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Original Article

^{137}Cs, ^{40}K and ^{210}Po in abiotic components of aquatic ecosystems two rivers in the Can Gio biosphere reserve, Vietnam

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ABSTRACT

Determination of ^{137}Cs, ^{40}K and ^{210}Po in water, bottom sediments and suspended matter of river systems of the Can Gio Biosphere Reserve, Vietnam was carried out. The average activity concentration of ^{137}Cs in waters of Ca Gau and Long Tau was 0.89 ± 0.14 and 1.08 ± 0.15 Bq m^{-3} and was comparable to the levels of this radioisotope in waters of the East Sea. The activity concentration of ^{137}Cs in bottom sediments was 2.23 ± 0.81 and 3.63 ± 1.24 Bq kg^{-1}. The activity concentration of ^{137}Cs in water and bottom sediments could be characterized as low. So, the water areas of the Ca Gau and Long Tau rivers could be attributed to areas with insignificant pollution by technogenic radionuclides. The ^{210}Po activity concentration in bottom sediments of the Ca Gau and Long Tau rivers ranged from 9.2 ± 1.2 to 25.5 ± 2.1 Bq kg^{-1}, which is typical for river bottom sediments. Such values indicate the absence of anthropogenic enhancement of the entry of this radionuclide into the Can Gio river systems. The ^{40}K activity concentration varied within 467 ± 42–651 ± 39 Bq kg^{-1} and represented typical values of potassium content in the bottom sediments of coastal water bodies, subject to a significant influence of the lithogenic component of suspended matter.

1. Introduction

Water ecosystems of protected areas, which have constant volumetric water exchange with adjacent seas, can be subject to man-made radioactive contamination as a result of even remote accidents at nuclear facilities. This can occur as a result of the entry of artificial radionuclides into the World Ocean and their subsequent migration with sea waters. As it was observed, for example, after the accident at the Chernobyl nuclear power plant in 1986 or the accident at the Fukushima Daiichi nuclear power plant in 2011 [1–3]. The radioisotope ^{137}Cs is a representative of radioecologically important technogenic radionuclides. Also, anthropogenic activities, such as the production and use of fertilizers, can increase the fluxes of natural radionuclides with surface water from the catchment basin into river waters. These natural most radioecologically significant radionuclides include ^{40}K and ^{210}Po. Monitoring radioecological studies of the main dose-forming technogenic and natural radionuclides in protected areas are important for ensuring the safety of biota in the reserve and radiation protection of environment, non-human biota and humans. In addition, they can serve as comparison background area for studying the consequences of possible future nuclear incidents. Therefore, our work is devoted to the study of radioecologically significant radionuclides ^{137}Cs, ^{40}K and ^{210}Po in the water areas of the Ka Gau and Long Tau Rivers in the Can Gio Biosphere Reserve.

Vietnam's Can Gio biosphere reserve is located southeast of Ho Chi Minh City. There are various ecosystems in the reserve, including the downstream mangroves of the Saigon and Dong Nai Rivers. The Can Gio coast is washed by the East Sea. During high tides, seawater rises and flows into the branched system of rivers and tidal water channels on the Can Gio [4].

Considering the protected status of the region on the one hand and the proximity to Ho Chi Minh City, the largest industrial city in Vietnam, on the other hand, close attention is paid to the study of Can Gio. There are dozens of types of industrial enterprises, agricultural land, forestry, fish farming and other types of aquaculture

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in Ho Chi Minh City. The studies are mainly related to the research of various aspects of anthropogenic impact on the flora and fauna of the reserve, see, for example, [3,5]. At the same time, there are practically no works on the river radioecology of Can Gio, except for some information on the distribution of radionuclides in the sediment cores, which were used for geochronological dating of the layers of sediments [6].

In Can Gio, as in many other areas of Vietnam, aquatic ecosystems are an important source of mineral resources and hydrobionts for food and other purposes. Hydrobionts were not only caught in natural habitats, but also grown in widespread aquaculture farms. Therefore, study of activity concentration level of the main dose-forming radionuclides of natural and anthropogenic origin is scientific and practical importance. In addition, bottom sediments and surface water, as well as atmospheric air, soil and biota, are recommended as monitoring objects in the study of radiation protection of water ecosystems. The purpose of our research was determination of the ^{137}Cs, ^{40}K, ^{210}Po activity concentrations in abiotic components of water areas of the Ca Gau and Long Tau rivers in the Can Gio. Besides, to evaluate the accumulation ability of bottom sediments and suspended matter in relation to ^{137}Cs, the sediment inventory of three radionuclides in the upper 0–5 cm layer and evaluate the radiation situation in river areas as well as identification of possible sources of radionuclides entering the waters of the rivers of the Can Gio Reserve.

2. Materials and methods

2.1. Location and objet of study

For research, the water areas of the rivers were chosen in the inner region of Can Gio (area 1) and in the outer area – on the border of the river-sea (area 2) (Fig. 1). The tropical climate of Can Gio is typically monsoonal. The dry season is from November to May and the rainy season is from June to October. The reserve is located in the lower reaches of various rivers, the flow of which carries out a lot of particulate matter of continental origin [4].

Samples of water, bottom sediments and suspended matter in two areas: in the Ca Gau River (area 1, sampling date 30 may 2021) and the Long Tau River (area 2, sampling date 28 may 2021) were taken. These rivers are located on the border of the core zone and the buffer zone of the reserve (Fig. 1). In each area, water and bottom sediments were sampled at three stations – off the coasts and in the central part of the riverbed, at different water levels (during low and high tide). This was done to account for tide-related factors such as salinity fluctuations, different inflow directions, and different types of suspended matter. Activity concentration of ^{137}Cs was determined in water, bottom sediments, and suspended matter; ^{40}K, in bottom sediments and suspended matter; and ^{210}Po, in bottom sediments. The choice of these radionuclides is due to their importance in the formation of the radiation background in ecosystem, which is currently formed by both natural and technogenic radionuclides. ^{40}K is one of the most abundant natural radionuclides in the earth's crust [7]. ^{210}Po is included in the ^{238}U decay chain, its radiological significance is associated with the fact that this radionuclide is a 100% alpha-emitter with a high alpha particle energy of 5.305 MeV. The dose conversion factor for ^{210}Po has one of the highest values established for radioactive elements [8,9]. ^{137}Cs is an important component of anthropogenic radioactive contamination of the biosphere [10], and is one of the main dose-forming technogenic radionuclides.

The salinity and station coordinates were determined using a HI9829 multivariable analyzer (HANNA, Romania) with a built-in GPS navigator (Table 1).

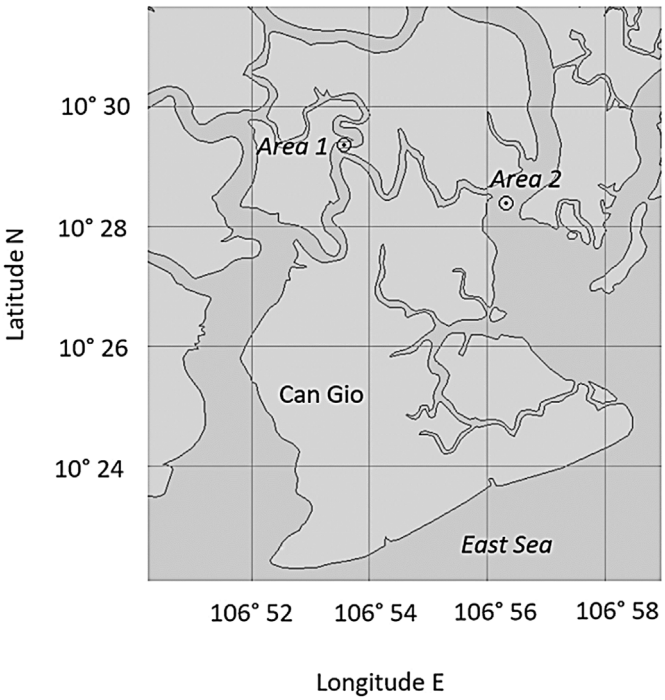

Fig. 1. Location sampling water areas at Ca Gau River and Long Tau River in the buffer zone of Biosphere Reserve Can Gio.

2.2. Method of determination of the dissolved form ^{137}Cs activity concentration in water

Activity concentration of ^{137}Cs in water samples (100 L) was determined by sorption method using two series-connected adsorbers with subsequent measurement of ^{137}Cs content via its gamma-emitting daughter radionuclide ^{137m}Ba with an energy of 661.6 keV by NaI(Tl) well-type gamma spectrometer [11]. Water sample taken was first filtered through a polypropylene filter with a nominal pore size of 0.5 μm to remove suspended matter. Then, the filtrate was passed through plastic 10-mL adsorbers filled with a bulk sorbent. This inorganic composite sorbent is a thin film of mixed nickel-potassium ferrocyanide, obtained by a chemical method from water solutions on a carrier, being delignified wood flour. The water filtered was passed through the adsorbers using a peristaltic pump at a rate of 0.07 L min^{-1}. Then the sorbents were sent for gamma-spectrometric measurements. Sorption efficiency was assessed by the difference in activity on the first and second adsorbers [11].

2.3. Method of determination of the ^{137}Cs and ^{40}K activity concentration in suspended mater and bottom sediment

Suspended matter was taken by filtration of water samples on polypropylene filter with a nominal pore size of 0.5 μm. The total mass of the filtered dry suspended matter was determined after vacuum filtration of water, based on the difference in matter concentrations at the inlet and outlet of the filter cartridges and the total volume of filtered water. The breakthrough rate of flow filtration did not exceed 5%.

Concentration of total suspended matter in water was determined by the gravimetric method after vacuum filtration through membrane filters made of nitrocellulose fiber with a pore diameter of 0.45 μm, which were then washed with distilled water to remove salts. After heating at 60 ° C in a drying oven, the membrane filters

Table 1
Location of sampling station, water salinity and suspended matter concentration in water at areas of Ca Gau River (area 1) and Long Tau River (area 2) in Can Gio, where L – high tide, R – low tide.

Sampling station number	Location of sampling station		Salinity±0.01 (psu)	Suspended matter concentration in water (mg L^{-1})
	North Latitude (°)	East Longitude (°)		
1.2 L	10.48825	106.89331	23.54	45.3
1.1 L	10.48859	106.89310	23.54	20.3
1.3 L	10.48758	106.89233	22.89	32.7
1.2 R	10.48822	106.89346	22.57	149.9
1.1 R	10.48841	106.89326	22.46	146.8
1.3 R	10.48770	106.89254	22.44	133.3
2.2 L	10.47263	106.94114	26.07	17.9
2.1 L	10.47134	106.94568	26.49	17.2
2.3 L	10.47557	106.93325	26.73	47.3
2.2 R	10.46809	106.94664	22.67	208.1
2.1 R	10.47114	106.94181	19.95	1001.2
2.3 R	10.47228	106.93646	21.36	406.5

(before and after filtration) were weighed on an analytical balance with an error of 0.0001 g. The relative error in determining the concentration of total suspended matter did not exceed 5%.

After filtration, the polypropylene filters were dried in air and ashed in a muffle furnace with oxygen access at a temperature of 330°C. Then the ash was sent for gamma-spectrometric measurements.

The upper, 5 cm layer of bottom sediments was collected using an acrylic ring with an inner diameter of 58 mm and a height of 5 cm. The obtained samples were dried in a drying oven to constant weight at a temperature of 80°C, crushed, and homogenized in a porcelain mortar. Prepared samples of standard geometry were measured on a gamma-spectrometer.

^{137}Cs activity in bottom sediment samples and suspended matter was determined by ^{137}Cs gamma-emitting daughter radionuclide ^{137m}Ba with energy of 661.6 keV and ^{40}K – by its 1460.8 keV gamma-radiation on a NaI (Tl) gamma-spectrometer.

2.4. Method of determination of the ^{210}Po activity concentration in sediment

Extraction of ^{210}Po from bottom sediment samples was carried out using radiochemical methods according to a known technique [12]. The chemical yield of polonium was 85–90%. The obtained samples were measured using the OctêtêPlus α-spectrometric complex ORTEC-Ametek (USA), based on the laboratory of general radioecology of the Institute of Plant and Animal Ecology, Ural Branch of the Russian Academy of Sciences (Zarechny, Sverdlovsk Region).

Activity concentration of radionuclides in samples was calculated on dry weight of sample. The error in determining activity concentration of radionuclides (1σ) was calculated in accordance with the generally accepted approach [13].

3. Results and discussion

3.1. The ^{137}Cs activity concentration in water

The average value of the activity concentration of ^{137}Cs in the water areas of Ca Gau (area 1) and Long Tau (area 2) in Can Gio was 0.89 and 1.08 Bq m^{-3}, and the range of activity concentration was 0.38–1.49 Bq m^{-3} and 0.73–1.65 Bq m^{-3}, respectively (Table 2). The main sources of man-made radionuclides, including ^{137}Cs, in the East Sea were global fallouts after nuclear weapons tests in open environments in the 20th century, and also, probably to a very small extent, the accident at the Fukushima nuclear power plant [2,10,14]. According to monitoring studies in March–April 2011, during the period of emissions after the accident at the Fukushima nuclear power plant in Ho Chi Minh City, the maximum air activity concentration for ^{137}Cs was 37×10^{-6} Bq m^{-3} due to exponential decrease in the activity concentration of ^{137}Cs with increasing distance from the epicenter of the accident for Ho Chi Minh City was about 4500 km [2]. Also, attempts to take into account effect of transboundary transfers on the transfer of activity by a radioactive cloud based on global circulation model [15] have shown that effect of these processes at low latitudes is very insignificant. According to the literature data, in the East Sea in the modern period, the activity concentration of ^{137}Cs in the surface water layer, depending on the region, is in the range from 0.43 to 3.60 Bq m^{-3}, but in general in the waters of the East Sea off the coast of Vietnam it is about 1.25–1.58 Bq m^{-3} [16–19]. Therefore, it is obvious that the values of ^{137}Cs activity concentration found by us in the Ca Gau and Long Tau rivers were comparable with those for the East Sea. This suggests that the levels of ^{137}Cs activity concentration observed in the rivers are associated with the inflow of waters from the East Sea into the rivers during high tides. However, Table 2 shows that at low tide, higher activity concentration of ^{137}Cs were observed in water and sediment. During tide, the water level difference was significant. During the period of observation in the river Ca Gau in the central part of the riverbed, the water height varied from 4.5 m to 9.0 m, and in the river Long Tau – from 28.8 to 34.5 m. With such a drop in the tidal level, the existing upper layer of bottom sediments is regularly resuspension and re-settles, and additional portions of suspended matter come from the sea (at high tide) and from the upper reaches of the river (at low tide). It is also necessary to take into account the difference in salinity (see Table 1) and the change sorption ability of suspended matter in relation to cesium. Such conditions, probably, lead to regular cyclic sorption of cesium on suspended matter with subsequent supply into bottom sediments and then to resuspension and desorption into a dissolved form. Based on the above, it is impossible to unequivocally rule out an additional source of ^{137}Cs inflow - with terrigenous runoff from the upper reaches of the rivers. Further research is needed to resolve this issue.

By the beginning of 2000, the ^{137}Cs activity concentration in surface waters in the Equatorial Pacific was 1.3 ± 0.3 Bq m^{-3} on average [1]. The literature data [16–19] and our results for surface waters of the Can Gio rivers were close values and indicate a stable radioecological situation in surface waters of this region for last 2 decades.

The levels of ^{137}Cs activity concentration that were determined in the course of our studies in the water of the Can Gio rivers were an order of magnitude lower than those levels in water areas subjected to significant technogenic radioactive impact. So, for

Table 2
^{137}Cs, ^{40}K, ^{210}Po activity concentration in bottom sediment (suspended matter), dry weight, d. w., and ^{137}Cs activity concentration in surface water from Ca Gau River (area 1) and Long Tau River (area 2) in Can Gio, where L – high tide, R – low tide.

Area number	Station number	Activity concentration in bottom sediments (suspended matter) (Bq kg^{-1} d. w.)			Activity concentration in water (Bq m^{-3})
		^{137}Cs	^{40}K	^{210}Po	^{137}Cs
1	1.1 L	0.71 ± 0.18	651 ± 39	20.8 ± 1.6	0.81 ± 0.07
	1.1 R	<BDL[a]	586 ± 41	13.4 ± 1.1	-
	1.2 L	<BDL[a]	597 ± 30	18.0 ± 1.5	0.38 ± 0.04
	1.2 R	6.55 ± 0.78	604 ± 42	17.8 ± 1.6	1.49 ± 0.13
	1.3 L	2.70 ± 0.51	607 ± 36	25.5 ± 2.1	-
	1.3 R	3.42 ± 0.48	507 ± 30	14.9 ± 1.6	-
Average		2.23 ± 0.81 (2.83 ± 0.23)	592 ± 90 (437 ± 26)	18.4 ± 1.6	0.89 ± 0.14
2	2.1 L	4.13 ± 0.70	475 ± 33	9.4 ± 1.0	-
	2.2 L	-	-	-	0.85 ± 0.07
	2.1 R	6.34 ± 0.95	504 ± 35	10.0 ± 1.1	0.73 ± 0.04
	2.2 R	-	-	-	1.65 ± 0.17
	2.3 L	2.96 ± 0.56	467 ± 42	9.2 ± 1.2	-
	2.3 R	1.09 ± 0.18	473 ± 33	12.1 ± 1.1	-
Average		3.63 ± 1.24 (0.27 ± 0.02)	480 ± 72 (64 ± 5)	10.2 ± 1.1	1.08 ± 0.15

- no data.
[a] Below the detection limit, ~0.1 Bq kg^{-1}

example, in the Baltic Sea, the ^{137}Cs activity concentration for surface waters in 2017 was at least 28.49 ± 1.30 Bq m^{-3} [14], for the Black Sea which was affected by the nuclear accident at the Chernobyl NPP ranged from 13.8 ± 0.57 to 15.6 ± 0.68 Bq m^{-3} [20].

3.2. The ^{137}Cs activity concentration in bottom sediments

In surface layer of 0–5 cm of bottom sediments, the ^{137}Cs activity concentration ranged from less than 0.1 Bq kg^{-1} (i.e., below the detection limit) to 6.55 Bq kg^{-1} (Table 2). For area 1, the average ^{137}Cs activity concentration was 2.23 Bq kg^{-1}, for area 2 it was 3.63 Bq kg^{-1}. As noted above, the highest content of ^{137}Cs in bottom sediments (about 6 Bq kg^{-1}) was recorded for both regions at low tide levels. This may indicate the influx of additional amounts of ^{137}Cs with particulate matter runoff from the upper reaches of the rivers.

The levels of activity concentration of this radioisotope in bottom sediments observed in the study areas can be characterized as low. So, the areas of the Ca Gau and Long Tau rivers can be attributed to regions with an insignificant level of contamination by technogenic radionuclides. For comparison, for example, in such a clean region of the world in terms of anthropogenic radioactive contamination as the Antarctic, the ^{137}Cs activity concentration in bottom sediments reached 7.09 Bq kg^{-1} [21]. Whereas in the Black Sea, which was subject to pollution not only by global radioactive fallout, but also by radionuclides of Chernobyl origin, the ^{137}Cs activity concentration was an order of magnitude higher in current period and reached an average of 95.5 ± 8.9 Bq kg^{-1} in coastal areas [22].

3.3. The ^{210}Po activity concentration in bottom sediments

The results of determining the ^{210}Po activity concentration in bottom sediments are presented in Table 2. The ^{210}Po activity concentrations in the bottom sediments of the study area were relatively low and varied within a fairly wide range from 9.2 to 25.5 Bq kg^{-1}. A comparison of our results with data (very limited) available in the literature showed that, in general, they correspond to the values noted for river sediments. In particular, for bottom sediments of the Kaveri River (India), the activity concentration of ^{210}Po was 14.4–26.5 Bq kg^{-1} [23]. It is noted that a significant impact on the arrival of ^{210}Po into river systems is influenced by local sources, where, as a result of anthropogenic activity, the arrival of ^{210}Po into the environment increases. The results of previous studies have shown that in areas associated with the extraction and processing of uranium ores, the McArthur River bottom sediments (Saskatchewan, Canada) contained from 50 to 240 Bq kg^{-1} ^{210}Po [24,25]. The background values of the ^{210}Po activity concentration in the bottom sediments of the Ca Gau and Long Tau rivers indicated the absence of anthropogenic increase in the ^{210}Po input into the Can Gio river systems.

3.4. The ^{40}K activity concentration in bottom sediments and sediment inventory of three radionuclides and assessment of radiation protection

The ^{40}K activity concentration at area 1 ranged from 507 to 651 Bq kg^{-1}, at area 2 it varied from 467 to 504 Bq kg^{-1} (Table 2). The mean values were of 592 and 480 Bq kg^{-1}, respectively. Potassium is a fairly common chemical element in the earth's crust (7th most abundant) with an average concentration of about 25 gK kg^{-1} [7]. This element consists of a mixture of three isotopes, two stable – ^{39}K and ^{41}K and one radioactive – ^{40}K. The ^{40}K half-life is about 1.2 billion years. With this isotope, the activity of 1 g of natural potassium is 30.65 Bq. Based on this ratio, we can recalculate our data on the activity of ^{40}K in bottom sediments into the concentration of the chemical element potassium in bottom sediments, which was 19 and 15 gK kg^{-1}, respectively, in water areas 1 and 2. These values are typical for the potassium concentration in the bottom sediments of coastal water bodies, which are significantly affected by lithogenic component [26].

Based on the data on the ^{137}Cs, ^{40}K and ^{210}Po activity concentration in bottom sediments, their sediment inventories for surface layer 0–5 cm were calculated (Fig. 2).

According to the national recommendation documents [27], developed in accordance with international documents on the radiation protection of living organisms [28,29], control (reference) levels of concentration activity of radionuclides for bottom sediments of marine aquatic ecosystems have been accepted. Control levels serve as criteria for assessing the radiation situation for operational monitoring, analysis of the radiation situation in a water body in order to identify its changes under the influence of

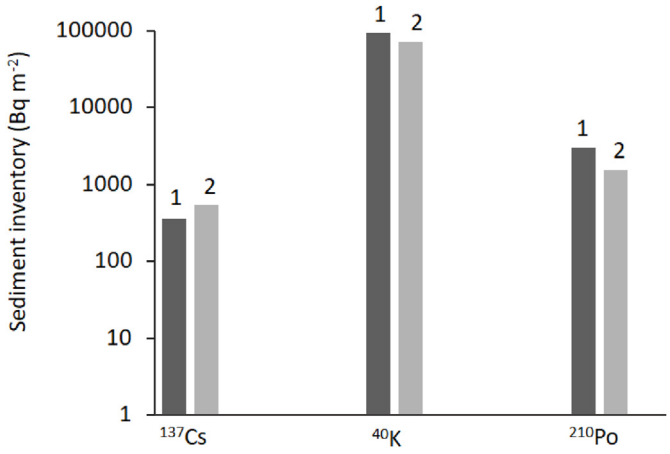

Fig. 2. Inventories of anthropogenic and natural radionuclides in upper 0–5 cm layer of bottom sediment, where 1 – area of Ca Gau River and 2 – area of Long Tau River.

natural and anthropogenic factors, ensure environmental protection and preserve a favorable natural environment. Control levels of radioisotopes were determined in marine bottom sediments separately according to radiation, radiation-hygienic and ecological criteria or according to the final control level, which includes the three criteria listed above. Radiation criterion is a concentration activity that not exceed of the lowest level of concentration activity characteristic of radioactive waste. The radiation-hygienic criterion ensures that the allowable dose quota from the consumption of seafood is not exceeded [30]. The ecological criterion is based on the value of the criterion of the maximum permissible radiation environmental impact on objects of marine aquatic biota: for marine aquatic vertebrates dose rate (Pmax) equal to 1.0 mGy per day; for marine aquatic invertebrates and marine aquatic plants Pmax equal to 10 mGy per day [29; 27]. The final criterion focuses on the lowest concentration activity of a radioisotope in bottom sediments among the three criteria and thus aims to protect the environment, non-human biota and humans. The obtained results of ^{137}Cs, ^{40}K and ^{210}Po concentration activity and values of their control levels in bottom sediments are given in Table 3.

Comparison of the obtained results with the control levels showed that the radiological situation in the water areas of the rivers remains favorable in relation to all three studied radionuclides. The obtained values of the concentration of radioisotope activities can serve as a background level in the study of the radiation situation or its changes in the case of radiation incidents.

3.5. The activity concentration of ^{137}Cs and ^{40}K on suspended matter

The activity concentration of ^{137}Cs and ^{40}K on suspended matter was determined in total samples for each area. The ^{137}Cs activity concentration in water areas 1 and 2 was 2.83 ± 0.23 and 0.27 ± 0.02 Bq kg^{-1}, and the ^{40}K activity concentration was 437 ± 26 and 64 ± 5 Bq kg^{-1}, respectively.

Attention is notice to the difference in the distribution of these radionuclides between the stations in bottom sediments and suspended matter. In the water area of the river Ca Gau, both in suspended matter and in bottom sediments, values of the ^{40}K activity concentration were higher, than in the water area of the river Long Tau that is associated with the biogeochemical features of this element.

The lower levels of the ^{40}K activity concentration water area 2 are obviously associated with a more significant contribution of biogenic matter, due to the location of this station at the sea outlet. It is known that the content of ^{40}K on biogenic matter is much lower than on lithogenic matter and is about 3 gK kg^{-1} [7,26,31–34]. It is also known that in the coastal areas of the seas of Southeast Asia, including the East Sea, plankton concentrations are high and these seas are characterized by high bioproductivity [35,36]. In this regard, the lower ^{40}K activity concentration in bottom sediments and suspended matter in the water area of the Long Tau River can be explained by a higher contribution of nutrients in these components. This, in turn, entails a lower content of the chemical element potassium in them, and, consequently, a lower level of the ^{40}K activity concentration in bottom sediments and suspended matter of the Long Tau River water area, as the water area directly adjacent to the sea waters.

Cesium is a chemical analogue of potassium, and therefore the difference in the distribution of ^{137}Cs in particulate matter between stations is due to the same biogeochemical reasons. It is known that ^{137}Cs accumulates to a greater extent on fine-grained lithogenic matter, which is associated with the presence of clay minerals in it [37,38]. On the other hand, the organic components of biogenic suspended matter are mostly non-polar in nature and substances that are in ionic form, such as cesium, accumulate to a lesser extent [39,40].

At the same time, in the water area of the Ca Gau, the ^{40}K activity concentration in bottom sediments exceeded that in the water area of the river Long Tau by about 1.2 times, while in the case of suspended matter – already more than 6. This can be explained by the fact that the concentration and composition of suspended matter is determined by more dynamic and variable conditions of the aquatic environment, while a 0–5 cm layer of bottom sediments forms for a long time and reflects the average long-term dynamics of processes in the water area. Taking into account the uncertainty, difference in the average ^{40}K activity concentration in the bottom sediments of water areas 1 and 2 was small, and in the case of ^{137}Cs, it was not significant (Table 2). The regular influx of suspended matter with river runoff and in the opposite direction with the sea tide obviously leads to resuspension and mixing of the material of the surface layer of bottom sediments with the sedimentary matter of bottom waters. And this leads to equalize the differences in the average activity concentration of ^{40}K and ^{137}Cs between the stations of the two studied water areas.

Table 3
Concentration activity of radionuclides in bottom sediment (wet weight, w. w.) in investigated areas of rivers and control levels of concentration activity for bottom sediments.

Radionuclide	Concentration activity of bottom sediment (Bq·kg^{-1} w.w.)		Control level of concentration activity (Bq·kg^{-1} w.w.)			
			Ecological criterion	Radiation-hygienic criterion	radiation criterion	Final criterion
	Station 1	Station 2				
^{137}Cs	0.95	1.54	7.2 x 10^5	1.5 x 10^3	1.0 x 10^4	1.5 x 10^3
^{40}K	2.5 x 10^2	2.0 x 10^2	1.5 x 10^7	9.7 x 10^3	1.0 x 10^5	9.7 x 10^3
^{210}Po	7.8	4.3	1.3 x 10^5	2.1 x 10^2	1.0 x 10^4	2.1 x 10^2

3.6. Accumulation ability of bottom sediments and suspended matter of rivers in relation to ^{137}Cs

To quantify accumulation ability of bottom sediments and suspended matter of rivers in relation to ^{137}Cs, the concentration factor of ^{137}Cs (CFs (^{137}Cs)) were calculated. Based on the average values of the ^{137}Cs activity concentration in water and in bottom sediments at area 1, CFs (^{137}Cs) by bottom sediments was 2.5×10^3, and at area 2 it was 3.4×10^3. According to the generalized data for marine areas presented by the IAEA, value of the ^{137}Cs concentration factor in bottom sediments ranged from $n \times 10^3$ to $n \times 10^4$ [37]. The CFs (^{137}Cs) values obtained by bottom sediments in the water areas of the Can Gio Rivers fit into the reported range of values, which is obviously associated with a high level of water salinity in these rivers. Salinity in them varied from 19.95 to 26.07 psu (Table 1) and indicated that these rivers belong to saline water ecosystems.

The concentration factor of ^{137}Cs by suspended matter in water area 1 was 3.2×10^3, in water area 2–250. Cs is a geochemical analogue of K and, like it, mainly accumulates on lithogenic matter; therefore, seawaters could have a greater effect on the accumulation ability of suspended matter due to the above reasons. In addition, according to the literature data, the concentration factors of ^{137}Cs by biota and, in general, by biogenic matter are lower than by lithogenic matter and are about $n \times 10^2$ [41]. In any case, the issue of studying accumulation capacity of different components of aquatic ecosystems in the Can Gio Rivers and the processes that affect the levels of accumulation of substances of both natural and technogenic origin requires further research.

4. Conclusion

Thus, it can be concluded that the studied water area of the Can Gio Reserve is one of the least polluted regions with technogenic ^{137}Cs.

With regard to natural radionuclides ^{210}Po and ^{40}K, the radioecological situation was also favorable. The ^{40}K levels were one order of magnitude and these of ^{210}Po were two orders of magnitude lower than the control levels for these radionuclides in bottom sediments. The ^{210}Po concentration activity was low and corresponded to that in river bottom sediments not subject to significant anthropogenic impact. The ^{40}K concentration activity levels of corresponded to coastal regions subject, on the one hand, to the river runoff of significant amounts of lithogenic matter, and, on the other hand sea waters, characterized by increased trophicity and biological productivity.

The ^{137}Cs concentration factor by bottom sediments in Can Gio Rivers was quite high and varied within $2.5–3.4 \times 10^3$.

The sediment inventories of anthropogenic ^{137}Cs and natural radionuclides ^{210}Po and ^{40}K in upper 0–5 cm layer of bottom sediment in Ca Gau River were 357 ± 130, 2946 ± 324, 94780 ± 14405 and in Long Tau River − 543 ± 185, 1525 ± 183 and 71762 ± 10836 Bq m^{-2}, respectively.

The studied water areas of Can Gio Reserve can serve as comparison background area for studying the consequences of possible future nuclear incidents.

Declaration of competing 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.

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