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Original Article

Influence of operation of thermal and fast reactors of the Beloyarsk NPP on the radioecological situation in the cooling pond: Part II, Macrophytes and fish

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ABSTRACT

The influence of waste technological waters of thermal and fast reactors of Beloyarsk NPP (Russia) on the accumulation of ^{60}Co, ^{90}Sr and ^{137}Cs in macrophytes and ichthyofauna of the cooling pond has been studied. Critical radionuclides, routes of their entry into the ecosystem and periods of maximum discharge of radioisotopes into the cooling pond have been determined. It is shown that the technology of electricity generation at the Beloyarsk NPP, based on fast reactors, has a much smaller effect on the release of artificial radionuclides into the environment. Therefore, during the entire period of monitoring studies (1976–2019), the decrease in the specific activity of radionuclides of NPP origin in macrophytes was 13–25800 times, in ichthyofauna 1.5-44.5 times. The maximum discharge of artificial radionuclides into the Beloyarsk reservoir was noted during the period of restoration and decontamination work aimed at eliminating the emergencies at the AMB reactors of NPP. The factors influencing the accumulation of artificial radionuclides in the components of the freshwater ecosystem of the Beloyarsk cooling pond have been determined, including: the physicochemical nature of radioisotopes, their concentration in surface water, the temperature of the aquatic environment, the trophicity of the reservoir, the species of hydrobionts.

1. Introduction

Prospects for the development of nuclear power are largely determined by resolving a number of radioecological problems: substantiation of the radiation safety of humans and biota during the operation of radiation-hazardous facilities and related releases and discharges of radionuclides into the environment; radioactive waste management; addressing nuclear legacy issues (including decommissioning nuclear installations and disposing of nuclear weapons); elimination of the consequences of radiation accidents and incidents [1–6]. The solution of radioecological problems has acquired particular urgency in recent decades, when the concept of the need for radiation protection of biota, along with ensuring the radiation safety of humans, was formed at the international level [7–12]. Among the radiation hazardous facilities, nuclear power plants (NPPs) are the most potentially dangerous, since in the event of a large-scale radiation accident, the radioecological consequences for humans and the environment can be both transboundary and long-term. Terrestrial (natural and agricultural) and aquatic ecosystems can be exposed to radioactive contamination [13].

Cooling ponds of natural or artificial origin are often used to cool nuclear power plants [14–16]. As a rule, freshwater reservoirs can be used not only for cooling the reactors of a nuclear power plant, but also for other economic purposes: water supply (drinking and technical), fish farming and fishing, irrigation of fields, watering for farm animals, recreational needs, etc. Therefore, it is very important to study accumulation and migration of artificial radionuclides in

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the components of aquatic ecosystems exposed to NPP [17,18]. The implementation of these tasks is impossible without creating a system of radiation and environmental monitoring in the regions where NPP is located, defined by the IAEA as monitoring the content of radionuclides in the environment in order to assess the radiation doses to humans and biota [11,19,20].

The study was carried out in the Ural region of Russia, which is characterized by radionuclide contamination due to nuclear weapons tests at the Novaya Zemlya test site, long-term discharges and accidents at the Mayak Production Association ("Mayak" PA), conducting nuclear explosions for peaceful purposes, mining uranium ore, and the operation of the Beloyarsk NPP [21–23].

Beloyarsk NPP is the only nuclear power plant in Russia with different types of power units. The first two thermal reactors (AMB-100 and AMB-200), launched in 1964 and 1967, were shut down more than 30 years ago and are now at the stage of decommissioning. Reactors # 3 (BN-600 has been operating since 1980) and # 4 (BN-800 was commissioned in 2016) are operating on fast neutrons. The BN-800 power unit with liquid sodium as a coolant is by far the largest fast breeder reactor in the world. To establish a cooling system for reactors and technical water supply NPP in 1959–1963 the Beloyarsk reservoir was created [24]. The objects of research were hydrobionts of the freshwater ecosystem (macrophytes and ichthyofauna) of the cooling reservoir of the Beloyarsk NPP.

The aim of the work was to assess the impact of the operation of thermal and fast reactors of the Beloyarsk NPP on the accumulation of artificial radionuclides in hydrobionts of the cooling pond based on the analysis of the results of long-term (1976–2019) radioecological monitoring of the reservoir.

2. Description of research objects

2.1. Description of Beloyarsk NPP

In the first part of the study [24], the Beloyarsk NPP has been described in detail as a source of artificial radionuclides entering the freshwater ecosystem of the reservoir during normal operation of reactor facilities and deviations from normal operation. The influence of waste technological waters of thermal (AMB-100 and AMB-200) and fast (BN-600 and BN-800) NPP reactors on the content of artificial radionuclides in surface waters and bottom sediments of the Beloyarsk reservoir for the period 1976–2019 has been shown. The long-term dynamics of the specific activity of ^{60}Co, ^{90}Sr, ^{137}Cs and ^{3}H in the main components of the freshwater ecosystem (surface waters and bottom sediments) at different distances from the source of radionuclide discharge have been estimated.

2.2. Description of hydrobionts of the cooling pond of the Beloyarsk NPP

The length of the cooling reservoir of the Beloyarsk NPP is 20 km, the maximum width is 3 km opposite the Beloyarsk NPP [24,25]. The cooling pond is inhabited by 4 species of green algae and 25 species of higher aquatic plants belonging to 18 genera and 16 families [26]. The discharge of warm water from the nuclear power plant into the Warm Bay of the reservoir contributes to an increase in biomass and an extension of the growing season of plants living here, which is used for breeding cultured carp in this zone of the cooling pond [27].

The ichthyofauna of the Beloyarsk reservoir is represented by 8 fish species: roach (*Rutilus rutilus*), bream (*Abramis brama*), tench (*Tinca tinca*), crucian carp (*Carassius carassius*), carp (*Cyprinus carpio*), pike (*Esox lucius*), perch (*Perca fluviatilis*) and pike perch (*Sander lucioperca*) [28].

3. Material and methods

3.1. Sites description

The radioecological monitoring network of the Beloyarsk Reservoir includes 6 control sites (Table 1), which make it possible to give a comprehensive description of the radionuclide content in hydrobionts of the freshwater ecosystem and take into account the influence of the nuclear power plant [24].

3.2. Sampling of freshwater components

The sampling of the components of the freshwater ecosystem, sample preparation and measurement of the content of radionuclides in them were carried out in accordance with the regulatory and methodological documents in force in Russia [29–32]. Samples were taken in two or three replicates in the summer-autumn period of the year [33].

Macrophytes were sampled 3–5 kg of wet weight for replication. The plants were washed from bottom sediments, weighed and dried to an air-dry state, after which they were ashed at $t = 450$ °C in a muffle furnace.

Fish of about the same age (2–3 years) of both sexes were caught with nets. The weight of one sample was 3 kg wet weight. For different fish species, one sample included on average: roach - 30, pike - 3, bream - 4, tench - 22, crucian carp - 20, carp - 5 specimens. Fish carcasses (without internal organs) were dried and ashed at $t = 450$ °C.

3.3. Measurements

In aquatic organisms, γ-emitting radionuclides were determined by instrumental methods. The measurements were carried out on a low-background semiconductor gamma-spectrometer of Ortec (USA) with a coaxial detector system based on high-purity germanium (HPGe) and a gamma-spectrometer of Canberra Packard (USA) with a germanium semiconductor detector with a measurement error of no more than 15% and the lower limit of detection is 1 Bq/kg.

The method for the determination of ^{90}Sr is based on the leaching of the radionuclide with 6 N hydrochloric acid, the isolation of ^{90}Sr in the form of oxalates, the separation of ^{90}Y from ^{90}Sr, and the radiometric measurement of the obtained preparations. The chemically pure precipitate of strontium oxalate was dried, calcined, weighed, and β-activity was measured on a low-background device UMF-2000 (Russia) with a lower detection limit of 0.4 Bq/kg and a statistical measurement error of no more than 10%.

The quantitative content of radionuclides in macrophytes was calculated on a dry weight, and for fish - on a wet weight, as is customary in the scientific literature.

3.4. Data analysis

Radioecological monitoring of the cooling pond was carried out in the most detail in 1976–1988 and in 2002–2019. In this study, 275 statistically processed results of measurements of the content of radionuclides in aquatic organisms were analyzed, including:

- macrophytes - 119 measurements (^{60}Co - 29%, ^{90}Sr - 26%, ^{137}Cs - 45%);

Table 1
Description of the radioecological monitoring network of the cooling pond of the Beloyarsk NPP.

Site	Place of sampling	Coordinates	Source of radionuclide intake
S1	The upper reaches of the reservoir (15 km from the NPP)	N° 56.936 E° 61.145	Monitoring the background content of radionuclides in the cooling pond
S2	Pike Bay (8 km from the NPP)	N° 56.900 E° 61.262	Intermediate point between the background and the zone of close-range control of the NPP
S3	Biophysical Station Area	N° 56.849 E° 61.308	Beloyarsk NPP Bypass Canal
S4	Industrial Water Canal of NPP	N° 56.841 E° 61.310	Industrial sites of the Beloyarsk NPP and JSC "Institute of Reactor Materials"
S5	Warm Bay	N° 56.828 E° 61.312	Reactors AMB-100, AMB-200, BN-600
S6	Dam part of the reservoir	N° 56.792 E° 61.302	Radionuclide integral discharge from the Beloyarsk NPP into the river system

- ichthyofauna - 156 measurements (^{60}Co - 8%, ^{90}Sr - 30%, ^{137}Cs - 62%).

The reliability of the results was achieved by parallel selection and examination of all samples in 2–3 replicates. Statistical processing of the data obtained was to determine the arithmetic mean and standard deviation of the arithmetic mean. The measurement results were processed using the *t*-criterion and other generally accepted methods and were considered reliable at $p < 0.05$. They were verified with the data of the radiation monitoring of Roshydromet carried out at the cooling pond of the Beloyarsk NPP [25]. The results of the monitoring data analysis are presented in the form of the dynamics of the content of radionuclides in macrophytes separately for each sampling site [34]. Due to the migration of fish (with the exception of cultured carp in Warm Bay), it is possible to identify the degree of influence of the Beloyarsk NPP on the content of radionuclides in it, depending on the place of catch, with a sufficient degree of approximation. Therefore, for fish, materials are presented according to the type of each species.

Taking into account that during the operation of the Beloyarsk NPP, reactors of various types were operated, the analysis of the results identified six periods of the plant's impact on the freshwater ecosystem of the cooling pond: I – 3, II – 13, III – 2, IV – 8, V – 26 and VI – 4 years (Fig. 1).

The proposed approach made it possible to take into account the territorial features of the accumulation of radionuclides in the components of the freshwater ecosystem at different distances from the pollution source and to assess the impact of the operation of different types of reactors on the radioecological state of the cooling pond of the Beloyarsk NPP.

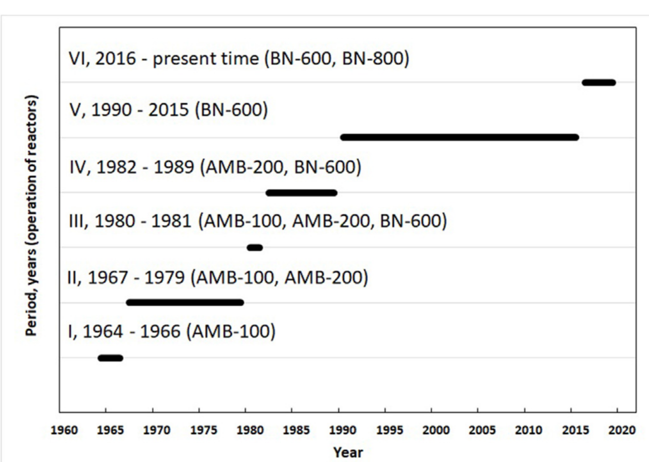

Fig. 1. Description of the study periods of radioecological conditions of the Beloyarsk NPP cooling pond.

4. Results and discussion

4.1. Dynamics of radionuclide specific activity in macrophytes

Water plants is the most important component of the freshwater ecosystem, which produces the bulk of the biomass of the reservoir and adsorbs radionuclides from the aquatic environment. Particularly high accumulators of radionuclides are macrophytes that float on the surface of the water or are completely submerged in its thickness. The concentration of radioisotopes in macrophytes can significantly exceed their content in water and remain at high levels for a long time. The degree of accumulation and a high retention of radionuclides in water plants is influenced by a number of factors: the chemical nature of radioisotopes, the physicochemical form of their presence in the freshwater ecosystem, biological characteristics of plants, the concentration of isotopic and non-isotopic carriers in water, water temperature, illumination, trophicity of the reservoir, season of the year and etc. [18,28].

Out of the 25 species of higher water plants inhabiting the cooling pond of the Beloyarsk NPP for the purposes of radioecological monitoring, in this study, we selected the two most common species of macrophytes: Canadian elodea (*Elodea canadensis*) and dark green hornwort (*Ceratophyllum demersum*). The results of many years of research on the content of ^{60}Co, ^{90}Sr and ^{137}Cs in test species of macrophytes are presented in Figs. 2 and 3, respectively.

4.1.1. Radiocobalt in macrophytes

Monitoring of ^{60}Co accumulation in macrophytes of the Beloyarsk reservoir showed that the maximum content of the radionuclide in 1976 was observed in plants inhabiting the Warm Bay (S5). Here, the specific activity of ^{60}Co was 20 thousand and 10 thousand Bq/kg dry weight of plants for hornwort and elodea, respectively (Fig. 2-A and Fig. 3-A). The high levels of radiocobalt accumulation in the macrophytes of this part of the reservoir, as in the case of bottom sediments, were significantly influenced by the emergency situation at the AMB-200 reactor in 1976, as well as by the temperature factor [24]. In the warm waters of the Warm Bay, the physiological processes of development of macrophytes are more intensive, which determines the high adsorption of the radionuclide in their biomass. The temperature factor is confirmed by comparing the content of ^{60}Co in the elodea of the Warm Bay (S5) and the Bypass Canal in the area of the Biophysical Station (S3). In 1976, the concentration of radionuclide in surface water in both parts of the reservoir was similar and amounted to 0.8–1.1 Bq/L [24], and the ^{60}Co content in the elodea of the Bypass Canal was 2.1

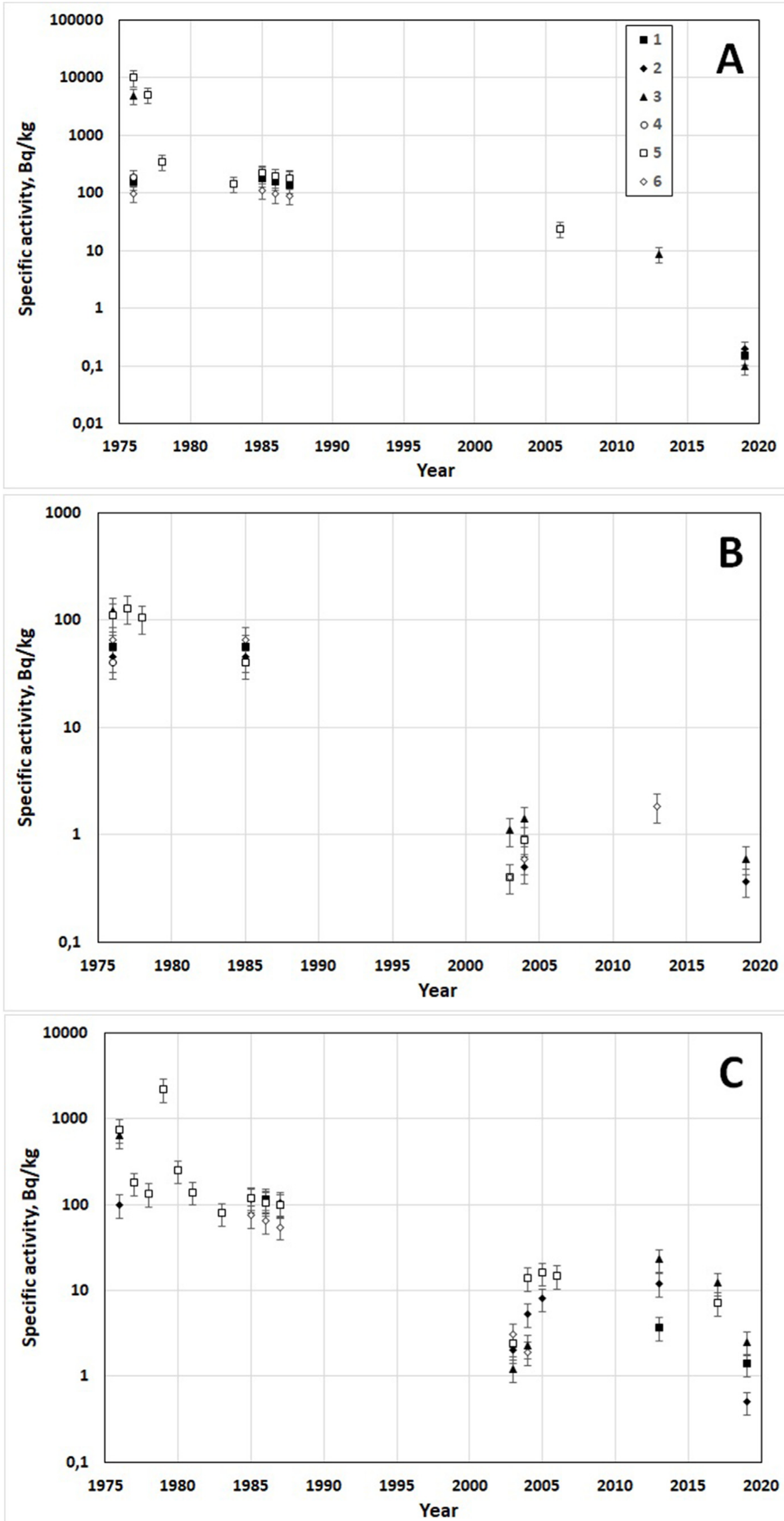

Fig. 2. Dynamics of radionuclides specific activity: A – ^{60}Co, B – ^{90}Sr, C – ^{137}Cs in elodea of the control sites of the Beloyarsk NPP cooling pond (1 – S1, 2 – S2, 3 – S3, 4 – S4, 5 – S5, 6 – S6).

times lower (4.85 thousand Bq/kg) in comparison with macrophytes of the Warm Bay. In other parts of the reservoir, the ^{60}Co content in macrophytes was in the range of 60–190 Bq/kg dry weight, and it was minimal in the Upper (S1) and Dam (S6) parts of the reservoir. In elodea, the accumulation of radionuclide was, on average, 30–40% higher than in hornwort in identical sampling sites, which is determined by the species characteristics of plants. It should be noted that elodea and hornwort belong to the same ecological group (aquatic plants). They are completely submerged in water and have a large absorbent surface. Therefore, accumulation of radionuclides in them are maximum and do not differ significantly. In another ecological group of water plants (coastal-aquatic), most of their stems and leaves are in the air and accumulation of radionuclides in several times lower than in the group of aquatic plants. To date, the specific activity of ^{60}Co in the macrophytes of the Beloyarsk reservoir is extremely low and amounts to 0.1–0.2 Bq/kg dry weight of plants.

4.1.2. Radiostrontium in macrophytes

During the initial period of monitoring studies of the Beloyarsk reservoir, ^{90}Sr was measured only in elodea (Fig. 2-B). The maximum levels of radionuclide accumulation are recorded in this type of macrophytes of the Bypass Canal in the area of the Biophysical Station (S3) - 122 Bq/kg and in Warm Bay (S5) - 110 Bq/kg, which correlates with the radionuclide content in water: 0.5 and 0.08 Bq/L, respectively [24]. Despite the lower specific activity of ^{90}Sr in the water of the Warm Bay, the temperature factor practically leveled the accumulation of radionuclide in the elodea of this area with a similar indicator in macrophytes of the Bypass Canal. In both parts of the cooling pond, the ^{90}Sr content in macrophytes was up to two times higher than in the upper reaches of the reservoir (S1), where it was 56 Bq/kg, and in the Dam part (S6), where it was slightly higher than - 65 Bq/kg. To date, the content of the radionuclide in the macrophytes of the Beloyarsk reservoir has decreased by more than 10 times. It is higher in hornwort, and to a lesser extent ^{90}Sr accumulates in elodea.

4.1.3. Radiocaesium in macrophytes

The patterns of ^{137}Cs accumulation by macrophytes of the Beloyarsk Reservoir were similar to ^{60}Co. Thus, the maximum levels of specific activity of ^{137}Cs in elodea and hornwort were observed in the warm waters of the Warm Bay (S5), amounting to 2200 Bq/kg and 1520 Bq/kg, respectively (Fig. 2-C and Fig. 3-C). Such high rates were noted in 1977–1979 during the period of recovery work after emergencies at the reactors of the first stage of the Beloyarsk NPP [24]. Compared to the control area of the Upper Reservoir (S1), they were 15–20 times higher. By 1980, the situation had stabilized, and in the waters of the Warm Bay, the ^{137}Cs content in macrophytes did not differ significantly from the analogous indicator typical for other parts of the cooling pond. In recent years, the specific activity of ^{137}Cs in elodea has varied from 0.5 to 12.5 Bq/kg dry weight, and in hornwort, in the range of 10.8–33.5 Bq/kg, which is determined by the species characteristics and the place of plant selection.

Analysis of the data allows us to conclude that the accumulation of artificial radionuclides in macrophytes of the Beloyarsk reservoir was influenced by the operating mode of the nuclear power plant and the increased discharge of radioisotopes into the reservoir associated with emergency situations in the 70s, the temperature factor, as well as the specific features of water plants. Thus, in the initial period of operation of the first stage NPP (AMB-100 and AMB-200 reactors), ^{60}Co was characterized by the highest degree of accumulation in macrophytes. At present, the radioecological role of this radionuclide has significantly decreased and ^{137}Cs has come to the fore.

4.2. Dynamics of radionuclide specific activity in ichthyofauna

The study of the accumulation of artificial radionuclides in the ichthyofauna of the cooling pond of the NPP is very important, since fish are both an important link in the food chain of a freshwater ecosystem and a human foodstuff that influences the formation of the internal exposure dose [28,35]. In the Beloyarsk reservoir in the warmed waters of the Warm Bay, a fish farm has been operating for many years breeding cultured carp. In addition, industrial and amateur fishing is carried out in the reservoir. Monitoring of the content of radionuclides in the ichthyofauna of the cooling pond of the Beloyarsk NPP was more focused on assessing the content of ^{137}Cs. ^{60}Co was reliably determined in the first years of observations (1977–1985) ^{90}Sr was measured mainly in recent years (Fig. 4).

4.2.1. Radiocobalt in ichthyofauna

In 1977, the maximum levels of ^{60}Co in fish were noted in bream (14.4 Bq/kg wet weight) and crucian carp (11.8 Bq/kg), and the lowest in tench (2.1 Bq/kg). However, in general, the data range of radionuclide content in the ichthyofauna was small (Fig. 4-A). During the observation period (1977–1985), the content of ^{60}Co decreased by 8.4 times in roach, and 8.0 times in bream. Further measurements of the ^{60}Co content in the ichthyofauna were not carried out due to the low concentration of the radionuclide in surface water and fish. In general, we can say that radiocobalt is accumulated by fish rather weakly, compared to ^{137}Cs. The difference in the accumulation of these radionuclides is 3.5–9.3 times, depending on the type of fish.

4.2.2. Radiostrontium in ichthyofauna

The ^{90}Sr content levels in the ichthyofauna were characterized by low variability during the entire observation period. So, in 1977 they fluctuated in the range of 2.1–4.5 Bq/kg, in 1994 they slightly increased to 4.6–8.3 Bq/kg (Fig. 4-B). By 2003, they were 0.3–6.2 Bq/kg and are currently in the range of 0.1–4.4 Bq/kg. Among the considered fish species, the maximum accumulation of ^{90}Sr has been found in pike, bream, and roach, and the minimum in cage carp. The difference between the radionuclide content in cage and free-living carp is up to 8-10 times, which is mainly determined by artificial feed for fish breeding, where there are no technogenic radionuclides. In general, during the period of monitoring studies, the decrease in the ^{90}Sr content in the ichthyofauna of the Beloyarsk reservoir was 1.4–2.9 times, depending on the fish species, which is even less compared to ^{60}Co. This suggests that the patterns of ^{90}Sr accumulation in fish were determined in the Beloyarsk reservoir to a greater extent by global fallouts of radionuclide and, to a lesser extent, by discharges of the nuclear power plant.

4.2.3. Radiocaesium in ichthyofauna

Among the studied radionuclides, ^{137}Cs accumulates to the greatest extent in the ichthyofauna of the cooling pond of the Beloyarsk NPP. So, in 1977, the average content of ^{60}Co in fish was 8.8 Bq/kg, ^{90}Sr - 3.4 Bq/kg, and ^{137}Cs was already 68.5 Bq/kg (Fig. 4-C). This ratio between the specific activities of ^{90}Sr and ^{137}Cs in fish remained until the mid-2000s. In recent years, the content of these radionuclides in fish has leveled off. Among the studied ichthyofauna species, the pike, which is a carnivorous species, accumulates more ^{137}Cs than other fish with a mixed diet or phytophages. Wild carp, other things being equal, accumulate ^{137}Cs less than roach. The specific activity of ^{137}Cs in cultured carp, which is grown in the warm waters of the Beloyarsk reservoir using artificial food, turned out to be lower than all the considered ichthyofauna species. This is due to the way of feeding, as well as the biological characteristics of

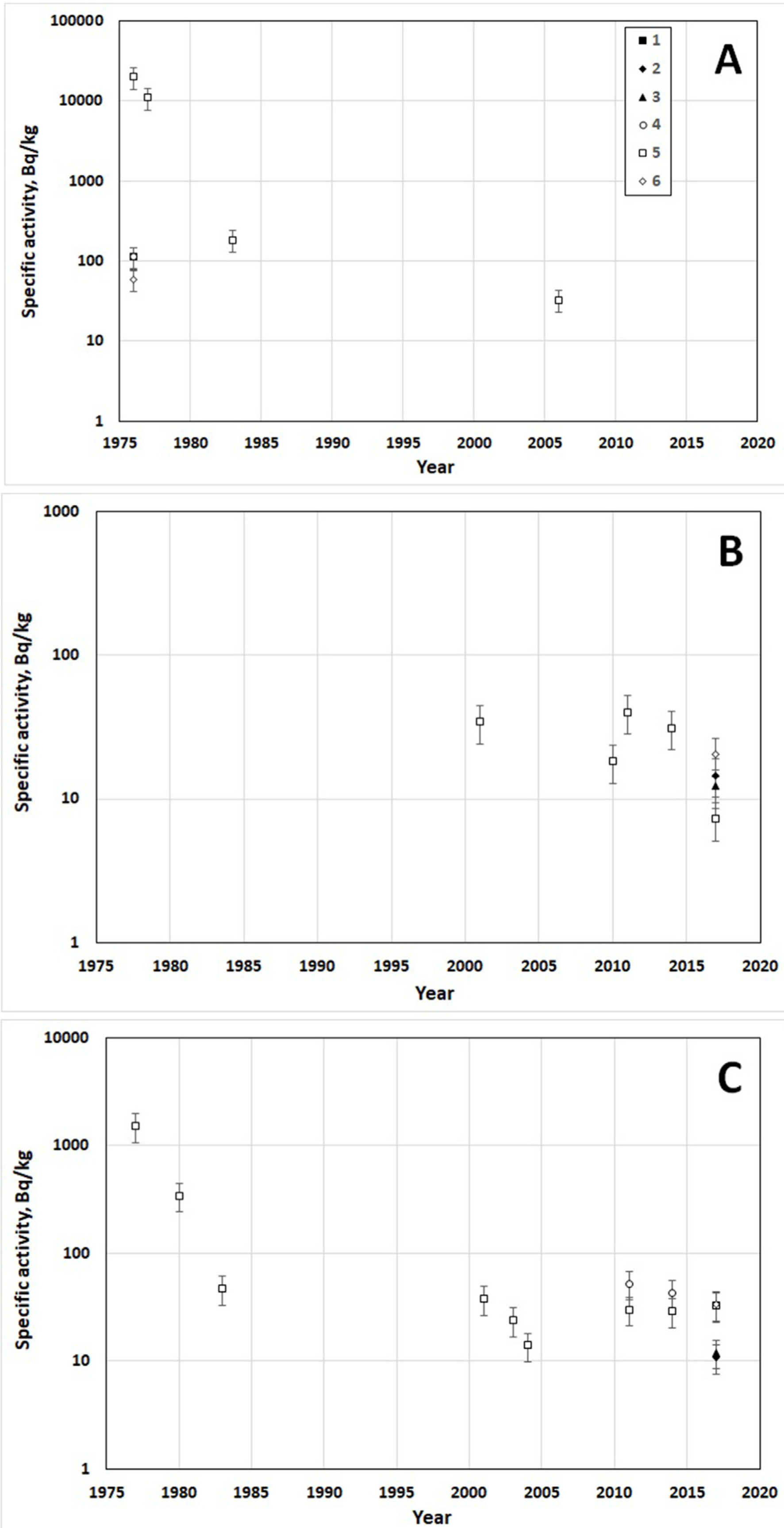

Fig. 3. Dynamics of radionuclides specific activity: A – ^{60}Co, B – ^{90}Sr, C – ^{137}Cs in hornwort of the control sites of the Beloyarsk NPP cooling pond (1 – S1, 2 – S2, 3 – S3, 4 – S4, 5 – S5, 6 – S6).

this type of fish. Cultured carp feeds on artificial food that does not contain ^{137}Cs, and species freely living in the reservoir use food enriched with radionuclide. Thus, the main route of ^{137}Cs entry into the fish organism is the food channel. Based on the data averaged over the entire observation period on the accumulation of ^{137}Cs by fish species inhabiting the cooling pond of the Beloyarsk NPP, they can be arranged in the following order: pike (average content 49.2 Bq/kg) > roach (45.1) > tench (29.3) > crucian carp (24.4) > bream (20.6) > wild carp (19.8) > perch (6.4) > cultured carp (3.8 Bq/kg). In terms of the degree of decrease in the ^{137}Cs content in fish over the entire observation period (1976–2019), the list of fish species will look somewhat different: pike (frequency of decrease 190 times) > roach (86.7) > crucian carp (58.3) > bream (35.7)> tench (35.1) > cultured carp (13.3) > perch (6.4) > wild carp (4.5 times). As for pike perch, due to the small volume of measurements, the results were not sufficiently representative. In general, the presented lists show the specific features of fish species in terms of the degree of ^{137}Cs accumulation and the rate of elimination of the radionuclide from the body.

4.3. Influence of Beloyarsk NPP reactors on the components of the freshwater ecosystem

To assess the impact of the operation of thermal and fast reactors of the Beloyarsk NPP on the accumulation of artificial radionuclides in the components of the freshwater ecosystem of the cooling reservoir of the Beloyarsk NPP, the monitoring results were averaged over the sampling sites and the periods of operation of power units. For such estimates, both the results of this research work on aquatic organisms and the data of previous studies on surface water and bottom sediments of the Beloyarsk reservoir were used [24]. This made it possible to level the extreme values of the content of radionuclides in the components of the freshwater ecosystem in certain years, when there were abnormal and emergency situations at NPPs and to estimate the integral concentration of radioisotopes in the cooling pond (Table 2).

From the data in Table 2, it can be seen that during the considered period of operation of the Beloyarsk NPP, there has been a significant improvement in the radioecological state of the cooling pond. The results obtained in this study and the data of [24] make it possible to formulate a number of important radioecological conclusions characterizing the freshwater ecosystem of the cooling pond in the area of the Beloyarsk nuclear power plant, which is one of the most significant radiation hazardous objects in the Ural region of Russia.

5. Conclusion

1. Increased levels of specific activity of artificial radionuclides (^{3}H, ^{60}Co, ^{90}Sr and ^{137}Cs) in the surface waters of the Beloyarsk reservoir were noted at the points of discharge of process waters of the first stage of the NPP (thermal reactors), mainly through the Industrial Water and Bypass canals, and their peak values coincide with the time of emergency situations at power units AMB-100 and AMB-200 and restoration work carried out at the site of a nuclear power plant in the period 1976–1980.
2. The total decrease in the content of artificial radionuclides in the components of the freshwater ecosystem of the Beloyarsk reservoir for the entire period of monitoring observations (1976–2019) was 4.3–74.5 times in surface waters, 10.1-505 times in bottom sediments (silty sapropel), 13.1-25800 times in macrophytes (elodea, hornwort), 1.3-44.6 times in ichthyofauna (9 fish species) for the studied radionuclides. This has proved the absence of a significant additional input of radioisotopes into the cooling pond after the change in electricity generation technologies due to the transition of the Beloyarsk NPP from thermal to fast reactors and the commissioning of new, higher capacities.
3. The start of operation of the BN-800 power unit in 2016 did not affect the increase in the content of artificial radionuclides in the freshwater ecosystem of the cooling pond of the Beloyarsk NPP. On the contrary, in comparison with the previous period of operation of only the BN-600 reactor (1990–2015), a decrease in the specific activity of radioisotopes in surface water has been

Table 2
Average content of artificial radionuclides in the components of the freshwater ecosystem of the Beloyarsk reservoir during the operation of the reactors AMB and BN, Bq/kg(L).

Radionuclide	Periods of Beloyarsk NPP work (years, reactors in operation)					
	I (1964–1966, AMB-100)	II (1967–1979, AMB-100, AMB-200)	III (1980–1981, AMB-100, AMB-200, BN-600)	IV (1982–1989, AMB-200, BN-600)	V (1990–2015, BN-600)	VI (2016–2019, BN-600, BN-800)
Surface water						
^{60}Co	No data	0.99 ± 0.51 (n = 20)	0.18 ± 0.01 (n = 10)	0.16 ± 0.06 (n = 37)	0.027 ± 0.025 (n = 16)	Below MDA
^{90}Sr	No data	0.12 ± 0.05 (n = 17)	0.03 ± 0.004 (n = 8)	0.05 ± 0.01 (n = 28)	0.016 ± 0.014 (n = 72)	0.018 ± 0.005 (n = 12)
^{137}Cs	No data	0.82 ± 0.71 (n = 18)	0.2 ± 0.18 (n = 8)	0.13 ± 0.11 (n = 31)	0.026 ± 0.019 (n = 85)	0.011 ± 0.007 (n = 18)
^{3}H	No data	No data	80.9 ± 0.1 (n = 12)	92.6 ± 68.7 (n = 40)	24.9 ± 17.4 (n = 124)	18.6 ± 2.1 (n = 17)
Bottom sediments (silty sapropel)						
^{60}Co	No data	3386 ± 2867 (n = 8)	No data	465 ± 293 (n = 5)	23 ± 21 (n = 50)	6.7 ± 0.4 (n = 24)
^{90}Sr	No data	28.7 ± 14.4 (n = 3)	No data	30.9 ± 15.1 (n = 18)	13.6 ± 11.1 (n = 33)	1.3 ± 0.4 (n = 3)
^{137}Cs	No data	1593 ± 1569 (n = 5)	No data	595 ± 191 (n = 13)	311 ± 258 (n = 75)	159 ± 5.2 (n = 24)
Macrophytes (average for elodea and hornwort)						
^{60}Co	No data	3869 ± 3861 (n = 14)	No data	164 ± 12 (n = 14)	19 ± 14 (n = 3)	0.15 ± 0.05 (n = 3)
^{90}Sr	No data	103 ± 36 (n = 8)	No data	52 ± 11 (n = 4)	18 ± 17 (n = 13)	7.9 ± 7.0 (n = 6)
^{137}Cs	No data	920 ± 902 (n = 7)	218 ± 111 (n = 3)	90 ± 19 (n = 14)	21 ± 15 (n = 21)	11.7 ± 9.8 (n = 9)
Fish (average for 9 species)						
^{60}Co	No data	8.8 ± 5.5 (n = 4)	3.8 ± 0.2 (n = 2)	1.7 ± 0.01 (n = 6)	No data	No data
^{90}Sr	No data	3.4 ± 1.1 (n = 4)	No data	No data	2.12 ± 2.06 (n = 33)	2.7 ± 0.4 (n = 10)
^{137}Cs	No data	80.3 ± 43.3 (n = 12)	43.3 ± 5.3 (n = 9)	37.8 ± 18.6 (n = 17)	9.9 ± 7.1 (n = 43)	1.8 ± 0.7 (n = 16)

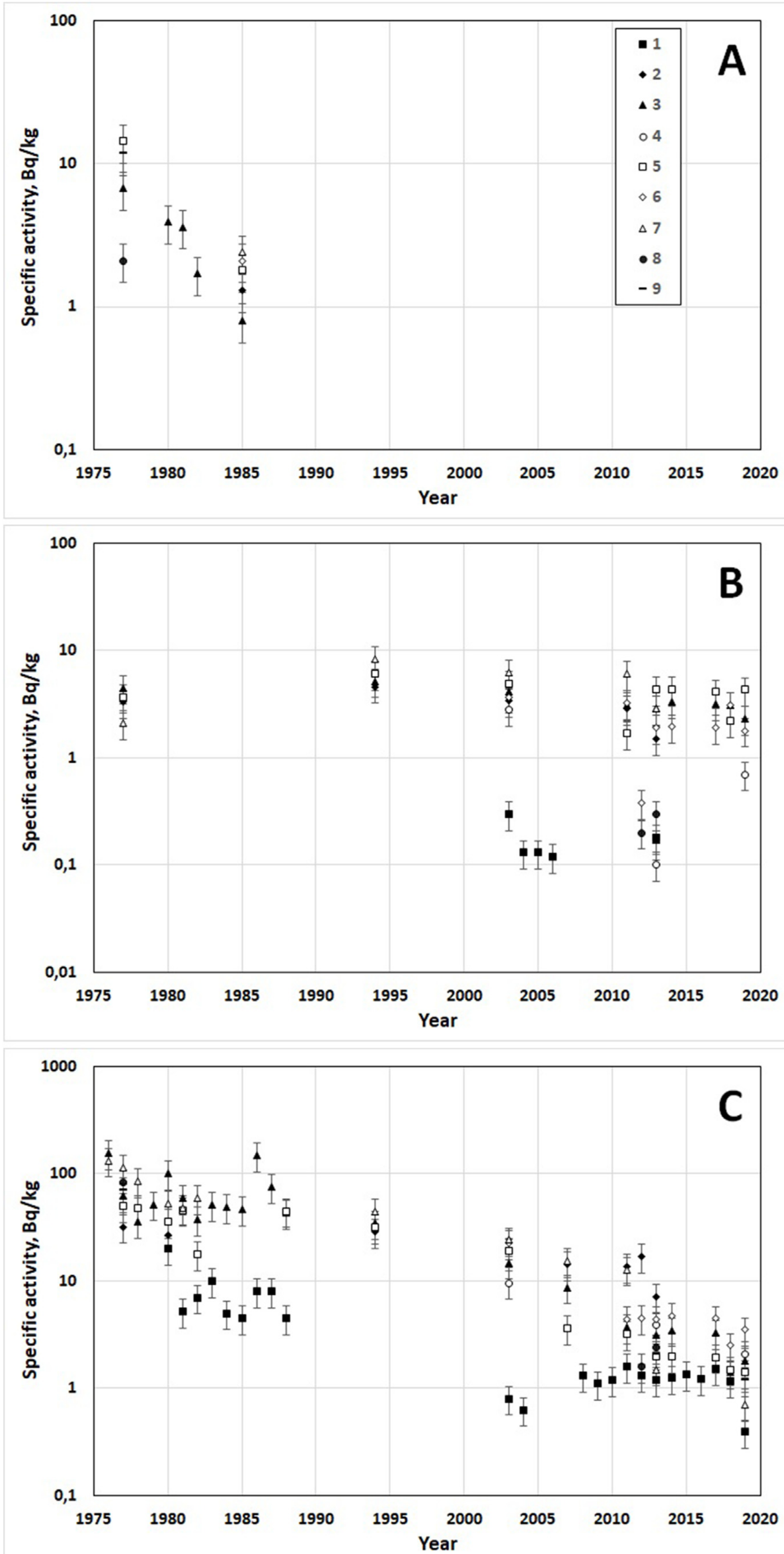

Fig. 4. Dynamics of radionuclides specific activity: A – ^{60}Co, B – ^{90}Sr, C – ^{137}Cs in fish of the Beloyarsk NPP cooling pond (1 – cultured carp, 2 – wild carp, 3 – roach, 4 – pike perch, 5 – bream, 6 – perch, 7 – pike, 8 – tench, 9 – crucian carp).

noted by 1.3–2.4 times, in bottom sediments by 1.9–10, 5 times, in macrophytes 1.8-125 times, in ichthyofauna up to 5.5 times.

4. Among the studied radionuclides, the highest level of specific activity in the first years of research was noted for surface water at ^{60}Co (0.99 Bq/L) and, to a somewhat lesser extent, at ^{137}Cs - 0.82 Bq/L. In bottom sediments (silty sapropel), the maximum specific activity was ^{60}Co (3386 Bq/kg) and half of ^{137}Cs - 1593 Bq/kg. A similar pattern has been observed for macrophytes: ^{60}Co - 3869 Bq/kg, ^{137}Cs - 920 Bq/kg. The high storage capacity of macrophytes is explained by the fact that they are entirely or for the most part in water and thus have a much larger absorbing surface. In fish, on the contrary, the maximum specific activity has been observed for ^{137}Cs - 80.3 Bq/kg and, to a lesser extent, for ^{60}Co - 8.8 Bq/kg.
5. The significance of the transition of the technology of electricity production at the Beloyarsk NPP from thermal to fast reactors in terms of the content in water of one of the most radiologically significant radionuclides - ^{3}H has been noted. So, after decommissioning the reactors of the first stage of the nuclear power plant (AMB-100 and AMB-200), the average tritium content in the surface water of the cooling reservoir of the Beloyarsk NPP decreased from 80-95 Bq/L to 20–25 Bq/L and tends to further decrease.
6. The specific activity of ^{90}Sr in the components of the freshwater ecosystem was minimal among the studied radionuclides, since it was determined by its low input with waste waters during the entire period of operation of the Beloyarsk NPP under consideration. Since the differences in the content of radiostrontium from the place of discharge of technological waters of the NPP to the upper reaches of the reservoir in recent years are not high, we can say that the concentration of the radioisotope in the cooling pond is currently determined to a greater extent by global fallouts and the local technogenic background than by discharges from the nuclear power plant.
7. The role of the temperature conditions of the cooling pond of the Beloyarsk NPP in the accumulation of radionuclides has been shown by the example of a number of components of the freshwater ecosystem. So, in the warmed waters of the Warm Bay of the reservoir, radionuclides accumulate to a greater extent in bottom sediments (up to 3.5 times higher than the average for the reservoir) and water plants (1.5-4.5 times higher than the average).
8. The specific features of the ichthyofauna of the Beloyarsk Reservoir are distinguished according to the degree of accumulation of radionuclides, which is important for the use of the reservoir for fishing and fish farming. It has been shown that the average content of radionuclides in cultured carp is 5.2 times lower than in free-living carp, which is due to the type of fish feeding - radioactively pure food in cultured carp. Studies have shown the prospects of breeding cultured carp and other fish species using artificial feed in the warm waste waters of the Beloyarsk NPP.
9. According to the monitoring observations of the cooling pond of the Beloyarsk NPP in recent years, the content of artificial radionuclides in the surface water, bottom sediments and hydrobionts of the reservoir is at a consistently low level, which indicates the absence of a significant effect of the nuclear power plant on the freshwater ecosystem.

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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