
26. ICRP (2008) The 2007 recommendations of the international commission of radiological protection. Ann ICRP 32:2–4
27. Lee SK, Wagiran H, Termizi Ramli A, Heru Apriantoro N, Khalik Wood A (2009) Radiological monitoring: terrestrial natural radionuclides in Kinta District, Perak, Malaysia. J Environ Radioact 100:368–374
28. Ibraheem AA, El-Taher A, Alruwaili MHM (2018) Assessment of natural radioactivity levels and radiation hazard indices for soil samples from Abha, Saudi Arabia. Results Phys 11:325–330. https://doi.org/10.1016/j.rinp.2018.09.013
29. Bozkurt A, Yorulmaz N, Kam E, Karahan G, Osmanlioglu AE (2007) Assessment of environmental radioactivity for Sanliurfa region of southeastern Turkey. Radiat Meas 42:1387–1391. https://doi.org/10.1016/j.radmeas.2007.05.052
30. Agbalagba EO, Onoja RA (2011) Evaluation of natural radioactivity in soil, sediment and water samples of Niger Delta (Biseni) flood plain lakes, Nigeria. J Environ Radioact 102:667–671. https://doi.org/10.1016/j.jenvrad.2011.03.002
31. Almayahi BA, Tajuddin AA, Jaafar MS (2012) Effect of the natural radioactivity concentrations and ^{226}Ra /^{238}U disequilibrium on cancer diseases in Penang, Malaysia. Radiat Phys Chem 81:1547–1558. https://doi.org/10.1016/j.radphyschem.2012.03.018
32. Song G, Chen D, Tang Z, Zhang Z, Xie W (2012) Natural radioactivity levels in topsoil from the Pearl River Delta Zone, Guangdong, China. J Environ Radioact 103:48–53. https://doi.org/10.1016/j.jenvrad.2011.06.014