Journal of Environmental Radioactivity 264 (2023) 107209

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Influence of operation of thermal and fast reactors of the Beloyarsk NPP on the radioecological situation in river ecosystems

Aleksei Panov [a,*], Alexander Trapeznikov [b], Vera Trapeznikova [b], Alexander Korzhavin [b]

[a] National Research Nuclear University MEPhI, Obninsk, Russian Federation
[b] Institute of Plant and Animal Ecology of the Ural Branch of the Russian Academy of Sciences, Yekaterinburg, Russian Federation

ARTICLE INFO

Keywords:
Nuclear power plant
Thermal and fast reactors
River
Freshwater ecosystem
Radioecological monitoring
Artificial radionuclides
Long-term dynamics

ABSTRACT

The results of long-term radioecological monitoring of seven rivers in the 15-km zone of influence of the Beloyarsk Nuclear Power Plant have been presented. A comparative analysis of the content of a wide range of natural and artificial radionuclides in the main components of river ecosystems: surface waters, bottom sediments, floodplain soils, macrophytes and ichthyofauna has been made. The influence of waste technological waters of thermal (AMB-100 and AMB-200) and fast (BN-600 and BN-800) reactors of the Beloyarsk NPP on the content of radiologically significant isotopes in the water and bottom sediments of the Pyshma and Olkhovka rivers has been evaluated. It has been studied that the transition from thermal to fast reactors contributed to a significant decrease in the intake of artificial radionuclides into the rivers of the area where the Beloyarsk NPP is located. So, in the water of the Olkhovka river for the period 1978–2019 the decrease in the specific activity of ^{137}Cs was 480, ^{3}H - 36, ^{90}Sr - 3.5 times. The maximum discharge of artificial radioisotopes into river ecosystems was noted during the period of recovery work after emergencies at the AMB-100 and AMB-200 reactors. In recent years, the content of artificial radionuclides in water, macrophytes and ichthyofauna of rivers in the zone of influence of the Beloyarsk NPP, except for the Olkhovka, is at the level of the regional background.

1. Introduction

Environmental safety of nuclear power plants (NPPs) is one of the key issues in the development of promising strategies for the development of nuclear power. At the beginning of the formation of the nuclear industry in the 60–70s of the last century, due to the technological imperfection of reactor facilities, there were many emergency situations in a number of NPPs. They led to an increased intake of artificial radionuclides into the environment. This has emphasized the importance of the issues of ensuring the radiation safety of the personnel of NPPs, the population and biota in the areas where the NPP is located (Olsen et al., 1981; Eisenbud and Gesell, 1997; Hu et al., 2010; Alexakhin, 2013). Therefore, at all stages of the life cycle of NPPs, special attention is paid to monitoring the radiation impact on humans and biota from emissions and discharges of radioactive substances into the atmosphere, water and terrestrial ecosystems (Djingova and Kuleff, 2002; Sohrabi et al., 2013; Kong et al., 2017; Lee et al., 2019).

For cooling the reactors of NPPs, cooling ponds are often used (Kim and Jeong, 2013; Song et al., 2020), especially those made on rivers (Kryshev, 1996; Mikailova et al., 2020). At the same time, aquatic ecosystems are subject to the direct impact of liquid discharges from NPPs due to water used to cool reactor plants, as well as the technological needs of the nuclear power plant infrastructure, for example, decontamination of equipment, premises, personnel, overalls, etc. (Trapeznikov et al., 2015). The study of the intake, migration and accumulation of artificial radionuclides in the river ecosystems of the NPP influence zone is a topical direction in radioecology. The radionuclides, inevitable consequences or by-products of NPP operations, that got into the river can be transported with the watercourse for tens of kilometers. They are unique markers that make it possible to assess the degree of impact of a NPP on humans and the environment. It is also important to study the barrier role of a number of components of river ecosystems (bottom sediments, floodplain soils, hydrobionts), which sorb radionuclides from surface waters and contribute to their purification (Trapeznikov and Trapeznikova, 2012).

It should be noted that river waters are actively used by the local population in the areas where the NPP is located for domestic and economic purposes: water supply to settlements, fishing, irrigation of fields, watering for farm animals, etc. Therefore, the assessment of the radioecological state of river ecosystems is an urgent task to ensure the

* Corresponding author.
E-mail addresses: riar@mail.ru (A. Panov), vera_zar@mail.ru (A. Trapeznikov), vera_zar@mail.ru (V. Trapeznikova), BFS_zar@mail.ru (A. Korzhavin).

https://doi.org/10.1016/j.jenvrad.2023.107209
Received 2 January 2023; Received in revised form 23 May 2023; Accepted 24 May 2023
Available online 27 May 2023

radiation safety of the population living near the rivers of the zone of influence of the NPP. The solution of the identified fundamental and applied radioecological problems is possible only on the basis of data of long-term observations (monitoring) of the content of radionuclides in the components of river ecosystems (IAEA, 2005; IAEA, 2010; IAEA, 2014).

The study of the influence of nuclear power plants on rivers was carried out using the example of the Beloyarsk NPP, which is one of the oldest in Russia (operation started in 1964) and has 4 power units: thermal (AMB-100 and AMB-200) and fast (BN-600 and BN-800) reactors (Oshkanov et al., 1994; Oshkanov and Govorov, 2009). The BN-800 power unit with liquid sodium as a coolant is by far the largest fast breeder reactor in the world.

The aim of the work was to assess the impact of the operation of thermal and fast reactors of the Beloyarsk NPP on the radioecological situation in the rivers of the near 15-km zone of the nuclear power plant based on the analysis of the results of long-term (1978–2019) radioecological monitoring.

2. Description of research objects

2.1. Description of the Beloyarsk NPP

Beloyarsk NPP has been operating for over 57 years, having started functioning with the operation of thermal light water graphite reactors AMB-100 and AMB-200 (Table 1). Due to the imperfection of the technology for generating electricity at AMB reactors, in the initial period of operation of the Beloyarsk NPP, their work was accompanied by a number of abnormal and emergency situations: in the period 1964–1974, in 1976 and 1978 (Koltik, 2001; Kuznetsov, 2003). This led to the need to decommission the AMB-100 and AMB-200 reactors 17 and 22 years after the start of their operation. In 1980, a fundamentally different fast neutron reactor BN-600 was launched at the Beloyarsk NPP, and in 2016, the BN-800 (Oshkanov et al., 1994; Oshkanov and Govorov, 2009; Koltik and Oshkanov, 2005). Currently, a new generation of this series of reactors is being designed BN-1200. Deviations in operation were also noted at the BN-600 reactor: in 1987, 1993, 1994 and 2000. A rather serious emergency occurred in the liquid radioactive waste storage facility of the Beloyarsk NPP in 1992 (Panov et al., 2022).

Accidents at the AMB and BN-600 reactors led to their unscheduled shutdown, lengthy repairs and equipment decontamination, which were accompanied by the release of increased activity of artificial radionuclides into the environment, mainly water. The increase in the content of radioisotopes in the emissions and discharges of the Beloyarsk NPP due to emergencies in the 60s and 70s of the last century, required the organization of monitoring the radiation situation in the adjacent territory and the creation of a radioecological monitoring system. In previous studies, the impact of the Beloyarsk NPP on the pollution of natural terrestrial (Panov et al., 2021a) and agrarian (Panov et al., 2021b) ecosystems with artificial radionuclides was assessed. The largest aquatic ecosystem in the area of the nuclear power plant is the Beloyarsk reservoir, which is formed in the Pyshma river bed and is used as a cooling reservoir for NPP. In (Panov et al., 2022, 2023), the Beloyarsk NPP is characterized as a source of artificial radionuclides being released into the reservoir. It has been noticed that in the waste waters of the Beloyarsk NPP during its normal operation, the most radiologically significant isotopes are ^{137}Cs, ^{60}Co, ^{3}H and, to some extent, ^{90}Sr. The volumes of radionuclides being discharged by the NPP into the environment were determined by the design and operation features of thermal and fast reactors, as well as emergency situations and repairs of the AMB-100, AMB-200 and BN-600 power units. Based on the data of long-term observations, two main ways of discharging artificial radionuclides of the Beloyarsk NPP have been determined: into the cooling pond (reservoir) and the Olkhovsky swamp-river system. From the reservoir directly, as well as with the waters of the river Olkhovka, which flows out of the Olkhovsky swamp, radioisotopes are released into the river Pyshma. In the 15-km zone around the NPP, there are five more small rivers, on the banks of which there are numerous settlements. Therefore, it is important to study the impact of the Beloyarsk NPP on radionuclide pollution of river ecosystems in the area of the NPP.

2.2. Description of the rivers in the vicinity of Beloyarsk NPP

The largest river system in the area of the Beloyarsk NPP is the river Pyshma, as a result of the regulation of which in 1964 a reservoir was made to cool the reactors of the NPP. The river bed Pyshma is moderately sinuous, unbranched. The depth of the river is 0.7–3.0 m, the bottom is smooth, silty-sandy or sandy-rocky on the rifts. The height of the river banks varies within 1–8 m. In the extended sections of the river, the channel is overgrown with aquatic vegetation. Average speed of the river Pyshma is 0.1–0.5 m/s. The river is fed by snow melt waters (up to 55% of the annual runoff).

The second in terms of radioecological significance in the study area is the river Olkhovka. This is the left tributary of the river Pyshma, which originates from the Olkhovsky swamp. The swamp area is 0.47 km^2. In the western part of the swamp, industrial water was discharged from the treatment facilities of the industrial site of the Beloyarsk NPP. The Olkhovka River flows out of the eastern part of the swamp. Despite the fact that the effluents of the NPP are discharged into the upper part of the swamp, the water content in it is low, since water flows through the swamp through the channel, which passes into the river Olkhovka. Swamp and the river Olkhovka are included in the sanitary protection zone of the Beloyarsk NPP.

According to the state water register of Russia (Resolution of the Government), the rest of the rivers in the near zone of the NPP are also tributaries of the river. Pyshma and their length does not exceed 10 km (Table 2). These rivers are not directly affected by discharges from the

Table 2
Description of the rivers in the vicinity of Beloyarsk NPP (Resolution of the Government).

River name	Watercourse length, km	Drainage area, km^2
Pyshma	603	19700
Olkhovka	3.2	no data
Gagarka	4.7	no data
Kamyshenka	5.2	120
Mezenka	6.6	30.8
Rezhik	3.8	no data
Kamenka	9.1	101

Table 1
Description of Beloyarsk NPP reactors (Panov et al., 2022).

Reactor type	Unit	Coolant	MWe net, each	Start or commercial operation	Licensed to, or scheduled close	Year of fuel unloading
Light water graphite reactor (LWGR)	AMB-100	Water	108	1964	1981	1986
	AMB-200		160	1967	1989	1993
Fast neutron reactor (FNR)	BN-600	Liquid sodium	560	1980	Planned, 2030	–
	BN-800		882	2016	Planned, 2056	–
	BN-1200		1220	Planned, 2030	–	–

Beloyarsk NPP, however, the study of their radioecological state is important for understanding the processes of migration of radionuclides in the Pyshma river system and assessing its radiation safety.

3. Material and methods

3.1. Sites description

When creating a radioecological monitoring network in the 15-km zone of the Beloyarsk NPP, 10 control sites were selected on seven rivers (Fig. 1). Special attention was paid to two rivers (Pyshma and Olkhovka), since they are subject to the direct impact of discharges of technological waters of the NPP. The remaining five small rivers are located in the near zone of the NPP and are used by the population for household needs. On the river Pyshma, four control sites were selected. First, before (S1) and after (S2) of the Beloyarsk reservoir, where artificial radionuclides are supplied from the site of the NPP through the industrial water and bypass canals (Panov et al., 2022, 2023). Further, downstream on the river Pyshma, two control sites were established before (S3) and after (S4) the confluence of the river Olkhovka. Site (S5) has been selected at the mouth on the river Olkhovka before its confluence with the river Pyshma to control the intake of artificial radionuclides, inevitable consequences or by-products of NPP operations, through the Olkhovsky swamp. On the control sites (S1) and (S4), it is possible to record the integral influence of the Beloyarsk NPP on the aquatic ecosystem of the river Pyshma. Site (S1) also serves to assess the background content of radionuclides in the river ecosystems of the NPP region. The rest of the control sites (S6–S10) were selected on five small rivers in the 15-km zone around the Beloyarsk NPP: Gagarka, Kamyshenka, Mezenka, Rezhik and Kamenka (Table 3). In the rivers, the content of radionuclides in the main components of aquatic ecosystems was studied: water, bottom sediments, floodplain soils, macrophytes and ichthyofauna.

In the surface waters of rivers, the following data has been analyzed: gross alpha activity and gross beta activity, 13 natural (^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{222}Rn, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra, ^{228}Th) and nine artificial (^{3}H, ^{14}C, ^{60}Co, ^{90}Sr, ^{134}Cs, ^{137}Cs, ^{238}Pu, ^{239,240}Pu, ^{241}Am) radionuclides. In bottom sediments the following data has been assessed gross beta activity, eight natural (^{230}Th, ^{226}Ra, ^{214}Bi, ^{210}Pb, ^{232}Th, ^{228}Ra, ^{228}Th, ^{40}K) and seven artificial (^{3}H, ^{60}Co, ^{90}Sr, ^{134}Cs, ^{137}Cs, ^{239,240}Pu, ^{241}Am) radionuclides. In samples of river floodplain soils the following radionuclides have been analyzed: ^{90}Sr, ^{137}Cs, ^{40}K, ^{239,240}Pu. For studying macrophytes, six species of aquatic plants most common in the river ecosystems of the region have been selected: cladophora (*Cladophora fracta*), elodea (*Elodea canadensis*), hornwort (*Ceratophyllum demersum*), pondweeds (*Potamogeton pectinatus* and *perfoliatus*) and duckweed (*Lemna minor*). ^{137}Cs and ^{90}Sr have been determined in them. Ichthyofauna has been represented by two species of fish: northern pike (*Esox lucius*) and roach (*Rutilus rutilus*). ^{137}Cs, ^{90}Sr and ^{40}K have been determined in the fish.

In the rivers Pyshma and Olkhovka, long-term (1978–2019)

Table 3
Description of the radioecological monitoring network of the rivers in the 15-km zone of Beloyarsk NPP.

Site	River	Direction and distance from NPP, km	Coordinates
S1	Pyshma before flowing into Beloyarsk reservoir	N–W, 15	N° 56.913, E° 61.080
S2	Pyshma below the dam of Beloyarsk reservoir	S, 6	N° 56.786, E° 61.308
S3	Pyshma before the confluence of Olkhovka river	E, 8	N° 56.811, E° 61.446
S4	Pyshma after the confluence of Olkhovka river	E, 7	N° 56.831, E° 61.442
S5	Olkhovka	S-E, 6.5	N° 56.814, E° 61.419
S6	Gagarka	S–W, 9	N° 56.764, E° 61.265
S7	Kamyshenka	S, 8	N° 56.778, E° 61.264
S8	Mezenka	S, 10	N° 56.753, E° 61.328
S9	Rezhik	E, 6.5	N° 56.850, E° 61.430
S10	Kamenka	N-E, 10	N° 56.897, E° 61.446

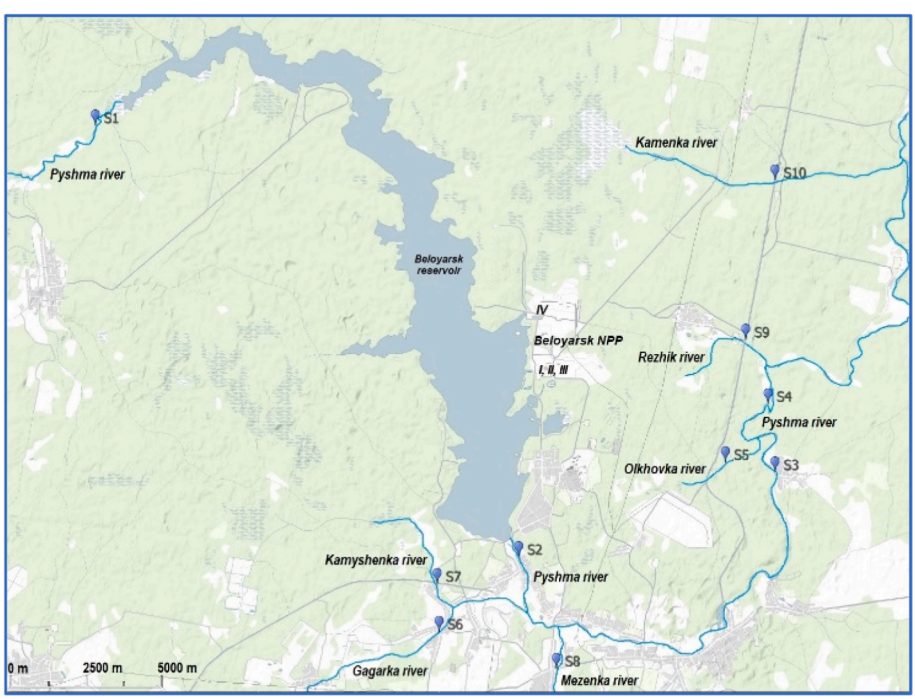

Fig. 1. Schematic map of radioecological monitoring network of the river freshwater ecosystems in the vicinity of Beloyarsk NPP: S1–S10 – sampling sites; reactors of Beloyarsk NPP: *I* – AMB-100, *II* – AMB-200, *III* – BN-600, *IV* – BN-800.

migration and levels of ^{3}H (T½ = 12.32 years), ^{60}Co (T½ = 5.27 years), ^{90}Sr (T½ = 28.78 years) and ^{137}Cs (T½ = 30.07 years) have been evaluated. These radiologically significant radionuclides, entering the rivers as part of the waste waters of the Beloyarsk nuclear power plant, pollute the water environment. Tritium mainly accumulates in water, while the remaining radionuclides migrate with the watercourse, gradually being sorbed by bottom sediments, floodplain soils and hydrobionts (macrophytes and ichthyofauna). Thus, the created monitoring system made it possible to take into account the territorial features of the accumulation of radionuclides in the components of river ecosystems at different distances from the Beloyarsk NPP and to assess the impact of the operation of different types of reactors on the radioecological state of rivers in the zone of influence of the nuclear power plant.

3.2. Sampling of freshwater components

The components of river ecosystems were sampled in three replicates for each point in the summer (July–August) period of the year in accordance with the current regulatory and methodological documents (Methodological recommendations, 1980; Methodological recommendations, 1986; Guidelines for organizing monitoring of the state, 1990; Manual for hydrometeorological stations and posts, 2015). River water samples were taken into new plastic canisters and immediately acidified with a small amount of nitric acid to prevent the sorption of radionuclides on the walls of the vessels. The volume of each water sample was 200–300 L for repetition. Bottom sediments and floodplain soils were taken using a special sampler to a depth of 20–40 cm. The sample weight of bottom sediments and soils was 2–3 kg per replicate. Macrophytes were sampled 3–5 kg of wet weight for replication. Fish (2–3 years old, both sexes) with a wet weight of 3 kg were caught for replication with nets with a mesh of 28–70 mm. One fish sample included on average: pike - 3, roach - 30 individuals (Trapeznikov and Trapeznikova, 2012).

Aliquot of water samples for radionuclides determination were filtered and evaporated. The dry residue was ashed at $t = 450$ °C in a muffle furnace for 8 h. After cooling, the residue was ground with a pestle to a fine powder. In the first years of investigations for the quantitative determination of ^{3}H, water samples were preliminarily enriched by the method of one-stage electrolysis with one or two toppings. The tritium concentration was determined by a relative method, by comparison with a standard solution. In later years, the determination of ^{3}H was carried out by liquid scintillation spectrometry. Water samples were filtered prior to the ^{3}H measurement. The Ultima Gold cocktail was used as a scintillator. The sample-to-cocktail ratio was 7:13. The accuracy of the analysis was controlled by periodic measurement of a standard water sample with a known content of ^{3}H. ^{210}Po in water was determined without the samples' evaporation (Trapeznikov and Trapeznikova, 2012; Panov et al., 2022).

Samples of bottom sediments and floodplain soils were dried to an air-dry state, ground, sieved through a sieve 1 mm in diameter, then ashed at $t = 400$–500 °C in a muffle furnace for 6 h to remove the organic component. Macrophytes were washed from contamination, weighed and dried to an air-dry state, after which they were ashed at $t = 450$°C in a muffle furnace. Fish carcasses (without internal organs) were dried at $t = 105$°C and ashed at $t = 450$°C (Trapeznikov and Trapeznikova, 2012).

3.3. Measurements

The determination of the specific activity of radionuclides in the components of river ecosystems was carried out in the accredited laboratories IPAE UB RAS using highly sensitive spectrometric and radiometric complexes and interlaboratory comparative analysis of the results. Gamma-emitting radionuclides were determined by a GAMMA-1P spectrometer with two measuring paths with semiconductor detectors made of ultrapure germanium (LSRM, Russia, EG&G ORTEC, USA) and a CANBERRA multichannel gamma spectrometer (Canberra Industries, Inc., USA). The gross alpha and beta activity of the preparations was measured on a TRI-CARB 4810 TR liquid scintillation spectrometer (Perkin Elmer, USA) and an alpha-beta radiometer with a UMF-2000 silicon detector (NPP "Doza", Russia). To determine low-energy radionuclides in water using gamma spectrometry, the samples were filtered through cotton filters from mechanical impurities and evaporated in special boilers to obtain a concentrate with a volume of 1–2 L, which was also evaporated in chemical glass to a dry residue. The measurement time varied from minutes to hours. ^{241}Am in the samples was determined by γ-spectrometry. The characteristic of gamma peak for determination of ^{241}Am 59.5 keV. Uranium and thorium isotopes were determined by a modified radiochemical method, which included four stages: decomposition and transfer of the sample into solution; chromatographic separation on an anion exchanger; release from interfering elements; photocalorimetric determination of the content of uranium and thorium in the sample. ^{210}Po was determined by the alpha-spectrometric method after its auto-deposition from water onto a nickel disk. ^{210}Po previously to the auto-deposition not preconcentrated. ^{222}Rn was determined with a radon radiometer. Radionuclides were leached from samples with a mixture of acids to determine plutonium isotopes in water and bottom sediments. The sample was completely decomposed in a mixture acids HF (70%) and HNO_3 (3:1). Next, a 2-fold purification of the solution on an ion-exchange column, electrolytic precipitation, and alpha spectrometry of the obtained samples were carried out (Trapeznikov and Trapeznikova, 2012; Edomskaya et al., 2022; Panov et al., 2022). For the measurement of ^{14}C activity concentration in samples was used liquid scintillation counting. Tritium in the samples was determined on Isocap-300 and Delta-300 liquid scintillation counters. In bottom sediments, tritium was determined from filtered moisture (Trapeznikov and Trapeznikova, 2012; Panov et al., 2022). The relative error in measuring the activity of radioisotopes was 10–15%, depending on the instrument used and the measurement method (Panov et al., 2022, 2023).

3.4. Data analysis

Radioecological monitoring of rivers was carried out in 1978–1981 (Pyshma and Olkhovka rivers) and in 2000–2019 (all rivers). In total, 862 statistically processed results of measurements of the content of radionuclides in the components of the freshwater ecosystem were analyzed, including:

- surface water −456 measurements (natural radionuclides − 24%, artificial radionuclides − 76%);
- bottom sediments − 321 measurements (natural radionuclides − 27%, artificial radionuclides − 73%);
- floodplain soil − 12 measurements (natural radionuclides − 25%, artificial radionuclides − 75%);
- macrophytes − 37 measurements (^{137}Cs − 62%, ^{90}Sr − 38%);
- ichthyofauna −36 measurements (^{137}Cs − 33.3%, ^{90}Sr − 33.3%, ^{40}K − 33.3%).

The reliability of the monitoring results was achieved by parallel selection and study of all ecosystem components in triplicate. Statistical processing of the data obtained included an assessment of the arithmetic mean and standard deviation of the arithmetic mean. The measurement results were processed using the *t*-test and other statistical methods and were considered reliable at $p < 0.05$. The obtained monitoring data were verified with the results of radiation monitoring by Roshydromet carried out in the area of the Beloyarsk NPP (The radiation situation), as well as with the data of other researchers obtained in different years (Molchanova et al., 1982, 1985; Chebotina et al., 1992; Chebotina and Nikolin, 2005). The analysis of long-term monitoring data is presented in the form of the dynamics of the content of radionuclides in surface water and bottom sediments for two rivers Pyshma and Olkhovka, which are most affected by the Beloyarsk NPP.

4. Results and discussion

4.1. Dynamics of radionuclide specific activity in surface water

River water is the main component of these freshwater ecosystems. At the first stage of the analysis of the results of the content of radionuclides in the surface waters of rivers, carried out in the period 2011–2019, an assessment of their radiation safety was conducted according to the integral quality indicators used for drinking water: gross alpha activity, the criterion of compliance with the requirements radiation safety (control level - CL) is 0.2 Bq/L and gross beta activity, the compliance criterion is 1.0 Bq/L (Sanitary Rules and Norms). In accordance with the data in Table 4 it can be seen that the indices gross alpha activity in the river water of the Beloyarsk NPP region can differ up to 6 times and average 41.5 mBq/L with a variation of 13.8–85.0 mBq/L. The maximum value of gross alpha activity was recorded in the water of the river Pyshma, however, this indicator is 2.35 times lower than the corresponding CL. The average value gross beta activity of radioisotopes in the water of the studied rivers is at the level of 98.8 mBq/L and varies in the range of 13.7–174.5 mBq/L, which is 5.7–73 times less than CL according to this safety criterion. The maximum indices of gross beta activity were also recorded in the water of the river Pyshma. In general, the obtained results of gross alpha and gross beta activity of isotopes indicate the radiation safety of all river water in the zone of influence of the Beloyarsk NPP according to the most stringent criteria established for drinking water.

In previous studies of groundwater in the area of the Beloyarsk NPP, it was shown (Panov et al., 2021c) that the main contribution to the formation of the internal exposure dose of the population (98.9%) from drinking water consumption is made by natural radionuclides, and of them the maximum contribution from ^{210}Po is 43% (specific activity 20–110 mBq/L) and ^{210}Pb - 25% (content 20–200 mBq/L). In the river water of all sampling points, the content of ^{210}Po and ^{210}Pb is lower than in groundwater and is at the level of 18–44 mBq/L. This difference is quite natural, since groundwater, passing through water-bearing rocks, is saturated with natural radionuclides. Therefore, if the river water of the region of the Beloyarsk NPP is potentially used, after appropriate purification as drinking water, the dose of internal exposure of the population from natural radionuclides of river water will be even lower. The specific activity of ^{40}K in all water samples of rivers in the Beloyarsk NPP region was below the minimum detectable values.

From the point of view of the radiation safety of the population living in the area where the Beloyarsk NPP is located, it is more significant to assess the impact of the NPP on the pollution of surface waters of rivers with artificial radionuclides. Out of all the studied river ecosystems, the maximum content of technogenic radionuclides in 2011–2019 (operating reactors BN-600 and BN-800) are noted in the water of the r. Olkhovka, into which, through the Olkhovsky swamp, since the beginning of the operation of the first thermal reactors (AMB-100 and AMB-200) of the Beloyarsk NPP, weakly radioactive discharges from the NPP were transmitted in transit. Thus, the specific activity of ^{137}Cs in the water of the r. Olkhovka exceeds the same indicator for other rivers from 4.55 to 38 times (Table 4). At the same time, according to the criterion of radiation safety for drinking water CL (11 Bq/L), the content of the radionuclide in the water of the r. Olkhovka is more than 200 times lower than the standard. As for ^{90}Sr, the differences in the concentration of the radioisotope in water in comparison with other rivers are 5.8–14.8 times higher, and according to the CL standard (4.9 Bq/L), it is more than 50 times lower than the established safety criterion. Specific activity of other radiologically significant radionuclides in the water of the mouth of the river Olkhovka is also increased: ^{3}H by 5.0–17.8 times, in relation to other rivers, ^{60}Co by 6.6–12.4 times. However, these levels of concentration of radionuclides in the water of the river Olkhovka is significantly lower than the established CL: by ^{3}H (CL - 7600 Bq/L) by 78 times, by ^{60}Co (CL - 40 Bq/L) by almost 18 thousand times. In the waters of the mouth of the river Olkhovka, higher concentrations of other artificial radionuclides are observed compared to other rivers: ^{14}C, ^{238}Pu and ^{239,240}Pu; however, they are also much lower than the current standards: 9.6, 1.4 and 1.3 thousand times, respectively. Thus, despite the fact that in the river Olkhovka continues to be drained from the Olkhovsky swamp by radionuclides of stationary origin, the water at the mouth of this river currently meets the requirements of radiation safety. The second place in terms of the content of ^{137}Cs and ^{3}H in surface waters is the r. Pyshma, also experiencing a certain influence of the discharges of the NPP. In other rivers of the 15-km zone around the Beloyarsk NPP, no increased concentrations of artificial radionuclides were found in surface waters, and their content is close to the regional background.

Table 4
Specific activity of radionuclides in river waters in the vicinity of Beloyarsk NPP in 2011–2019, mBq/L (mean ± standard deviation).

Nuclide	Pyshma (S1–S4)	Olkhovka (S5)	Gagarka (S6)	Kamyshenka (S7)	Mezenka (S8)	Rezhik (S9)	Kamenka (S10)
Gross α	85 ± 47	43 ± 10	39 ± 12	37 ± 7	32 ± 5	41 ± 7	14 ± 2
Gross β	175 ± 66	156 ± 5	163 ± 16	63 ± 1	44 ± 3	77 ± 6	14 ± 3
Natural radionuclides							
^{238}U	–	8.2 ± 3.2	8.4 ± 3.3	9.1 ± 3.7	7.7 ± 3.2	9.6 ± 4.3	9.2 ± 3.2
^{234}U	–	<180	<59	335 ± 170	310 ± 120	<150	<89
^{230}Th	–	13 ± 2	4.1 ± 0.4	11 ± 2	7.5 ± 0.7	9.6 ± 0.4	11 ± 1
^{226}Ra	<7.0	12 ± 3	4.7 ± 1.9	<3.0	<4.5	<2.3	<5.5
^{222}Rn	–	2700 ± 283	2750 ± 354	2550 ± 636	3100 ± 141	<3100	<3100
^{214}Pb	–	6.7 ± 0.5	6.6 ± 0.6	6.3 ± 1.4	5.2 ± 0.5	7.2 ± 0.1	7.1 ± 0.5
^{214}Bi	–	<1.5	<0.5	<1.2	<0.5	<0.3	<0.7
^{214}Po	–	<32	<26	<20	<18	<32	<44
^{210}Pb	–	<32	<26	<20	<18	<32	<44
^{210}Po	–	<32	<26	<20	<18	<32	<44
^{232}Th	–	<13	0.9 ± 0.3	0.9 ± 0.2	1.1 ± 0.1	1.1 ± 0.2	<5.4
^{228}Ra	<0.7	<0.7	<0.7	<0.7	<0.7	<0.7	<0.7
^{228}Th	–	12 ± 3	3.2 ± 0.6	11 ± 2	7.6 ± 1.3	2.2 ± 0.4	6.8 ± 1.4
Artificial radionuclides							
^{3}H	19600 ± 4970	98000 ± 40840	7467 ± 902	12500 ± 2121	5500 ± 700	6250 ± 1060	6066 ± 1006
^{14}C	–	25 ± 8	<7.5	<7.5	<7.5	<7.5	<7.5
^{60}Co	<0.3	2.2 ± 0.1	<0.2	<0.2	<0.3	<0.3	<0.3
^{90}Sr	15 ± 9	92 ± 60	12 ± 6	16 ± 4	16 ± 6	6.5 ± 0.8	6.2 ± 0.2
^{134}Cs	<1	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	<0.14	0.3 ± 0.03	<0.2
^{137}Cs	12 ± 6	54 ± 20	4.7 ± 2.4	2.6 ± 1.2	3.4 ± 1.6	1.4 ± 0.6	1.6 ± 0.7
^{238}Pu	–	0.4 ± 0.2	0.03 ± 0.01	0.1 ± 0.05	0.2 ± 0.05	0.05 ± 0.02	<0.5
^{239,240}Pu	0.3 ± 0.2	0.4 ± 0.2	0.06 ± 0.02	0.3 ± 0.1	0.02 ± 0.01	0.02 ± 0.01	0.3 ± 0.02
^{241}Am	<0.9	<0.1	<0.2	<0.4	<0.2	0.7 ± 0.2	0.3 ± 0.2

Table 4 shows the averaged data of the specific activity of radionuclides in the water of the river Pyshma over the last 10 years, when the BN-600 (since 1980) and BN-800 (since 2016) reactors were operated at the Beloyarsk NPP, and the annual variability in isotope concentration was insignificant. At the same time, the length of the Pyshma River from point (S1) to (S4) is almost 50 km, and the specific activity of artificial radionuclides in its waters in the early period of operation of the Beloyarsk NPP (operation of the AMB-100 and AMB-200 reactors) was territorially significantly different. For assessing the impact of the Beloyarsk NPP on river ecosystems, the long-term dynamics of the content of ^{137}Cs, ^{90}Sr and ^{3}H in the waters of the Pyshma and Olkhovka rivers, exposed to the direct impact of discharges from the nuclear power plant, was analyzed (Molchanova et al., 1985; Chebotina et al., 1992; Chebotina and Nikolin, 2005). Fig. 2 shows a significant decrease in the content of ^{137}Cs and ^{3}H in the studied rivers over a 40-year period of operation of the Beloyarsk NPP. Thus, the specific activity of ^{137}Cs in the water of the mouth of the r. Olkhovka (S5) for the period 1978–2019 decreased 480 times from 12 to 0.025 Bq/L. In the water of the river Pyshma before the confluence of the Olkhovka (S3) this decrease was 14 times, from 0.07 to 0.005 Bq/L, and after the confluence (S4) - 810 times, from 5.66 to 0.007 Bq/L (Fig. 2-A). Such a significant decrease in the ^{137}Cs content in the waters of the Olkhovka and Pyshma rivers is associated with the transition in the operation of the NPP from thermal (AMB) to fast reactors. (BN). There is a certain data gap from 1980 to 2000 for river ecosystems for ^{137}Cs and ^{90}Sr, since at that time considerable attention was paid to assessing the radiation safety of the cooling pond of the Beloyarsk NPP. These are the studies of 1975–1990 and beyond, which are described in detail in (Panov et al., 2022, 2023). They confirm the patterns of improving the radiation situation in the freshwater ecosystems of the region of Beloyarsk NPP over time.

The decrease in the ^{90}Sr concentration in the water of the Pyshma and Olkhovka rivers was much smaller, because initially, during the operation of AMB reactors, the content of radionuclide in the waste water of a nuclear power plant was not as high as ^{137}Cs (Panov et al., 2022, 2023). So, in the r. Olkhovka (S5), over 40 years of operation of the Beloyarsk NPP, the decrease in the specific activity of ^{90}Sr r in water was 3.5 times, from 0.2 to 0.058 Bq/L. In the water of the river Pyshma at point (S3) this decrease was up to 2.9 times, from 0.02 to 0.007 Bq/L and at point (S4) - 5.5 times, from 0.11 to 0.02 Bq/L (Fig. 2-B).

^{3}H during the period under review decreased most of all in the water of the r. Olkhovka (S5) - up to 36 times, from 4120 to 112 Bq/L (Fig. 2-C). In the water of the river Pyshma, this decrease was to a lesser extent. At point (S3) it was 2.5 times, from 55 to 22 Bq/L; at point (S4) - 5.3 times, from 160 to 30 Bq/L. In the background area (S1), the concentration of tritium in water has remained practically unchanged over a 40-year period. If we consider the specific activity of ^{3}H in the initial period of operation of the Beloyarsk NPP, when the AMB-100, AMB-200 and BN-600 reactors were jointly operated (1980–1985), then territorially along the river Pyshma radionuclide concentration in surface water was distributed as follows: (S1) - 19 Bq/L, (S3) - 49 Bq/L, (S4) - 190 Bq/L. In r. Olkhovka (S5) in the same period, the specific activity of tritium was 2340 Bq/L. Thus, during the operation of three reactors, discharges of the Beloyarsk NPP into the reservoir increased the content of ^{3}H in the surface waters of the river Pyshma 2.6 times, and in the river Olkhovka 123 times. According to the vector of river water flow there was some dilution of the radionuclide, and its concentration in the water significantly decreased. In general, the integral increase in the content of ^{3}H in the waters of the r. Pyshma from the functioning of the Beloyarsk NPP in 1980–1985 was 10 times, ^{137}Cs at least 80 times and ^{90}Sr more than 5 times.

In recent years, with the joint operation of the BN-600 and BN-800 reactors, the Beloyarsk NPP does not have a significant effect on the increase in the content of artificial radionuclides in the surface waters of the Pyshma River. Thus, the specific activity of the most radiologically significant ^{137}Cs in the river water practically does not change: (S1) - 0.0045, (S2) - 0.007, (S3) - 0.005, (S4) - 0.007 Bq/L. In r. Olkhovka (S5), the radionuclide content is slightly higher and is at the level of 0.03 Bq/L. Presented in Fig. 2, the results also show the absence of a significant additional input of artificial radioisotopes into the waters of the Pyshma and Olkhovka rivers after the start of operation of the new reactor BN-

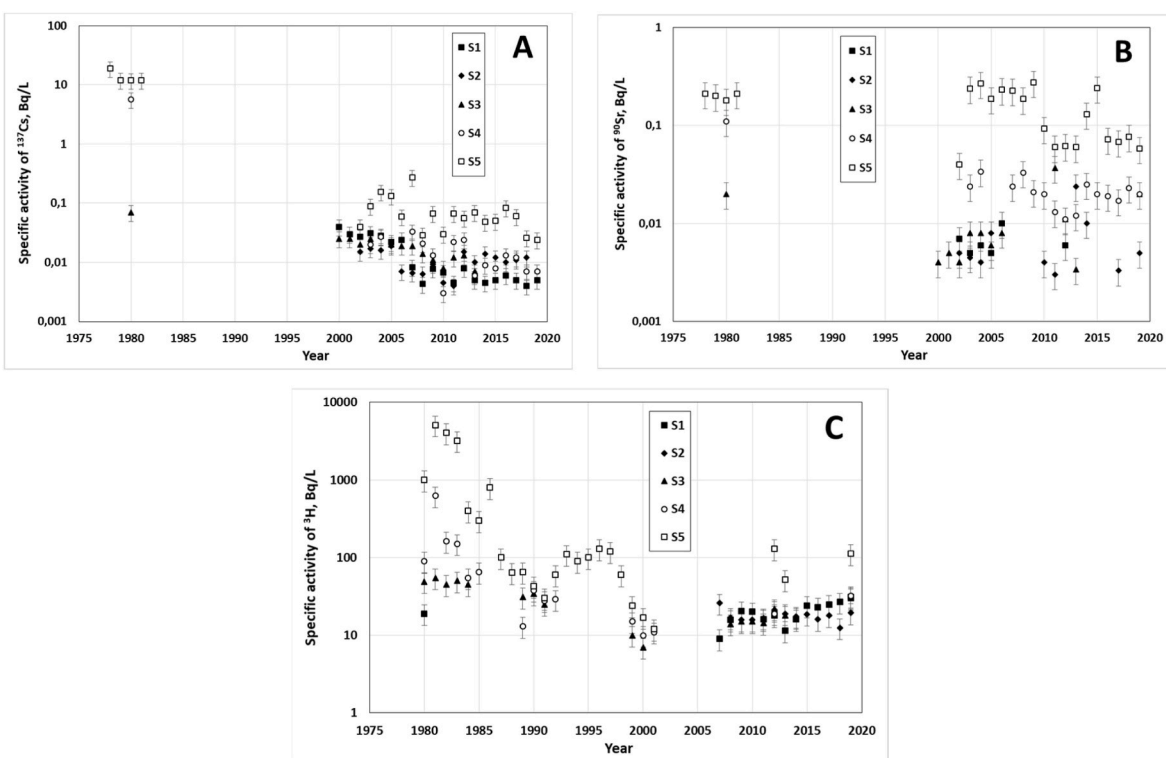

Fig. 2. Dynamics of radionuclides specific activity: A – ^{137}Cs, B – ^{90}Sr, C – ^{3}H in surface water of the control sites of Pyshma and Olkhovka rivers.

800 in 2016.

4.2. Dynamics of radionuclide specific activity in bottom sediments

The content of natural radionuclides in bottom sediments of the studied rivers varies within rather narrow limits and does not differ in abnormally high or low values at all sampling points (Table 5).

Artificial radionuclides from Beloyarsk NPP discharges, entering river ecosystems, migrate with the watercourse and are partially sorbed in bottom sediments, where they become a source of irradiation of bottom hydrobionts. At the same time, bottom sediments (mainly muddy sapropel), being a natural filter, play an important role in the purification of river water due to sorption processes. The maximum accumulation of technogenic radionuclides is observed in the bottom sediments of the r. Olkhovka (S5) and r. Pyshma downstream after the confluence of the r. Olkhovka (S4), where high concentrations of artificial radioisotopes in the water were noted. The data in Table 5 show that the content of ^{137}Cs in the bottom sediments of the r. Olkhovka (S5) is 29–418 times higher than the concentration of the radionuclide in other studied rivers. Specific activity of ^{90}Sr in bottom sediments of the r. Olkhovka is also slightly higher compared to other rivers in the zone of influence of the nuclear power plant (only 1.35–2.4 times). At the same time, it is necessary to note the wide variability of the specific activity of ^{137}Cs in the bottom sediments of the river Pyshma. So, before the confluence of the Olkhovka River (S3) into Pyshma, the radionuclide content in bottom sediments exceeds the background level of other rivers only 5–15 times (26.9 Bq/kg), and after the confluence of the river Olkhovka (S4) this difference increases up to 102–293 times (542 Bq/kg). And if in the first case such a ratio is due to the long-term contribution of ^{137}Cs discharges from the Beloyarsk NPP into the reservoir, in the second it is the role of radioactivity brought by the water of the Olkhovka river due to the drainage of isotopes from the swamp.

In general, the integral increase in the ^{137}Cs content in the bottom sediments of the Pyshma river from the long-term operation of the Beloyarsk NPP is currently more than 20 times compared to the regional background. At the same time, in addition to migration processes, the sorption of radionuclides by bottom sediments to a certain extent influenced the decrease in the specific activity of artificial radionuclides in the water of the Pyshma river.

In the initial period of the Beloyarsk NPP operation, ^{137}Cs and ^{90}Sr in bottom sediments were measured only at the most critical points S3, S4, and S5 (Molchanova et al., 1982, 1985). Analysis of the long-term (1978–2019) dynamics of the ^{137}Cs content in bottom sediments shows that the decrease in the specific activity of the radionuclide in this component of the freshwater ecosystem of the river Olkhovka (S5) was 38 times, from 29600 to 770 Bq/kg (Fig. 3-A).

In the bottom sediments of the Pyshma river, this decrease varied: before the confluence of the Olkhovka river (S3) 12 times, from 370 to 30 Bq/kg, and after the confluence of the Olkhovka river (S4) up to 87 times, from 29500 to 338 Bq/kg. Such a regularity of the decrease in the ^{137}Cs content in the bottom sediments of the studied river sections quite clearly correlates with a similar trend in the decrease in the radionuclide concentration in the water of the same sampling points.

Over 40 years of operation of the Beloyarsk NPP, the content of ^{90}Sr has also decreased in the bottom sediments of the Pyshma and Olkhovka rivers. In this component of the freshwater ecosystem of the r. Olkhovka (S5) it was 37 times, from 120 to 3.23 Bq/kg; in r. Pyshma (S3) - 12 times, from 5.9 to 0.49 Bq/kg; and at point (S4) - 27 times, from 13.3 to 0.49 Bq/kg (Fig. 3-B). Since over the same period of time, the decrease in the specific activity of the radionuclide in the water of the same sampling points was 2.5–5.3 times, it can be said that ^{90}Sr is sorbed to a lesser extent by bottom sediments, compared to ^{137}Cs.

Evaluation of the content of ^{60}Co in bottom sediments of rivers in the zone of influence of the Beloyarsk NPP began in the early 2000s (The radiation situation). However, this radionuclide also shows a significant decrease in its specific activity over the past 15 years: in the bottom sediments of the Olkhovka river (S5) it was 24.7 times, from 148 to 6 Bq/kg, and in the river Pyshma after the confluence of the Olkhovka river (S4) - 7.3 times, from 29 to 4 Bq/kg (Fig. 3-C). Considering that T½ ^{60}Co is 5.27 years, we can talk about the minimum additional intake of radionuclide in the waters of the Pyshma and Olkhovka rivers from the Beloyarsk NPP in recent years, and the decrease in its content in bottom sediments is mainly determined by radioactive decay.

Thus, the example of three radiologically important radionuclides shows a significant decrease in their content in the bottom sediments of the rivers in the zone of influence of the Beloyarsk NPP, due to the transition to the technology of electricity production from thermal to fast reactors, as well as the improvement of the protection and safety systems of the power units of the nuclear power plant.

4.3. Radionuclide specific activity in floodplain soil

Contamination of floodplain soils with artificial radionuclides usually occurs as a result of their flooding during river floods. The main content of radionuclides entering the soil is deposited in its upper 0–10 cm layer (Molchanova et al., 1982). The study in 2011 of the floodplain soils of the Olkhovka (S5), Gagarka (S6) and Mezenka (S8) rivers showed that if in terms of natural (^{40}K) and a number of artificial (^{90}Sr, ^{239,240}Pu) radionuclides these soils are similar, then in terms of specific activity of ^{137}Cs they differ significantly (Fig. 4).

Table 5
Specific activity of radionuclides in bottom sediments of the rivers near Beloyarsk NPP in 2011–2019, Bq/kg (mean ± standard deviation).

Nuclide	Pyshma (S1–S4)	Olkhovka (S5)	Gagarka (S6)	Kamyshenka (S7)	Mezenka (S8)	Rezhik (S9)	Kamenka (S10)
Gross β	505 ± 324	871 ± 438	226 ± 59	371 ± 75	363 ± 18	413 ± 11	284 ± 27
Natural radionuclides							
^{230}Th	57 ± 5	38 ± 4	57 ± 6	46 ± 4	69 ± 4	95 ± 11	93 ± 12
^{226}Ra	17 ± 6	16 ± 5	18 ± 7	31 ± 12	108 ± 63	<8.9	112 ± 48
^{214}Bi	<3.2	<1.5	<2.4	<5.8	<4.2	<1.2	<6.7
^{210}Pb	<100	<100	<100	<100	<100	<100	<100
^{232}Th	74 ± 8	62 ± 5	46 ± 5	74 ± 14	89 ± 11	81 ± 3	90 ± 13
^{228}Ra	17 ± 8	24 ± 14	27 ± 20	33 ± 19	79 ± 9	72 ± 3	79 ± 12
^{228}Th	163 ± 10	156 ± 5	120 ± 19	143 ± 14	174 ± 7	178 ± 3	187 ± 16
^{40}K	318 ± 63	100 ± 60	227 ± 38	354 ± 90	241 ± 13	216 ± 60	160 ± 98
Artificial radionuclides							
^{3}H	–	5400 ± 600	–	–	–	–	7000 ± 100
^{60}Co	4.0 ± 1.9	9.6 ± 5.2	0.7 ± 0.3	<0.4	0.3 ± 0.1	<0.4	<0.7
^{90}Sr	10 ± 6	19 ± 9	8.2 ± 5.3	14 ± 6	8.9 ± 3.8	12 ± 0.1	9.6 ± 0.7
^{134}Cs	<0.6	<0.4	0.8 ± 0.6	1.5 ± 0.8	<1.3	0.9 ± 0.3	0.8 ± 0.4
^{137}Cs	27 ± 17[a]	773 ± 74	5.3 ± 3.9	3.3 ± 1.8	1.9 ± 1.3	3.5 ± 0.8	4.3 ± 1.3
^{239,240}Pu	0.1 ± 0.01	1.7 ± 0.6	–	–	–	–	–
^{241}Am	0.7 ± 0.1	<0.7	<0.9	3.8 ± 2.0	<0.7	<0.5	<0.7

[a] - after the confluence of the river Olkhovka indicator is 542 ± 142 Bq/kg.

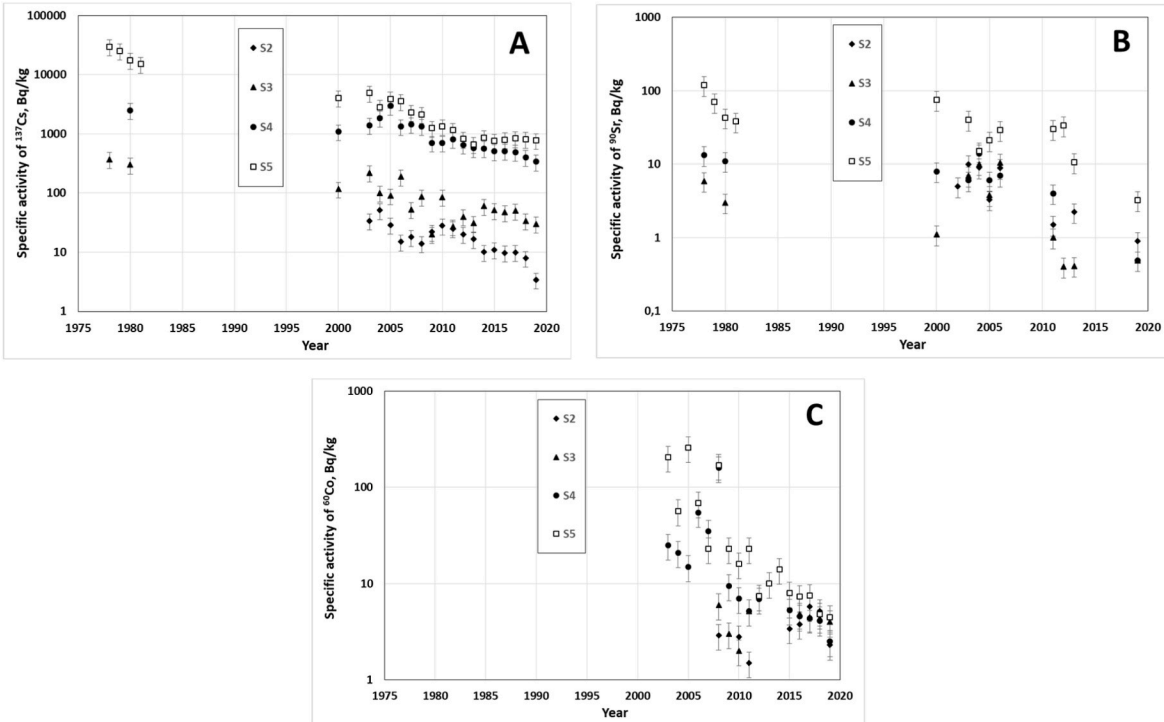

Fig. 3. Dynamics of radionuclides specific activity: A – ^{137}Cs, B – ^{90}Sr, C –^{60}Co in bottom sediments of the Pyshma and Olkhovka rivers in the vicinity of Beloyarsk NPP.

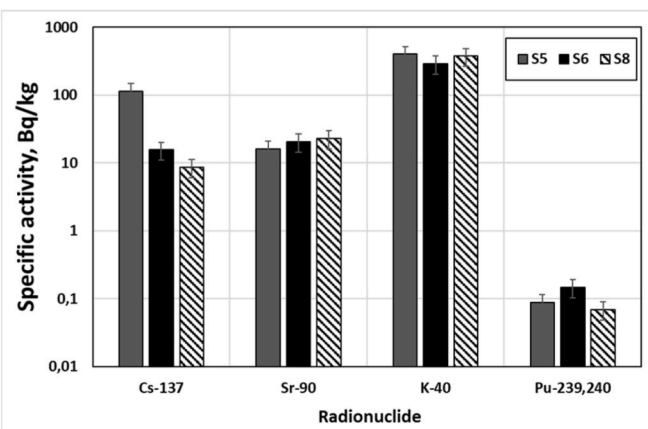

Fig. 4. Radionuclides specific activity in floodplain soil of the rivers in the vicinity of Beloyarsk NPP (2011): S5 - Olkhovka, S6 - Gagarka, S8 - Mezenka.

In the floodplain soils of the river Olkhovka, the concentration of ^{137}Cs is 7.3–13.3 times higher. Such differences are influenced by the dynamics of the watering level of the Olkhovsky swamp. The water discharge during the flood and the low-water season in it is 0.3 and 0.04 m^3/s, respectively. Therefore, the periodic floods of the Olkhovka river containing increased radionuclide activity leads to additional contamination of floodplain soils with ^{137}Cs, compared to the Gagarka and Mezenka rivers. At the same time, the area of such radioactively contaminated sections of the mouth of the Olkhovka river is limited to a few meters within the river bed.

4.4. Dynamics of radionuclide specific activity in macrophytes

Macrophytes are an important group of aquatic organisms that produce the main biomass of freshwater ecosystems and sorb radionuclides from surface waters. The content of radioisotopes in macrophytes is higher than in water. The degree of their accumulation in macrophytes is influenced by a large number of factors: the chemical nature of radionuclides, their physicochemical form, species characteristics of aquatic plants, concentration of isotopic and non-isotopic carriers in water, water temperature, illumination, trophicity of the reservoir, etc. (Trapeznikov and Trapeznikova, 2012).

Macrophytes of six species (combined sample) were taken in the rivers of the zone of influence of the Beloyarsk NPP in the period 2011–2019. A comprehensive analysis of the data obtained (Fig. 5) allowed us to form a series of sampling points of rivers according to the degree of decrease in the accumulation of the most radiologically significant ^{137}Cs in this group of aquatic plants: (S5) – average 1136 > (S4) – 64.3 > (S2) – 16.6 ≥ (S3) – 16.4 > (S1) – 14.5 > (S8) – 4.1 ≥ (S6) – 3.7 ≥ (S9) – 3.5 > (S10) – 1.8 ≥ (S7) – 1.6 Bq/kg.

The presented sequence of the average specific activity of ^{137}Cs in macrophytes confirms the above-identified regularities of the radionuclide content in other components of river ecosystems, primarily in water. Thus, the maximum levels of ^{137}Cs accumulation were noted in macrophytes of the Olkhovka river, which exceed the indicators of other rivers in the zone of influence of the nuclear power plant 18–710 times (Fig. 5-A). Significantly less radioisotope accumulates in the macrophytes of the Pyshma river after the confluence of the Olkhovka river (S4), where there are also elevated levels of ^{137}Cs in the water. In the macrophytes of the Pyshma river site in the area of the Beloyarsk reservoir, the radionuclide accumulates approximately the same, at a level of 15–17 Bq/kg, and minimally in other rivers in the zone of influence of the nuclear power plant (within 1.5–4.0 Bq/kg).

The patterns of ^{90}Sr accumulation in macrophytes are not as clear as for ^{137}Cs. Due to the lower concentrations of ^{90}Sr in water, they are largely determined by the species characteristics of macrophytes (Fig. 5-B). At the same time, over the almost 10-year period under consideration, there is a certain tendency towards a decrease in the ^{90}Sr content in aquatic plants at all sampling points. The lack of dynamics in the increase in the content of the considered artificial radionuclides in macrophytes in recent years confirms the absence of a significant

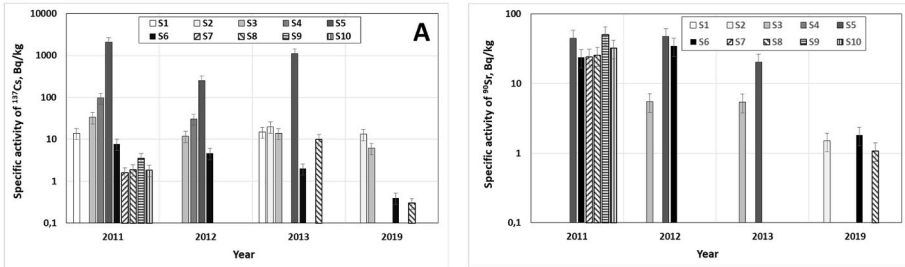

Fig. 5. Dynamics of radionuclides specific activity: A – ^{137}Cs, B – ^{90}Sr in macrophytes of the rivers in the vicinity of Beloyarsk NPP: S1 – Pyshma before flowing into Beloyarsk reservoir, S2 – Pyshma below the dam of Beloyarsk reservoir, S3 – Pyshma before the confluence of Olkhovka river, S4 – Pyshma after the confluence of Olkhovka river, S5 – Olkhovka, S6 – Gagarka, S7 – Kamyshenka, S8 – Mezenka, S9 – Rezhik, S10 - Kamenka.

additional intake of radioisotopes with the waste water during the operation of reactors BN-600 and BN-800.

4.5. Dynamics of radionuclide specific activity in ichthyofauna

Unlike aquatic plants, representatives of ichthyofauna actively migrate in the waters of river ecosystems, therefore, it is quite difficult to accurately record the effect of the place of discharges of artificial radionuclides of a NPP on fish. At the same time, the ichthyofauna is an important link in the food chain of the freshwater ecosystem, as well as a human food product that makes a certain contribution to the formation of its internal radiation dose. For a critical group of the population ("fishermen"), this contribution to dose can be significant. Monitoring of the content of radionuclides in the ichthyofauna of rivers in the zone of influence of the Beloyarsk NPP was focused on assessing the specific activity of ^{137}Cs and ^{90}Sr, which are subject to radiation control (Fig. 6).

Thus, the content of ^{137}Cs in the pike of rivers in the area where the NPP is located varies within 0.6–2.1 Bq/kg, in roach - in the range 0.8–2.1 Bq/kg. This is 62–217 times lower than the current in Russia criterion for the radiation safety of fish for this radionuclide (CL - 130 Bq/kg) (Sanitary Rules and Norms). ^{90}Sr accumulates in pike in the range 1.1–5.3 Bq/kg, in roach in the range 1.3–3.7 Bq/kg. This is 19–91 times lower than the standard for this radioisotope (CL - 100 Bq/kg). Thus, the ichthyofauna inhabiting the rivers of the zone of influence of the Beloyarsk NPP fully meets the requirements of radiation safety with a large safety factor.

In the first period of the Beloyarsk NPP operation, studies on the accumulation of artificial radionuclides in the ichthyofauna were carried out only in the reservoir, which has a common channel with the river Pyshma. According to (Chebotina et al., 1992), in the pike of the Beloyarsk reservoir in 1977, the ^{137}Cs content was 113 Bq/kg, and in the rivers in the zone of influence of the nuclear power plant in 2011, on average, 1.47 Bq/kg. The specific activity of the radionuclide in roach in 1977 was 62 Bq/kg, and in the studied rivers in 2011 on average - 1.25 Bq/kg. Despite the fact that these data characterize the content of ^{137}Cs in the ichthyofauna of different freshwater ecosystems (reservoir and rivers), the presence of the common basin of the river Pyshma and the migratory ability of fish suggest a tendency for the reduction in time of radioactive contamination of fish resources in aquatic ecosystems in the zone of influence of the Beloyarsk NPP. In general, the presented results demonstrate an improvement in the radioecological situation in river ecosystems and an increase in the level of radiation safety of the population in the area of the location of this largest radiation hazardous facility in the region.

5. Conclusion

1. The presented results of long-term monitoring studies allow us to conclude that the operation of the Beloyarsk NPP influenced the contamination of a number of river ecosystems located in a 15-km zone around the nuclear power plant with artificial radionuclides. This impact was especially significant on the Olkhovka and Pyshma rivers in the first years of the Beloyarsk NPP operation during the operation of the AMB-100 and AMB-200 thermal reactors and related emergencies. Moreover, in the surface waters of the largest river Pyshma ^{137}Cs content increased more than 80 times, ^{3}H more than 10 times, ^{90}Sr up to 5 times.
2. After the decommissioning of the AMB-100 and AMB-200 thermal reactors at the Beloyarsk NPP, the content of artificial radionuclides in all components of river ecosystems decreased tens and hundreds of times. So, in the Olkhovka river, which is subject to the greatest radioactive contamination from the discharges of the nuclear power plant, a decrease in the specific activity of ^{137}Cs in water in the period 1978–2019 was 480 times, ^{3}H - 36 times, ^{90}Sr - 3.5 times. First of all, this was due to the transition of the Beloyarsk NPP to the production of electricity from thermal (AMB) to fast (BN) reactors and a significant decrease in the activity of artificial radionuclides discharged into aquatic ecosystems (Beloyarsk reservoir and Olkhovsky swamp).
3. The second group of fundamental factors that influenced the self-cleaning of rivers from artificial radionuclides of the Beloyarsk NPP in a long time period were: migration of radioisotopes with a watercourse, mechanisms of redistribution of radionuclides from water to other components of the freshwater ecosystem, primarily

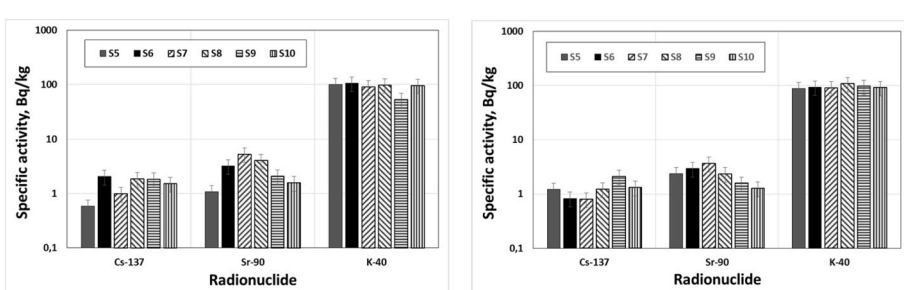

Fig. 6. Radionuclides specific activity in: A – pike, B –roach of the rivers near Beloyarsk NPP (2011): S5 – Olkhovka, S6 – Gagarka, S7 – Kamyshenka, S8 – Mezenka, S9 – Rezhik, S10 - Kamenka.

into bottom sediments, and partly into floodplain soils and macrophytes, as well as radioactive decay.

4. In recent years, during the operation of the BN-600 and BN-800 reactors at the Beloyarsk NPP, the content of artificial radionuclides in the main components of river ecosystems in the zone of influence of the NPP, with the exception of the river Olkhovka corresponds to the level of the regional background. In Olkhovka river, there are higher concentrations of artificial radionuclides in surface waters and bottom sediments. At the same time, the water of this river meets the radiation safety criteria that apply to drinking water. All this indicates a stable radiation situation in the rivers of the zone of influence of the Beloyarsk NPP and a steady trend towards its improvement in the future.

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.

Data availability

Data will be made available on request.

References

Alexakhin, R.M., 2013. Topical environmental problems of nuclear power. Atom. Energy 114 (5), 301–307.

Chebotina, M.Ya, Nikolin, O.A., 2005. Yekaterinburg. In: Bolshakov, V.N. (Ed.), Radioecological Studies of Tritium in the Ural Region, Ural Branch of the Russian Academy of Sciences, p. 91 (in Russ.).

Chebotina, M.Ya, Trapeznikov, A.V., Trapeznikova, V.N., Kulikov, V.N., 1992. Radioecological Studies of the Beloyarsk Reservoir. Sverdlovsk, Ural Branch of the Academy of Sciences of the USSR, p. 78 (in Russ.).

Djingova, R., Kuleff, I., 2002. Concentration of caesium-137, cobalt-60 and potassium-40 in some wild and edible plants around the nuclear power plant in Bulgaria. J. Environ. Radioat. 59 (1), 61–73.

Edomskaya, M.A., Lukashenko, S.N., Stupakova, G.A., Kharkin, P.V., Gluchshenko, V.N., Korovin, S.V., 2022. Estimation of radionuclides global fallout levels in the soils of CIS and Eastern Europe territory. J. Environ. Radioact. 247, 106865.

Eisenbud, M., Gesell, T., 1997. Environmental Radioactivity from Natural, Industrial and Military Sources, forth ed. Academic Press., San Diego, London, Boston, New York, Sydney, Tokyo, Toronto, p. 656.

Guidelines for organizing monitoring of the state of the natural environment in the area of NPP location. In: Makhonko, K.P. (Ed.), 1990. USSR State Committee for Hydrometeorology. Hydrometeoizdat, Leningrad. (in Russ.).

Hu, Q.H., Weng, J.Q., Wang, J.S., 2010. Sources of anthropogenic radionuclides in the environment: a review. J. Environ. Radioact. 101 (6), 426–437.

IAEA, 2005. RS-G-1.8. Environmental and Source Monitoring for Purposes of Radiation Protection. IAEA, Vienna.

IAEA, 2010. Safety Reports Series No. 64. Programmes and Systems for Source and Environmental Radiation Monitoring. IAEA, Vienna.

IAEA, 2014. IAEA Safety Standards. Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards. IAEA, No. GSR, Vienna. Part 3.

Kim, B.K., Jeong, Y.H., 2013. High cooling water temperature effects on design and operational safety of NPPs in the gulf region. Nucl. Eng. Technol. 45 (7), 961–968.

Koltik, I.I., 2001. Nuclear Power Plants and Radiation Safety. USTU-UPI, Ekaterinburg, p. 366 (in Russ.).

Koltik, I.I., Oshkanov, N.N., 2005. Evaluation of the radiation risks related to the Beloyarsk NPP BN600 power unit operation on general public. Izvestiya vuzov. Nuclear energy. 1, 35–38 (in Russ.).

Kong, T.Y., Kim, S., Lee, Y., Son, J.K., Maeng, S.J., 2017. Radioactive effluents released from Korean nuclear power plants and the resulting radiation doses to members of the public. Nucl. Eng. Technol. 49 (8), 1772–1777.

Kryshev, I.I., 1996. Radioactive contamination of aquatic ecosystems in the areas of nuclear power plants and other nuclear facilities in Russia. Radiochim. Acta 74 (S1), 199–202.

Kuznetsov, V.M., 2003. The Main Problems and the Current State of Safety at Nuclear Fuel Cycle Enterprises in Russia. Rakurs Production Agency, Moscow, p. 242 (in Russ.).

Lee, U., Lee, C., Kim, M., Kim, H.R., 2019. Analysis of the influence of nuclear facilities on environmental radiation by monitoring the highest nuclear power plant density region. Nucl. Eng. Technol. 51 (6), 1626–1632.

Manual for Hydrometeorological Stations and Posts. Iss. 12. Observations of Radioactive Contamination of Components of the Natural Environment: a Guidance Document RD 52.18.826-2015, 2015. Roshydromet, FSBI "NPO" Typhoon", Obninsk (in Russ.).

Vakulovsky, S.M. (Ed.), 1986. Methodological Recommendations for Determining Radioactive Contamination of Water Bodies. Hydrometeoizdat, Moscow (in Russ.).

Methodological recommendations for sanitary control over the content of radioactive substances in objects of the external environment. In: Mareya, A.N., Zykova, A.S. (Eds.), 1980. Ministry of Health of the USSR. Moscow. (in Russ.).

Mikailova, R.A., Kurbakov, D.N., Sidorova, E.V., Geshel, I.V., Andreeva, N.V., Sorokin, YuV., Panov, A.V., 2020. Comprehensive radioecological monitoring of freshwater ecosystems in the vicinity of Rooppur NPP (People's Republic of Bangladesh). Mar. Biol. (Berl.) J. 5 (3), 30–54.

Molchanova, I.V., Karavaeva, E.N., Chebotina, M.Ya, Kulikov, N.V., 1982. The distribution of 90Sr и 137Cs over components of the swamp-river ecosystem. Ecology 2, 45–49.

Molchanova, I.V., Karavaeva, E.N., Kulikov, N.V., 1985. Some results of radioecological studies on natural ecosystems in the region of the Beloyarskaya Nuclear Power Plant. Ecology 5, 30–34.

Olsen, C.R., Larsen, I.L., Cutshall, N.H., Donoghue, J.F., Bricker, O.P., Simpson, H.J., 1981. Reactor-released radionuclides in susquehanna river sediments. Nature 294, 242–245.

Oshkanov, N.N., Govorov, P.P., 2009. BN-600 Liquid metal reactor - main features and operating experience. Izvestiya vuzov. Nucl. Energy. 2, 7–20 (in Russ.).

Oshkanov, N.N., Sheinkman, A.G., Govorov, P.P., 1994. Analysis of the operational reliability of a power-generating unit with a BN-600 reactor during the period 1980-1993. Atom. Energy 76 (3), 165–168.

Panov, A.V., Kuznetsov, V.K., Isamov, N.N., Geshel, I.V., Trapeznikov, A.V., Korzhavin, A.V., 2021a. Assessment of the influence of BN-800 operation on the radioecological situation in the vicinity of Beloyarsk NPP. Atom. Energy 129 (5), 297–304.

Panov, A.V., Trapeznikov, A.V., Korzhavin, A.V., Geshel, I.V., Korovin, S.V., Edomskaya, M.A., 2021c. Radiation monitoring of drinking water in the vicinity of the Beloyarsk NPP. Radiation Hygiene 14 (1), 86–101.

Panov, A.V., Trapeznikov, A.V., Kuznetsov, V.K., Korzhavin, A.V., Isamov, N.N., Geshel, I.V., 2021b. Radioecological monitoring of agroecosystems in the vicinity of Beloyarsk NPP. Bull. Tomsk Polyt. Univ., Geo Ass. Eng. 332 (3), 146–157.

Panov, A.V., Trapeznikov, A.V., Trapeznikova, V.N., Korzhavin, A.V., 2022. Influence of operation of thermal and fast reactors of the Beloyarsk NPP on the radioecological situation in the cooling pond. Part 1: surface water and bottom sediments. Nucl. Eng. Technol. 54 (8), 3034–3042.

Panov, A.V., Trapeznikov, A.V., Trapeznikova, V.N., Korzhavin, A.V., 2023. Influence of operation of thermal and fast reactors of the Beloyarsk NPP on the radioecological situation in the cooling pond. Part 2: macrophytes and fish. Nucl. Eng. Technol. 55 (2), 707–716.

Resolution of the Government of the Russian Federation, 2007. N 253 "On the Procedure for Maintaining the State Water Register in Russ.

Sanitary Rules and Norms 2.3.2.2650-10 Additions and Changes N 18 to Sanitary Rules and Norms 2.3.2.1078-01 "Hygienic Requirements for Food Safety and Nutritional Value", 2010. Ministry of Health of the Russian Federation, Moscow (In Russ.).

Sanitary Rules and Norms 2.6.1, 2010. In: Russ (Ed.), 2800-10 "Hygienic Requirements to Limitation of Population Exposure from Natural Ionizing Irradiation Sources".

Sohrabi, M., Parsouzi, Z., Amrollahi, R., Khamooshy, C., Ghasemi, M., 2013. Public exposure from environmental release of radioactive material under normal operation of unit-1 Bushehr nuclear power plant. Ann. Nucl. Energy 55, 351–358.

Song, J.H., Kim, T.J., Yeon, J.W., 2020. Radioactivity data analysis of ^{137}Cs in marine sediments near severely damaged Chernobyl and Fukushima nuclear power plants. Nucl. Eng. Technol. 52 (2), 366–372.

The Radiation Situation, 1991. on the Territory of Russia and Neighboring States in. Yearbook. Roshydromet, FSBI "NPO" Typhoon", Obninsk (in Russ.).

Trapeznikov, A.V., Trapeznikova, V.N., 2012. Yekaterinburg. In: AcademNauka, I.M. Donnik (Ed.), Freshwater Radioecology, p. 544 (in Russ.).

Trapeznikov, A.V., Trapeznikova, V.N., Korjavin, A.V., 2015. Dynamics of radioecological state of the fresh-water ecosystems affected by a long-term impact from nuclear power plant in the frontiers of the zone under observation. Radiation biology. Radioecology 55 (3), 302–313 (in Russ.).

Aleksei Valerievich Panov Dr. Sc., prof. RAS, acting director, National Research Nuclear University MEPhI, Obninsk, Kaluga region, 249040, Russia.

Alexander Viktorovich Trapeznikov, Dr. Sc., head of department, Institute of Plant and Animal Ecology, Russian Academy of Science, Ural branch, 8 Marta str., 202, Yekaterinburg, 620144, Russia.

Vera Nikolaevna Trapeznikova, Cand. Sc., senior researcher, Institute of Plant and Animal Ecology, Russian Academy of Science, Ural branch, 8 Marta str., 202, Yekaterinburg, 620144, Russia.

Alexander Vasilievich Korzhavin, Cand. Sc., senior researcher, Institute of Plant and Animal Ecology, Russian Academy of Science, Ural branch, 8 Marta str., 202, Yekaterinburg, 620144, Russia.