ISSN 1995-0829, Inland Water Biology, 2022, Vol. 15, No. 3, pp. 324–330. © Pleiades Publishing, Ltd., 2022.
Russian Text © The Author(s), 2022, published in Biologiya Vnutrennykh Vod, 2022, No. 3, pp. 310–316.

AQUATIC TOXICOLOGY

Dose Power Estimation for Fish in the Lower Reaches of the Ob River

V. G. Gorodetsky[a, *], A. V. Trapeznikov[a], V. N. Trapeznikova[a], and A. V. Korzhavin[a]

[a] *Institute of Plant and Animal Ecology, Russian Academy of Science, Ural Branch, Yekaterinburg, Russia*

**e-mail: vgorodetsky@mail.ru*

Received June 8, 2021; revised August 18, 2021; accepted November 15, 2021

Abstract—The power of radiation exposure to ^{90}Sr and ^{137}Cs on fish in the lower reaches of the Ob River has been assessed. We use the long-term results of radioecological monitoring of the Ob-Irtysh river system for the period of 2004–2017. The data from laboratory analyses of studies on the radionuclides content in water, bottom sediments, and ichthyofauna of the lower Ob River within the boundaries of the Khanty-Mansi (2004–2010) and Yamalo-Nenets autonomous okrugs (2014–2017), etc., are included. The ERICA Tool 1.3.1.49 (Tier 2) software is used to calculate the radiation power of exposure. The rates of total radiation power of exposure to ^{90}Sr and ^{137}Cs are calculated for all species of the studied fish. We also calculated the power of internal and external radiation exposure, both to ^{90}Sr and ^{137}Cs in seven fish species in the Khanty-Mansi Autonomous Okrug and eight species in the Yamalo-Nenets Autonomous Okrug. The calculations are carried out taking into account the body length and weight of the studied fish. The power exposure to radiation for all species of studied fish does not exceed the ICRP-recommended levels of the conservative ecologically safe radiation level. The power of exposure to radiation due to the internal irradiation in all species of fish is higher than that determined by the external irradiation. The main contribution to the formation of the radiation exposure power for all the fish studied is determined by ^{90}Sr accumulated in the fish organisms. A comparison is made of the radiation dose power for fish from the downstream Ob River and fish in the Techa River near the Mayak Production Association, in the Romashka and Tom rivers, near the Siberian Chemical Combine, in the Yenisei River near the Mining and Chemical Combine, in the Beloyarsk Reservoir near the Beloyarsk NPP, and in the Neman River.

Keywords: downstream Ob River, technogenic radionuclides, bottom sediments, fish fauna, exposure to radiation, PA Mayak, Siberian Chemical Combine, Mining and Chemical Combine, Beloyarsk NPP, Neman River

DOI: 10.1134/S1995082922030051

INTRODUCTION

The radioecological situation in the downstream reaches of the Ob River and its floodplain is mainly determined by the process of radionuclide removal from the catchment area. The radionuclides appear in the catchment by the global precipitation from the atmosphere and the enter the Ob-Irtysh river network as a result of the activities of nuclear complex enterprises situated in the Ob-Irtysh basin (*Ecology* ..., 2006).

In 1949–1951, PA Mayak discharged into the Techa River ~10^{17} Bq of liquid radioactive waste. A significant part of the radioactivity transited along the Techa, Tobol, Irtysh, and lower Ob rivers to the Ob Guba (gulf) (Trapeznikov et al., 2018). The other part (~4.6 Pbq ^{137}Cs and ~4.3 PBq ^{90}Sr) is deposited in bottom sediments of rivers and their floodplain soils (Trapeznikov, 2010).

Abbreviations: PA, production association; KhMAO, Khanty-Mansi Autonomous Okrug; YaNAO, Yamalo-Nenets Autonomous Okrug.

In 1993, as a result of an accident at the Siberian Chemical Combine, 30.9 TBq of activity was discharged into the environment, including 6.3 GBq of ^{239}Pu. A >7-km-long radioactive trace was formed on the earth's surface (Aleksakhin et al., 2001; Tetenev et al., 2008). Before the shutdown of the last reactor in 2008, liquid waste containing radionuclides entered the Romashka River and further to the Tom River (right-bank tributary of the Ob River) (Nikitin et al., 2010). Floodplain soils and bottom sediments were contaminated (*Radioecological* ..., 2015).

The northern part of the Ob-Irtysh river system catchment area is contaminated with atmospheric precipitation of radioactive substances as a result of nuclear weapons testing at the Novaya Zemlya test site and the southern part as a result of testing at the Semipalatinsk test site and the Lobnor test site (China). Part of the radioactive contamination from the catchment area of the Ob-Irtysh basin, with river discharge entering the Ob Guba, is concentrated in bottom sediments in the mixing zone of fresh and salt water (Semenkov et al., 2015; Miroshnikov et al., 2020).

The input of ^{90}Sr and ^{137}Cs with water into the downstream Ob from the midstream Ob exceeds the input of these radionuclides from the Irtysh River (Trapeznikov et al., 2016). During the flood period and prolonged rains, the secondary pollution of rivers occurs through floodplain areas, which requires constant monitoring of the radioecological situation of the river system (*Conclusion* ..., 2008).

Commercial fishing is carried out in the downstream Ob basin. This is why monitoring the content of technogenic radionuclides in the fish fauna is extremely topical. Fish accumulate radionuclides through the food chain and directly from the water.

On the one hand, it is important to determine the content of radionuclides in fish as a food product from the point of view of sanitary and hygienic requirements; on the other hand, it is important to assess the radioecological risks for the fish itself due to its internal and external exposure from the radionuclides in the environment (water and bottom sediments).

The goal of this paper is to assess the power of the doses of radioactive contamination in the fish of the lower Ob within the borders of KhMAO and YaNAO and provide a comparative analysis of this indicator with that of fish in rivers flowing in the zones of influence of Rosatom enterprises: PA Mayak Production Association, Siberian Chemical Combine, Mining and Chemical Plant, and Beloyarsk Nuclear Power Plant.

MATERIALS AND METHODS

To estimate the dose rate of fish fauna of the downstream Ob, field research data from the Department of Continental Radioecology of the Institute of Plant and Animal Ecology, Russian Academy of Science, Ural Branch, in KhMAO (2004–2010) and YaNAO (2014–2017) were used. These data were summarized in papers by G.A. Trapeznikov et al. (2014, 2016, 2018).

The results of a study on the content of ^{90}Sr and ^{137}Cs in fish, water, and bottom sediments in the lower Ob were processes to prepare the initial data for calculating the radiation dose rate in the ERICA Tool 1.3.1.49 program (http://www.erica-tool.com), taking into account the body length and weight of the studied fish species. The power of the radiation dose was estimated for two sections of the lower Ob downstream from Khanty-Mansiysk, 20 km (KhMAO) and ~1000 km (YaNAO, 10 km upstream of the city of Labytnangy).

Upon an assessment of external exposure doses from bottom sediments in the ERICA Tool 1.3.1.49 (Tier 2) software, data on the content of radionuclides in the 10-cm upper layer of sediments were used. The dry weight of bottom sediments was taken as 70% of the wet weight.

The following fish species were analyzed:

Goldfish *Carassius carassius* (Linnaeus, 1758), age 2–3 years, bottom dweller. Feeds on zooplankton, zoobenthos, nektobenthos, and algae. Body is short and laterally compressed.

Bream *Abramis brama* (L., 1758), age 3–5 years, bottom dweller, feeds on zoobenthos. Relatively large fish with a high body, laterally compressed.

Burbot *Lota lota* (L., 1758), age 3–5 years, bottom dweller, feeds on fish and small invertebrates, body elongated–rounded in the frontal part.

Perch *Perca fluviatilis* (L., 1758), age 2–3 years, feeds on fish and invertebrates. The body is laterally compressed.

Peled (northern whitefish) *Coregonus peled* (Gmelin, 1789), age 2–3 years. It feeds on zoobenthos, nektobenthos, zooplankton, and phytoplankton. The body is high, laterally compressed. Semianadromous fish.

Common whitefish (European whitefish) *Coregonus lavaretus* (L., 1758), age 4–6 years. It feeds on benthos and nektobenthos. The body is elongated, laterally flattened. Semi-anadromous fish.

Roach *Rutilus rutilus* (L., 1758), age 3–5 years. Feeds on zooplankton, zoobenthos, algae and hydrophytes. The body is somewhat laterally compressed.

Sardine cisco *Coregonus sardinella* (Valenciennes, 1848), age from 4 to 6 years. Feeds mainly on zooplankton. The body is elongated, herring-shaped.

Broad whitefish *Coregonus nasus* (Pallas, 1776), age 5–7 years. A typical benthivore. The body is high, laterally flattened. Semi-anadromous fish.

Pike *Esox lucius* (L., 1758), age 3–6 years. Piscivore. Body elongated, torpedo-shaped, somewhat laterally compressed.

Ide *Leuciscus idus* (L., 1758), age 5–7 years. Feeds on zoobenthos. Body moderately elongated, oval.

The ERICA Tool 1.3.1.49 (Tier 2) software was used when assessing the power of radiation doses. The parameters of ellipsoids approximating the shape of each fish species were calculated. The parameters were entered into the program. Dose powers were calculated for each of the three replicates in all fish species.

RESULTS

Parameters of approximating ellipsoids. For each fish species, the parameters of an ellipsoid approximating its shape (height, width, and length) were calculated. The dimensions of the axes of the approximating ellipsoid were chosen so that the volume of the ellipsoid was equal to the volume of the fish, taking its density equal to that of water. The ratios between the dimensions of the ellipsoid axes were chosen taking into account the mass of fish prevailing in the catches and the ratio of the proportions of time spent by fish in the water column and near the bottom, considering the modes of life and feeding (Table 1).

Table 1. Parameters of ellipsoids approximating the shape of fish

Fish species	Body weight, kg	Sizes of approximating ellipsoid, m			Share of time spending in water/at the bottom
		height	width	length	
Goldfish	0.20	0.074	0.037	0.143	0.2/0.8
Bream	0.50	0.120	0.030	0.265	0.2/0.8
Burbot	0.50	0.060	0.043	0.370	0.2/0.8
Perch	0.10	0.048	0.027	0.150	0.8/0.2
Peled	0.40	0.080	0.033	0.290	0.5/0.5
Roach	0.06	0.045	0.023	0.110	0.5/0.5
Common whitefish	0.30	0.062	0.040	0.230	0.5/0.5
Sardine cisco	0.15	0.048	0.026	0.230	0.5/0.5
Broad whitefish	1.10	0.100	0.055	0.380	0.2/0.8
Pike	1.50	0.080	0.070	0.510	0.8/0.2
Ide	0.95	0.090	0.065	0.310	0.2/0.8

Table 2. Content of ^{90}Sr and ^{371}Cs in water (mBq/L) and in 10-cm bottom sediments (Bq/kg) in the lower Ob section 20 km downstream from Khanty-Mansiysk

Component of environment	Radionuclide	Content of radionuclides				Mean
		2004	2006	2008	2010	
Water	^{90}Sr	12.5 ± 3.5	125.0 ± 13.0	23.7 ± 4.9	20.0 ± 4.0	45.0 ± 8.0
	^{137}Cs	0.17 ± 0.09	10.6 ± 1.8	0.39 ± 0.08	1.87 ± 0.19	3.26 ± 0.76
Bottom sediments	^{90}Sr	0.52 ± 0.23	1.70 ± 0.99	19.9 ± 1.3	10.0 ± 2.0	8.04 ± 2.15
	^{137}Cs	2.56 ± 1.03	0.33 ± 0.09	1.05 ± 0.05	<0.01	0.98 ± 0.39

Table 3. Total power of radiation doses from ^{90}Sr and ^{137}Cs (nGy/day) in fish at the lower Ob cross section 20 km downstream from Khanty-Mansiysk

Fish species	2004	2006	2008	2010	Mean
Goldfish	–	–	164 ± 84	96 ± 56	130 ± 35
Bream	111 ± 9	815 ± 560	–	81 ± 6	336 ± 164
Burbot	134 ± 11	–	55 ± 22	63 ± 16	64 ± 15
Perch	161 ± 8	1515 ± 660	327 ± 44	96 ± 23	525 ± 202
Roach	146 ± 3	–	75 ± 4	48 ± 17	90 ± 16
Pike	142 ± 3	–	65 ± 24	38 ± 21	81 ± 18
Ide	152 ± 3	413 ± 360	95 ± 60	95 ± 41	188 ± 63

Here and in Tables 4, 6, and 7, a dash indicates no data.

Fish fauna of the Khanty-Mansi Autonomous Okrug. The results of the annual monitoring of the Ob-Irtysh system (Trapeznikov et al., 2014, 2016) from 2004 to 2010 were used. The years for which the most complete set of data required for calculations was obtained were selected. In 2006, a significant increase in the content of radionuclides in water was recorded due to their increased entry into the downstream Ob from midstream Ob (Table 2). Radionuclide inputs from the Irtysh River remained at the same level (Trapeznikov et al., 2016).

The total power of radiation doses from ^{90}Sr and ^{137}Cs over the entire period were within 142 ± 3 nGy/day for pike in 2004 and 1515 ± 660 nGy/day for perch in 2006 (Table 3).

Table 4. Power of internal radiation doses by ^{90}Sr and ^{137}Cs (nGy/day) in fish at the lower Ob cross section 20 km downstream from Khanty-Mansiysk

Fish species	^{90}Sr				^{137}Cs			
	2004	2006	2008	2010	2004	2006	2008	2010
Goldfish	–	–	127 ± 70	77 ± 65	–	–	30.5 ± 15.9	16.7 ± 10.7
Bream	105 ± 8	809 ± 570	–	78 ± 6	0.82 ± 0.75	4.81 ± 2.79	–	<0.01
Burbot	125 ± 10	–	45 ± 22	60 ± 15	4.07 ± 1.77	–	4.15 ± 0.05	<0.01
Perch	157 ± 6	1488 ± 660	319 ± 44	94 ± 22	2.52 ± 1.32	26.2 ± 2.8	6.32 ± 0.98	<0.01
Roach	139 ± 3	–	67 ± 5	46 ± 17	3.64 ± 1.22	–	3.93 ± 2.65	<0.01
Pike	137 ± 4	–	58 ± 24	18.5 ± 17.9	3.99 ± 1.38	–	3.83 ± 2.97	17.9 ± 3.4
Ide	145 ± 4	408 ± 360	89 ± 59	92 ± 41	1.90 ± 0.55	3.23 ± 0.25	2.16 ± 1.70	<0.01

Table 5. Content of ^{90}Sr and ^{137}Cs (mBq/L) in water and 10 cm of bottom sediments (Bq/kg) in 2014–2017 in the cross section of lower Ob ~1000 km downstream of Khanty-Mansiysk

Component of environment	Radionuclilde	Content of radionuclides				Mean
		2014	2015	2016	2017	
Water	^{90}Sr	8.2 ± 2.2	12.5 ± 1.5	15.0 ± 4.0	9.0 ± 1.0	11.2 ± 1.3
	^{137}Cs	7.4 ± 2.7	4.0 ± 1.0	18.4 ± 2.4	1.7 ± 0.2	7.8 ± 1.5
Bottom sediments	^{90}Sr	13.6 ± 3.3	8.6 ± 1.9	11.1 ± 1.3	21.5 ± 8.5	13.7 ± 1.6
	^{137}Cs	2.3 ± 1.5	2.3 ± 0.6	6.2 ± 1.1	8.0 ± 5.3	4.7 ± 1.4

Table 6. Total power of doses of radiation from ^{90}Sr and ^{137}Cs (nGy/day) in fish at the cross section of the lower Ob ~1000 km downstream of Khanty-Mansiysk

Fish species	2014	2015	2016	2017	Mean
Perch	–	–	107 ± 20	80 ± 9	93 ± 11
Peled	97 ± 7	282 ± 124	–	–	171 ± 57
Roach	52 ± 5	–	78 ± 15	65 ± 9	63 ± 5
Common whitefish	–	234 ± 11	–	39 ± 9	136 ± 77
Sardine cisco	–	–	64 ± 7	50 ± 7	57 ± 6
Broad whitefish	57 ± 9	107 ± 86	52 ± 12	56 ± 8	66 ± 9
Pike	113 ± 9	237 ± 73	85 ± 14	67 ± 8	124 ± 25
Ide	–	158 ± 100	75 ± 18	65 ± 7	99 ± 23

For all fish species of the Khanty-Mansi Autonomous Okrug, the radiation impact was determined mainly by the internal exposure from ^{90}Sr (Table 4).

Fish fauna of Yamalo-Nenets Autonomous Okrug. To calculate the external dose rate in fish, we used the data of the annual monitoring of the lower Ob (Trapeznikov et al., 2018) from 2014 to 2017 on the content of radionuclides in the water and in the 10-cm layer of bottom sediments (Table 5). For all presented fish species of the Yamal-Nenets Autonomous Okrug, calculations similar to those for fish of the Khanty-Mansiysk Autonomous Okrug were carried out. The total dose rates for each species due to ^{90}Sr and ^{137}Cs in the fish body and in the environment are given in Table. 6. In all fish species of the Yamal-Nenets Autonomous Okrug, the main radiation dose rate is formed due to the internal dose; the main dose-determining radionuclide is ^{90}Sr (Table 7).

DISCUSSION

The power of sum radiation doses from ^{90}Sr and ^{137}Cs for all species of fish studied are significantly below the safe levels recommended by the ERICA project, 10 μGy/h (Lavrent'eva et al., 2020), and the

Table 7. Power of internal radiation doses from ^{90}Sr and ^{137}Cs (nGy/day) in fish at the cross section of the lower Ob ~1000 km downstream of Khanty-Mansiysk

Fish	^{90}Sr				^{137}Cs			
	2014	2015	2016	2017	2014	2015	2016	2017
Perch	–	–	91 ± 17	66 ± 12	–	–	12.3 ± 2.8	8.17 ± 2.42
Peled	79 ± 3	268 ± 133	–	–	9.73 ± 4.28	7.65 ± 7.05	–	–
Roach	40 ± 7	–	59 ± 13	47 ± 10	5.17 ± 2.68	–	7.71 ± 2.04	3.48 ± 0.85
Common whitefish	–	221 ± 13	–	16 ± 9	–	5.75 ± 2.57	–	1.39 ± 0.55
Sardine cisco	–	–	45 ± 8	25 ± 8	–	–	2.62 ± 1.31	1.79 ± 0.87
Broad whitefish	46 ± 8	95 ± 81	34 ± 11	34 ± 9	4.53 ± 0.85	6.56 ± 5.06	3.97 ± 1.59	2.89 ± 1.29
Pike	102 ± 9	215 ± 68	73 ± 16	56 ± 10	8.86 ± 0.95	21.13 ± 5.47	7.93 ± 1.21	5.59 ± 2.23
Ide	–	139 ± 95	54 ± 15	43 ± 6	–	13.20 ± 4.77	7.09 ± 2.79	3.68 ± 1.39

International Commission on Radiological Protection, 1 mGy/day (*ICRP* ..., 2008).

The total power of radiation dose. Content of ^{90}Sr and ^{137}Cs in 2006 in water at the cross section of the lower Ob 20 km downstream from Khanty-Mansiysk City was an order higher than that in 2004 (Table 2). This was determined by the increased input of radionuclides to downstream Ob from midstream Ob in Tomsk oblast (Trapeznikov, et al., 2016). The sum powers of doses in 2006 were higher than that in in 2004 in bream by factor of seven, in perch by factor of more than nine, and in ide by factor of about three (Table 3).

At the river cross section studied in YaNAO, the range of fluctuations in the content of ^{90}Sr and ^{137}Cs in water over the years was less than in KhMAO (Tables 2, 5). The maximal difference in total dose rate found in common whitefish in 2015 is six times higher than in 2017. A comparison of total mean dose powers in fish of the same species studied at two cross sections of the downstream Ob revealed that the dose rate in perch, roach, and ide was higher in KhMAO, and only in pike did the mean dose rate exceed that in YaNAO (Tables 3, 6).

Power of dose of internal radiation. The share of the dose rate from radionuclides in the body of all fish in the total dose to fish in KhMAO was >95% (Tables 3, 4); it was from 64 to 98% in YaNAO (Tables 6, 7). The internal power of the dose due to ^{90}Sr exceeded 74% in fish in KhMAO; it was 90% in YaNAO.

Radioactive contamination in the lower Ob comes from the most contaminated areas of the Ob-Irtysh basin near PA Mayak and the Siberian Chemical Combine: from PA Mayak along the Techa, Iset', Tobol, and Irtysh rivers, and downstream Ob; from the side of the Siberian Chemical Combine, it was along the Romashka–Tom–midstream Ob–downstream Ob river system.

It is reasonable to compare the powers of radiation dose in fish from the rivers of these areas.

PA Mayak. In the 2012–2013 summer-spring period, the total power of radiation dose in fish, as determined by ^{90}Sr and ^{137}Cs, in the Techa River decreased downstream in a section of 33–184 km from the PA Mayak liquid radioactive waste dump site (Tryapitsyna et al., 2017, 2019). In perch, the total dose rate decreased from 124 to 4 μGy/day, in roach it was from 108 to 9 μGy/day, and in pike from 150 to 3 μGy/day.

In the lower Ob at a distance of ~1500 km (river cross section in KhMAO) and ~2500 km (river cross section in YaNAO) from PA Mayak, the averaged dose rates in perch, roach, and pike (Tables 3, 6) were three orders of magnitude less than in the Techa River at a distance of 33 km from the liquid radioactive waste dump point and one or two orders of magnitude less at a distance of 184 km.

With distance from the liquid radioactive waste dumping point in the Techa River, the share of power of internal radiation in the total exposure power increased from 17.6 to 89% and became comparable for roach in KhMAO (99%) and in YaNAO (95%).

Siberian Chemical Combine. Between 2000 and 2008, before the shutdown of the last reactor, the total radiation dose power of bottom dwelling fish in the Romashka River (into which the waste containing radionuclides were directly dumped), reached 200 μGy/day; the share of the internal exposure rate exceeded 97% (*Radioecological* ..., 2015). At the same time, in the Chernil'shchikovskaya branch in the Tom River, the total dose power was 42 μGy/day. In both cases, internal exposure predominated. The main contribution to the dose power of about 90% was made by ^{32}P.

After the shutdown of the last reactor, the dose power in 2009–2014 in bottom dwelling fish decreased by two to three orders of magnitude: in the Romashka River to 880 nGy/day and in the Chernil'shchikovskaya branch to 140 nGy/day. The share of external exposure due to ^{60}Co, ^{137}Cs, and ^{152}Eu in bottom sediments predominated.

In the lower Ob River, goldfish and bream may be considered bottom dwellers. Averaged powers of radiation dose in these species for 2004–2010 were 130 and 336 nGy/day, respectively. This is comparable to the estimates for bottom dwelling fish in the Chernil'shchikovskaya branch in the Tom River (*Radioecological* ..., 2015).

As in the case of PA Mayak, the power of radiation dose in fish decreased by more than an order of magnitude at a distance of ~100 km downstream from the point of liquid radioactive waste dumping. Estimates of the rate of the averaged dose of irradiation of fish for 2012–2013 in the Techa River is higher than that of fish in the Romashka River in 2009–2014. It should be taken into account that the fish in these rivers have a different composition of dose-determining radionuclides.

Mining and Chemical Combine. In 2006–2009, during the operation of the third reactor of the Mining and Chemical Combine, the dose power due to ^{137}Cs in grayling (*Thymallus arcticus* Pallas) reached 22.3 μGy/day 5 km from the main discharge site of wastewater containing radionuclides downstream of the Yenisei River; in pike it was 36.4 μGy/day (Rakitsky et al., 2018).

In the papers (Luneva and Kryshev, 2014; *Radioecological* ..., 2015), the averaged radiation dose in the Yenisei River fish in the Mining and Chemical Combine area, 16 km from the downstream wastewater discharge site, was estimated. Before the shutdown of the last reactor, the radiation dose in 2000–2009 in pelagic fish reached 1.92 μGy/day; for bottom dwelling fish, it was 1.90 μGy/day. Taking into account $^{239+240}Pu$, it was 6.6 μGy/day (Buryakova et al., 2020). Internal exposure dominated. The main dose-determining radionuclide, excluding $^{239+240}Pu$, was ^{32}P (70%); ^{24}Na accounted for 30% (Luneva and Kryshev, 2014). After the shutdown of the last reactor in 2011–2014. the dose power decreased for pelagic fish to 25 nGy/day; for bottom dwelling fish, it fell to 106 nGy/day. The dose power of external exposure due to ^{60}Co and ^{137}Cs accumulated in bottom sediments was predominant. Thus, after the shutdown of the reactors at the Mining and Chemical Combine, the total dose powers for fish in the Yenisei River at a distance of 16 km from the site of liquid radioactive waste dumping are comparable to those for fish in the lower Ob.

Beloyarsk Nuclear Power Station. Based on the data on the content of radionuclides in fish, water, and bottom sediments given in the paper (Berzin et al., 2020), the radiation doses in goldfish and bream in the Beloyarsk Reservoir in the area of the industrial storm canal of the Beloyarsk Nuclear Power Station were assessed. The total dose rate of internal and external exposure in goldfish reached 257 nGy/day; in bream, it was 225 nGy/day. The dose power of external exposure due to ^{137}Cs accumulated in the bottom sediments prevailed: in goldfish it was 65% and in bream it was 73%. Internal exposure in these fish species was mainly due to the accumulation of ^{137}Cs. The contribution of ^{137}Cs to the formation of the internal dose rate reached 75% in goldfish and 59% in bream.

The total radiation dose in fish of the Beloyarsk Reservoir is comparable to the doses in fish of the same species in the downstream Ob. However, the main dose-determining radionuclide in the Ob River was ^{137}Cs, accumulated in the fish body; in the Beloyarsk Reservoir fish, it was ^{137}Cs, located in the bottom sediments and in the fish body.

The Neman River. The radiation doses in perch and silver bream in 2014 in the Neman River near the projected water intake of the Baltiysk nuclear power station under construction were estimated based on the data given in paper (Luneva, 2018). The total dose power of internal and external exposure due to ^{137}Cs and ^{137}Cs was 8.65 nGy/day in perch and 13.58 nGy/day in silver bream. The total irradiation dose in fish of the Neman River is more than an order of magnitude less than in the same species in the downstream Ob.

CONCLUSIONS

Doses of exposure to radiation in all studied fish species in KhMAO (2004–2010) and YaNAO (2014–2017) do not exceed the conservative environmentally safe exposure level of 1 mGy/day recommended by the International Commission on Radiological Protection. The dose power determined by the radionuclides accumulated in fish is higher than the external dose power from radionuclides in the environment. The main contribution to the radiation impact on fish in the lower Ob is made by ^{90}Sr accumulated in the fish body.

FUNDING

This study was funded by the state budget.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest. The authors declare that they have no conflicts of interest.

Statement on the welfare of animals. This article does not contain any studies involving animals or human participants performed by any of the authors.

REFERENCES

Aleksakhin, R.M., Buldakov, L.A., Gubanov, V.A., et al., *Krupnye radiatsionnye avarii: posledstviya i zashchitnye mery* (Large Radiation Accidents: Consequences and Protective Measures), Moscow: IzdAT, 2001.

Berzin, D.L., Chebotina, M.Ja., and Guseva, V.P., Accumulation of radionuclides in the marsh frog *Pelophylax ridibundus* in the zone of a nuclear plant, *Inland Water Biol.*,

2020, vol. 13, no. 4, p. 691.
https://doi.org/10.1134/S1995082920060048

Buryakova, A.A., Kryshev, I.I., Sazykina, T.G., et al., Assessment of dose and environmental risk for biota in the area of Mining and Chemical Combine (Krasnoyarsk), *Radiats. Biol., Radioekol.*, 2020, vol. 60, no. 6, p. 661.
https://doi.org/10.31857/S0869803120060156

Conclusion of the Russian Scientific Commission on Radiation Protection on the report "Radioecological monitoring of the Techa-Ob river system," Radiats. Risk, 2008, vol. 17, no. 3, p. 5.

Ekologiya ryb Ob-Irtyshskogo basseina (*Fish Ecology of the Ob-Irtysh Basin*), Moscow: KMK, 2006.

ICRP Publication 108: Environmental protection: the concept and use of reference animals and plants, *Ann. ICRP*, 2008, vol. 38, nos. 4–6.

Lavrent'eva, G.V. and Synzynys, B.I., Current assessment of radiation environmental risk: a review, *Radiats. Risk*, 2020, vol. 29, no. 2, p. 128.
https://doi.org/10.21870/0131-3878-2020-29-2-128-138

Luneva, E.V., Radionuclides in surface waters, bottom sediments, and hydrobionts in the Neman River, *Inland Water Biol.*, 2018, vol. 11, no. 1, p. 97.
https://doi.org/10.1134/S1995082918010108

Luneva, K.V. and Kryshev, A.I., Analysis of the radioecological impact of Mining and Chemical Combine (Krasnoyarsk) on river biota in 2000–2012, *Radiats. Risk*, 2014, vol. 23, no. 1, p. 89.

Miroshnikov, A.Yu., Flint, M.V., Asadulin, En.E., and Komarov, Vl.B., Radiation-geochemical stability of bottom sediments in the Ob and Yenisei estuaries and adjacent shoal area of the Kara Sea, *Oceanology* (Engl. Transl.), 2020, vol. 60, no. 6, p. 817.
https://doi.org/10.1134/S0001437020060065

Nikitin, A.I., Chumichev, V.B., Valetova, N.K., et al., Current content of ^{90}Sr, ^{137}Cs, ^{239,240}Pu and tritium in the water of the Tobol-Irtysh river system (from the mouth of the Iset' River to the mixture zone with the Ob River), *Izv. Vyssh. Uchebn. Zaved., Yad. Energ.*, 2005, no. 3, p. 26.

Radioekologicheskaya obstanovka v regionakh raspolozheniya predpriyatii Rosatoma (*Radioecological Situation in the Regions of Localization of Rosatom Enterprises*), Moscow: SAM Poligrafist, 2015.

Rakitskii, V.N., Bondareva, L.G., and Fedorova, N.E., Calculation of the exposure dose for some components of the trophic chain of the freshwater ecosystem of the Yenisei River during the operation of the nuclear fuel cycle at Mining and Chemical Combine (Krasnoyarsk), *Radiats. Gig.*, 2018, vol. 11, no. 3, p. 22.
https://doi.org/10.21514/1998-426X-2018-11-3-22-29

Semenkov, I.N., Miroshnikov, A.Yu., Asadulin, E.E., et al., The Ob River basin as a source of Kara Sea contamination with global fallout of cesium-137, *Dokl. Earth Sci.*, 2015, vol. 463, no. 1, p. 704.
https://doi.org/10.1134/S1028334X1507003X

Tetenev, F.F., Ryzhov, A.I., and Porovskii, Ya.V., Evolution of permissible doses of ionizing radiation and role of the 1993 accident at the Siberian Chemical Combine in public exposure, *Byull. Sib. Med.*, 2008, no. 4, p. 104.

Trapeznikov, A.V., *^{60}So, ^{90}Sr, ^{137}Cs i ^{239,240}Pu v presnovodnykh ekosistemakh* (^{60}Co, ^{90}Sr, ^{137}Cs and ^{239,240}Pu in Freshwater Ecosystems), Yekaterinburg: AkademNauka, 2010.

Trapeznikov, A.V., Trapeznikova, V.N., Korzhavin, A.V., and Nikolkin, V.N., *Radioekologicheskii monitoring presnovodnykh ekosistem* (Radioecological Monitoring of Freshwater Ecosystems), Yekaterinburg: AkademNauka, 2014, vol. 1.

Trapeznikov, A.V., Trapeznikova, V.N., Korzhavin, A.V., and Nikolkin, V.N., *Radioekologicheskii monitoring presnovodnykh ekosistem* (Radioecological Monitoring of Freshwater Ecosystems), Yekaterinburg: AkademNauka, 2016, vol. 2.

Trapeznikov, A.V., Trapeznikova, V.N., Korzhavin, A.V., and Nikolkin, V.N., *Radioekologicheskii monitoring presnovodnykh ekosistem* (Radioecological Monitoring of Freshwater Ecosystems), Yekaterinburg: AkademNauka, 2018, vol. 3.

Tryapitsyna, G.A., Osipov, D.I., Egoreichenkov, E.A., et al., Assessment of erythropoiesis in roach (*Rutilus rutilus*) from the radioactively contaminated Techa River, *Radiats. Biol., Radioekol.*, 2017, vol. 57, no. 1, p. 98.
https://doi.org/10.7868/S0869803117010131

Tryapitsyna, G.A., Pryakhin, E.A., Osipov, D.I., et al., Response of erythropoiesis to trypanosomal invasion in fishes from the radioactively contaminated Techa River, *Radiats. Biol., Radioekol.*, 2019, vol. 59, no. 1, p. 82.
https://doi.org/10.1134/S0869803119010119

Translated by D. Pavlov