



# Radiological Hazard Assessment of High-Level Natural Radionuclides in Surface Sediments Along Red River, Vietnam

Van-Hao Duong<sup>1</sup> · Duc-Thang Duong<sup>2</sup> · Loat Van Bui<sup>3</sup> · Thanh Tien Kim<sup>4</sup> · Hue Minh Bui<sup>4</sup> · Trong Dinh Tran<sup>4</sup> · Trinh Trong Phan<sup>5</sup> · Thanh-Duong Nguyen<sup>6</sup>

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## Abstract

The Red River is one of the largest rivers that plays an important role in the economic development of North Vietnam. There are many radionuclides bearing rare earth, uranium ore mines, mining industrial zones and magma intrusive formations along this river. The contamination and accumulation of radionuclides could exist at high concentration in surface sediments of this river. Thus, the present investigation aims to study the activity concentrations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ),  $^{40}\text{K}$ , and  $^{137}\text{Cs}$  in Red River surface sediments. Thirty sediment samples were collected, and their activity concentration was calculated using high-purity germanium gamma-ray detector. The observed results ranged from  $51.0 \pm 2.1$  to  $73.6 \pm 3.7$  for  $^{226}\text{Ra}$ ,  $71.4 \pm 3.6$  to  $103 \pm 5.2$  for  $^{232}\text{Th}$ ,  $507 \pm 24.0$  to  $846 \pm 42.3$  for  $^{40}\text{K}$ , and ND (not detected) to  $1.33 \pm 0.06$  Bq/kg for  $^{137}\text{Cs}$ , respectively. In general, the natural radionuclides concentration of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ), and  $^{40}\text{K}$  is higher than the average world average values. This indicated that the natural radionuclides could contribute from similar and principal sources surrounding the upstream of Lao Cai where distributed uranium ore mines, radionuclide bearing rare earth mines, mining industrial zones and intrusive formations. Regarding the radiological hazard assessment, results of the indices computed such as absorbed gamma dose rate (D), the excess lifetime cancer risk (ELCR), and the annual effective dose equivalent (AEDE) were nearly two times higher than world average values.

In nature, radionuclides could exist in various environments such as air, water (surface and underground water), sediments, soil, and rock. The presence of radioactivity in the environments is responsible for the radiation exposure to humans and the consequent health effects developed. The

concentration and distribution of radionuclides play an important role in human health and environmental research, thereby signifying the need for various research investigations to be carried out in this domain.

✉ Van-Hao Duong  
haodnth@gmail.com

✉ Loat Van Bui  
buiivanloat@hus.edu.vn

Duc-Thang Duong  
thangdd@vinatom.gov.vn

Thanh Tien Kim  
ktthanh@iop.vast.vn

Hue Minh Bui  
bmhue@iop.vast.vn

Trong Dinh Tran  
tdtrong@iop.vast.ac.vn

Trinh Trong Phan  
phantrongt@yahoo.com

Thanh-Duong Nguyen  
nguyenthanhduong@humg.edu.vn

<sup>1</sup> VNU School of Interdisciplinary Studies, Vietnam National University, Hanoi, Vietnam

<sup>2</sup> Institute for Nuclear Science and Technology, Vinatom, 179 Hoang Quoc Viet, Cau Giay, Hanoi 100000, Vietnam

<sup>3</sup> Faculty of Physics, University of Science, Vietnam National University, 334 Nguyen Trai, Hanoi 100000, Vietnam

<sup>4</sup> Centre of Nuclear Physics, Institute of Physics, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Cau Giay, Hanoi 100000, Vietnam

<sup>5</sup> Institute of Geological Sciences, Vietnam Academy of Science and Technology, Hanoi, Vietnam

<sup>6</sup> Hanoi University of Mining and Geology (HUMG), 18 Vien, Duc Thang, Bac Tu Liem, Hanoi 100000, Vietnam

Composition of sediments at the bottom of rivers can reflect the ecological state of rivers and their catchment areas as well as their tasks in agriculture or construction sectors. The radionuclides concentration in sediments will provide useful information regarding the status of environmental and geochemical pollution. Accordingly, the distribution and concentration of radionuclides in river sediments have been widely investigated in different parts of the world (Alokhina and Gudzenko 2021; de Carvalho et al. 2016; Fallah et al. 2019; Semizhon et al. 2010; Suresh et al. 2011; Wang et al. 2016; Yakovlev et al. 2020; Abbasi & Mirekhtari 2019, 2020; Abbasi et al. 2022). Research of Semizhon et al. (2010) investigated the radioactive contamination of sediments at the Yenisei River from 1999 to 2006 due to the discharges from the Krasnoyarsk Mining and Chemical Industrial Complex (KMCIC), indicated that the levels of artificial radionuclides ( $^{137}\text{Cs}$ ,  $^{60}\text{Co}$ ,  $^{152}\text{Eu}$ , and  $^{241}\text{Am}$ ) were dependent on the distance downstream from KMCIC. Accordingly, the radionuclide concentrations increased as the distance from KMCIC decreased. Suresh et al. (2011) investigated the natural radionuclides (including  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ ) in sediments samples of Ponnaiyar River, India and highlighted that the concentration of these radionuclides in sediments significantly depends on the content of kaolinite mineral. The report of Yakovlev et al. (2020) revealed that several patterns of radionuclide accumulation ( $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ , and  $^{137}\text{Cs}$ ) in the sediments of Zolotitsa River and its tributaries depend on the physicochemical parameters of river sediments. Recently, Alokhina and Gudzenko (2021) investigated the distribution of radionuclides in modern

sediments of the rivers flowing into the Dneiper-Bug estuary and indicated that the presence of natural radionuclides in river sediment was from geological, hydrological and chemical processes. In general, research investigations conducted so far showed that the concentration and distribution of radionuclides in river sediments vary from place to place and depend on the clay mineral, the physicochemical parameters, such as geological, hydrological and chemical processes and the distance from radioactive sources.

The Red River also known as the Hong River (Vietnamese), is the largest river in North Vietnam (510 km). It originates at Yunan province in China, flows through Vietnam and ends in the Gulf of Tonkin at Ba Lat estuary (Fig. 2). It gets its name as Thao River when flowing through Lao Cai province. The Red River has four major upstream tributaries, including the Chay River, the Lo River, and the Gam River on the left side; the Da River on the right side. The main river ends up at the Ba Lat estuary, Nam Dinh province. The Red River plays an important role in economic development of northern Vietnam. This river provides water for agricultural irrigation, alluvium for agricultural development (about 15,000 km<sup>2</sup>, and 18 million residents), and building material such as sand, gravel for construction activities. The Red River starts from Lao Cai province where distributed many radionuclides bearing rare earth elements and uranium mines such as Sin Quyen, Muong Hum, Nam Xe, Dong Pao, Yen Phu (Yen Bai province), Thanh Son (Phu Tho province), and Dai Tu (Thai Nguyen province) (Fig. 2). These areas have been reported as high radiation background areas (Chau et al. 2017; Duong et al. 2021; Hao

**Fig. 1** The distribution of magmatic formation in the North Vietnam

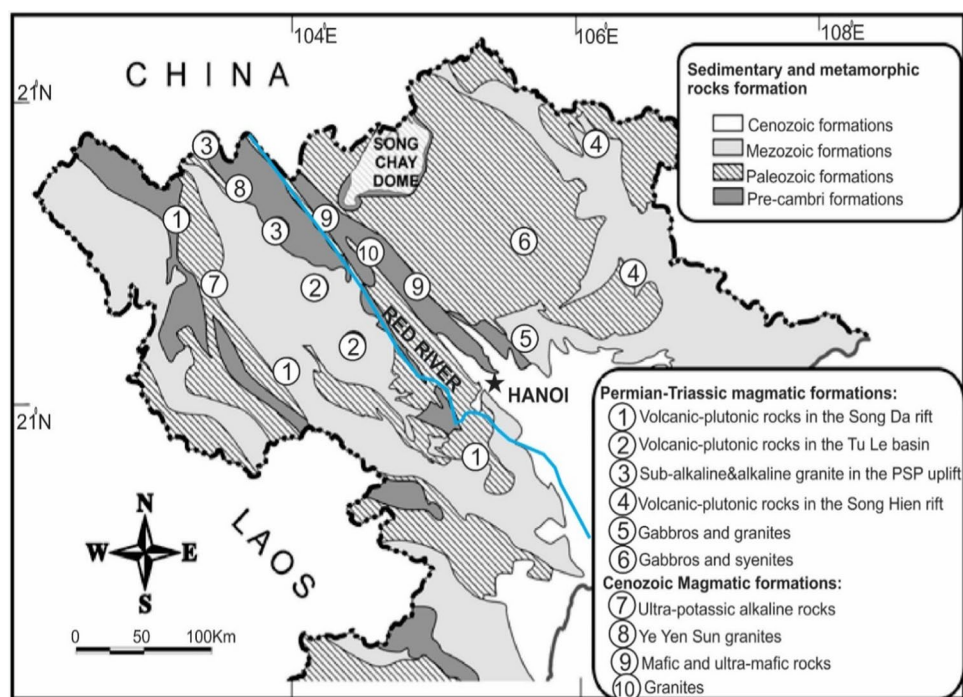
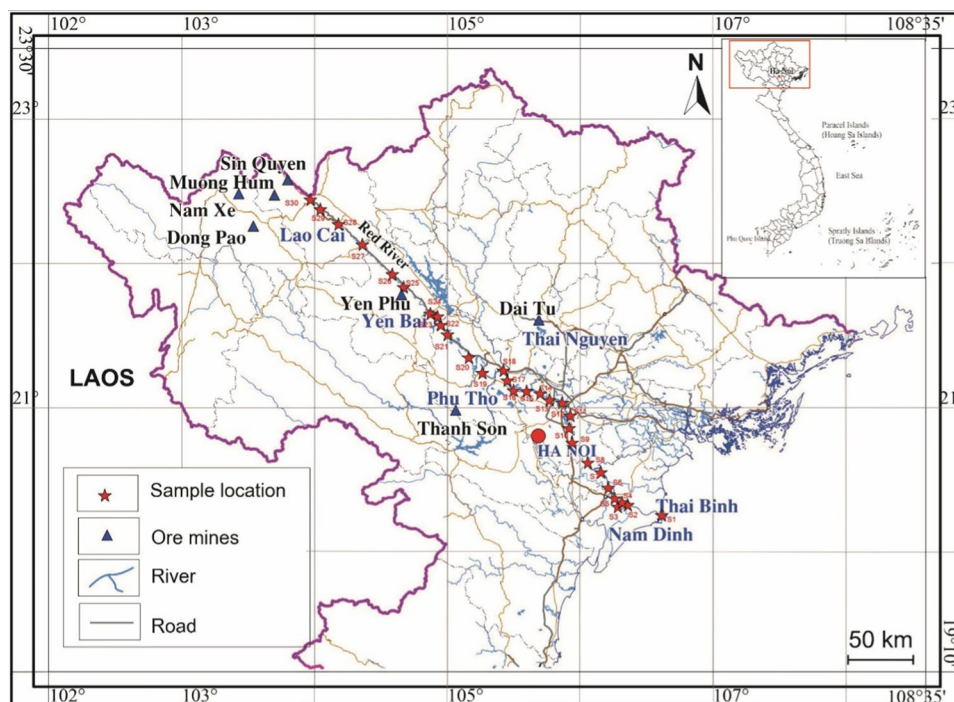


**Fig. 2** Sampling locations

et al. 2021; Nguyen et al. 2016; Phan et al. 2019). In addition to this, the river has many magma intrusive formations, especially granite and gabbro formations such as granite in the PSP uplift, gabbros and syenites, Ye Yen Sun granites and granites (3), (6), (8), (9), (10) (Fig. 1). The granites were known to have high amounts of natural radionuclides. Each day, the contamination rate is increasing due to discharge of radionuclides into the sediments of the river from various mining companies, industrial zone, erosion weathering, and human activities. On the other hand, the  $^{137}\text{Cs}$  is a man-made induced radionuclide, which originates from the atmospheric nuclear weapon tests and nuclear power plant accidents and releases from the country's borders with the North Vietnam and others. Regarding the radiation risks and potential presence of natural and man-made radioisotopes in surface sediments of the Red River, the present study will investigate the concentration and characteristics of high-level natural radionuclides in surface sediments of the Red River from Lao Cai to Ba Lat estuary and as well as the radiological hazard assessment to the inhabitants.

## Materials and Methods

### Sample Collection and Processing

Random sampling method was performed for collecting the sediment samples from the bottom of the river with the help of Van Veen Grab sampler. Sediment samples were taken in triplicates from 30 locations along the Red River that

is from Ba Lat estuary (S1) to Cau Moi, Lao Cai province (S30), as shown in (Fig. 2). The selected sampling locations are usually at lower kinetic energy than those in the surrounding based on visual observation. The sample locations were recorded in terms of coordinates (longitudinal and latitudinal position) using a hand GPS model GARMIN. Each sample weighing around 3 kg was scooped, stored in a sterile polythene bag and labelled carefully as S1-S30. They were brought to the laboratory in sterile conditions without any contamination. The samples were then dried in an oven at  $105^\circ\text{C}$  and then milled and passed to a sieve of less than 2 mm in size. Then the already samples were weighted and sealed in for 30 days to reach a secular equilibrium between the radium and its daughter radionuclides.

### Estimation of Radionuclide Activity

The radionuclides concentration in samples of the present study was measured using a high-resolution HPGe gamma-ray detector (Canberra-GC5019) with 50% relative efficiency, the energy resolution of the detector is 1.9 keV FWHM for the 1332 keV of  $^{60}\text{Co}$  gamma line, following the methodology as followed in previous studies (Chau et al. 2017; Duong et al. 2021; Hao et al. 2021; Nguyen et al. 2016; Van et al. 2019; Van et al. 2020). The activity concentration was calculated based on its respective gamma lines of 609.3 keV, 1120.3 keV, and 1764.5 keV for  $^{226}\text{Ra}$ , the gamma line of 1460.8 keV for  $^{40}\text{K}$  and the lines of 911.6 keV, 2614.5 keV, 583.2 keV were used for  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ). The  $^{232}\text{Th}$  was measured with the assumption of

equilibrium between  $^{232}\text{Th}$  and  $^{228}\text{Ra}$  ( $^{228}\text{Th}$ ) in sedimentary samples (Adesiji and Ademola 2019; Duong et al. 2021; UNSCEAR 2000; Van et al. 2019). The Minimum Detection Limit (MDA) was performed following the previous studies (Duong et al. 2021; Van et al. 2020; 2021). Based on the ISO/IEC 17,025 certificate of laboratory, the QA/QC used standard reference materials (IAEA - 375—Soil and IAEA standard material RGU-1, RGTh-1, RGK-1, produced by International Atomic Energy Agency). The deviations of the activities are less than 5%, which is acceptable for further use in the study sample measurement. The corrected factor was following the method described by (Debertin and Helmer 1988) and (Jodlowski et al., 2010). To lessen the photo effect absorption in the sample, all the gamma lines used were higher than 500 keV. The activity concentration of the radionuclides was estimated using the following formula:

$$A_{sp} = \frac{N_{sp} M_{st} A_{st} C_i}{N_{st} M_{sp}} \quad (1)$$

where:  $M_{st}$ ,  $M_{sp}$  and  $N_{st}$ ,  $N_{sp}$  are mass and the net intensity of the standard, measured samples, respectively;  $A_{sp}$  and  $A_{st}$  is activity of calculated and standard samples;  $C_i$  is corrected factor (which concern to the differences between densities of the measured and standard samples).

The MDA is based on the below equation (Currie 1968; Debertin and Helmer 1988).

$$\text{MDA (Bq/kg)} = \frac{2,71 + 4,65\sqrt{N_B}}{t \times \varepsilon \times I_\gamma \times M} \quad (2)$$

where:  $N_B$ : is the background count numbers;  $\varepsilon$ : is the absolute efficiency of the detector (%);  $t$ : is the measured time (s);  $M$ : is the mass of the sample (kg);  $I_\gamma$ : is the gamma emission probability.

## Calculation of Radiological Risk Indices

The calculation of radiation hazard indices including the absorbed gamma dose rate (D), the annual effective dose equivalent (AEDE), and the excess lifetime cancer risk (ELCR) was conducted following the methods which were presented in (Duong et al. 2021). The formulas used for the computation of results are presented as follows:

The  $D$  is used as follows (UNSCEAR 2000):

$$D(\text{nGy/h}) = 0.46A_{Ra} + 0.62A_{Th} + 0.042A_K \quad (3)$$

where:  $A_K$ ,  $A_{Th}$  and  $A_{Ra}$  are activities of  $^{40}\text{K}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ), and  $^{226}\text{Ra}$ , respectively.

The outdoor AEDE was calculated using the following equation:

$$\text{AEDE } (\mu\text{Sv/y}) = D (\text{nGy/h}) \times D_{cf} (\text{Sv/Gy}) \times \text{OF} \times T \quad (4)$$

where  $D_{cf}$  equal 0.7 Sv/Gy as an outdoor dose convention factor; OF equal 0.2 as an outdoor occupancy factor (UNSCEAR 2008);  $T$  equal 8760 h.

Based on the AEDE values, the ELCR were calculated using the following equation of (ICRP 1990) as:

$$\text{ELCR} = \text{AEDE} \times \text{Life expectancy (LE)} \times \text{Risk factor (RF)} \quad (5)$$

In this study, the life expectancy of Vietnamese people has been taken as 75.6 years (<https://www.macrotrends.net/countries/VNM/vietnam/life-expectancy>). RF is a fatal risk factor per Sievert which is equal to  $0.057 \text{ Sv}^{-1}$  (ICRP 1990).

## Results and Discussion

### Activity Concentration

The average activity concentration of natural radionuclides in surface sediments at each sampling point was calculated and listed in Table 1. As shown in Table 1, the average activity concentrations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ),  $^{40}\text{K}$ , and  $^{137}\text{Cs}$  vary from  $(51.0 \pm 2.6) \text{ Bq/kg}$  to  $(73.6 \pm 3.7) \text{ Bq/kg}$  ( $59.6 \pm 3.0 \text{ Bq/kg}$  on average), from  $(71.4 \pm 3.6) \text{ Bq/kg}$  to  $(103 \pm 5.2) \text{ Bq/kg}$  ( $83.7 \pm 4.2 \text{ Bq/kg}$  on average), from  $(507 \pm 24.0) \text{ Bq/kg}$  to  $(846 \pm 42.3) \text{ Bq/kg}$  ( $685 \pm 34.4 \text{ Bq/kg}$  on average), and from ND (not detected) to  $(1.33 \pm 0.06) \text{ Bq/kg}$  ( $0.53 \pm 0.03 \text{ Bq/kg}$  on average), respectively. The average concentration of  $^{40}\text{K}$  was significantly higher than that of the other radionuclides, with the activity falling in the descending order as follows:  $^{40}\text{K} > ^{232}\text{Th} > ^{226}\text{Ra} > ^{137}\text{Cs}$ . The average concentration values of natural radionuclides ( $^{40}\text{K}$ ,  $^{226}\text{Ra}$ , and  $^{232}\text{Th}$ ) in this study are higher than the global average values which are 32 Bq/kg for  $^{226}\text{Ra}$ , 45 Bq/kg for  $^{232}\text{Th}$  and 420 Bq/kg for  $^{40}\text{K}$  (UNSCEAR 2000). The existence of  $^{137}\text{Cs}$  in river sediments of the Red River indicates that it might have originated from nuclear testing and nuclear power plants around the studied area.

The asymmetric distribution curve of natural radionuclides as shown in Fig. 3 depicts the highest positive Skewness for  $^{226}\text{Ra}$ , followed by  $^{137}\text{Cs}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ) and  $^{40}\text{K}$ , in which, the concentration of  $^{40}\text{K}$  has nearly normal distribution with the Skewness value of 0.16. Further, highest variation in measured activity concentration was observed for  $^{40}\text{K}$  with the standard deviation of 79.3 Bq/kg, while the variation of  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  concentrations was insignificant, as the SD values were 6.3 and 8.9 only, respectively. Such high variation of  $^{40}\text{K}$  is due to its high mobility and transportation in water (Kumar et al. 2008; Zeng and Brown 2000). However, the variation of  $^{40}\text{K}$  in surface sediments in this study is

**Table 1** Activity concentration of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  and  $^{137}\text{Cs}$  in Red River samples

| Sample location | Coordinates |           | Activity concentration (Bq/kg) |                   |                 |                   |
|-----------------|-------------|-----------|--------------------------------|-------------------|-----------------|-------------------|
|                 | X           | Y         | $^{226}\text{Ra}$              | $^{232}\text{Th}$ | $^{40}\text{K}$ | $^{137}\text{Cs}$ |
| S1              | 664,321     | 2,244,233 | 58.1 ± 2.9                     | 81.3 ± 4.1        | 668 ± 33.3      | 0.35 ± 0.007      |
| S2              | 638,234     | 2,252,029 | 51.0 ± 2.6                     | 71.4 ± 3.6        | 587 ± 29.3      | ND                |
| S3              | 630,705     | 2,250,725 | 54.4 ± 2.7                     | 76.1 ± 3.8        | 625 ± 31.3      | 0.47 ± 0.02       |
| S4              | 634,063     | 2,254,026 | 57.1 ± 2.9                     | 78.0 ± 4.0        | 657 ± 32.8      | 0.53 ± 0.02       |
| S5              | 628,250     | 2,257,087 | 51.5 ± 2.6                     | 72.1 ± 3.6        | 592 ± 29.6      | 0.98 ± 0.05       |
| S6              | 623,551     | 2,265,538 | 55.8 ± 2.8                     | 78.1 ± 3.9        | 642 ± 32.1      | 0.6 ± 0.03        |
| S7              | 617,879     | 2,277,121 | 56.0 ± 2.8                     | 78.4 ± 3.9        | 644 ± 32.2      | 0.78 ± 0.04       |
| S8              | 607,611     | 2,284,647 | 56.8 ± 2.8                     | 79.5 ± 4.0        | 653 ± 32.6      | ND                |
| S9              | 595,604     | 2,300,026 | 73.6 ± 3.7                     | 103 ± 5.2         | 846 ± 42.3      | 1.2 ± 0.06        |
| S10             | 593,270     | 2,311,144 | 57.9 ± 2.9                     | 81.0 ± 4.1        | 666 ± 33.3      | 0.49 ± 0.02       |
| S11             | 594,094     | 2,320,752 | 51.6 ± 2.6                     | 72.3 ± 3.6        | 593 ± 29.7      | 0.72 ± 0.03       |
| S12             | 587,917     | 2,330,634 | 73.6 ± 3.0                     | 102 ± 4.9         | 845 ± 40.2      | 0.34 ± 0.02       |
| S13             | 578,035     | 2,332,555 | 51.2 ± 2.6                     | 71.7 ± 3.6        | 589 ± 29.5      | ND                |
| S14             | 571,035     | 2,337,771 | 62.2 ± 3.1                     | 87.1 ± 4.4        | 715 ± 35.8      | 0.96 ± 0.05       |
| S15             | 560,741     | 2,339,555 | 61.6 ± 3.1                     | 86.2 ± 4.3        | 708 ± 35.4      | 0.76 ± 0.03       |
| S16             | 550,584     | 2,340,104 | 58.0 ± 2.9                     | 81.3 ± 4.1        | 667 ± 33.4      | ND                |
| S17             | 545,917     | 2,347,653 | 69.6 ± 3.5                     | 97.4 ± 5.1        | 800 ± 42.3      | 0.47 ± 0.02       |
| S18             | 542,813     | 2,355,425 | 62.4 ± 3.3                     | 87.4 ± 4.6        | 718 ± 38.2      | 0.71 ± 0.03       |
| S19             | 526,884     | 2,353,681 | 63.0 ± 3.2                     | 88.2 ± 4.4        | 724 ± 36.2      | 0.71 ± 0.03       |
| S20             | 516,153     | 2,365,350 | 65.9 ± 3.3                     | 92.2 ± 4.6        | 758 ± 37.9      | 0.53 ± 0.02       |
| S21             | 500,595     | 2,382,958 | 58.5 ± 2.9                     | 81.9 ± 4.1        | 673 ± 33.6      | ND                |
| S22             | 495,170     | 2,390,215 | 64.6 ± 3.4                     | 90.0 ± 4.8        | 744 ± 39.4      | ND                |
| S23             | 495,174     | 2,402,420 | 53.5 ± 2.8                     | 74.6 ± 4.1        | 616 ± 33.1      | 0.59 ± 0.03       |
| S24             | 486,811     | 2,399,012 | 68.0 ± 3.4                     | 95.2 ± 4.7        | 782 ± 39.1      | 0.4 ± 0.02        |
| S25             | 466,367     | 2,419,304 | 51.8 ± 2.8                     | 72.3 ± 3.9        | 507 ± 31.9      | 0.46 ± 0.02       |
| S26             | 457,699     | 2,429,409 | 63.0 ± 3.2                     | 88.3 ± 4.4        | 725 ± 36.3      | 0.59 ± 0.03       |
| S27             | 434,702     | 2,452,057 | 57.4 ± 3.1                     | 80.3 ± 4.2        | 660 ± 35.3      | 0.93 ± 0.04       |
| S28             | 416,374     | 2,467,703 | 64.5 ± 2.6                     | 90.3 ± 3.7        | 742 ± 37.1      | ND                |
| S29             | 402,549     | 2,479,307 | 58.8 ± 2.1                     | 82.3 ± 3.6        | 676 ± 24.0      | 1.3 ± 0.06        |
| S30             | 394,946     | 2,486,818 | 55.8 ± 2.8                     | 78.2 ± 3.9        | 642 ± 32.1      | 0.62 ± 0.03       |
| Average         |             |           | 59.6 ± 3.0                     | 83.7 ± 4.2        | 685 ± 34.4      | 0.53 ± 0.03       |
| Min             |             |           | 51.0 ± 2.6                     | 71.4 ± 3.6        | 507 ± 24.0      | ND                |
| Max             |             |           | 73.6 ± 3.7                     | 103 ± 5.2         | 846 ± 42.3      | 1.3 ± 0.06        |
| Median          |             |           | 58.0                           | 81.3              | 668             | 0.53              |
| Skewness        |             |           | 0.64                           | 0.49              | 0.16            | 0.34              |
| Kurtosis        |             |           | −0.16                          | −0.48             | −0.06           | −0.20             |
| SD              |             |           | 6.3                            | 8.9               | 79.3            | 0.34              |

\*ND: Not Detected

lower than that in surface soils of some previous studies. For example, significant variation of  $^{40}\text{K}$  concentration with the SD of 1096 Bq/kg was found in soil sample outside the ore body in Muong Hum, Viet Nam (Duong et al. 2021); or the SD of 200 Bq/kg was found in surface soil sample in Khammouan, Laos (Leuangtakoun et al. 2020). The small variation of  $^{40}\text{K}$  in this river sediments in comparison with that in surface soil can be explained based on the characteristics of water flow related to type of environment and condition. On surface soil, the water flow is irregular and can be obstructed

by many objects such as buildings, trees and the changing of environment and matrices is responsible for such variations.

Statistical analysis was carried out to check the interrelationship between different radionuclides. The results of correlation analysis showed that the three radionuclides ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ ) exhibited very strong positive correlation among themselves but  $^{137}\text{Cs}$  did not correlate with any of the other radionuclides (Table 2).

Low variation in radionuclide concentration from upstream Lao Cai to downstream Ba Lat estuary was not

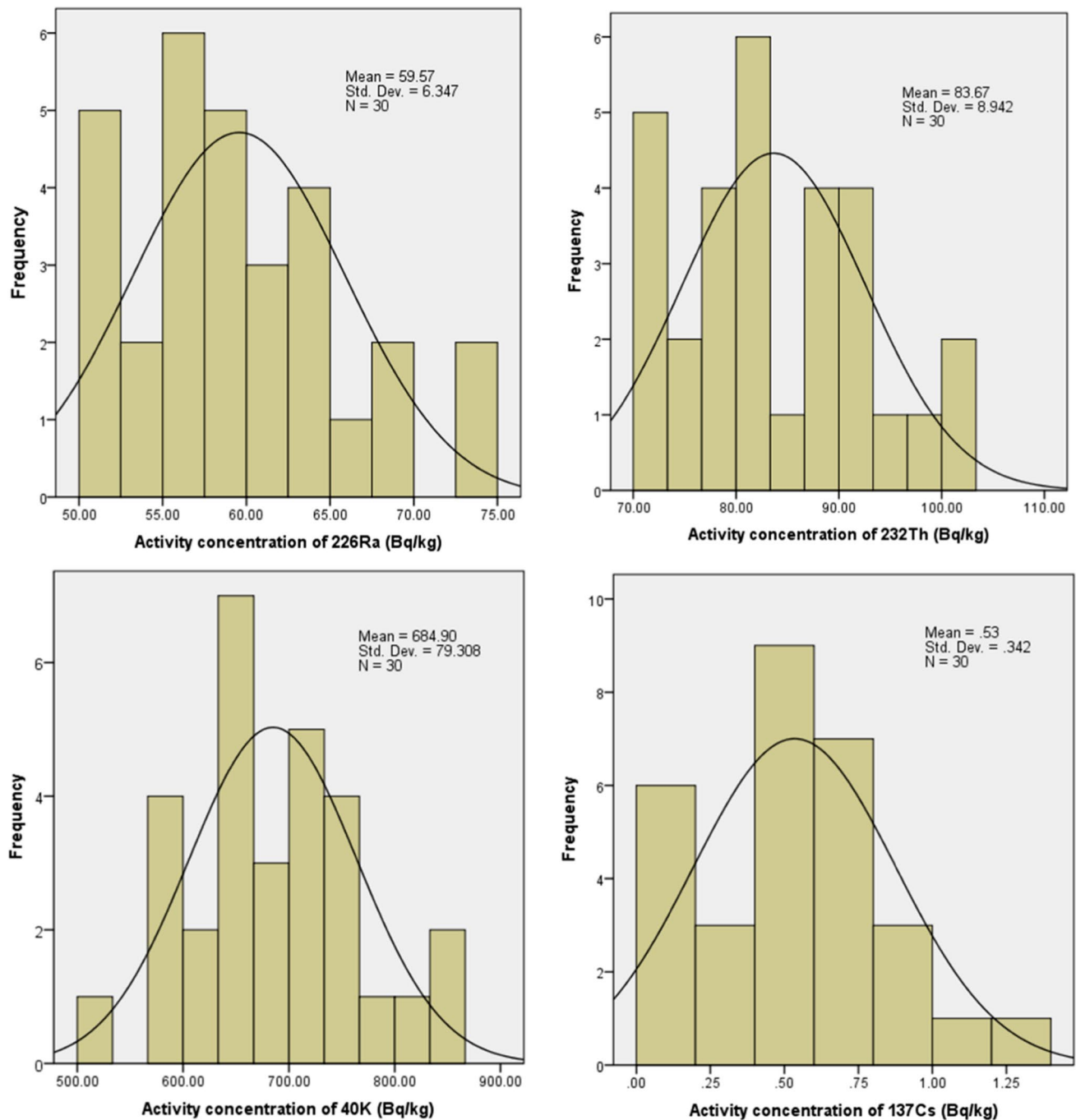


**Fig. 3** Distribution curve of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ),  $^{40}\text{K}$ , and  $^{137}\text{Cs}$  activities in the Red River sediment samples

only observed for  $^{40}\text{K}$ , but also for  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{137}\text{Cs}$ . Based on the natural and anthropogenic characteristics from Lao Cai to Ba Lat estuary, Red river can be divided into three segments (Table 3), namely from Lao Cai to Ha Noi, within Hanoi and from Ha Noi to Ba Lat. The variations in radionuclide concentration in each segment is presented in Table 3. From Lao Cai to Ha Noi (segment 1), the segment has three rivers ending (Fig. 1) in each

along with and many radionuclides-bearing mines (Chau et al. 2017; Duong et al. 2021; Hao et al. 2021; Nguyen et al. 2016; Phan et al. 2019) and intrusive formations (Fig. 2). In the Red River segment within Hanoi area (segment 2), the surface sediments could be disturbed due to the sand exploitation. From Ha Noi to Ba Lat (segment 3), the main activity is agriculture production. It can be seen that the highest concentration of natural radionuclides

**Table 2** The Pearson correlation analysis of between different radionuclides in Red River sediments (\*\*  $p < 0.01$ ; \*  $p < 0.05$ )

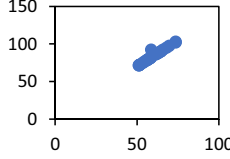
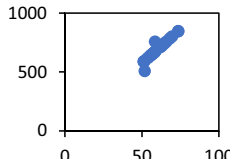
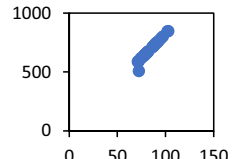
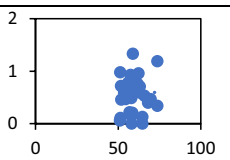
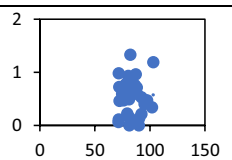
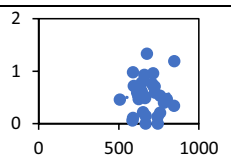
|                   | $^{226}\text{Ra}$                                                                 | $^{232}\text{Th}$                                                                  | $^{40}\text{K}$                                                                     | $^{137}\text{Cs}$ |
|-------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------|
| $^{226}\text{Ra}$ | 1                                                                                 | 0.977**                                                                            | 0.958**                                                                             | 0.089             |
| $^{232}\text{Th}$ |  | 1                                                                                  | 0.981**                                                                             | 0.056             |
| $^{40}\text{K}$   |  |  | 1                                                                                   | 0.055             |
| $^{137}\text{Cs}$ |  |  |  | 1                 |

**Table 3** The radionuclide activities in Red River sediment samples at three segments

| Radionuclide                            | $^{226}\text{Ra}$ (Bq/kg) | $^{232}\text{Th}$ (Bq/kg) | $^{40}\text{K}$ (Bq/kg) | $^{137}\text{Cs}$ (Bq/kg) |
|-----------------------------------------|---------------------------|---------------------------|-------------------------|---------------------------|
| Segment 1 (S30 → S12) (Lao Cai – Hanoi) |                           |                           |                         |                           |
| Average                                 | 61.2                      | 86.2                      | 704                     | 0.52                      |
| Min                                     | 51.2                      | 71.7                      | 507                     | ND                        |
| Max                                     | 73.6                      | 102                       | 845                     | 1.33                      |
| Segment 2 (S11 → S9) (Within Hanoi)     |                           |                           |                         |                           |
| Average                                 | 61.0                      | 85.4                      | 702                     | 0.80                      |
| Min                                     | 51.6                      | 72.3                      | 593                     | 0.49                      |
| Max                                     | 73.6                      | 103                       | 846                     | 1.19                      |
| Segment 3 (S8 → S1) (Hanoi – Ba Lat)    |                           |                           |                         |                           |
| Average                                 | 55.0                      | 77.1                      | 633                     | 0.47                      |
| Min                                     | 51.0                      | 71.4                      | 587                     | 0.06                      |
| Max                                     | 58.1                      | 81.3                      | 668                     | 0.98                      |

( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ ) is observed in segment 1, followed by segment 2 and segment 3. In contrast, the highest concentration of man-made radionuclide ( $^{137}\text{Cs}$ ) is found in segment 2, followed by segment 1 and segment 3. One of the key explanations for the observed results is geomorphological features of each segment, for example segment 2 was affected by the easy washout of materials (including of  $^{137}\text{Cs}$ ) from surface related to process of urbanization and concreting. The fallout material was washed and moved following the surface flow to river. The segment 1 was a high mountainous area and the geomorphological features were also quite advantage for the washing and

movement of the fallout materials from surface to valley or river but the forest and plants acted as significant factors in preserving the materials from leaching. The segment 3, downstream of the Red River with the flat geomorphological features served to be advantageous for distribution of alluvium and fallout material anywhere and did not concentrate in the river. The highest concentration of natural radionuclides in segment 1 could be attributed to the distribution of many radionuclide-bearing ore mines, mining industrial zones, and intrusive formations along this segment. However, differences in radionuclide concentrations along different segments are insignificant. Based on this minor difference of natural radionuclides in the river sediments, another conclusion is drawn that those radionuclides in Red River sediments could come from the similar source which originates from the upstream of its river. It should be noted here that the contribution of natural radionuclides from surrounding activities, weathering of soil and rock (sources) along the Red River to the sediments is quite a small contribution and insignificant, indicating that natural radioactive sources along the Red River such as ore mining (uranium and rare earth mines) and the agriculture production as mentioned above do not enhance much the activity concentration being in the Red River sediments.

The comparison of natural radionuclides activity in the Red River sediment samples and in soil samples in different provinces along the Red River is shown in Table 4. It can be seen that the concentration of natural radionuclides in this river sediments is higher than that in most soil samples in Table 4 (Huy et al. 2012), except for soil samples in Muong

**Table 4** Comparison of radionuclide concentration in the Red River sediments and in soil samples in different provinces along the Red river

| Locations          | Activity concentration (Bq/kg) |                   |                 |                   | References          |
|--------------------|--------------------------------|-------------------|-----------------|-------------------|---------------------|
|                    | <sup>226</sup> Ra              | <sup>232</sup> Th | <sup>40</sup> K | <sup>137</sup> Cs |                     |
| Red river, Vietnam | 59.6 ± 3.0                     | 83.7 ± 4.2        | 685 ± 34.4      | 0.53 ± 0.03       | This study          |
| Muong Hum, Lao Cai | 156                            | 647               | 908             | –                 | Duong et al. (2021) |
| Lao Cai            | 52.0                           | 83.5              | 496             | –                 | Huy et al. (2012)   |
| Yen Bai            | 111.6                          | 78.3              | 216.8           | –                 |                     |
| Phu Tho            | 43.1                           | 70.0              | 274.7           | –                 |                     |
| Ha Noi             | 37.9                           | 52.1              | 502.5           | –                 |                     |
| Hung Yen           | 30.6                           | 51.0              | 408.2           | –                 |                     |
| Thai Binh          | 36.6                           | 57.0              | 652.4           | –                 |                     |
| Nam Dinh           | 38.7                           | 63.5              | 652.2           | –                 |                     |

Hum, Lao Cai, which is a high radiation background area of rare earth elements mine (Duong et al. 2021). The high radionuclides concentration in study samples could be related to the deposition and accumulation processes of the sediments on the bottom of river. As evidenced in this study, the supply and enrichment of natural radionuclide sources could be come from the intrusive formations along Red River (Fig. 2), thereby leading to their accumulation in river sediments.

The radionuclides concentrations in river sediments in this study are comparable to those in river sediment samples from different countries, as shown in Table 5. It can be seen that the concentrations of <sup>226</sup>Ra and <sup>232</sup>Th in sediment samples in this study are higher than those in almost all the river sediments that have been listed in Table 5 (Alokhina and Gudzenko 2021; Cukrov et al. 2009; de Carvalho et al. 2016; Ergül et al. 2013; Yakovlev et al. 2020), excluding Juru river, Penang (Mei-Wo et al. 2020). Similarly, the <sup>40</sup>K concentration in this study is also higher than that in almost

river sediments presented in this table, except for sediments in Wei River, China (Lu et al. 2008) and Palar river, India (Ramasamy et al. 2006). For <sup>137</sup>Cs radionuclide, its concentration in the Red River sediments is lower than that in some areas such as Krka river Estuary, Croatia (Cukrov et al. 2009), Izmit Bay, Turkey (Ergül et al. 2013), Zolotitsa River, Russia (Yakovlev et al. 2020) and higher than that in an inlet in Rio de Janeiro State, Brazil (de Carvalho et al. 2016). In an inlet in Rio de Janeiro State, Brazil, the <sup>137</sup>Cs concentration of 0.5 ± 0.2 Bq/kg was found in one of the sediment samples. The difference could be explained based on the changes in the location, sediment sources, the distance to the sources or the geochemistry of water, and geomorphological features surrounding both sides of the river.

**Table 5** Average concentration of radionuclides in sediment samples from different countries

| Locations                   | Activity concentration (Bq/kg) |                   |                 |                   | References                   |
|-----------------------------|--------------------------------|-------------------|-----------------|-------------------|------------------------------|
|                             | <sup>226</sup> Ra              | <sup>232</sup> Th | <sup>40</sup> K | <sup>137</sup> Cs |                              |
| Red River, Vietnam          | 59.4 ± 3.0                     | 83.4 ± 4.2        | 681 ± 34.8      | 0.54 ± 0.03       | This study                   |
| Danube River, Serbia        | –                              | 26                | 395             |                   | Bikit et al. (2006)          |
| Nile River, Egypt           | –                              | 12.9              | 52.9            |                   | El-Gamal et al. (2007)       |
| Krka river Estuary, Croatia | 29.5                           | –                 | –               | 11.7              | Cukrov et al. (2009)         |
| Ogun River, Nigeria         | –                              | 11.7              | 499.4           |                   | Jibiri and Okeyode (2011)    |
| Wei River, China            | –                              | 33.1              | 833.1           |                   | Lu et al. (2008)             |
| Palar River, India          | –                              | 36.4              | 742.4           |                   | Ramasamy et al. (2006)       |
| Ponnaiyar River, India      | –                              | 46.9              | 384             |                   | Suresh et al. 2011           |
| Izmit Bay, Turkey           | 18                             | 24                | 568             | 21                | Ergül et al. (2013)          |
| Inlet in Brazil             | 24                             | 44                | 678             | 0.5 ± 0.2*        | de Carvalho et al. (2016)    |
| Juru River, Penang          | 125                            | 165               | 485             |                   | Mei-Wo et al. (2020)         |
| Zolotitsa River, Russia     | 9.0                            | 11.2              | 318.8           | 5.4               | Yakovlev et al. (2020)       |
| Inhul River, Ukraine        | 27.5–50.0                      | 31.7–54.0         | 285.0–420.0     |                   | Alokhina and Gudzenko (2021) |
| Inhulet River, Ukraine      | 16.0–19.1                      | 21.0–28.0         | 241.0–297.5     |                   |                              |

\*The value of <sup>137</sup>Cs concentration is observed in only one sediment sample

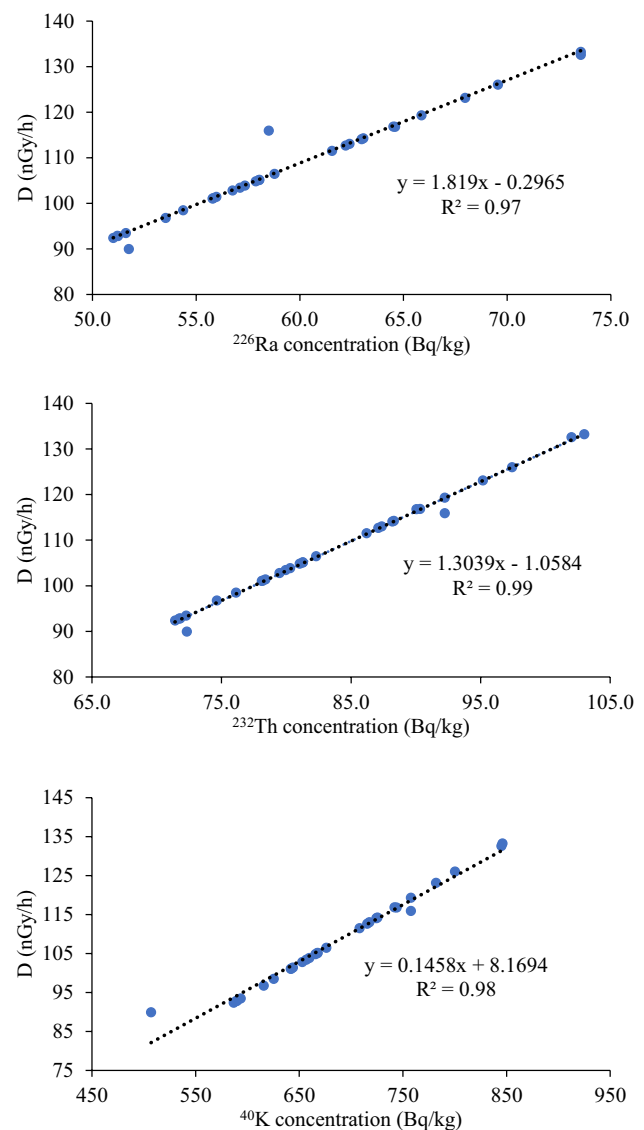
**Table 6** Calculated results of radiological hazard indices for Red river sediment samples

| Sample location              | D (nGy/h) | AEDE ( $\mu\text{Sv/y}$ ) | ELCR ( $\times 10^{-3}$ ) |
|------------------------------|-----------|---------------------------|---------------------------|
| S1                           | 105       | 129                       | 0.51                      |
| S2                           | 92.4      | 113                       | 0.44                      |
| S3                           | 98.5      | 121                       | 0.47                      |
| S4                           | 103       | 127                       | 0.50                      |
| S5                           | 92.8      | 114                       | 0.45                      |
| S6                           | 101       | 124                       | 0.49                      |
| S7                           | 101       | 124                       | 0.49                      |
| S8                           | 103       | 126                       | 0.50                      |
| S9                           | 133       | 163                       | 0.64                      |
| S10                          | 105       | 129                       | 0.50                      |
| S11                          | 93.5      | 115                       | 0.45                      |
| S12                          | 133       | 163                       | 0.64                      |
| S13                          | 92.8      | 114                       | 0.45                      |
| S14                          | 113       | 138                       | 0.54                      |
| S15                          | 111       | 137                       | 0.54                      |
| S16                          | 105       | 129                       | 0.51                      |
| S17                          | 126       | 155                       | 0.61                      |
| S18                          | 113       | 139                       | 0.54                      |
| S19                          | 114       | 140                       | 0.55                      |
| S20                          | 119       | 146                       | 0.57                      |
| S21                          | 116       | 142                       | 0.56                      |
| S22                          | 117       | 143                       | 0.56                      |
| S23                          | 96.8      | 119                       | 0.47                      |
| S24                          | 123       | 151                       | 0.59                      |
| S25                          | 89.9      | 110                       | 0.43                      |
| S26                          | 114       | 140                       | 0.55                      |
| S27                          | 104       | 127                       | 0.50                      |
| S28                          | 117       | 143                       | 0.56                      |
| S29                          | 106       | 131                       | 0.51                      |
| S30                          | 101       | 124                       | 0.49                      |
| Average                      | 108       | 132                       | 0.52                      |
| Min                          | 89.9      | 110                       | 0.43                      |
| Max                          | 133       | 163                       | 0.64                      |
| World average (UNSCEAR 2000) | 57        | 70                        | 0.29                      |

## Radiological Hazard Assessment

The calculated results of radiological hazard indices (radium equivalent activity, absorbed dose rate, annual effective dose equivalent, and excess lifetime cancer risk) for surface sediments in the Red River are listed in Table 6.

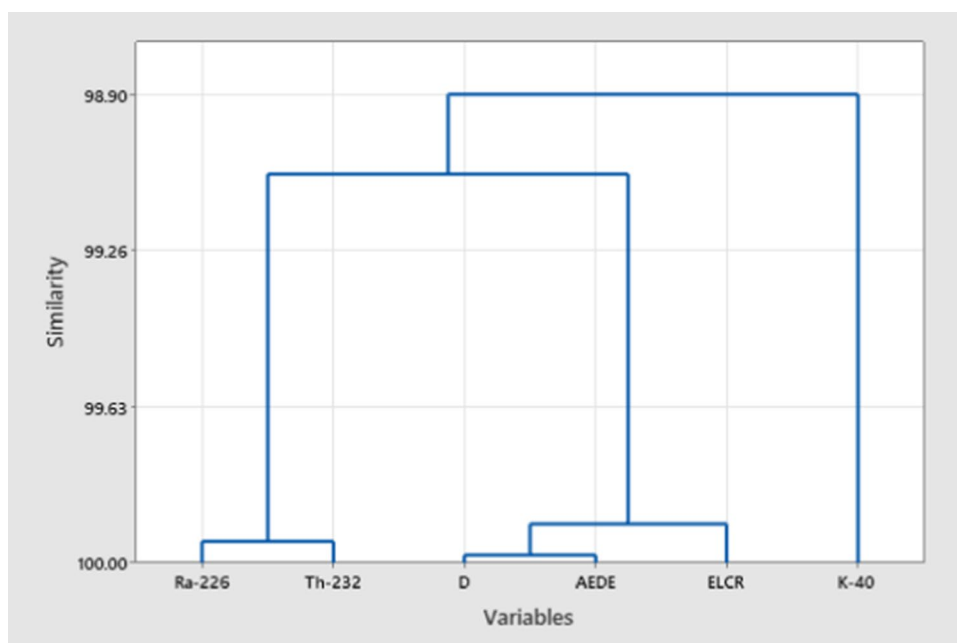
As shown in Table 6, the total absorbed dose rate (D) varies from 89.9 nGy/h to 133 nGy/h with a mean value of 108 nGy/h. The average value of D is about 2 times higher than the world average value of 57 nGy/h (UNSCEAR 2000). The contribution of each radionuclide to the D value is almost similar at all sampling locations. In which, the contributions

**Fig. 4** Relationship between the total absorbed dose rate (D) and radionuclide concentration

of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  to the D value are in the range from 23.2–26.5% (25.4% on average), from 47.7–49.9% (48.0% on average), and from 23.7–27.5% (26.6% on average), respectively. The highest contribution to the D value is observed for  $^{232}\text{Th}$ . As shown in some previous studies, the  $^{232}\text{Th}$  radionuclide in soil samples along Red river also contributed to the largest proportion to the D value (Duong et al. 2021; Huy et al. 2012). As shown in Fig. 4, the concentration of study natural radionuclides ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ),  $^{40}\text{K}$ ) has strong positive correlation with the total dose rate ( $R^2 = 0.97$ , 0.99, 0.98), respectively.

Regarding other radiological hazard indices, as presented in Table 6, the AEDE values vary from 110 to 163  $\mu\text{Sv/y}$  (mean value of 132  $\mu\text{Sv/y}$ ), and the ELCR values range from

**Figure. 5** The cluster analysis of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  with radiological hazards



$0.43 \times 10^{-3}$  to  $0.64 \times 10^{-3}$  (mean value of  $0.52 \times 10^{-3}$ ). In general, the average values AEDE and ELCR are about 2 times higher than the world average values of  $70\mu\text{Sv/y}$  for AEDE and  $0.29 \times 10^{-3}$  for ELCR (UNSCEAR 2000).

The similarity level between the activity concentrations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  and the radiological hazards were determined from cluster analysis using Minitab software (Fig. 5). Figure 5 shows the two main clusters plotted in the dendrogram of the examined data. Cluster I consists of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , D, AEDE and ELCR. This result indicates that activity concentrations of  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  are the main radiological hazard indexes. And cluster II includes  $^{40}\text{K}$ , which suggests that the  $^{40}\text{K}$  activity concentration contributes less than  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  to the radiological hazard indexes. These results are in good agreement with Pearson correlation.

## Conclusions

The characteristics and distribution of radionuclides ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ),  $^{40}\text{K}$ , and  $^{137}\text{Cs}$ ) at 30 locations in the Red River sediment, Vietnam have been thoroughly investigated and used to estimate the radiological hazard indices. Some main conclusions are made as follows:

The  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ),  $^{40}\text{K}$  activities were higher than the world average values. Highest concentration variation was observed for the high mobility of  $^{40}\text{K}$  radionuclide. There is a slight difference of radionuclides at different segments (Lao Cai to Ha Noi; within Hanoi; and from Ha Noi to Ba Lat) which can be attributed to the geological and geomorphological features of each segments. However, the

natural radionuclide concentrations in the Red River sediment samples from upstream of Lao Cai to downstream of Ba Lat estuary vary insignificantly. This indicated that the natural and human activities such as weathering, ore mining and the agriculture production along both side of Red River have insignificantly reflected in radionuclide variation in river bottom sediments. Activity concentration of  $^{137}\text{Cs}$  significantly changes in the three of segments which could be also related to the geomorphological features of surrounding of both sides of the Red river.

The average concentrations of natural radionuclides in Red River sediments are higher than those in soil samples in different provinces along the Red River and also higher than the world average values. There is an enrichment process of natural radionuclides in the Red River sediment as a question for further studies.

Regarding the radiation hazards, the values of D, AEDE, and ELCR are about two times higher than the world average values. There is an interesting observation that the natural radionuclide activities in Red river sediments have a strong correlation with the  $D$  value.

This study provided the first baseline data for understanding the distribution and characteristics of natural and artificial radionuclides in Red River sedimentary samples. As the huge river in North Vietnam, the baseline data of this study will be important for assessment of potential pollution and radiological hazards relating to human activities surrounding such as mining of uranium, rare earth element, nuclear test, nuclear power plant, industry, and agriculture. Further studies could be carried out to trace the origin and enrichment of radionuclides in this area.

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## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

- Abbasi A, Mirekhtiary SF (2019) Risk assessment due to various terrestrial radionuclides concentrations scenarios. *Int J Radiat Biol* 95(2):179–185
- Abbasi A, Mirekhtiary F (2020) Heavy metals and natural radioactivity concentration in sediments of the Mediterranean Sea coast. *Mar Pollut Bull* 154:111041
- Abbasi A, Algethami M, Bawazeer O, Zakaly HM (2022) Distribution of natural and anthropogenic radionuclides and associated radiation indices in the Southwestern coastline of Caspian Sea. *Mar Pollut Bull* 178:113593
- Adesiji NE, Ademola JA (2019) Soil-to-cassava plant transfer factor of natural radionuclides on a mining impacted soil in a tropical ecosystem of Nigeria. *J Environ Radioact* 201:1–4
- Alokhina T, Gudzenko V (2021) Distribution of radionuclides in modern sediments of the rivers flowing into the Dnieper-Bug Estuary. *E3S Web Conf.* <https://doi.org/10.1051/e3sconf/202128011003>
- Chau ND, Jadwiga P, Adam P, Van Hao D, Le Khanh Phon JP (2017) General characteristics of rare earth and radioactive elements in Dong Pao deposit Lai Chau Vietnam. *Vietnam J Earth Sci* 39:14–26
- Cukrov N, Mlakar M, Cuculić V, Barišić D (2009) Origin and transport of <sup>238</sup>U and <sup>226</sup>Ra in riverine estuarine and marine sediments of the Krka River Croatia. *J Environ Radioact* 100:497–504
- Currie LA (1968) Limits of qualitative detection and quantitative determination. *Anal Chem* 40(3):586–593. <https://doi.org/10.1021/ac60259a007>
- de Carvalho FM, da Costa LD, Ribeiro FCA, Fonseca RT, da Silva PS, Martins NSF (2016) Natural and man-made radionuclides in sediments of an inlet in Rio de Janeiro State Brazil. *Mar Pollut Bull* 107:269–276
- Debertin K, Helmer RG (1988) Gamma-and X-ray spectrometry with semiconductor detectors. Elsevier Science and Technology
- Duong NT, Van Hao D, Duong DT, Phan TT, Le Xuan H (2021) Natural radionuclides and assessment of radiological hazards in MuongHum Lao Cai Vietnam. *Chemosphere* 270:128671
- Ergül HA, Belivermiş M, Kılıç Ö, Topcuoğlu S, Çotuk Y (2013) Natural and artificial radionuclide activity concentrations in surface sediments of Izmit Bay Turkey. *J Environ Radioact* 126:125–132
- Fallah M, Jahangiri S, Janadeleh H, Kameli MA (2019) Distribution and risk assessment of radionuclides in river sediments along the Arvand River Iran. *Microchem J* 146:1090–1094
- Hao DV, Nguyen TD, Kocsis E, Csordas A, Hegedus M, Kovacs T (2021) Transfer of radionuclides from soil to *Acacia auriculiformis* trees in high radioactive background areas in North Vietnam. *J Environ Radioact* 229:106530
- Huy NQ, Hien PD, Luyen TV, Hoang DV, Hiep HT, Quang NH, Long NQ, Nhan DD, Binh NT, Hai PS (2012) Natural radioactivity and external dose assessment of surface soils in Vietnam. *Radiat Prot Dosimetry* 151:522–531
- ICRP., 1990. Publication 60. Recommendations of the International Commission on Radiological Protection. *Ann. ICRP* 21 (1–3).
- Jodłowski P, Kalita SJ (2010) Gamma-ray spectrometry laboratory for high-precision measurements of radionuclide concentrations in environmental samples. *Nukleonika* 55:143–148
- Kumar A, Singhal RK, Preetha J, Rupali K, Narayanan U, Suresh S, Mishra MK, Ranade AK (2008) Impact of tropical ecosystem on the migrational behavior of K-40 Cs-137 Th-232 U-238 in perennial plants. *Water Air Soil Pollut* 192:293
- Leuangtakoun S, Phan GT, Duong TD, Le N-T, Khong NK, Sing-soupho S, Tran H-N (2020) Natural radioactivity measurement and radiological hazard evaluation in surface soils in a gold mining area and surrounding regions in Bolikhamxay province Laos. *J Radioanal Nucl Chem* 326:997–1007
- Lu X, Zhang X, Wang F (2008) Natural radioactivity in sediment of Wei River China. *Environ Geol* 53:1475–1481
- Mei-Wo Y, Mahmood ZUW, Elias MS, Abdullah Y (2020) The distribution of heavy metals and natural radionuclides within the surface sediments of the Juru River Penang in: AIP Conference Proceedings, AIP Publishing LLC pp 020006
- Nguyen DC, Le Khanh P, Jodłowski P, Pieczonka J, Pięstrzyński A, Van HD, Nowak J (2016) Natural radioactivity at the sin quyen iron-oxide-copper-gold deposit in North Vietnam. *Acta Geophys* 64:2305–2321
- Phan QV, Dao TT, Nguyen P, Trinh DH, Heinig T (2019) An assessment of natural radioactivity in the namxe rare Earth deposit Laichau Province Vietnam. *Minerals* 9:602
- Ramasamy V, Murugesan S, Mullainathan S (2006) Natural activity concentration and radiological hazards of Palar river sediments Tamilnadu India. *The Indian Mineralogist* 40:9–23
- Semizhon T, Röllin S, Spasova Y, Klemt E (2010) Transport and distribution of artificial gamma-emitting radionuclides in the River Yenisei and its sediment. *J Environ Radioact* 101:385–402
- Suresh G, Ramasamy V, Meenakshisundaram V, Venkatachalapathy R, Ponnusamy V (2011) Influence of mineralogical and heavy metal composition on natural radionuclide concentrations in the river sediments. *Appl Radiat Isot* 69:1466–1474
- UNSCEAR (2000) Sources and effects of ionizing radiation ANNEX B Exposures from natural radiation sources. *N Y* 1:97–99
- UNSCEAR (2008) Sources and effects of ionizing radiation. Annex B: exposures of the public and workers from various sources of radiation. United Nations, New York
- Van HD, Dinh CN, Jodłowski P, Kovacs T (2019) High-level natural radionuclides from the Mandena deposit South Madagascar. *J Radioanal Nucl Chem* 319:1331–1338
- Van HD, Nguyen TD, Peka A, Hegedus M, Csordas A, Kovacs T (2020) Study of soil to plant transfer factors of <sup>226</sup>Ra <sup>232</sup>Th <sup>40</sup>K and <sup>137</sup>Cs in Vietnamese crops. *J Environ Radioact* 223:106416
- Wang Q, Song J, Li X, Yuan H, Li N, Cao L (2016) Environmental evolution records reflected by radionuclides in the sediment of coastal wetlands: a case study in the Yellow River Estuary wetland. *J Environ Radioact* 162:87–96
- Yakovlev EY, Malov AI, Druzhinin SV, Zykova EN, Orlov AS (2020) Transformation of the radionuclides composition of

river sediments in the area of the exploited Lomonosov diamond deposit (NW Russia). *J Environ Radioact* 213:106142

Zeng Q, Brown PH (2000) Soil potassium mobility and uptake by corn under differential soil moisture regimes. *Plant Soil* 221:121–134

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