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AQUATIC TOXICOLOGY

Radioecological Studies of the Marsh Frog in Reservoirs of the Middle Urals

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Abstract—A study of the accumulation of radionuclides ^{90}Sr, ^{134}Cs, and ^{137}Cs by the marsh frog *Pelophylax ridibundus* Pall., 1771 living in the areas of the reservoirs of the Middle Urals has been carried out. The variability of size and mass indicators and concentrations of radionuclides in animals in the surveyed area is noted. Increased concentrations of ^{137}Cs and ^{134}Cs are detected in some amphibian representatives when compared with average values. A significant decrease in the concentration of ^{90}Sr in frogs with an increase in raw body weight is found in much statistical material. An analysis of the data obtained on the concentrations of ^{90}Sr and ^{137}Cs in frogs of different sexes did not reveal a significant difference in the accumulation of either radionuclides between male and female animals or ^{90}Sr by striata and strieless amphibians. It is shown that radionuclides ^{90}Sr and ^{137}Cs enter the body of an animal from water much more than from the ground, while, with an increase in the concentration of radionuclide in the habitat, the coefficients of their transition into the animal body decrease.

Keywords: marsh frog, radionuclides ^{90}Sr, ^{134}Cs, ^{137}Cs, concentration, hydrobionts, Middle Urals

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INTRODUCTION

Interest in marsh frogs (*Pelophylax ridibundus* Pall., 1771) as an object of scientific research is largely due to their use for food production in a number of countries (China, Vietnam, France, Belgium, Korea, Italy, Spain, Holland, etc.), where these amphibians are actively cultivated in artificial and natural reservoirs. The global catch of animals reaches hundreds of thousands of tons per year (Omoniy et al., 2012; Zhelankin, 2020). Ensuring the radiation purity of products from natural bodies of water is an important condition for the use of amphibians for food purposes. In addition, the importance of their research is explained by the fact that frogs serve as complex indicators of the ecological state of the environment, since most of their species live in both aquatic and terrestrial environments. Frog skin is highly sensitive due to its permeability to water, gases, and radioactive and chemical pollutants present in the environment.

The problem of accumulation of radionuclides by the marsh frog in the Ural region is of particular interest due to the widespread use of radionuclides and ionizing radiation in various areas of human production activity, which may result in their uncontrolled release into the environment, including natural bodies of water. The country's largest energy facilities are located in the Ural region (PO Mayak and Beloyarsk Nuclear Power Station (BNPS)); a severe radiation disaster occurred there, leaving behind radioactive traces; massive underground technological explosions were carried out; nuclear weapons tests were carried out; the production and storage of nuclear weapons ammunition was concentrated; nuclear fuel is processed; and mining and the primary processing of uranium and thorium are carried out. In addition, the region experiences contamination from natural radioactive sources. Against the background of radioactive contamination of the environment in the Ural region, severe contamination with heavy metals is recorded. In this regard, in a number of industrial centers and more remote areas, atmospheric air, surface and groundwater, and soil are polluted, and the morbidity rate of the population is increasing (Pervushkina, 1998; Utkin et al., 2004; Kalinkin et al., 2020).

To solve radioecological problems that arose with the development of the nuclear industry in the Urals, scientific centers were created in a number of large cities (Yekaterinburg, Chelyabinsk, Ozersk, etc.) for systematically monitoring the state of the environment in the region and conducting fundamental scientific research on this issue. These studies resulted in monographs (Distant ..., 2000; Mokrov, 2002, 2003; Utkin et al., 2004; Smagin, 2013; Kiselev et al., 2016, etc.) and a large number of articles in scientific journals. The objects of research in the works were various natural environments (water, air, and soils), representatives of the flora and fauna (terrestrial and aquatic

Fig. 1. Map of the study area. (*1*) Beloyarsk reservoir, ISC of BNPS; (*2*) zone for the discharge of heated water from the cooling systems of the nuclear power plant into the Beloyarsk reservoir; (*3*) pond in the forest behind the fourth power unit of the BNPS; (*4*) Reftinskoye Reservoir, coastal part of the reservoir opposite the Reftinskoye SDPP; (*5*) Reftinskoe Reservoir, warm canal; (*6*) Reftinskoe reservoir, canal opposite the waterworks; (*7*) Verkhnetagilskoe Reservoir in the area of the SDPP; (*8*) Tagil River behind the dam of the Verkhnetagil Reservoir; (9) isolated reservoir below the dam near point *8*; (*10*) Verkh-Neyvinskoye reservoir in the area of the railway station; and (*11*) small body of water between waste outlets channels of the Ural Electrochemical Plant.

plants, lichens, mouselike rodents, fish, plankton, livestock, etc.), and humans. At the same time, radioecological studies of the marsh frog in the Ural region are sporadic and limited to our works (Berzin et al., 2020; Chebotina et al., 2021).

The marsh frog, a widespread alien amphibian species, accidentally found its way into the water bodies of the Ural region and settled over a large part of its territory. It is believed that the marsh frog appeared in the Urals in the 1970s (Toporkova et al., 1979; Vershinin, 2007a). The ecological features of this species have been studied and described in works (Ivanova, 1995; Vershinin and Ivanova, 2006; Ivanova and Zhigalsky, 2011). Due to its high ecological plasticity, the marsh frog is widely distributed in aquatic ecosystems of various geographical areas around the world. Its favorite habitat is the heating zones of cooling ponds of thermal and nuclear power plants, where there are favorable conditions for life and reproduction throughout the year. However, in temperate latitudes, it lives safely and reproduces at lower temperatures.

The purpose of this work is to give a comparative assessment of the accumulation of ^{90}Sr, ^{134}Cs, and ^{137}Cs radionuclides by the marsh frog *P. ridibundus* living in water bodies of the Middle Urals.

MATERIAL AND METHODS

This work was carried out at the end of July 2014–2019. The materials were marsh frogs, water, aquatic plants, and soil in water bodies of the Middle Urals within Sverdlovsk oblast, including the cooling reservoir of the BNPS (Beloyarsk Reservoir), cooling reservoirs of the Reftinskaya and Verkhnetagilskaya state district power plants (SDPP) (Reftinskaya and Verkhnetagilskaya Reservoirs), the Verkh-Neyvinskaya Reservoir, the Tagil River, and other smaller aquatic ecosystems (Fig. 1). Below is a brief description of large bodies of water.

The Beloyarsk Reservoir, a cooling reservoir for the BNPS, was formed in 1959–1963 by regulating the river bed. Pyshma is 75 km from its source. The length of the reservoir is ~20 km; the width at the nuclear power plant level is ~3 km. The depth along the Pyshma River fairway is 15–20 m, and the average depth is 8–9 m. The reservoir surface area is ~47 km^2. The BNPS is located on the left bank of the reservoir, 7 km from the dam. Put into operation in 1964, the first and second power units of the station have already been decommissioned. Currently, the BNPS has two power units in operation, the third (operating since 1980) and the fourth (launched in 2014). During the operation of the first three power units, the main route for radionuclides to enter the Beloyarsk Reservoir is the industrial storm canal (ISC), where unbalanced water from the station is discharged (water that has undergone special water treatment, water from special laundries, showers, and melt and storm water from the territory of the station). In addition, water flows into the canal from the neighboring enterprise of the Institute of Reactor Materials (IRM), where an experimental reactor operates. The predominant plants in the canal are comb pondweed and cladophora; less common are duckweed, curly pondweed, and elodea. Plankton is represented by 30 species of phytoplankton and 10 species of zooplankton. There are many fish fry in the canal; in addition, there are crucian carp, bream, chebak, and perch, and an abundance of marsh frogs is noted, especially during the breeding season.

The Reftinskoe Reservoir is a cooling reservoir for the Reftinskaya SDPP, the largest thermal power plant in Russia, located 100 km northeast of Yekaterinburg. The reservoir area is 25.3 km^2; the maximum and average lengths are 14 and 4 km, and the maximum and average depths are 22 and 5 m, respectively. The Reftinskoe reservoir was created in 1968 on the Reft River, a left tributary of the Pyshma River. It is used for technical water supply to the Reftinskaya SDPP. The water temperature during the period of maximum heating exceeds the natural temperature by 4.3–4.8°C, and the temperature difference in different parts of the reservoir due to the discharge of heated water can reach 10°C. Features of the ecology of the marsh frog introduced into the Reftinskoye Reservoir are described in the works (Bolshakov, Ivanova, 2013; Ivanova, 2017).

The Verkhnetagil reservoir was formed in 1960 at the confluence of the Tagil and Vogulka rivers. The surface area of the reservoir is 3.5 km^2, average depth is 3.8 m, and maximum depth is 5 m. The reservoir serves as a cooling reservoir for the Verkhnetagil SDPP. Heated water is used to provide hot water to the population and enterprises of Verkhniy Tagil. According to the nature of the heat balance, the Verkhnetagil Reservoir belongs to the category of reservoirs with severe overheating, since the water temperature in it constantly exceeds the water temperature in natural reservoirs by ≥6°C. The marsh frog was brought into the reservoir from Krasnodar krai in the 1980s, when the reservoir was stocked with grass carp (Toporkova et al., 1979; Vershinin, 2007a).

The Verkh-Neivinskoye Reservoir is a pond artificially created in 1762 in the upper reaches of the Neyva River. It is located in the southwestern part of the Ural Electrochemical Plant in Sverdlovsk oblast. Its area is 13 km^2; the average and maximum depths are 3 and 9 m, respectively. The pond is fed by the runoff of small rivers ≤10 km in length. On the northwestern shore of the reservoir there are transport and industrial facilities: the Verkh-Neyvinsk railway station, access roads, and the industrial site of the Verkh-Neyvinsky plant (now a branch of Production of Non-Ferrous Metal Alloys AO Uralelektromed', as well as a pumping station. Along the southeastern border of the Verkh-Neivinsky plant, there is a pond dam from which the Neyva River flows. The eastern shore of the reservoir is occupied by forests, behind which stretches the chain of mountains of the Verkh-Isetsky range. There are many wetlands in the reservoir. The predominant fish species are pike, roach, perch, bream, burbot, and crucian carp.

During the work, the frogs were caught using a water net and then euthanized using ether. Plants and fish were collected in triplicate, each of which weighed 2–3 kg. The soil was taken with a sampler to a depth of 0–5 cm. Samples of 70 L of water at each observation point were acidified with hydrochloric acid. After collection, all samples were transported to the laboratory. The frogs were weighed and their length, body weight, sex, and striata morph were determined. All samples after drying and ashing at a temperature 500°C were analyzed for the content of radionuclides in them. The concentration of ^{90}Sr in ash samples was determined by the radiochemical method (Trapeznikov et al., 2008). Radiometry of the resulting sediments was carried out using a UMF-2000 low-background installation (Russia) in triplicate with a statistical counting error of 10–15%. The concentration of ^{134,137}Cs was determined using multichannel γ analyzers from Canberra-Packard and ORTEC (United States) with error measurements of ≤10–20%. When performing radiometry on ^{90}Sr, each frog was analyzed separately and, on ^{134}Cs and ^{137}Cs, two or three samples were combined by gender to increase the accuracy of determinations.

In the process of statistical data processing, Pearson correlation coefficients and coefficients of variation were calculated using Statistica v. 6.0, StatSoft, 2001, Untied States, license no. AXXR003A622407-FAN8. Differences were considered significant at the level $p < 0.05$. The mean square error was calculated using tables by L.B. Strelkova (1966).

RESULTS

Morphometric indicators and coefficients of variation were obtained for marsh frogs from various habitats (Table 1). At most observation points, marsh frogs

Table 1. Characteristics of the marsh frog at sampling points

Points	Coordinates		*N*		Body length, mm		Wet body weight, g	
	North	East	♀	♂				
1	56°51′10″	61°18′16″	11	32	79.4 ± 1.3 / 57.1–93.5*	(11)	56.6 ± 2.7 / 21.5–105.5	(34)
2	56°49′53″	61°19′03″	11	39	75.2 ± 1.2 / 48.2–86.4	(11)	50.9 ± 1.7 / 19.1–80.8	(24)
3	56°53′11″	61°16′33″	3	18	95.5 ± 1.9 / 86.0–118.1	(13)	102.2 ± 6.8 / 190.1–75.6	(33)
4	57°10′13″	61°72′71″	9	33	70.6 ± 4.8 / 57.4–90.0	(14)	55.1 ± 5.0 / 15.0–96.6	(31)
5	57°06′18″	61°42′21″	34	20	86.2 ± 1.6 / 60.1–115.2	(15)	62.4 ± 3.1 / 26.0–130.2	(43)
6	57°06′25″	61°45′49″	18	13	73.3 ± 2.0 / 55.2–100.1	(15)	39.2 ± 3.4 / 14.4–92.6	(53)
7	57°21′21″	59°58′03″	21	15	77.3 ± 1.4 / 56.0–92.1	(12)	53.7 ± 2.4 / 19.1–79.9	(29)
8	57°22′43″	59°57′46″	12	21	85.6 ± 3.2 / 63.5–140.1	(14)	58.7 ± 3.2 / 31.2 ± 108.0	(31)
9	57°23′06″	59°57′41″	2	12	72.8 ± 8.3 / 10.1–110.8	(39)	94.4 ± 8.3 / 12.0–113.1	(31)
10	57°15′27″	60°07′04″	12	23	86.3 ± 2.2 / 60.1–115.0	(11)	66.6 ± 3.8 / 23.9–118.9	(25)
11	57°18′58″	60°05′01″	4	46	81.3 ± 1.1 / 67.2–102.1	(11)	53.6 ± 2.8 / 30.6–121.3	(33)

The average and its error is above the line, the range of fluctuations of the characteristic is below the line, the coefficient of variation is in parentheses (%), * spread of data, and *n* in number of individual specimens.

were characterized by similar length (70–86 mm) and body weight (53–62 g), with the exception of animals from two small, almost isolated reservoirs (points 3 and 9), where their body weight was noticeably greater (94–102 g). This may be due to the favorable living conditions of frogs in these reservoirs (the absence of fast water flow and storm waves, good heating the water at a shallow depth of the reservoir, abundant food supply, etc.).

Individual and average values of radionuclide concentrations in frogs selected in the study areas of the Middle Urals were revealed (Fig. 2). Average concentration levels of ^{90}Sr in frogs of different habitats are similar to each other (5.6–11.5 Bq/kg dry weight), while individual indicators in some water bodies are characterized by noticeable variability. The latter mainly include large bodies of water: the coastal part of the Reftinsky Reservoir near the SDPP (point 4), the coast of the Verkhnetagil Reservoir near the thermal power plant (point 7), the coastal part of the Verkh-Neyvinsky reservoir in the area of the railway station (point 10), and adjacent to the BNPS area of the Beloyarsk Reservoir (points 1 and 2). Coefficients of variation of concentrations of ^{90}Sr in frogs for the indicated observation points are within 60–75%. The radionuclide content in frogs living in shallow reservoirs and canals is, as a rule, more uniform, and the coefficients of variation are characterized by lower values (24–32%).

A similar situation was observed for ^{137}Cs. The average values of radionuclide concentrations in frogs at different observation sites varied from 4.3 to 21.1 Bq/kg. A high variability of indicators was noted for points 3 (a reservoir in the forest behind the fourth power unit of the BNPS), 4 (the coastal part of the Reftinsky Reservoir opposite the SDPP), 8 (the Tagil River behind the dam of the Verkhnetagil reservoir), and 11 (a reservoir between the discharge canals of the Ural Electrochemical Plant). Coefficients of variation of ^{137}Cs at these observation points had the highest high rates (51–62%).

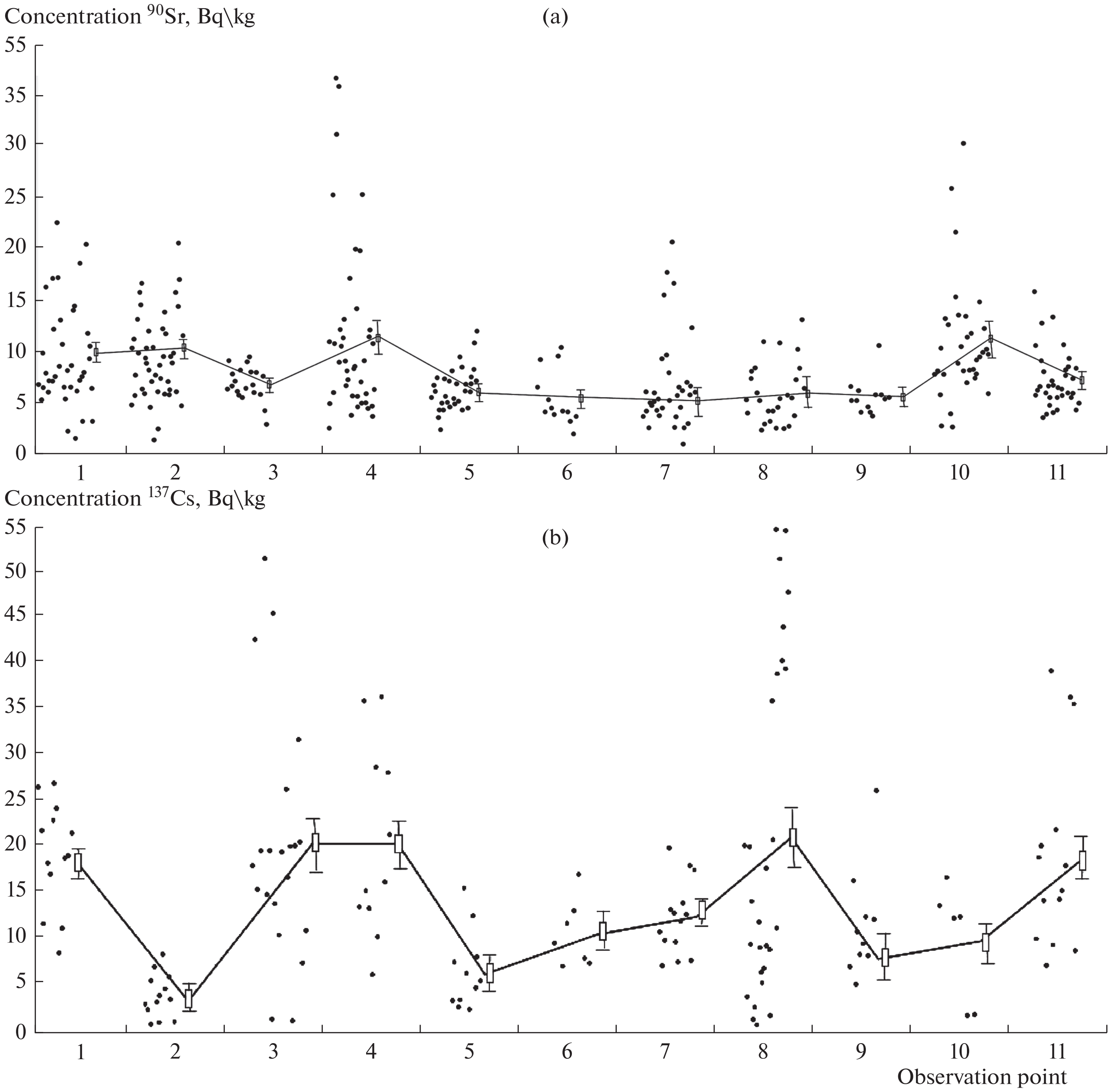

Fig. 2. Individual and average concentrations of ^{90}Sr(a) and ^{137}Cs (b) in frogs selected in the study areas of the Middle Urals.

Against the background of the general picture characterizing the average levels of radionuclide concentrations in frogs of the studied area, increased concentrations of ^{137}Cs and ^{134}Cs were noted in individual amphibians. In particular, one frog at point 1 contained 45000 Bq/kg ^{137}Cs; in another frog, from point 8, 52904 Bq/kg of radiocesium was detected. These two individuals showed an increased content of ^{134}Cs (441 and 320 Bq/kg, respectively). An increased concentration of ^{137}Cs (6914 Bq/kg) was also detected in an individual from the Verkh-Neivinsky Reservoir (point 10), in three individuals from the Reftinsky Reservoir opposite the SDPP (101, 229, and 912 Bq/kg) (point 4), and in an individual with an abnormal appearance and a body weight of 11 g caught in the area of the Kedrovaya Roshcha recreation center on the right bank of the Beloyarsk reservoir (155 Bq/kg).

Based on much statistical material, a significant decrease in the concentration of ^{90}Sr in frogs with increasing wet body weight ($p < 0.0002$) was established (Fig. 3). For ^{137}Cs it was not possible to establish such a connection, since in the process of radiometry some frog samples were combined to increase the accuracy of the determinations.

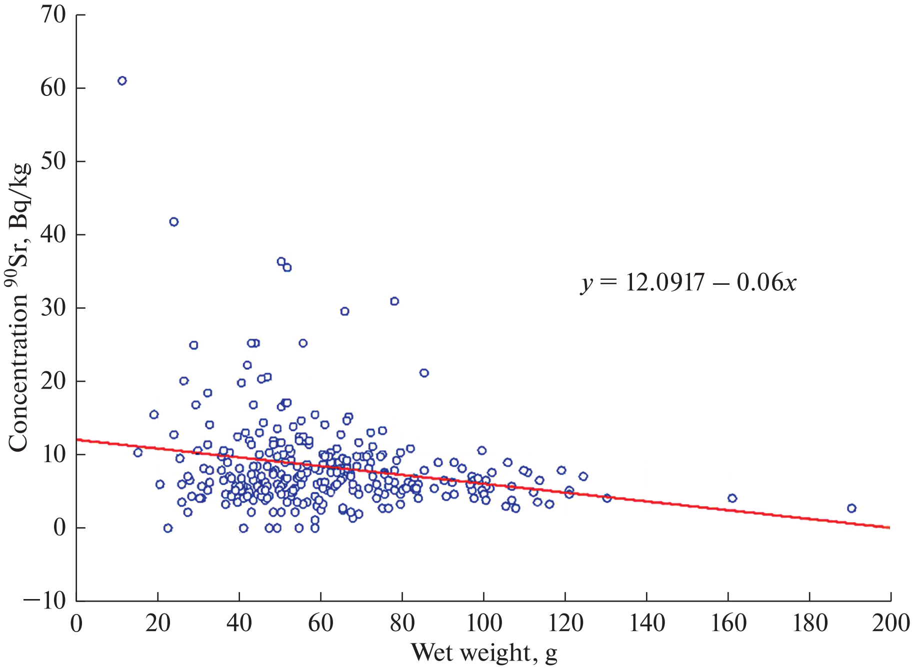

Fig. 3. Concentration dependence of ^{90}Sr from the wet weight of frogs.

An analysis of the data on the concentration of ^{90}Sr and ^{137}Cs in frogs of different sexes in the surveyed territory of the Middle Urals did not reveal a significant difference ($p > 0.05$) in the accumulation of radionuclides between males and females (6.7 ± 0.8 and 8.5 ± 0.6 for ^{90}Sr and 12.7 ± 1.2 Bq/kg and 15.1 ± 1.0 Bq/kg for ^{137}Cs, respectively).

Due to the frequent occurrence of striped frogs (striata) in some observation points (points 5–8) in the Urals, data on the accumulation of ^{90}Sr in animals differ in this trait. In the sample, represented by 54 individuals, no significant differences were revealed between striped (5.6 ± 0.5 Bq/kg) and non-striped (5.4 ± 0.4 Bq/kg) individuals ($p > 0.05$).

A comparative analysis of concentrations of ^{90}Sr and ^{137}Cs in the components of aquatic ecosystems of the surveyed territory in the Middle Urals (Table 2) indicates variations of these indicators at various observation points. In some places, increased levels of one or another radionuclide were noted in one or another component of the aquatic biocenosis. In particular, increased concentrations of both radionuclides in water were noted in the BNPS industrial storm channel (point 1), as well as ^{137}Cs in the Verkhnetagil Reservoir in the area of the SDPP (point 7). In these same points, increased concentrations of ^{137}Cs were recorded in soil and plants. At two observation points (points 1 and 5), the content of the studied radionuclides in frogs on average exceeded that in fish.

Transition coefficients of ^{90}Sr and ^{137}Cs were obtained in the body of frogs from water and soil, depending on the radionuclide content in the habitat (Fig. 4). To estimate the transfer coefficients of a radionuclide from water (Bq/L) or soil (Bq/kg) into a frog's body, we used the ratio of the average concentration of a particular radionuclide in the dry mass of the amphibian at each observation point to its concentration in water or soil. Figure 4 shows that the studied radionuclides come from water into the body of amphibians.

DISCUSSION OF THE RESULTS

In terms of discussing the role of the marsh frog as an object of radioecological research, it should be emphasized that there is a small amount of data on the issue of their accumulation of radionuclides. The works available in the literature relate mainly to heavily contaminated areas in the postaccident period at the Fukushima and Chernobyl nuclear power plants (ChNPP) and the Savannah River in South Carolina (Dapson and Kaplan, 1975; Jagoe et al., 2002; Matsushima et al., 2015; Beresford et al., 2020; Burraco et al., 2021). The results presented in these works indicate that, at high levels of radioactive contamination of the natural environment, in particular, during accidents at nuclear enterprises, frogs are capable of accumulating radionuclides in high concentrations, reaching the level of radioactive waste (Methodological ..., 1998). The work (Stark et al., 2004) showed that, in the wetland ecosystems of central–eastern Sweden 17 years after the Chernobyl accident, the average concentration of ^{137}Cs in the frog reached 1.7 ± 1.1 kBq/kg

Table 2. Average concentrations of ^{90}Sr and ^{137}Cs in aqueous components ecosystems from various observation points

Object of study	Radio nuclide	1	2	3	4	5	6	7	8	9	10	11
Water	^{90}Sr	20 ± 3	12 ± 2	3.3 ± 0.2	12 ± 1	4.1 ± 0.1	4.3 ± 0.2	16.5 ± 1.3	3.6 ± 0.2	4.5 ± 0.5	10 ± 2	6.9 ± 1.0
	^{137}Cs	33 ± 1.2	22 ± 6	13 ± 6	17 ± 7	7.8 ± 1.2	3.4 ± 1.1	36 ± 7	3.1 ± 1.2	2.9 ± 1.8	20 ± 10	5 ± 2.2
Soil	^{90}Sr	6.4 ± 1.5	2.8 ± 1.3	11.4 ± 2.0	8.3 ± 1.0	22.9 ± 3.3	–	13.1 ± 1.6	26.0 ± 2.6	9.8 ± 0.1	9.1 ± 1.9	21.2 ± 1.7
	^{137}Cs	81 ± 9	120.4 ± 8	46.2 ± 3	8.3 ± 1.9	25.4 ± 7.5	–	34.6 ± 10.8	10.7 ± 0.9	10.8 ± 1.2	26 ± 4.9	10.8 ± 0.8
Frog	^{90}Sr	9.7 ± 0.9	10.1 ± 2.1	6.6 ± 0.4	11.1 ± 1.2	5.8 ± 0.3	5.6 ± 0.7	6.5 ± 0.8	5.2 ± 0.7	5.7 ± 0.9	11.5 ± 1.6	6.6 ± 0.5
	^{137}Cs	18.1 ± 1.7	4.3 ± 0.6	22.3 ± 2.6	20.3 ± 3	6.3 ± 0.5	10.4 ± 1.5	11.8 ± 1.0	11.7 ± 2.1	11.6 ± 2.2	10.1 ± 2.8	19 ± 2.6
Cladophora	^{90}Sr	21.6 ± 2.2	14.2 ± 2.4	7.3 ± 1.1	7.9 ± 0.9	4.5 ± 0.9	–	9.9 ± 2.2	4.4 ± 0.3	–	BDL	3.9 ± 0.9
	^{137}Cs	1156 ± 150	20.4 ± 1.4	6.9 ± 1.9	17.5 ± 5.1	5.2 ± 2.9	–	44.8 ± 13.4	11.2 ± 1.4	–	19.4 ± 4.6	15.5 ± 5
Hornwort	^{90}Sr	–	14.1 ± 1.8	–	–	–	–	4.1 ± 0.4	–	–	BDL	–
	^{137}Cs	–	22.3 ± 1.3	–	–	–	–	103.6 ± 30.6	–	–	3.4 ± 0.9	–
Cage carp	^{90}Sr	–	–	–	–	3.9 ± 0.3	–	–	–	–	–	–
	^{137}Cs	–	–	–	–	2.9 ± 0.9	–	–	–	–	–	–
Perch	^{90}Sr	–	–	–	–	3.7 ± 0.1	–	–	–	–	–	–
	^{137}Cs	–	–	–	–	2.1 ± 0.7	–	–	–	–	–	–
Crucian carp	^{90}Sr	1.5 ± 0.1	–	–	–	–	–	–	–	–	–	–
	^{137}Cs	17.3 ± 0.6	–	–	–	–	–	–	–	–	–	–
Bream	^{90}Sr	1.7 ± 0.6	–	–	–	–	–	–	–	–	–	–
	^{137}Cs	8.8 ± 1.8	–	–	–	–	–	–	–	–	–	–

Units of measurement of indicators: water, Bq/m^3; other components: Bq/kg, dry mass; BDL, below the detection limit; and a dash indicates no data available. (1–11) Observation points.

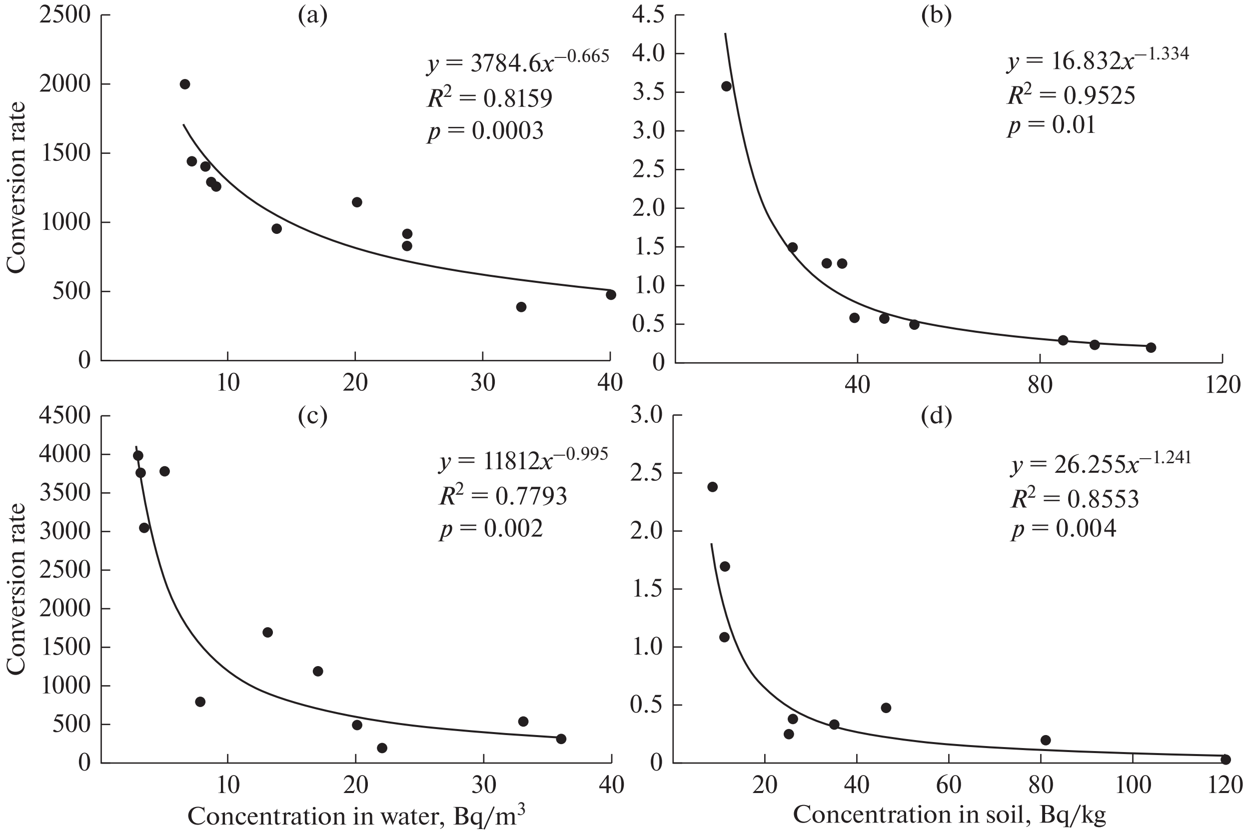

Fig. 4. Conversion rates of ^{90}Sr and ^{137}Cs into the body of frogs depending on the concentration of radionuclide in the habitat from water (a, c) and soil (b, d), respectively.

wet weight, with the highest values noted for the smallest amphibians (3.5 kBq/kg wet weight). Using the example of the areayyy of the ChNPP, it was established that, during a long stay of amphibians in the reservoirs of this zone, the accumulation of ^{90}Sr and ^{137}Cs in skeletal bones can lead to the development of fibrous osteodystrophy (Rodionova et al., 1994). The pollution of the natural environment with heavy metals creates additional negative stress on the animal body, causing mutations and damage to chromosomes. In particular, in the work (Akynbek kyzy, 2010), when studying the karyotype of rodents and amphibians living near the Mailysu radioactive tailing dump with a high content of heavy metals, structural changes in chromosomes were discovered, expressed in the rupture of chromosome arms and the appearance of dicentric figures. In the work (Pyastolova et al., 1996), physiological and genetic differences in the frog population were identified in frogs living in radioactively contaminated areas in the PO Mayak zone when compared with the control region. According to (Vershinin, 2007b), there were changes in the liver, blood, genitals, and lifespan of frogs on the territory of the Ural radioactive trace compared to the control. A review of the results of a study of genetic and cytogenetic parameters in frogs from impact territories (Komi Republic) under exposure to hazardous pollutants is given in (Yushkova et al., 2018).

This paper presents the results of a study of radionuclide accumulation of ^{90}Sr and ^{137}Cs in marsh frogs living in the areas of large reservoirs of the Middle Urals (Beloyarskoye, Reftinskoye, Verkhnetagilskoye, and Verkh-Neyvinskoye reservoirs). The area was not subject to major radiation impacts or accidental pollution, although such areas exist in the Urals (Utkin et al., 2004). It has been established that, for the bulk of animals, the average concentration levels of ^{90}Sr in different habitats are similar (5.6–11.5 Bq/kg) and, in the case of ^{137}Cs, they vary in more wide range of concentrations (4.3–21.1 Bq/kg). At the same time, the results indicate significant variability in ^{90}Sr and ^{137}Cs at most observation points. For the entire data set, the variability in accumulation can be explained by a variety of hydrochemical conditions, characteristics of the food supply of animals, and other environmental factors in different locations. In some cases, the high accumulation of ^{137}Cs and the appearance in the body of frogs of ^{134}Cs may result from the close contact of the animal with a radioactive environment, e.g., the BNPS (travel to a radioactive zone, contact with a hot particle, etc.). Since the analysis of possible routes of entry of radionuclides into the body of frogs (uncontrolled discharges, the presence of temporary storage facilities for radioactive materials and radioactive waste, etc.) was not part of the purpose of the study, it is not possible to explain the increased accumulation of ^{134}Cs and ^{137}Cs in individual specimens of the marsh frog. It should be noted that frogs can migrate over long distances (up to 15 km (Tunner, 1992)), so they may be carriers of absorbed radionuclides from other territories.

In this study, using large statistical material, it is shown that the concentration of ^{90}Sr significantly decreases with the increasing body weight of frogs. The latter can be explained by the fact that the parameters of the mass and age of animals are inversely related to each other. Therefore, according to numerous studies, with increasing age, the amount of osteotropic deposition of ^{90}Sr in animal skeletons decreases (Shvedov and Akleev, 2001; Kalistratova et al., 2016; etc.).

The data confirmed earlier research results about the absence of differences in the accumulation of radionuclides by male and female amphibians (Berzin et al., 2020).

The work evaluates the comparative transition coefficients of ^{90}Sr and ^{137}Cs radionuclides into the body of frogs from water and soil, indicating a greater transfer of radionuclides with water. Obviously, this is due to the high permeability of the skin of frogs to water, from which radionuclides enter the body mainly through diffusion, but it is possible that they enter with food. Similar data on large transition rates of ^{137}Cs into the body of the frog *Rana alvaris* from water relative to soil (bioconcentration factor) are presented in (Stark et al., 2004). Evidence we found on reductions in conversion rates of ^{90}Sr and ^{137}Cs into the body of frogs with an increase in their concentration in the habitat are consistent with the data of other authors on other natural sites (Beresford and Wright, 2005; Sobakin et al., 2014; Mikhailovskaya et al., 2022); however, at present there is no explanation for this dependence.

The data presented in this work on the accumulation of radionuclides in frogs in water bodies of the Middle Urals can be used as reference indicators for similar studies in other territories.

CONCLUSIONS

The data on the accumulation of ^{90}Sr and ^{137}Cs in marsh frogs given in this work indicate a variability in their concentrations at different observation points, which can be explained by a variety of hydrochemical conditions, characteristics of the food supply of animals, and other environmental factors. A large quantity of statistical material shows a significant decrease in the concentration of ^{90}Sr in frogs with increasing body mass. Transition coefficients of ^{90}Sr and ^{137}Cs into the body of frogs from water and soil, indicating a greater intake of radionuclides with water, were estimated.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The work was carried out in accordance with the permission and approval of the Bioethics Committee of the Institute of Plant and Animal Ecology of the Ural Branch of the Russian Academy of Sciences when working with animals (protocol no. 13 of November 1, 2022).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

Akynbek Kyzy, S., Study of the karyotype of some vertebrates near the Mailuu-Suu radioactive tailing dump, *Izv. Vyssh. Uchebn. Zaved. Kyrg.*, 2010, no. 2, p. 32.

Beresford, N.A. and Wright, S.M., Non-linearity in radiocaesium soil to plant transfer: Fact or fiction?, *Radioprotection*, 2005, vol. 40, p. 67. https://doi.org/10.1051/radiopro:2005s1-011

Beresford, N.A., Barnett, C.L., Gashchak, S., et al., Radionuclide transfer to wildlife at a 'Reference site' in the Chernobyl Exclusion Zone and resultant radiation exposures, *J. Environ. Radioact.*, 2020, vol. 211, p. 1. https://doi.org/10.1016/j.jenvrad.2018.02.007

Berzin, D.L., Chebotina, M.J., 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. 709. https://doi.org/10.1134/S1995082920060048

Bol'shakov, V.N. and Ivanova, N.L., Lake frog (*Rana ridibunda* Pall.) as an object of the watercooling reservoir monitoring at the Reftinsky HEPS, *Izv. Orenb. Agrar. Univ.*, 2013, no. 1, p. 245.

Burraco, P., Car, C., Bonzom, J.-M., et al., Assessment of exposure to ionizing radiation in Chernobyl tree frogs (*Hyla orientalis*), *Sci. Rep.*, 2021, vol. 11, p. e20509. https://doi.org/10.1038/s41598-021-00125-9

Chebotina, M.Ya., Guseva, V.P., and Berzin, D.L., Accumulation of long-lived radionuclides by the marsh frog in the cooling pond of the Beloyarsky NPP, *Radiats. Biol., Radioekol.*, 2021, vol. 61, no. 1, p. 79. https://doi.org/10.31857/S0869803121010045

Dapson, R.W. and Kaplan, L., Biological half-life and distribution of radiocesium in a contaminated population of green treefrogs *Hyla cinerea, Oikos*, 1975, vol. 26, no. 1, p. 39. https://doi.org/10.2307/3543274

Ivanova, N.L., Features of ecology of the marsh frog (*Rana ridibunda* Pall.) introduced into cooling ponds, *Ekologiya*, 1995, no. 6, p. 473.

Ivanova, N.L., Growth characteristics and rates of the mash frog *Pelophylax ridibundus* Pall. introduced into water bodies of the Middle Urals, *Biol. Bull.*, 2017, vol. 44, p. 412. https://doi.org/10.1134/S1062359017040057

Ivanova, N.L. and Zhigal'skii, O.A., Demographic features of populations of the marsh frog (*Rana ridibunda* Pall.) introduced into water bodies of the Middle Urals, *Russ. J. Ecol.*, 2011, vol. 42, no. 5, pp. 400–406.

Jagoe, C.H., Majeske, A.J., Oleksyk, T.K., et al., Radiocesium concentrations and DNA strand breakage in two species of amphibians from the Chornobyl exclusion zone, *Radioprotection*, 2002, vol. 37, p. 873. https://doi.org/10.1051/radiopro/2002217

Kalinkin, D.E., Takhauov, R.M., Karpov, A.B., et al., Factors influencing the health condition of the adult population residing in the activity area of atomic industry enterprise, *Med. Radiol. Radiats. Bezop.*, 2020, vol. 65, no. 4, p. 5. https://doi.org/10.12737/1024-6177-2020-65-4-5-11

Kalistratova, V.S., Belyaev, I.K., Zhorova, E.S., et al., *Radiobiologiya inkorporirovannykh radionuklidov* (Radiobiology of Incorporated Radionuclides), Moscow: Fed. Med. Biofiz. Tsentr im. A.I. Burnazyana, 2016.

Kiselev, S.M., Zhukovskii, M.V., Stamat, I.P., et al., *Radon: ot fundamental'nykh issledovanii k praktike regulirovaniya* (Radon. From Basic Research to Regulatory Practice), Moscow: Fed. Med. Biofiz. Tsentr im. A.I. Burnazyana, 2016.

Matsushima, N., Ihara, S., Takase, M., et al., Assessment of radiocesium contamination in frogs 18 months after the Fukushima Daiichi nuclear disaster, *Sci. Rep.*, 2015, vol. 5, p. 1. https://doi.org/10.038/srep09712

Metodicheskie ukazaniya po metodam kontrolya MUK 2.6.1.717-98 (Guidelines for Control Methods MUK 2.6.1.717-98), Moscow: Minzdrav Rossii, 1998.

Mikhailovskaya, L.N., Pozolotina, V.N., Modorov, M.V., et al., Accumulation of ^{90}SR by *Betula pendula* within the East Ural Radioactive Trace zone, *J. Environ. Radioact.*, 2022, vol. 250, p. 106914. https://doi.org/10.1016/j.jenvrad.2022.106914

Mokrov, Yu.G., *Rekonstruktsiya i prognoz radioaktivnogo zagryazneniya reki Techa* (Reconstruction and Forecast of Radioactive Contamination of the Techa River), Ch. 1. Ozersk: Redaktsionno-Izd. Tsentr, 2002, part 1.

Mokrov, Yu.G., *Rekonstruktsiya i prognoz radioaktivnogo zagryazneniya reki Techa* (Reconstruction and Forecast of Radioactive Contamination of the Techa River), Ch. 1. Ozersk: Redaktsionno-Izd. Tsentr, 2003, part 2.

Omoniy, L.O., Ajibola, M.E., and Bifarin, J.O., Demand Analysis for Frog Meat in Ondo State, Nigeria, *Global J. Sci. Front. Res. Agric. Biol.*, 2012, vol. 12, p. 8. https://doi.org/10.1007/s10935-020-00619-8

Otdalennye ekologo-geneticheskie posledstviya radiatsionnykh intsidentov: Totskii yadernyi vzryv (Remote Ecological and Genetic Consequences of Radiation Accidents: The Totsk Nuclear Explosion, Orenburg Oblast, 1954), Ekaterinburg: Ekaterinburg, 2000.

Pervushkina, N.L., *Zdorov'e potomkov rabotnikov predpriyatiya atomnoi promyshlennosti—Proizvodstvennogo ob"edineniya "MAYaK"* (Health of Offsprings of Employees of Nuclear Industry - "Mayak" Production Association), Moscow: RADEKON, 1998.

Pyastolova, O.A., Vershinin, V.L., Trubetskaya, E.A., et al., Using amphibians in the bioindicatoring studies in the territory of the East-Ural radioactive trace, *Ekologiya*, 1996, no. 5, p. 378.

Rodionova, N.V., Mazhuga, P.M., Domashevskaya, E.I., et al., Changes in the histostructure of the bone skeleton in amphibians living in the Chernobyl exclusion zone, *Probl. Chernobyl'skoi Zony Otchuzhdeniya*, 1994, vol. 1, p. 139

Shvedov, V.L. and Akleev, A.V., *Radiobiologiya strontsiya-90* (Radiobiology of Strontium-90), Chelyabinsk: Ural. Nauchno-Prakt. Tsentr Radiats. Med., 2001.

Smagin, A.I., *Ekologiya vodoemov v zone tekhnogennoi radionuklidnoi geokhimicheskoi anomalii na Yuzhnom Urale* (Ecology of Reservoirs in the Zone of Man-Made Radionuclide Geochemical Anomaly in the Southern Urals), Chelyabinsk: Izd. Tsentr Yuzhno-Ural. Gos. Univ., 2013.

Sobakin, P.I., Gerasimov, Y.R., Chevychelov, A.P., et al., Radioecological situation in the impact zone of the accidental underground nuclear explosion "Kraton-3" in the Republic of Sakha (Yakutia), *Radiats. Biol., Radioecol.*, 2014, vol. 54, p. 641. https://doi.org/10.7868/ S0869803114060125

Stark, K., Avila, R., and Wallberg, P., Estimation of radiation doses from ^{137}Cs to frogs in a wetland ecosystem, *J. Environ. Radioact.*, 2004, vol. 75, p. 1. https://doi.org/10.1016/j.jenvrad.2003.12.011

Strelkov, L.B., *Metod vychisleniya standartnoi oshibki i doveritel'nykh intervalov srednikh arifmeticheskikh velichin s pomoshch'yu tablitsy* (Method for Calculating the Standard Error and Confidence Intervals of Arithmetic Means using a Table), Sukhumi: Alashara, 1966.

Toporkova, L.Ya., Bogolyubova, T.V., and Khafizova, R.T., On the ecology of the lake frog induced into water bodies of the mountain taiga zone of the Middle Urals, in *Fauna Urala i Evropeiskogo Severa* (Fauna of the Urals and the European North), Sverdlovsk: Ural. Gos. Univ., 1979, p. 108.

Trapeznikov, A.V., Chebotina, M.Ya., Trapeznikova, V.N., et al., *Vliyanie AES na radioekologicheskoe sostoyanie vodoema-okhladitelya* (Impact of NPP on the Radioecological Condition of the Cooling Pond), Yekaterinburg: Akadem-Nauka, 2008.

Tunner, H.G., Locomotory behaviour in water frogs from Neusiedlersee (Austria, Hungari). 15 km migration of *Rana lessonae* and ist hybridogenetic associate *Rana esculenta, Proceedings of the 6th Ordinary General Meeting of the SAH*, Budapest: Hungarian Natural History Museum, 1992, p. 449.

Utkin, V.I., Chebotina, M.Ya., Evstigneev, A.V., et al., *Osobennosti radiatsionnoi obstanovki na Urale* (Features of the Radiation Situation in the Urals), Ekaterinburg: Ural. Otd. Ross. Akad. Nauk, 2004.

Vershinin, V.L., *Amfibii i reptilii Urala* (Amphibians and Reptiles of the Urals), Ekaterinburg: Ural. Otd. Ross. Akad. Nauk, 2007a.

Vershinin, V.A., Peculiar features of the life cycle of *R. arvalis* Nills. on the territory of the East Ural radioactive trace, *Sib. Ekol. Zh.*, 2007b, vol. 4, p. 677.

Vershinin, V.L. and Ivanova, N.L., Peculiar features of the trophic relations of an introduced species *Rana ridibunda* (Pallas, 1771) depending on habitat conditions, *Povolzh. Ekol. Zh.*, 2006, no. 3, p. 12.

Yushkova, E.A., Bodnar, I.S., Shadrin, D.M., Pylina, Y.I., and Zainullin, V.GCytogenetic and molecular genetic indexes in populations of Anura (*Rana arvalis* Nilsson) under conditions of radioactive and chemical pollution of an aquatic environment, *Inland Water Biol.*, 2018, vol. 11, no. 3, p. 349.
https://doi.org/10.1134/s1995082918030239

Zhelankin, R.V., The economic importance of the genetic and biotechnical features of the edible frog (*Pelophylax esculentus*) as an object of aquaculture, *Krolikovod. Zverovod.*, 2020, vol. 2, no. 5, p. 49.
https://doi.org/10.24411/0023-4885-2020-105020