



## Evaluation of radioactive pollution in sediment samples of Borçka Dam Lake, Turkey

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**Abstract.** In this research, the concentrations of natural ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ ) and anthropogenic ( $^{137}\text{Cs}$ ) radionuclides were measured in sediment samples collected from the Borçka Dam Lake using a high purity germanium detector (HPGe). The activity values ranged from 4.79-21.46, 9.36-20.65, 238.01-721.26 and 0.79-6.81 Bq kg<sup>-1</sup> for  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  and  $^{137}\text{Cs}$  respectively. The average  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  activity concentrations calculated for the sediment samples were found to be lower compared to world average values reported by UNSCEAR. In addition, radiological hazard indices were determined and compared with the international permissible values. The results of this study revealed that there is no significant health risk for people exposed to sediment samples in this region.

**Keywords:** Borçka Dam Lake, Radioactivity, Sediment, Lifetime cancer risk.

## Türkiye’de Borçka Baraj Gölünün Sediment Örneklerinde Radyoaktif Kirliliğin Değerlendirmesi

**Özet.** Bu araştırmada, Borçka Baraj Gölü’nden toplanan sediment örneklerinde doğal ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ve  $^{40}\text{K}$ ) ve yapay ( $^{137}\text{Cs}$ ) radyonüklidlerin konsantrasyonları yüksek saflıkta germanyum dedektörü (HPGe) kullanılarak ölçülmüştür. Aktivite değerleri  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  ve  $^{137}\text{Cs}$  için sırasıyla 4.79-21.46, 9.36-20.65, 238.01-721.26 ve 0.79-6.81 Bq kg<sup>-1</sup> aralığında değişmiştir. Sediment örnekleri için hesaplanan ortalama  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ve  $^{40}\text{K}$  aktivite konsantrasyonları UNSCEAR tarafından rapor edilen dünya ortalaması değerlerinden daha düşük bulunmuştur. Ayrıca, radyolojik tehlike indisleri belirlenmiş ve uluslararası izin verilen değerlerle karşılaştırılmıştır. Bu çalışmanın sonuçları, bu bölgedeki sediment örneklerine maruz kalan insanlar için önemli bir sağlık riski olmadığını ortaya çıkarmıştır.

**Anahtar Kelimeler:** Borçka Baraj Gölü, Radyoaktivite, Sediment, Yaşam boyu kanser riski.

### 1. INTRODUCTION

Naturally radioisotopes ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ ) are connected with rock, sand, soil and sediments in an environment. The man-made radionuclides left in our environment come from anthropogenic sources such as nuclear weapons tests and nuclear accidents [1]. Human source radionuclides, accidents in nuclear reactors, and fission products resulting from nuclear tests or industrial activities are also sources of pollution that may have a significant impact on the water environment [2]. Natural and anthropogenic radioisotopes can be transported to different

distances after different processes and finally accumulate in sediment particles [3-4]. Due to the Chernobyl nuclear power plant accident, the Marmara and the Black Sea region of Turkey was contaminated with high artificial radioisotopes [5]. After the Chernobyl accident, the north-eastern of Turkey in particular has been contaminated by artificial radionuclides. The radioactive cloud resulting from the nuclear accident arrived the territory of Turkey on 5 May 1986 and the country's different regions and ecosystems significantly polluted [6]. Therefore, the determination of the distribution of natural and anthropogenic radionuclides in the environmental environment is extremely important for environmental monitoring, nuclear protection and nuclear forensic studies [5].

It is stated that the river sediments are the wear products of the rocks and they have mineralogical properties of the original rock formation. Sediments play an important role in aquatic radioecology, because they carry and accumulate pollutants (radioactivity, heavy metal, etc.) in the environmental area. Therefore, the investigation of radioactivity levels in sediments in rivers and lakes provides useful information related to environmental pollution. For these reasons, monitoring and determining the activity concentrations and gamma-dose ratios of radionuclides is an important issue for humanity [7].

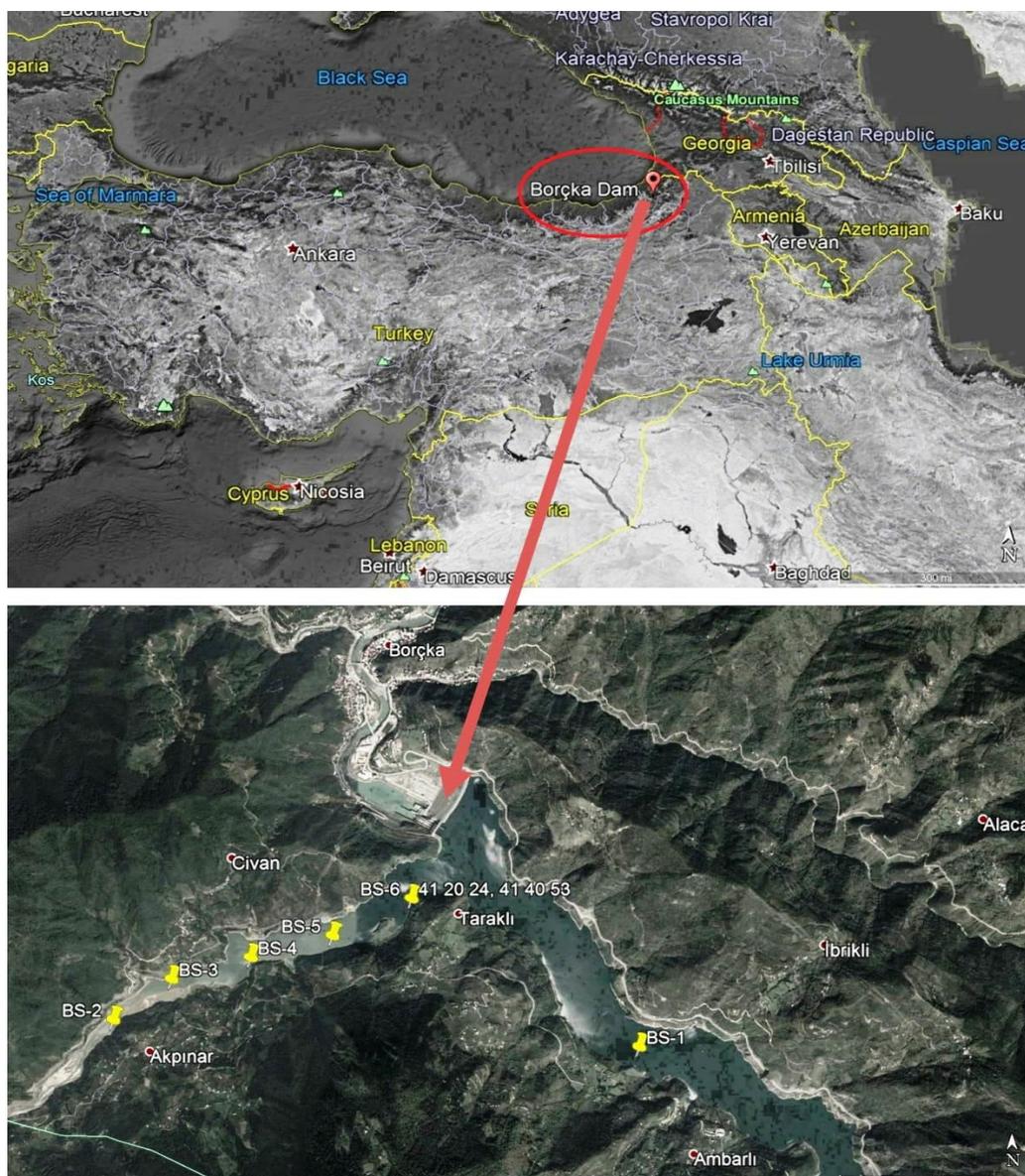
Rivers play an important role in transporting sedimental particles and organic matter from land to seas, but man-made obstacles such as dams prevent the transporting of these substances to marine environment and so these particulate matters accumulate at the bottom of the Dam lakes.

In time, sediments deposited at the bottom of the lake are an important component for monitoring the change of radioactive pollution in the region. In addition, radionuclides accumulating in the lake contaminate the water environment in which they are in contact. Dam waters are frequently used to irrigate agricultural lands located in the nearby area and therefore the determination of radioactive pollution in sediment samples in lake environment shows the importance of this research study [8].

To determine radioactivity levels at the dam lake and river sediments, some investigations have been carried out in Turkey [1, 8-11]. However, the studies conducted to determine the radioactivity levels of the sediment samples of the Dam lakes are limited in Turkey. Therefore, in the present study, the activity concentrations of natural ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ ) and anthropogenic ( $^{137}\text{Cs}$ ) radionuclides in sediment samples collected from Borçka Dam Lake have been surveyed. Besides, radiological hazard indices such as the radium equivalent activity ( $\text{Ra}_{\text{eq}}$ ), the external hazard index ( $\text{H}_{\text{ex}}$ ), the absorbed dose rate in air (D), the annual effective dose equivalent (AEDE) and the excess lifetime cancer risk (ELCR) were calculated and compared with the international permissible values.

## 2. MATERIALS AND METHODS

### 2.1. Study area and sampling



**Figure 1.** The sampling stations in the Borçka Dam Lake (Gedik et al., 2018)

Borçka Dam is a dam built on the Çoruh River in Artvin between 1998 and 2005 to produce energy. Turkey's Northeast Anatolia region is located on the Coruh River Basin is located in the lower Coruh basin. It is producing hydroelectric power. The body volume of the dam, which is the type of the soil trunk filling, is  $7.785.000 \text{ m}^3$ , the height from the stream bed is  $86,00 \text{ m}$ , the lake volume is  $419,00 \text{ hm}^3$  in the normal water level, and the water area in the normal water level is  $10.84 \text{ km}^2$ . The dam produces energy of  $1.039 \text{ GWh}$  per year with  $300 \text{ MW}$  power.

In this research, three lake sediment samples were collected from each of the six sampling points determined in Borçka Dam Lake in April 2016. The sampling stations in the Borçka Dam Lake are presented in Figure 1 and the coordinates of the sampling points and some physico-chemical properties of the sediment samples collected from Borçka Dam Lake are given in Table 1. The coordinates of all sampling points were recorded using a GPS tool. Approximately 1-2 kg of sediment samples were collected from each sampling point by means of an Ekman-Birge sampler; then the collected samples were transferred to nylon bags and the bags were tightly sealed by labeling them to prevent mixing and contamination of the samples. Subsequently, all samples were transferred to the cold chain box and transported to the laboratory for the necessary analyses. [12-13].

**Table 1.** The coordinates of sampling points and some physico-chemical properties in sediment samples collected from Borçka Dam Lake.

<b>Sampling location</b>	<b>North latitude</b>	<b>East longitude</b>	<b>Sampling depth (m)</b>	<b>pH</b>	<b>Sand (%)</b>	<b>Silt+Clay (%)</b>	<b>Total organic carbon (TOC) (%)</b>
BS-1	41° 19' 36" N	41° 42' 28" E	35	7.36	87.45	12.55	1.84
BS-2	41° 19' 45" N	41° 38' 49" E	1.3	8.17	98.13	1.87	0.79
BS-3	41° 19' 58" N	41° 39' 13" E	3.8	8.01	92.68	7.32	1.24
BS-4	41° 20' 05" N	41° 39' 46" E	7.6	7.90	21.57	78.43	1.62
BS-5	41° 20' 12" N	41° 40' 20" E	22.4	7.89	31.22	68.78	1.67
BS-6	41° 20' 24" N	41° 40' 53" E	33.7	7.90	89.92	10.08	1.19

## 2.2. Characterization of sediments

Granulometric analysis of the samples was performed with the help of Retsch brand (Germany) AS 200 model vibratory sieve shaker. After Granulometric analysis, sediments were classified as sand (0.063-2 mm) and silt + clay (<0.063 mm) based on grain size. To determine the pH values of the sediment samples, the samples were sieved by a 2 mm sieve and then left to dry in the oven at 105 °C. Then 10 g of sediment sample was placed in the flask and 50 mL of deionized water (1 sediment: 5 water) was added. After the prepared mixture is stirred for about 1 hour, measurements were made with the pH probe in the YSI brand multi-parameter probe [13]. A Shimadzu SSM5000A Total Organic Carbon Analyzer device was used to measure the total organic carbon (TOC) level of the sediment samples. The TOC content in the samples was determined by the difference between total carbon (TC) and inorganic carbon (IC) values [14].

## 2.3. Sample preparation for activity measurements

After the sediment samples were transferred to the laboratory, the first stone particles and visible impurities were removed. Each sample of the sediment was then homogenized in a mortar and allowed to dry in an oven at 105 °C for 24 hours to remove moisture. Dried samples were sieved with a 400 mesh (63 µm) sieve. Approximately 118 g of each sample was placed in polyethylene containers with cylindrical screw cap (5.5 cm diameter and 5 cm height) for gamma measurement and sealed tightly [15]. Before starting the gamma activity analysis, the vessels were kept closed for four weeks to achieve a balance between <sup>226</sup>Ra and the short-lived generation [16].

## 2.4. Gamma spectrometry measurement

The activity levels of <sup>226</sup>Ra, <sup>232</sup>Th, <sup>40</sup>K and <sup>137</sup>Cs in all samples were measured using a coaxial HPGe detector (Ortec, GEM55P4-95 model). Detailed explanations about the measurement system are previously presented elsewhere [12, 16].

The gamma-energy lines of 351.9 keV (<sup>214</sup>Pb) and 609.3 keV (<sup>214</sup>Bi) were used to represent the <sup>226</sup>Ra series, while 911.1 keV (<sup>228</sup>Ac) and 583.1 keV (<sup>208</sup>Tl) were used to represent the <sup>232</sup>Th series. The activity values of <sup>40</sup>K and <sup>137</sup>Cs were determined using their peaks at 1460.8 keV and 661.6 keV, respectively. In the calculation of activity, dry weight (dw) was taken into account for all samples [12, 17].

The activity concentrations of the studied radionuclides (<sup>226</sup>Ra, <sup>232</sup>Th, <sup>40</sup>K and <sup>137</sup>Cs) in the samples measured by utilizing the equation given below were determined:

$$C = \frac{N}{\varepsilon \cdot P_{\gamma} \cdot t \cdot m} \text{ (Bq kg}^{-1}\text{)} \quad (1)$$

where N is the net count rate of the gamma ray;  $\epsilon$  is the photo peak yield of the detector,  $P_{\gamma}$  is the absolute transition of gamma decay, t is the counting time in seconds, and m, the mass of the sample from the kilogram unit.

The MDA of the current gamma system was determined using the equation presented below [18]:

$$MDA = \frac{\sigma\sqrt{B}}{\epsilon.I_{\gamma}.t.w} \quad (2)$$

where MDA is in Bq kg<sup>-1</sup>,  $\sigma$  is the statistical coverage factor, which is equal to 1.645 (confidence level 95%), and B is the background value for a certain radionuclide [12]. The MDA for the studied radionuclides was calculated as 0.16, 0.24, 1.69 and 0.02 Bq kg<sup>-1</sup> for <sup>226</sup>Ra, <sup>232</sup>Th, <sup>137</sup>Cs and <sup>40</sup>K, respectively. In order to determine the accuracy of the measurement system, an example of the certified reference material IAEA-447 was read in the system in triplicate in a similar manner to the samples. In the reference sample, the concentrations of <sup>226</sup>Ra, <sup>232</sup>Th, <sup>137</sup>Cs and <sup>40</sup>K were given as 25.04, 37.3, 371.11 and 550 Bq kg<sup>-1</sup>, respectively. For the measurement system, <sup>226</sup>Ra, <sup>232</sup>Th, <sup>137</sup>Cs and <sup>40</sup>K values were calculated as 23.96, 35.7, 362.55 and 521 Bq kg<sup>-1</sup>, respectively. Accuracy, expressed as recovery of the reference substance, was found in the range of 95-98 % for all radionuclides.

### 3. RESULTS AND DISCUSSION

#### 3.1. Physiochemical properties of sediments

The physico-chemical parameters determined in sediment samples are presented in Table 1. In the current study, it was found that the values of pH, Sand, Silt+Clay, and TOC ranged between 7.36–8.17, 21.57–98.13%, 1.87–78.43%, and 0.79–1.84%, respectively. The lowest pH and highest TOC content were determined at the BS-1 location. It is known that this station is under the influence of water culture and causes high organic substances due to uneaten feed, decayed plants and live wastes and feces in such areas [13].

#### 3.2. Natural radioactivity in sediment

The activity concentrations of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K radionuclides detected in sediment samples gathered from Borçka Dam Lake are shown in Table 2. It was observed that the concentrations determined in this study ranged from 4.79 to 21.46 Bq kg<sup>-1</sup> (the mean concentration of 12.19 Bq kg<sup>-1</sup>) for <sup>226</sup>Ra, from 9.36 to 20.65 Bq kg<sup>-1</sup> the mean concentration of 14.05 Bq kg<sup>-1</sup>) for <sup>232</sup>Th, and from 238.01 to 721.26 Bq kg<sup>-1</sup> (the mean concentration of 396.41 Bq kg<sup>-1</sup>) for <sup>40</sup>K. Also, the highest <sup>226</sup>Ra and <sup>40</sup>K concentration were detected in the BS-6 station, while the highest <sup>232</sup>Th concentration was detected in the BS-1 station

**Table 2.** The activity concentrations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{137}\text{Cs}$  and  $^{40}\text{K}$  in sediment samples of Borçka Dam Lake.

Sampling location (N = 18)	$^{226}\text{Ra}$	$^{232}\text{Th}$	$^{137}\text{Cs}$	$^{40}\text{K}$
BS-1	14.01 ± 0.49	20.65 ± 0.83	6.81 ± 0.34	464.79 ± 23.24
BS-2	8.94 ± 0.36	9.36 ± 0.56	0.79 ± 0.05	238.01 ± 9.52
BS-3	4.79 ± 0.24	10.78 ± 0.54	1.03 ± 0.06	244.96 ± 11.76
BS-4	11.80 ± 0.50	14.14 ± 0.57	5.69 ± 0.20	343.58 ± 13.03
BS-5	12.16 ± 0.61	14.96 ± 0.48	5.76 ± 0.26	365.84 ± 21.95
BS-6	21.46 ± 1.07	14.40 ± 0.94	5.10 ± 0.19	721.26 ± 46.88
<b>Range</b>	<b>4.79-21.46</b>	<b>9.36-20.65</b>	<b>0.79-6.81</b>	<b>238.01-721.26</b>
<b>Mean</b>	<b>12.19</b>	<b>14.05</b>	<b>4.20</b>	<b>396.41</b>

(N= Sampling size)

Moreover, the comparison of mean activity concentrations of the present study with published results in sediment samples is shown in Table 3. The  $^{226}\text{Ra}$  activity concentrations reported in the Van Lake [1], the Metiterranean Central Basin [19], the Altinkaya Dam Lake [8], the Derbent Dam Lake [8], the Kızılırmak Delta [11] and the Yangtze Estuary [20] are higher than our values, but those for the Deriner, Borçka and Muratlı Dam Lakes [10] and the Vaigai River [21] are not.

The  $^{232}\text{Th}$  levels reported in the in the Van Lake [1], the Metiterranean Central Basin [19], the Altinkaya Dam Lake [8], the Derbent Dam Lake [8], the Deriner, Borçka and Muratlı Dam Lakes [10], the Vaigai River [21], the Kızılırmak Delta [11] and the Yangtze Estuary [20] are higher than our values.

The  $^{40}\text{K}$  levels reported in the Van Lake [1], the Metiterranean Central Basin [19], the Altinkaya Dam Lake [8], the Derbent Dam Lake [8], the Deriner, Borçka and Muratlı Dam Lakes [10], the Vaigai River [21] and the Yangtze Estuary [20] are higher than our values, but those for the the Kızılırmak Delta [11] are not.

Consequently, the average values of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  found in Borçka Dam Lake are lower than the values recommended by UNSCEAR [22].

### 3.3. Artificial radioactivity in sediment

$^{137}\text{Cs}$  activity concentrations determined in this study were presented in Table 2. The mean activity concentrations of  $^{137}\text{Cs}$  in sediment samples ranged from 0.79 to 6.81 Bq kg<sup>-1</sup> (with a mean value of 4.20 Bq kg<sup>-1</sup>). When the mean activity concentrations were compared according to the sampling

stations, the highest concentration ( $6.81 \text{ Bq kg}^{-1}$ ) was detected in BS-1 and the lowest concentration ( $0.79 \text{ Bq kg}^{-1}$ ) in the BS-2 station.

Furthermore, the results obtained in this study are compared with the results published in many studies in the literature as shown in Table 3. As shown in Table 3, the values reported in all previous studies for  $^{137}\text{Cs}$  were higher than those of this study.

**Table 3.** Comparison of mean activity concentrations of the present study with published results in sediment samples.

Location	<sup>226</sup> Ra (Bq <sup>-1</sup> )	<sup>232</sup> Th Bqkg <sup>-1</sup> )	<sup>137</sup> Cs (Bq kg <sup>-1</sup> )	<sup>40</sup> K (Bq kg <sup>-1</sup> )	References
Turkey (Van Lake)	47.48	57.87	4.37	524	[1]
Italy (Mediterranean Central Basin)	25.1	28.1		809.8	[19]
Turkey (Altinkaya Dam Lake)	19.5*	27.7		460	[8]
Turkey (Derbent Dam Lake)	18.8*	25.5		365	[8]
Turkey (Deriner, Borçka and Muratlı Dam Lakes)	11.4*	18.3	13.5	510.2	[10]
Indian (Tamilnadu, Vaigai River)	7.45*	33.81		448.24	[21]
Turkey (Kızılırmak Delta)	27.898*	14.184	9.890	62.372	[11]
China (Yangtze Estuary)	24.3	40.9		628	[20]
Worldwide	35	30		400	[22]
<b>Turkey (Borçka Dam Lake)</b>	<b>12.19</b>	<b>14.05</b>	<b>4.20</b>	<b>396.41</b>	<b>Present Study</b>

\*<sup>238</sup>U

### 3.4. Radiological hazard indices

#### 3.4.1. Radium equivalent activity ( $Ra_{eq}$ ):

Radium equivalent activity is calculated using the equation given below [23].

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K \quad (3)$$

where,  $C_{Ra}$ ,  $C_{Th}$  and  $C_K$  were the activities of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K (Bq kg<sup>-1</sup>), respectively. The results of radium equivalent activities ( $Ra_{eq}$ ) for sediment are presented in Table 4. As noted in Table 4, the radium equivalent activity value varied from 39.07 Bq kg<sup>-1</sup> to 97.59 Bq kg<sup>-1</sup> with the average of 62.81 Bq kg<sup>-1</sup>. The determined average value were found to be less than the recommended maximum permissible value of 370 Bq kg<sup>-1</sup> [24].

#### 3.4.2. External Hazard Index ( $H_{ex}$ )

The main aim of this index is to limit the radiation dose to dose equivalent limit of 1 mSv<sup>-1</sup> [25].  $H_{ex}$  should not exceed the unity limit in order to ensure that the level of risk generated by the radiation is negligible.  $H_{ex}$  was determined using the formula described below [26].

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \quad (4)$$

Table 4 showed that the average hazard index values for all samples were less than unity, which revealed that there was no harm to the farmers and populations living in the area studied.

### 3.4.3. Absorbed dose rate in air (D)

The gamma dose rate absorbed in outdoor air exposed at 1 meter above the surface by knowing the activity concentrations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  and  $^{137}\text{Cs}$  in the sediment can be determined using the formula defined below [22, 27]:

$$D \text{ (nGyh}^{-1}\text{)} = 0.461 \times C_{\text{Ra}} + 0.623 \times C_{\text{Th}} + 0.0417 \times C_{\text{K}} + 0.1243 \times C_{\text{Cs}} \quad (5)$$

where  $C_{\text{Ra}}$ ,  $C_{\text{Th}}$ ,  $C_{\text{K}}$  and  $C_{\text{Cs}}$  are the activity concentration values (in  $\text{Bq kg}^{-1}$ ) of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  and  $^{137}\text{Cs}$ , respectively, in the sediment samples. The detected activity concentrations were converted into doses using dose conversion factors of 0.461, 0.623, 0.0417 and 0.1243 for  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  and  $^{137}\text{Cs}$ , respectively [22]. Looking at Table 4, the determined values of absorbed gamma dose rate for the sediment samples ranged from 19.27 to 49.57  $\text{nGyh}^{-1}$  with an average value of 31.43  $\text{nGyh}^{-1}$ . The determined average doses for all samples is lower than the world average value of 60  $\text{nGy h}^{-1}$  [28].

### 3.4.4. Annual effective dose equivalent (AEDE)

The annual effective dose equivalent (AEDE) was determined using the equation given below [22]:

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

According to Table 4, the determined values of the annual effective dose for the sediment samples ranged from 0.024 and 0.061  $\text{mSvy}^{-1}$ , with a mean value of 0.039  $\text{mSvy}^{-1}$  [22]. However, the determined mean dose values for all samples was lower than the recommended limit value of 0.080  $\text{mSvy}^{-1}$ .

### 3.4.5. Excess lifetime cancer risk (ELCR)

The excess lifetime cancer risk (ELCR) values were determined with the help of the relation given below [22]:

$$ELCR = AEDE \times DL \times RF \quad (7)$$

DL Here is the average life expectancy (about 78 years in Turkey) [15] and RF are factors indicating the probability of a deadly carcinogen per sievert ( $\text{Sv}^{-1}$ ). Because of stochastic effects, ICRP 60 considers 0.05 for public [29]. When Table 4 was examined, it was seen that the ELCR values ranged from  $0.09 \times 10^{-3}$  to  $0.24 \times 10^{-3}$  (with a mean value  $0.15 \times 10^{-3}$ ). This average value of ELCR is less than the world average ( $0.29 \times 10^{-3}$ ) [27].

In addition, looking at Table 4, the average lifetime total dose rate was determined as 3.01 mSv. This determined mean value is lower than recommended maximum permissible value of 4.90 mSv [22].

**Table 4.** Radiological parameters of the sediment samples collected from the Borçka Dam Lake.

Sampling location	R <sub>aeq</sub> (Bq kg <sup>-1</sup> )	H <sub>ex</sub>	D (nGy h <sup>-1</sup> )	AEDE (mSv y <sup>-1</sup> )	Lifetime total dose (mSv)	ELCR (×10 <sup>-3</sup> )
BS-1	79.33	0.21	39.55	0.049	3.78	0.19
BS-2	40.65	0.11	19.98	0.024	1.91	0.10
BS-3	39.07	0.11	19.27	0.024	1.84	0.09
BS-4	58.48	0.16	29.28	0.036	2.80	0.14
BS-5	61.72	0.17	30.90	0.038	2.96	0.15
BS-6	97.59	0.26	49.57	0.061	4.74	0.24
<b>Min</b>	<b>39.07</b>	<b>0.11</b>	<b>19.27</b>	<b>0.024</b>	<b>1.84</b>	<b>0.09</b>
<b>Max</b>	<b>97.59</b>	<b>0.26</b>	<b>49.57</b>	<b>0.061</b>	<b>4.74</b>	<b>0.24</b>
<b>Mean</b>	<b>62.81</b>	<b>0.17</b>	<b>31.43</b>	<b>0.039</b>	<b>3.01</b>	<b>0.15</b>

### 3.5. Statistical Analyses

Pearson's correlation coefficients were determined to evaluate the relationship between radionuclides and some physico-chemical parameters in sediment samples and given in Table 5. The correlation analysis revealed that 40K was substantially correlated with 226Ra ( $r = 0.957$ ,  $p < 0.01$ ), pH was substantially correlated with 232Th ( $r = -0.970$ ,  $p < 0.01$ ) and Silt + Clay was substantially correlated with Sand ( $r = -1.000$ ,  $p < 0.01$ ). Besides, TOC was moderately correlated with 232Th ( $r = 0.848$ ,  $p < 0.05$ ) and 137Cs ( $r = 0.849$ ,  $p < 0.05$ ), Depth was moderately correlated with 232Th ( $r = 0.827$ ,  $p < 0.05$ ) and 40K ( $r = 0.844$ ,  $p < 0.05$ ) and 137Cs was moderately correlated with 232Th ( $r = 0.888$ ,  $p < 0.05$ ). The strong relationship between 226Ra and 40K shows that their origin and behavior in the lake is the same, while the weak positive relationship between 232Th and the other two radionuclides (226Ra and 40K) indicates that they may have the same origin but their behavior in the lake environment differ [30]. It seems that there is no clear relationship between pH and the activity concentrations of 226Ra, 40K and 137Cs in the sediment of the dam lake, while there is a considerable negative relationship between pH of the sediment and the activity of 232Th. For these relationships can be said that the radionuclides extracted from a leached sediment into the water in neutral and alkaline media could decrease and weaken the fixation of nuclides in the sediment [31]. The similar results of this study were consistent with the

finding of literature [31-32] concerning about the effect of soil properties. In light of this information, it can be said that the activity levels of artificial and natural radionuclides decrease in sediment samples with increasing pH. Although no significant correlation was found between  $^{137}\text{Cs}$  and depth, a positive correlation was found between the two parameters. This can be explained by the fact that  $^{137}\text{Cs}$  is correlated with the depth of the sediment, as expressed by Szarlowicz et al. (2018) [33]. The concentration of  $^{137}\text{Cs}$  varies depending on the particle size of the sediment, mineral composition, organic matter and total organic carbon content. The amount of total organic carbon was found to be important in the deposition of  $^{137}\text{Cs}$  radionuclides in sediments [14] and a significant relationship between the amount of total organic matter and  $^{137}\text{Cs}$  was reported in some studies in the literature [14, 34-35]. In this study, a positive correlation was found between the amount of total organic carbon and  $^{137}\text{Cs}$  radioisotope in accordance with the literature.

**Table 5.** Pearson correlation coefficients between radionuclides and some physico-chemical parameters in sediment samples.

	$^{226}\text{Ra}$	$^{232}\text{Th}$	$^{137}\text{Cs}$	$^{40}\text{K}$	pH	Sand	Silt+Clay	TOC	Depth
$^{226}\text{Ra}$	1								
$^{232}\text{Th}$	0.500	1							
$^{137}\text{Cs}$	0.649	<b>0.888*</b>	1						
$^{40}\text{K}$	<b>0.957**</b>	0.501	0.582	1					
pH	-0.352	<b>-0.970**</b>	-0.758	-0.391	1				
Sand	-0.024	-0.184	-0.532	0.114	0.023	1			
Silt+Clay	0.024	0.184	0.532	-0.114	-0.023	<b>-1.000**</b>	1		
TOC	0.181	<b>0.848*</b>	<b>0.849*</b>	0.184	-0.800	-0.0577	0.577	1	
Depth	0.809	<b>0.827*</b>	0.771	<b>0.844*</b>	-0.748	0.059	-0.059	0.530	1

Correlation is significant at the 0.01 level (two-tailed).

Correlation is significant at the 0.05 level (two-tailed).

#### 4. CONCLUSION

The activity values of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{137}\text{Cs}$  and  $^{40}\text{K}$  were determined in sediment samples collected from the Borçka Dam Lake using gamma ray spectroscopy. The mean activity concentrations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{137}\text{Cs}$  and  $^{40}\text{K}$  were found to be  $12.19 \text{ Bq kg}^{-1}$ ,  $14.05 \text{ Bq kg}^{-1}$ ,  $4.20 \text{ Bq kg}^{-1}$  and  $396.41 \text{ Bq kg}^{-1}$ , respectively. The results show that the mean activity concentration values of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in the Borçka Dam Lake were lower than the world average values suggested by UNSCEAR. Also, the mean activity concentration of  $^{137}\text{Cs}$  is lower than the results of previous studies in the literature. Additionally, the radiological hazard

indices ( $Ra_{eq}$ ,  $H_{ex}$ , D, AEDE, and ELCR) were determined and compared with international permissible values, and the results were lower than the limit values. The data obtained can be used by the researchers as reference data for monitoring possible radioactive contamination of the Borçka Dam Lake in the future.

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