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RADIOACTIVE CONTAMINATION OF THE ICHTHYOFAUNA OF THE CHORNOBYL EXCLUSION ZONE. GLYBOKE LAKE.

The results of the assessment of the dynamics of radionuclide contamination of fish in one of the heavily contaminated water bodies of the Chornobyl Exclusion Zone (ChEZ) - Glyboke Lake for the period 2011-2024 are presented. It was established that the specific activity of ^{137}Cs in the lake's fish fauna continued to decrease during the study period, while the activity of ^{90}Sr, with some exceptions, remained unchanged or increased. In 2021 (before the full-scale invasion of Ukraine by Russian aggressors and their occupation of the ChEZ), the content of radionuclides in fish in the studied reservoir was 180-597 times higher for ^{90}Sr and 7-28 times higher for ^{137}Cs than the permissible levels for fish products in Ukraine. As of 2021, the content of ^{90}Sr in 'peaceful' fish species in the lake exceeded the content of ^{137}Cs by 4.5-13.3 times, and in predatory fish this figure was only 1.8-4.2. The absorbed radiation dose rate for fish in Glyboke Lake for 2021 was also calculated.
Keywords: Chornobyl Exclusion Zone, Glyboke Lake, fish, activity concentration, radionuclides, ^{137}Cs, ^{90}Sr, absorbed irradiation dose rate.

1. Introduction

Radionuclides entering water bodies are involved in biogeochemical processes of distribution of substances between bottom sediments, water and biological components of ecosystems, accumulating in fish organisms. In water bodies subjected to intensive radionuclide contamination as a result of accidents at nuclear fuel cycle facilities, the accumulation of radionuclides by aquatic biota can occur to biologically hazardous levels [1-12].

The Chornobyl Nuclear Power Plant (ChNPP) accident is the largest catastrophe in the history of the nuclear industry, both in terms of the amount of radionuclides released into the environment and the area of contaminated territories. As a result of atmospheric and water transport of a wide range of radionuclides that were present in Unit 4 at the time of the accident, huge catchments and water areas were heavily contaminated. At present, ^{90}Sr and ^{137}Cs are the main dose-forming radionuclides for biota in the water bodies of the Chornobyl Exclusion Zone (ChEZ) [13-23, 30]. In Ukraine, the State Hygienic Standards 'Permissible Levels of ^{137}Cs and ^{90}Sr in Food and Drinking Water' were approved, which set the permissible activity concentration (specific activity or content) of these radionuclides in fish at 150 and 35 Bq/kg, respectively [24].

The main objective of our research was to analyse the levels and dynamics of activity concentration of ^{90}Sr and ^{137}Cs in fish of different species inhabiting Glyboke Lake.

2. Material and research methods

The study was carried out in 2011-2021 in the heavily contaminated ChEZ in Glyboke Lake. Fish were selected for the study in accordance with the regulations on radioecological monitoring of aquatic biocenoses and in cooperation with the State Specialized Enterprise "Ecocenter"of the SAEZ of Ukraine.

In total, 7 fish species were studied - 2 predatory and 5 ‘peaceful’(nonpredatory) fish. Among the predatory fish, we analysed Pike *Esox lucius* L. (1 - 11 years old) and European perch *Perca fluviatilis* L. (4 - 9 years old). Among the ‘peaceful’ species, phytophages were studied: Rudd *Scardinius erythrophthalmus* L. (2 - 9 years); pelagic zooplanktonophages and planktonophages - Common verkhovka or Sunbleak *Leucaspius delineatus* Heckel (1 - 3 years); benthic phages – Prussian carp *Carassius gibelio* Bloch (1 - 12 years), Common tench *Tinca tinca* L. (7 - 9 years) and Roach *Rutilus rutilus* L. (4 - 9 years). The classification of fish is based on the predominant type of food for these age groups according to [25, 26]. In total, more than 700 fish specimens were analysed. The average number of fish in an annual sample for each species was 9-15 specimens.

Measurements of ^{137}Cs activity concentration in water, sediments and fish were performed on the basis of a γ-spectrometric complex consisting of a semiconductor coaxial detector GC4018-DET; Lynx digital spectrum analyser, S502C GENIE-2000 basic software, and LS06067 lead shielding (Mirion Technologies - Canberra, Japan). The determination of ^{90}Sr content was performed by the radiochemical method using the oxalate technique with the measurement of the ^{90}Y daughter product using a low background unit (UMF-2000) [27]. Some of the samples were measured without a preliminary radiochemical procedure using a beta energy spectrometer (SEB-01-70). For some species, methods for determining the specific activity of radionuclides were used according to [28, 29]. The values of specific activity of radionuclides are given in the whole organism of fish in Bq/kg of mass at natural humidity. The measurement error was 10-25%. The calculated standard deviation fully characterised the sample variations according to [31].

The absorbed dose rate of fish was determined using our modified methodology described in [14], based on software [32], using the peculiarities of seasonal and migratory behaviour of different fish species [25,26].

3. Research results and their discussion

Studies of the ichthyofauna of water bodies with ChEZ indicate a significant heterogeneity of activity concentration of ^{90}Sr and ^{137}Cs and its ratio in the organism of fish in Glyboke Lake. This is determined primarily by the intensity and composition of radionuclide contamination of water bodies and adjacent territories during the active stage of the Chornobyl accident, further processes of transformation and secondary intake of radioactive substances into the water body, as well as peculiarities of their hydrochemical regime, which affects the forms of radionuclides and the degree of their availability to biota. The environment is an important source of radionuclides in fish, both directly (due to diffusion processes through gills and skin) and indirectly (as a result of transition through trophic chains). Specific activity of radionuclides in water and limits of their content in bottom sediments of different ecological zones of the investigated water body are given in Table 1.

Table 1: **Average annual activity concentration of radionuclides in water (Bq/l)**

and limits of radionuclide content in the bottom sediments of Glyboke Lake in 2021

Radionuclides	**Water, Bq/l**	**Bottom sediments, coastal area (fish spawning), Bq/kg**	**Bottom sediments (fish feeding area), Bq/kg**	**Bottom sediments (pits, fish wintering grounds), Bq/kg**
^{90}Sr	81,0 ± 20,9	384 - 3660	2871 - 20830	20100 - 124000
^{137}Cs	4,8 ± 1,1	3200 - 39015	27800 - 359800	124000 - 1281000

As our previous studies [17-19, 22, 33-37] show, the highest values of activity concentration of radionuclides are characterised by fish in lake ecosystems located in the territory of the western and southwestern traces of ChNPP accidental releases. Such reservoirs include Glyboke Lake, located in the dyke area of the Krasnianska (Krasnian) floodplain, where rather high levels of radionuclide contamination of fish fauna among the water bodies in the ChEZ studied by us were recorded (Table 2).

Table 2**. Limits of activity concentration of radionuclides in fish in Glyboke Lake (average annual value in parentheses) as of 2021**

Fish	**^{90}Sr**	**^{137}Cs**
Rudd	17884 – 20900 (18928±891)	1698 – 3968 (2391±289)
Prussian carp	17000 – 18870 (17884±785)	1415 – 1738 (1577±162)
Roache	13000 – 15400 (14367±1007)	1320 – 1841 (1602±214)
Tench	10500 – 14590 (12545±1955)	1314 – 1634 (1479±131)
Sunbleak	6284 – 6872 (6578±294)	1076 – 1584 (1330±259)
Perch	7844 – 9940 (8490±744)	2830 – 4273 (3339±546)
Pike	7240 – 11000 (9747±1774)	2607 – 3460 (3175±402)

In general, for all the studied fish of Glyboke Lake, the activity concentration of ^{90}Sr was 6284 - 20900 (12827 ± 4171), and ^{137}Cs - 1076 - 4273 (2167 ± 727) Bq/kg.

Among the species of Glyboke Lake with a high ability to accumulate ^{90}Sr, it should be noted that the rudd is characterised by the highest levels of activity concentration of the radionuclide. Very high levels of radionuclide accumulation by rudd are associated with the peculiarities of feeding on plant foods and, in particular, algae [25, 26], which are characterised by an extremely high ability to accumulate radionuclides [38].

Predatory fish are traditionally considered to be a group that intensively accumulates ^{137}Cs. In the water bodies we studied, they were represented mainly by perch and pike. High levels of ^{137}Cs accumulation in predatory fish are a well-known phenomenon in radioecology, which is associated with the effect of trophic levels during the assimilation of the radionuclide from the muscle tissues of fish food and its increased accumulation in the body of predators. ^{90}Sr in fish is contained mainly in tissues that are poorly digested - bones and scales, head, fins, so its accumulation by predatory species is less efficient compared to 'peaceful' species [1, 3, 8, 14, 16, 41].

During the study period, the specific activity of radionuclides in fish of the Glyboke Lake in all cases exceeded the permissible levels according to the standards for fish products adopted in Ukraine [24] - 180-597 times for ^{90}Sr and 7-28 times for ^{137}Cs.

For comparison, we present the levels of radionuclide contamination of ichthyofauna representatives from other studied water bodies of the Chornobyl Exclusion Zone for 2021.(Tabl.3)

Table 3**. Limits of radionuclide activity concentration in fish from other studied water bodies of the Ch.EZ (average annual value in brackets) as of 2021.**

Water Bodies	**Prussian carp**		**Pike**	
	^{90}**Sr**	^{137}**Cs**	^{90}**Sr**	^{137}**Cs**
Vershyna Lake	105860-139290 (125430±14232)	980-2960 (1950±527)	36400-59860 (49980±6022)	3630-6230 (5000±815)
Azbuchyn Lake	15030-49800 (29420±7793)	1440-3880 (2050±461)	9230-30140 (21850±5224)	2350-4210 (3430±591)
Cooling Pond ChNPP (Northwestern reservoir)	580-1210 (890±157)	610-1520 (1040±276)	320-900* (550±212)	533-960 (602±207)

* In our opinion, due to the fact that there are many catfish in the cooling pond, pike are very rare in catches. Only 4 specimens were caught for analysis. Therefore, the analysis has such a large deviation (error) value.

As can be seen from Table 3, the level of radionuclide contamination of representatives of the ichthyofauna of Glyboke Lake by ^{90}Sr is, on average, 5-7 times lower than in Vershyna Lake and 18-20 times higher than in the Chornobyl NPP Cooling Pond. The levels of contamination of the ichthyofauna of Glyboke Lake with the radionuclide ^{137}Cs from Vershyna Lake and Cooling Pond are in most cases comparable.

Figs. 1 and 2 show the dynamics of activity concentration of radionuclides in fish from Glyboke Lake using the example of two fish species - rudd and perch, which dominated the catches during 2011-2021 and are the most common in the ChEZ water bodies.

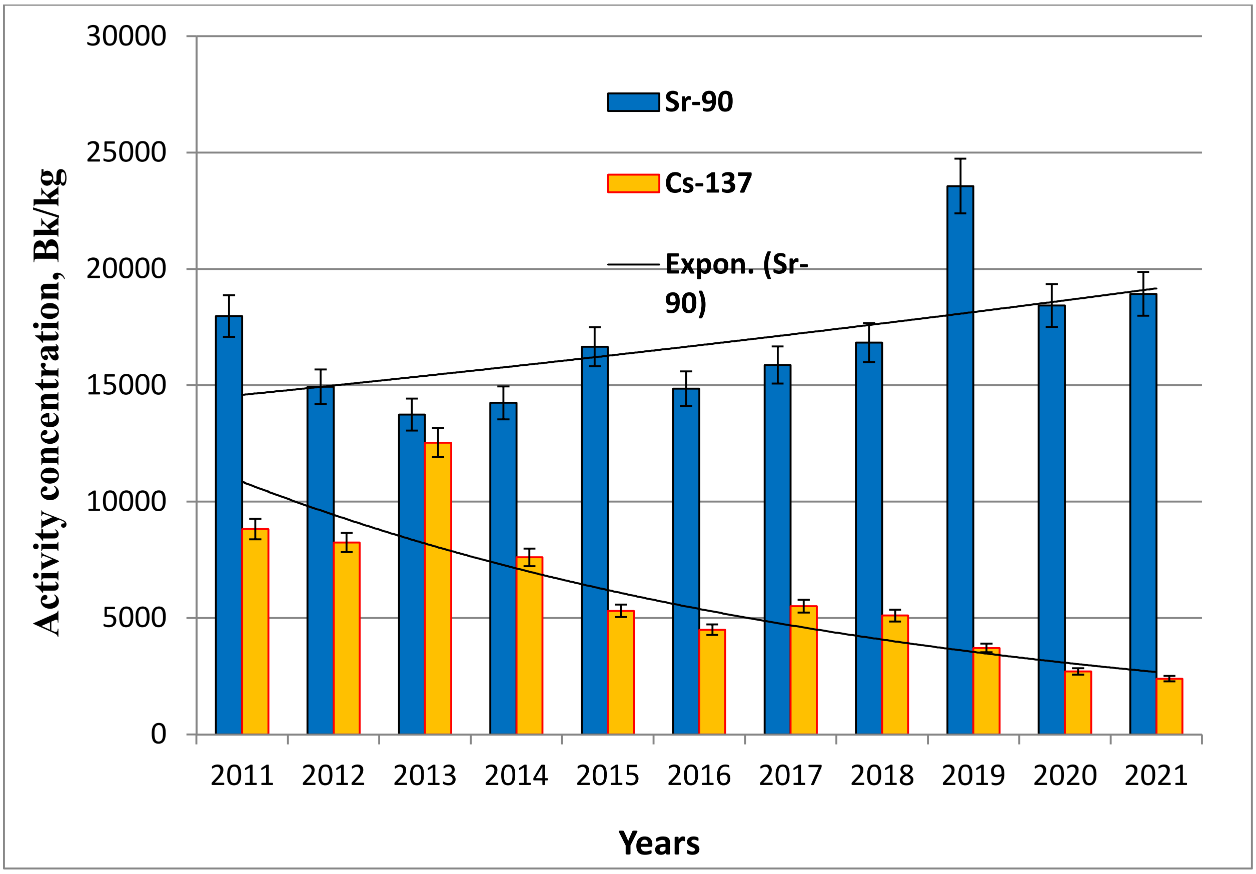

Fig. 1. Dynamics of the average annual activity concentration of radionuclides in rudd in Glyboke Lake from 2011 to 2021, Bq/kg

Analysis of the data obtained for the study period shows that the activity concentration of ^{137}Cs in all representatives of the fish fauna from Glyboke Lake continues to decrease with certain fluctuations, as shown in Fig. 1 on the example of rudd and perch. The ^{90}Sr content in representatives of different fish species either remains unchanged (as in the case of representatives of the facultative predator of perch in Fig. 2) or tends to increase (as in the case of rudd in Fig. 1). This is primarily due to an increase in the specific activity of ^{90}Sr in the groundwater of the adjacent territories, and, accordingly, in the water of Glyboke Lake, which has been observed since the late 1990s [4, 8, 17, 39, 42]. These processes became most intense under conditions of waterlogging and waterlogging of the territories of the left bank of the Prypiat River, in particular the Krasnianska floodplain, which was subjected to the most intense radionuclide contamination. Subsequently, an increase in ^{90}Sr concentrations was recorded in terrestrial plants and aquatic organisms, such as higher aquatic plants, molluscs and fish [2, 19, 22, 37, 40, 43].

The fish in the studied reservoir differ significantly not only in the total activity concentration of radionuclides but also in their ratio in the body. As of 2021, the content of ^{90}Sr in the ‘peaceful’ fish species of the lake exceeds the content of ^{137}Cs by 4.5-13.3 times, while in predatory fish this figure is only 1.8-4.2. Representatives of ‘peaceful’ fish species accumulate ^{90}Sr better, while ichthyophagous fish accumulate ^{137}Cs more. The ^{137}Cs radionuclide is mainly located in muscle tissues of fish that are eaten by predatory fish, while ^{90}Sr is mainly concentrated in calcium-containing organs and tissues (scales, bones, head, fins) that transit through the body of predatory fish.

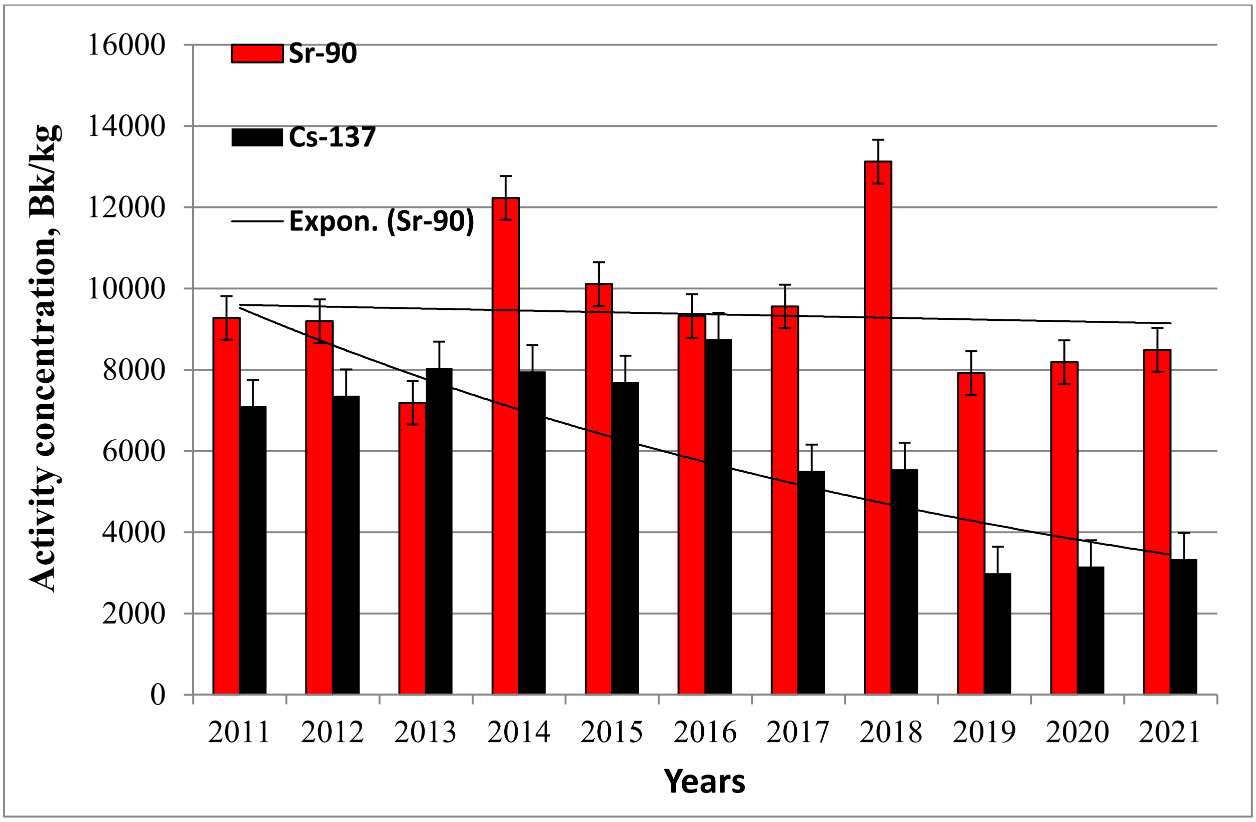

Fig.2. Dynamics of average annual activity concentration of radionuclides in perch in Glyboke Lake from 2011 to 2021, Bq/kg

Using the example of the rudd and perch in Glyboke Lake, an increase in the $^{90}Sr/^{137}Cs$ ratio for both species was observed during the study period, which is primarily due to an increase in the specific activity of ^{90}Sr in fish tissues.

Therefore, knowing the activity concentrations in the abiotic components of the lake ecosystem and the content of radionuclides in fish, it is possible to calculate the dose load experienced by the representatives of the ichthyofauna of Glyboke Lake during the study period. According to our calculations, the average total dose rate of different fish species (except for surface tops) as of 2021 was in the range of 10.1 - 63.1 μGy/h, and for representatives of the tops species, the usual total dose rate was from 4.5 to 7.5 μGy/h.

Thus, the recorded levels of the average annual absorbed total dose rate for all studied fish exceed the screening dose of 2 μGy/h and in most cases exceed the safe level of 10 μGy/h recommended by the European Commission's PROTECT project [44,45].

4. Conclusions

The studies of the ichthyofauna of Glyboke Lake ChEZ with a rather high level of radionuclide contamination and for the period 2011-2021 have established that:

1. The content of radionuclides in fish of the Glyboke Lake during the studies repeatedly exceeded the permissible levels according to the standards for fish products adopted in Ukraine - 180 - 597 (366 times on average) times for ^{90}Sr and 7 - 28 (14 times on average) times for ^{137}Cs.

2. The activity concentration of ^{90}Sr in 'peaceful' fish species of Glyboke Lake was on average 1.7 times higher than in predatory fish (except for the Sunbleak), while ^{137}Cs was on average 2.6 times lower. As of 2021, the ^{90}Sr content in 'peaceful' fish species in Glyboke Lake was in the range of 6284-20900 (14845 on average), and in predatory fish species in the range of 7240-11000 (8993) Bq/kg, while the specific activity of ^{137}Cs in 'peaceful' and predatory fish species was 1076-3968 (1613) and 2607-4273 (3276) Bq/kg, respectively. Among the studied fish of the lake, the highest content of ^{90}Sr was noted for rudd.

3. The activity concentration of ^{137}Cs in fish of Glyboke Lake continued to decrease naturally during the study period with fluctuations within the range of variation for different samples. The level of ^{90}Sr content in the lake fish fauna remained practically at the same level or increased.

The work was supported by the National Research Foundation of Ukraine (project No. 2023.03/0156), the National Academy of Sciences of Ukraine, and in cooperation with the State Specialised Enterprise Ecocenter of the State Agency of Ukraine on Exclusion Zone Management and the Chornobyl Radiation and Ecological Biosphere Reserve.

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