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ORIGINAL ARTICLE

The contents of artificial and natural radionuclides in tissues of the *Percidae* fish from the Dnipro Reservoir

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The contents of artificial and natural radionuclides of ^{137}Cs, ^{90}Sr, ^{226}Ra, ^{232}Th, and ^{40}K had been investigated in muscle and bone tissues, gill petals, and scales of common perch *Perca fluviatilis* and pikeperch *Sander lucioperca* from two fishing areas of the Dnipro (Zaporizhzhia) Reservoir. The specific radionuclide activities were measured with the SEG-001 "AKP-C" and SEB-01-150 scintillation spectrometers of gamma- and beta-radiation energy in Bq/kg of wet weight. The radioactive elements of both natural and artificial origins were concentrated greatly in common perch tissues compared to pikeperch. The bone and muscle tissues contained the maximal levels of radionuclides, while respectively smaller amounts of radionuclides were found in gills and scales. The radionuclide levels in the tissues of investigated fish species were significantly higher in the Dnipro Reservoir area with weak flowage and slow water exchange.

Keywords: artificial radionuclides; natural radionuclides; common perch; pikeperch; specific activity; the Dnipro (Zaporizhzhia) Reservoir

Introduction

The radio-chemical load on water ecosystems has become more aggressive over the past 30 years due to anthropogenic disasters (Kaglyan et al., 2009; Romanenko et al., 2008, 2011; Zarubin et al., 2013). The accident at the Chernobyl nuclear power plant in 1986 with the explosion at the Fukushima-1 nuclear power plant in Japan in 2011 caused a problem that affects the entire global community. These situations confirmed the need to control environmental and human exposure to radiation (Tateda et al., 2016; Lee et al., 2018; Chernobyl Disaster..., 2018).

Previous papers have reported that hazard of contamination with technogenically enhanced radionuclides in the Dnipro basin reservoirs is due to the location and functioning of uranium mining and processing complexes (Dvoretsky et al., 2016). The enterprises of the primary nuclear cycle have been operating in the cities of Zhovti Vody and Kam'yanske since 1948; in Kam'yanske the Prydniprovsk chemical plant (now the enterprise «Barrier») and in Zhovti Vody the Eastern Mining and Processing Plant (Program..., 2003). The extracting and processing raw materials of uranium resulted in creation of 12 tailings, containing 90 million tons of radioactive waste. A particular threat is posed by the "Dniprovske", "Central Yar", and "Zakhidne" tailings, located on the upper part of the Dnipro (Zaporizhzhia) Reservoir (Bilokon et al., 2013; Dvoretsky et al., 2016). In this regard, the population of the Dnipropetrovsk region is exposed to low-intensity radiation due to the migration of radionuclides along the trophic chain, which leads to poor human health, malignant occurrence, immune inhibition, etc. According to the Health Department of the Dnipropetrovsk Regional State Administration, the incidence of cancer in the Dnipropetrovsk region has increased by 15 % since 2000, probably due to environmental pollution by radioisotopes.

The Dnipro (Zaporizhzhia) Reservoir is the source of fish for the population of the Dnipropetrovsk region. Therefore, the rational use and examination of its commercial fish stocks are of paramount importance in this region. In the Dnipro (Zaporizhzhia) Reservoir, two species of the *Percidae* family are of the most significant commercial importance: common perch *Perca fluviatilis* and pikeperch *Sander lucioperca*. Two main forms of coastal and deep-sea perches determine the diversity of representatives of perch fish. They differ in size, morphometric parameters, and nutrition. The common perch is a small facultative predator; it belongs to the boreal-plain faunistic complex. The nutritional spectrum of the ichthyophag perch includes small organisms; the modal size of its food objects ranges from 2–4 to 9–12 cm (roach, bleak). A near-bottom lifestyle characterizes a common perch, but sometimes it rises to the surface, preys on young fish or catches insects that have fallen into the water. The larvae of dragonflies are included in the diet of large individuals of the common perch (Grozea et al., 2016). The pikeperch belong to the more thermophilic Ponto-Caspian complex; they feed on small objects of the boreal-flat faunistic complex (perch, roach). The pikeperch, as active predators, hunt for living organisms and swallow them from their tails. Therefore, the modal size of the victims of these species is 3–6 cm, which is slightly larger than that of the common perch that are more likely ambush predators that swallow their prey from the head (Fortunatova & Popova, 1973; Grozea et al., 2016).

The statistics of commercial catches of pikeperch in the Dnipro (Zaporizhzhia) Reservoir in the period 2006–2016 is unstable and characterized by low indicators. At the moment, the pikeperch stock is accounted for by the 2012–2014 generations. According to last year's statistics, the number of two-year-old pikeperch in the littoral reached 0.98 ind./100 m^2 (Fedonenko & Marenkov, 2018). Based on the natural mortality rate (0.26) and the catch rate (0.27), the pikeperch stock in the Dnipro (Zaporizhzhia) Reservoir is estimated at 124 tons.

The common perch catch statistics for the last 3 years corresponds to the figure for the last 10 years – 10.9 tons. In the Dnipro (Zaporizhzhia) Reservoir, the common perch population has a stable age and size-weight structure; its reproductive performance is typical. 4–6 years (85.1 %) common perch individuals predominate. The commercial stock of common perch in the reservoir includes 7 age groups, with their average age of 4.88 in 2017. The allowable catch of common perch in the Dnipro (Zaporizhzhia) Reservoir is estimated at 30 tons when taking into account the natural mortality rate (0.27) and the percentage of the assimilation of the limit (80.4 %) (Fedonenko & Marenkov, 2018).

In this regard, the goal of this work was to investigate and compare patterns of accumulation of radionuclides in various tissues of the predatory fish of the *Percidae* family in the fishing areas of the Dnipro (Zaporizhzhia) Reservoir.

Materials and Methods

Samples of fish were selected with standard methods (Pravdin, 1966; Ozinkovska et al., 1998; Marenkov, 2018) in summer–autumn period at two fishing areas of the Dnipro (Zaporizhzhia) Reservoir (Fig. 1): the Samara Bay (48°53'40.21" N; 35°18'73.20" E) and the lower part near the Viiskove village (48°22'30.75" N; 35°20'80.05" E).

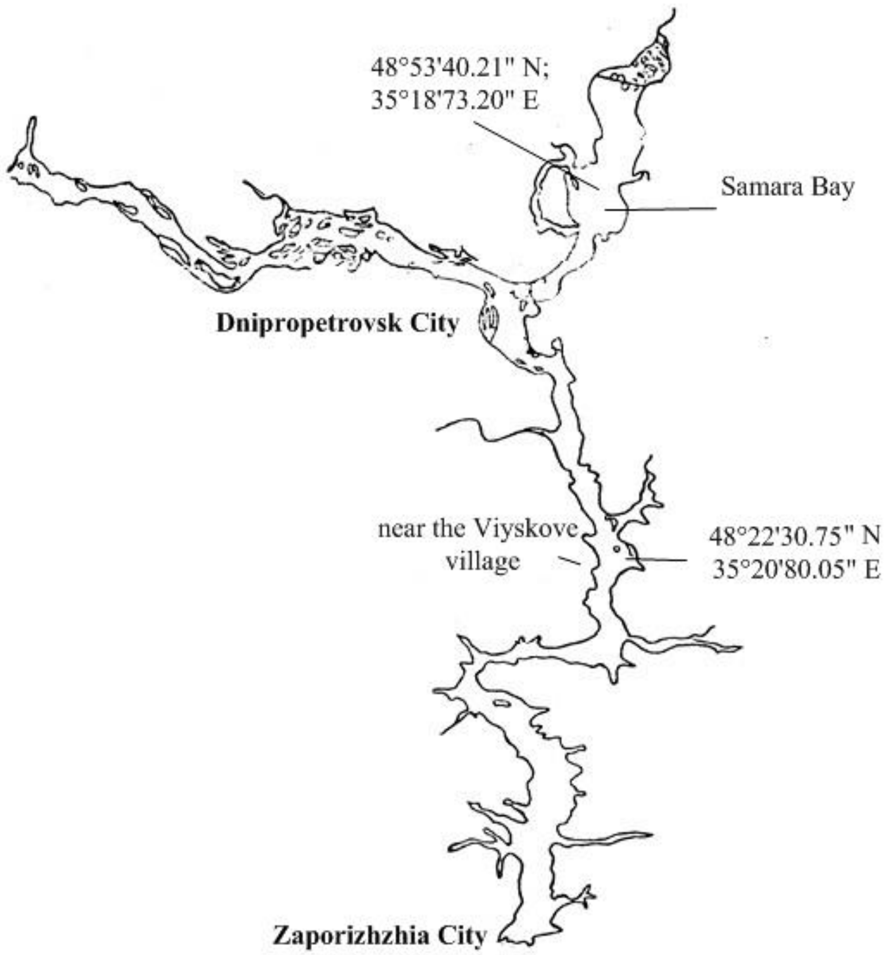

Fig. 1. The scheme of the Dnipro (Zaporizhzhia) Reservoir and the sites of samples location.

The lower section of the reservoir is considered to be a conditionally clean zone by hydrochemical standards; the Samara Bay is located under the influence of the mid-water Samara river (annual flow of 500 million m^3), where the wastewater of the West-Donetsk coal basin is dumped (Fedonenko et al., 2018). The water in the bay contains an enormous content of heavy metals that fall with sewage and has higher mineralization compared with the lower section. Also, the Samara Bay is characterized by a high degree of eutrophication, associated with weak flowage, a large area of shallow water, and significant anthropogenic pollution (Fedonenko & Marenkov, 2018).

The reservoir area from the mouth of the river Samara to the city of Zaporizhzhia is located at the rift of the Ukrainian crystalline shield covered with solid rocks, whose natural radioactive background is always higher than that of sedimentary rocks. In the Dnipro (Zaporizhzhia) Reservoir water (Shugurov & Knyazyuk, 2018), the total beta-activity is 0.22–0.34 Bq/L (Dvoretsky et al., 2016), the average concentrations of natural radionuclides: ^{226}Ra – 1.05 Bq/L, ^{232}Th – 0.47 Bq/L, ^{40}K – 4.89 Bq/L; the content of artificial radionuclides: ^{137}Cs – 0.04 Bq/L, ^{90}Sr – 0.07 Bq/L.

In this study, we investigated the biological tissues of mature individuals (3–4 years old) of common perch and pikeperch: muscle and bone tissues, gill petals, and scales. The average fishing length of a common perch was 20.81±0.83 cm, weight – 226.56±35.38 g. There was retardation in the growth of common perch individuals from the Samara Bay: weight – 146.26±21.10 g, fishing length – 21.41±0.75 cm.

Totally, 3 kg of investigated fish were selected by research control catches, 10 averaged samples of each type tissues were prepared for radiometric assays. Preliminary the samples of biological tissues were crushed with a scalpel or laboratory scissors, weighed and dried at 105°C to attain a constant weight in order to concentrate the radioactive elements contained in them. After drying the samples, they were homogenized in a porcelain mortar. The specific activity of radionuclides in a dry sample weighing 5–10 g was determined using an SEG-001 "AKP-C" gamma-ray energy scintillation spectrometer and SEB-01-150 beta-radiation spectrometer (Ukraine) in Bq/kg of wet weight (Babenko et al., 1998), taking into account the coefficient of shrinkage (the ratio of the mass of the wet sample to the mass of the dried sample). Digital data were processed by Microsoft Excel 2010. The table results were presented as M±m, n=10. The significance of differences between paired values was assessed using Student's t-factor at $p<0.05$.

Results

While working on fish tissues, the contents of artificial radionuclides ^{137}Cs and ^{90}Sr were investigated. Cesium-137 can be evenly distributed in organs and tissues, making it possible to estimate the radiation load in fish when penetrating the inside of radioisotopes. Strontium-90 refers to radionuclides with an osteotropic type of distribution is tissues (Kaglyan et al., 2009). As seen in table 1, the highest ^{137}Cs values in common perch specimens from the Samara Bay were recorded in the bone tissue – 8.90±0.89 Bq/kg. The same tendency of maximum radionuclide content in bones appears in pikeperch – 7.20 ± 0.01 Bq/kg. A higher level of ^{90}Sr accumulation was registered in all studied tissues of the common perch in the Samara Bay compared with pikeperch.

The highest values of ^{90}Sr were noted in common perch bones – 4.50±0.26 Bq/kg, while the value in pikeperch was 3.70±0.17 Bq/kg. The lowest values of ^{90}Sr were observed in scales (1.50±0.24 Bq/kg) and gills (1.50±0.35 Bq/kg), which were 63.8 % less than in the bone tissue. The obtained results indicate significant differences in all the studied common perch tissues compared with pikeperch. The order of the distribution of radioisotopes ^{137}Cs and ^{90}Sr was as follows: bones > muscles > scales > gills.

The natural dose-forming radionuclides include ^{226}Ra, ^{232}Th, and ^{40}K, whose activities has been determined in the ecosystem of the Dnipro (Zaporizhzhia) Reservoir (NRSU-97; Ananieva, 2015; Shapovalenko & Ananieva, 2018). Regardless of the chemical form of the compound, radium that enters the body is deposited in the bone tissues. It is known that ^{226}Ra is distributed in the body in two ways: via the formation of areas of excessive deposition («hot spots») and through a relatively uniform diffuse distribution (Bekman, 2013; Alimova & Utkina, 2016).

Table 1. The contents of artificial radionuclides in the organs and tissues of percid fish in the Samara Bay (Bq/kg, M±m, n=10)

Tissue type	The contents of radionuclides			
	^{137}Cs		^{90}Sr	
	Common perch	Pikeperch	Common perch	Pikeperch
Muscles	7.70±1.42	3.80±0.89*	2.30±0.31	1.15±0.14*
Bones	8.90±0.89	7.20±0.01*	4.50±0.26	3.70±0.17*
Gills	3.30±0.61	1.90±0.61*	1.50±0.24	1.0±0.23*
Scales	5.90±1.02	3.20±1.03*	1.50±0.35	1.10±0.09*

Note. *Here and later significant differences in paired data at $p<0.05$.

Table 2 shows that ^{226}Ra was found mainly in the bones of the common perch in the Samara Bay –46.20±3.3 Bq/kg.

Table 2. The contents of natural radionuclides in the organs and tissues of percid fish in the Samara Bay (Bq/kg, M±m, n=10)

Tissue type	The contents of radionuclides					
	^{226}Ra		^{232}Th		^{40}K	
	Common perch	Pikeperch	Common perch	Pikeperch	Common perch	Pikeperch
Muscles	35.80±4.90	22.50±1.1*	20.30±4.20	28.50±5.63	134.50±19.81	89.20±6.24*
Bones	46.20±3.30	40.10±6.75	57.00±5.11	52.60±5.31	126.40±24.20	114.30±1.92
Gills	28.40± 2.14	21.50±3.86*	35.60±4.21	51.40±0.80*	73.30±4.95	71.60±0.71
Scales	37.60±2.95	36.60±2.34	19.60±4.28	29.70±8.63	109.30±13.90	87.10±7.50*

The smaller accumulation degree was showed by ^{226}Ra in the gills of common perch – 28.40±2.14 Bq/kg. The same accumulation dynamics of ^{226}Ra was observed in pikeperch, the radioisotope was deposited mainly in the bones (40.1±6.75 Bq/kg), and least in the gills (21.50±3.86 Bq/kg). The level of accumulation of ^{226}Ra in the muscles and gills is also significantly higher in common perch than in pikeperch. The gradient of ^{226}Ra distribution in the tissues of both species was bones > scales > muscles > gills.

The natural radionuclide ^{232}Th, acting mainly in the blood, is usually deposited on the inner surface of the bone. The results obtained for the specific activity of ^{232}Th showed that its content was at the same level in the studied fish species, and averaged 24.0±3.3 Bq/kg in muscles, 53.10±5.1 Bq/kg in bones, and 24.20±4.6 Bq/kg in scales. As for the gills, there was a significant difference in the accumulation of ^{232}Th between two species. The level of ^{232}Th in the common perch gills was 19.06±4.28 Bq/kg, this was by 1.5 times lower than that in the gills of pikeperch. The gradient of distribution of the natural radionuclide ^{232}Th in common perch and pikeperch tissues was as follows: bones > gills > muscles > scales.

The distribution of ^{40}K in tissues of the studied fish species from the Samara Bay shows that the highest level of the content of natural radioisotope was registered in the muscles of the common perch – 134.50±19.81 Bq/kg, whereas, ^{40}K is found mainly in the bone tissue of pikeperch – 114.30±1.9 Bq/kg. Significant differences in the radionuclide content in the gills were not detected; the average level of ^{40}K was 72.10±3.21 Bq/kg in both species. The distribution gradient of the natural radioisotope ^{40}K in the tissues was as follows: in the common perch – muscles > bones > scales > gills; in the pikeperch – bones > muscles > scales > gills.

The comparison of low rates of dose-forming radionuclides in the gill epithelium to those of the muscle and bone tissue could be indicative of a preferential influx of radioisotopes into the fish's body through the digestive tract, accompanied by food objects and feed. At the same time, the deposition of radionuclides from water onto the surface of gills plays a much smaller role as the pathway of the radioisotope into the body. The highest rates of radionuclide content were identified in the tissues of the common perch in Samara Bay.

The study of ^{137}Cs and ^{90}Sr radionuclides in the tissues of common percid fish from the lower part of the Dnipro (Zaporizhzhia) Reservoir showed that the largest quantities of these radioisotopes were accumulated in the bones (Table 3). Thus, registered levels of these radionuclides were ^{137}Cs – 8.40±0.4 Bq/kg and ^{90}Sr – 3.85±0.14 Bq/kg; whereas for pikeperch the levels were ^{137}Cs – 7.10±0.06 Bq/kg and ^{90}Sr – 2.20±0.02 Bq/kg.

Table 3. The contents of artificial radionuclides in the organs and tissues of percid fish in the lower part of the Dnipro (Zaporizhzhia) Reservoir (Bq/kg, M±m, n=10)

Tissue type	The contents of radionuclides			
	^{137}Cs		^{90}Sr	
	Common perch	Pikeperch	Common perch	Pikeperch
Muscles	2.60±0.35	2.40±0.83	1.0±0.01	1.10±0.01
Bones	8.40±0.4	7.10±0.06*	3.80±0.14	2.20±0.02*
Gills	2.40±0.46	1.80±0.72*	0.90±0.14	1.10±0.03
Scales	2.30±0.03	1.80±0.03*	0.90±0.03	1.10±0.06

We registered significant differences between the concentrations of ^{137}Cs in the bones, gills, and scales between pikeperch and common perch. The differences in the accumulation of artificial radionuclide ^{90}Sr in the muscular and gill tissues between pike and common perches were insignificant and varied within 1.0 Bq/kg. At the same time, the content of ^{90}Sr in bone tissues was significantly different between pike and common perches. The gradient of ^{137}Cs and ^{90}Sr radioisotope distribution was as follows: bones > muscles > scales > gills.

The data of natural radionuclides distribution from the lower part of the Dnipro (Zaporizhzhia) Reservoir (Table 4), allow us to conclude that ^{226}Ra mainly accumulates in the bones of common perch (26.20±4.5 Bq/kg); the lowest level of ^{226}Ra was found in the gills of common perch – 22.30±2.14 Bq/kg.

The same dynamics of ^{226}Ra accumulation was also observed in pikeperch, that the radioisotope is deposited mainly in the bone tissue (26.4±3.64 Bq/kg), and deposited least of all in the muscle tissue (24.30±4.99 Bq/kg). Indexes of ^{226}Ra contents in biological tissues of the studied fish were approximately at the same levels with the observed difference ranges of the statistical deviation means.

Table 4. The contents of natural radionuclides in the organs and tissues of percid fish in the lower part of the Dnipro (Zaporizhzhia) Reservoir (Bq/kg, M±m, n=10)

Tissue type	The contents of radionuclides					
	^{226}Ra		^{232}Th		^{40}K	
	Common perch	Pikeperch	Common perch	Pikeperch	Common perch	Pikeperch
Muscles	23.90±2.86	24.30±4.99	47.90±3.95	44.50±3.68	73.20±2.77	71.30±2.60
Bones	26.20±4.50	26.40±3.64	42.10±3.52	45.90±4.01	93.70±2.10	101.80±2.02*
Gills	22.30±1.65	25.20±0.12	45.10±5.16	38.30±0.03*	81.20±0.58	117.40±0.12*
Scales	24.20±0.26	26.20±2.51	46.50±0.26	44.70±4.56	74.20±0.23	77.05± .34

Data on the accumulation of ^{232}Th indicate similar levels of the radioisotope in the tissues of the studied fish species, with average values 45.0±3.5 Bq/kg in the muscles, 43.0±3.1 Bq/kg in the bones, and 45.0±2.6 Bq/kg in the scales. Significant differences in the accumulation level of ^{232}Th were found in the gills of the pikeperch, with a content of 38.3±0.03 Bq/kg, which was by 15 % lower than that of the common perch. The gradient of ^{232}Th distribution in tissues appeared as follows: in common perch – muscles > scales > gills > bones; in pikeperch – bones > scales > muscles > gills.

The radioactive ^{40}K is distributed evenly in the organs of the common perch, with the highest amount recorded in the bones (93.70±2.1 Bq/kg). The lowest accumulation rates of this radioisotope were found in the muscles, amounting to 73.2±2.77 Bq/kg and 71.28±2.6 Bq/kg for common perch and pikeperch, respectively.

Discussion

The obtained data on the content of ^{40}K in all tissues was not different from the statistical accuracy in pikeperch and common perch, although indicators in pikeperch tended to increase.

Based on the data obtained, it can be concluded that radioactive elements of both natural and artificial origin are more concentrated in the tissues of river perch compared to pikeperch. The common perch appear to be the more polluted type of fish, as they hunt mainly in the bottom layer, whereas, the pikeperch inhabit the upper layers of water. Also, for the food-related processes of radionuclides accumulation, the composition of the diet, which differs among the fish studied, is of no small importance. The trophic spectrum of the predators in question involves a modal range of the victims of each species, which meets the characteristics of its morphology and needs, as well as the established system of food relationships; this is due to the peculiarities of the structure of the oral apparatus, the length and volume of the stomach, as well as the speed of digestion of food and energy costs for the production of food objects of various sizes (Fortunatova & Popova, 1973).

The distribution of radioisotopes in the tissues of common perch and pikeperch of both studied areas of the Dnipro (Zaporizhzhia) Reservoir was similar. The maximum content of radionuclides was found in bone and muscle tissues, with much smaller quantities recorded in the gills and scales. Apparently, at low concentrations of radioactive elements in the aquatic environment, the distribution of radionuclides depends not only on their tissue specificity but also, to a large extent, on the rate of metabolic processes in biological tissues. Since the gill epithelium is a rapidly renewing tissue, the accumulation of radioisotopes in it was not significant. However, in some cases, high concentrations of the radionuclide ^{232}Th were recorded in the gills of fish, with a reticuloendothelial type of distribution, which is probably due to its influx from the bloodstream during strong blood supply to the gill lobes.

It should be noted that the levels of both artificial and natural radionuclides in the tissues of the studied fish species in the Samara Bay were significantly higher than those in the lower part of the Dnipro (Zaporizhzhia) Reservoir. Although both fishing grounds situated rather far from the sources of anthropogenic radioactivity, it is obvious that the differences in the hydrological regime influence the rate of accumulation of radionuclides in perch fish. Since the Samara Bay is a low-flowing zone of a reservoir with a slow water exchange, the incoming radionuclides that trapped in the reservoir, are more actively absorbed by the biotic components of the ecosystem and deposited in the end links of the trophic aquatic food chains (Volkova & Beliaev, 2009).

At the same time, the contents of the studied radionuclides in commercial predatory fish species in the Dnipro (Zaporizhzhia) Reservoir do not exceed the permissible levels of radioactivity for fish as a food product (Permissible levels..., 2005, Hubanova et al., 2019).

Thus, obtained data should be used for predicting and organizing the monitoring of the levels of dose-forming radionuclides in the aquatic ecosystem. This also be extremely important during the fishing of aquatic organisms in areas at risk of radioactive contamination to prevent excessive intake of radioactive substances into the human body.

Conclusions

Natural radioisotopes ^{40}K, ^{226}Ra, and ^{232}Th, whose content in fish significantly exceeds the level of artificial radionuclides ^{137}Cs and ^{90}Sr, make the main contribution to the formation of dose load in aquatic ecosystems.

The level of radioactive elements of natural and artificial origin was higher in the tissues of common perch compared to pikeperch, probably due to nutrition and lifestyle peculiarities.

The distribution of radioisotopes in tissues was almost similar in common perch and pikeperch from both studied areas of the Dnipro (Zaporizhzhia) Reservoir, the maximum radionuclide content was found in bone and muscle tissues, much smaller amounts was recorded in the gills and scales. In the Samara Bay, the levels of both artificial and natural radionuclides in the tissues of the studied fish species were significantly higher compared with the lower part of the Dnipro (Zaporizhzhia) Reservoir, which could be explained by the weak flow-through and slowed down water exchange in this section of the reservoir.

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