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Article

Mercury content in the muscles of the European perch *Perca fluviatilis* L., 1758 of different ages from water bodies and streams of the Oka Nature Reserve

D.E. Kotikov[1*], V.A. Gremyachikh[1], T.B. Kamshilova[1], E.Yu. Ivancheva[2], V.P. Ivanchev[2], V.T. Komov[1]

[1] *I.D. Papanin Institute for Biology of Inland Waters, Russian Academy of Sciences, Borok 109, Nekouz District, Yaroslavl Oblast, 152742 Russia*

[2] *Oka State Natural Biosphere Reserve, Brykin Bor 51, Spassky District, RyazanOblast, 391072 Russia*

**daniil-kotikov@mail.ru*

Abstract. The total mercury (Hg) content in the muscles of European perch of different ages from water bodies and streams of the Oka Nature Reserve was studied. The material was collected in 2006–2016. A total of 222 individuals from five groups of water bodies were analyzed: the Pra River, other rivers, floodplain lakes, non-floodplain lakes, and a reclamation ditch. Hg concentrations were determined by atomic absorption spectrometry, and age was determined from opercula (gill covers). Considerable variability in Hg content (from 0.02 to 0.68 mg/kg wet weight) was revealed. The highest mean concentrations were recorded in the Pra River (0.30 mg/kg) and the reclamation ditch (0.24 mg/kg), and the lowest in other rivers (0.14 mg/kg). The intensity of Hg accumulation is highest during the first two years of life, which coincides with the perch's shift to piscivory. Differences in the dynamics of Hg accumulation among the groups of water bodies were found. Mean concentrations in the Pra River were at the maximum permissible level, while maximum concentrations exceeded it. The results highlight the importance of considering the age structure of the population when assessing mercury pollution of aquatic ecosystems.

Keywords: bioaccumulation, growth rate, methylmercury, freshwater ecosystems

ORCID:
D.E. Kotikov, https://orcid.org/0000-0003-2979-7896
V.A. Gremyachikh, https://orcid.org/0000-0002-2817-039X
T.B. Kamshilova, https://orcid.org/0000-0002-8535-9658
E.Yu. Ivancheva, https://orcid.org/0000-0002-9743-7641
V.P. Ivanchev, https://orcid.org/0000-0001-9578-4036
V.T. Komov, https://orcid.org/0000-0001-9124-7428

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Научная статья

Содержание ртути в мышцах речного окуня *Perca fluviatilis* L., 1758 разного возраста из водоемов и водотоков Окского заповедника

Д.Э. Котиков[1*], В.А. Гремячих[1], Т.Б. Камшилова[1], Е.Ю. Иванчева[2], В.П. Иванчев[2], В.Т. Комов[1]

[1] *Институт биологии внутренних вод им. И.Д. Папанина РАН, 152742, Россия, Ярославская обл., Некоузский р-н, пос. Борок, д. 109*

[2] *Окский государственный природный биосферный заповедник, 391072, Россия, Рязанская обл., Спасский, р-н, пос. Брыкин Бор, д. 51*

**daniil-kotikov@mail.ru*

Аннотация. Изучено содержание общей ртути (Hg) в мышцах речного окуня разного возраста из водоемов и водотоков Окского заповедника. Материал собран в 2006–2016 гг. Проанализировано 222 особи из пяти групп водоемов: р. Пра, другие реки, пойменные озера, внепойменные озера и мелиоративная канава. Концентрации Hg определяли атомно-абсорбционным методом, возраст – по жаберным крышкам. Выявлена значительная вариабельность содержания Hg (от 0.02 до 0.68 мг/кг сырой массы). Наиболее высокие средние концентрации отмечены в р. Пра (0.30 мг/кг) и мелиоративной канаве (0.24 мг/кг), наиболее низкие – в других реках (0.14 мг/кг). Интенсивность накопления Hg максимальна в первые два года жизни, что совпадает с переходом окуня на хищное питание. Выявлены различия в динамике накопления Hg между группами водоемов. Установлено, что средние концентрации в р. Пра находятся на предельно допустимом уровне, максимальные превышают его. Результаты подчеркивают важность учета возрастной структуры популяции при оценке загрязнений водных экосистем ртутью.

Ключевые слова: биоаккумуляция, темп роста, метилртуть, пресноводные экосистемы

ORCID:
Д.Э. Котиков, https://orcid.org/0000-0003-2979-7896
В.А. Гремячих, https://orcid.org/0000-0002-2817-039X
Т.Б. Камшилова, https://orcid.org/0000-0002-8535-9658

Е.Ю. Иванчева, https://orcid.org/0000-0002-9743-7641
В.П. Иванчев, https://orcid.org/0000-0001-9578-4036
В.Т. Комов, https://orcid.org/0000-0001-9124-7428

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Introduction

Intensive human use of mineral resources leads to changes in global and regional cycles of many chemical elements, including mercury (Bashkin, 2006). Mercury (Hg) is considered by the World Health Organization (WHO) as one of the ten main chemicals or groups of chemicals that pose a significant problem for human and animal health (WHO, 2017[1]). Deposited on the earth's surface by atmospheric precipitation and reaching water bodies via surface runoff, it is effectively accumulated in aquatic food webs in its most toxic form – methylmercury (MeHg). In particular, elevated metal levels are recorded in fish inhabiting low-mineralized and acidified lakes in Scandinavia (Hakanson et al., 1990), the USA (Greib et al., 1990), Canada (McMurty et al., 1989), and Russia (Haines et al., 1992; Stepanova and Komov, 1996). Low water pH and a high degree of catchment swampiness strongly contribute to Hg accumulation in fish (Greenfield et al., 2001; Waite et al., 2002). The spectrum of negative impacts of Hg on living organisms, populations, and aquatic ecosystems as a whole is wide and diverse (Scheuhammer et al., 2007; Wiener, 2013). Excessive consumption of fish with high Hg content leads to deterioration of many health indicators, including reproductive health, in both humans and animals (piscivorous birds and mammals) (Karagas et al., 2012; Mergler et al., 2007).

The MeHg content in fish muscle tissue is related to their size-age parameters, position in the food web and diet, and the biological productivity of the water bodies; the main reason for interspecific differences is different trophic strategies (piscivory, benthivory, planktivory) and diet composition (Piraino and Taylor, 2009). In piscivorous fish species, Hg concentration often positively correlates with body length (Burger and Gochfeld, 2011; Cizdziel et al., 2002; Gabriel et al., 2009) and trophic status (Chumchal and Hambright, 2009; Lavoie et al., 2013; Sonesten, 2003; Ward et al., 2012). A reduction in the levels of metal accumulated by fish is promoted by high nutrient content in the water bodies due to dilution of Hg entering the water body in primary producers (Kamman et al., 2004; Miller et al., 2012; Pickhardt et al., 2002), as well as by accelerated somatic growth of fish (Karimi et al., 2007a; Ward et al., 2010a).

Fish growth rates reflect their adaptation to the conditions in a water body and serve as an important characteristic of population status. Growth rates of individuals (increase in length or weight per chosen unit of time) are influenced by factors such as the composition and abundance of prey, the abundance of food competitors and predators, the density of the own population, fishing pressure, and climatic and physical characteristics of the habitat (Höhne et al., 2019; Popova et al., 1993). Perch growth, in particular, is affected by the availability of diverse food (including fish), which, due to the early shift to a piscivorous lifestyle, accelerates its growth (Dgebuadze, 2001; Popova et al., 1993).

There is an opinion that a low fish growth rate is the main biological factor contributing to the accumulation of large amounts of mercury (Verta, 1990). However, the facts reported in the scientific literature on the influence of growth rates on mercury accumulation are scarce, since the growth rate and Hg levels are often determined not so much by growth itself as by the trophic level and diet composition (Lavoie et al., 2013; Popova, 1971). The relationship between Hg accumulation in muscles and fish body growth in freshwater bodies is convenient to study using the example of the European perch, a representative of piscivorous and eurybiontic fish species. It is characterized by a wide geographical

[1] WHO, 2017. Ten chemicals of major health concern. Web page. URL: <http://www.who.int/ipcs/assessment/public_health/chemicals_phc/en/index.html> (accessed: 18.12.2025).

distribution and inhabitation of various types of water bodies, including those with low water pH (Haines, 1981). In naturally and anthropogenically acidified lakes, perch often becomes the sole representative of the ichthyofauna, as other species cannot tolerate such conditions (Grib and Stepanova, 1943). Previously, studies on mercury content in fish from the water bodies of the Oka Nature Reserve were conducted (Gremyachikh et al., 2012), but an analysis of the age-related dynamics of Hg accumulation in perch has not been performed. This determines the relevance of the present work.

Ryazan Oblast and the Oka State Natural Biosphere Reserve (OSNBR) located within its territory are situated in the center of the densely populated and industrially developed European part of Russia. Even in the absence of local sources of agricultural and industrial mercury pollution within the reserve, its constituent aquatic and terrestrial ecosystems are subject to atmospheric metal pollution (Tobratov et al., 2018). It is known that water bodies located in specially protected natural areas (SPNAs) can be used to study the background state of aquatic ecosystems in a specific region, as well as the impact of global environmental changes and transboundary transport of pollutants, including Hg (Pavlov et al., 2007).

The aim of this study is to determine the mercury content in the muscle tissue of European perch (*Perca fluviatilis* L., 1758) of different ages from water bodies and streams of the Oka Nature Reserve.

Materials and methods

The object of the study was the European perch *Perca fluviatilis*, a widespread species in the ichthyofauna of the reserve. A total of 222 individuals aged from 0+ to 9+ years were caught (detailed data for each group of water bodies are given in Table 1).

Fish were caught using gill nets (mesh size 10–50 mm, length 25–50 m, height 1.5–3 m) and a fine-mesh seine (mesh size 5–10 mm) in 2006–2016 in the water bodies of the OSNBR and adjacent territories that have no local industrial or agricultural sources of mercury pollution within their catchments (Fig. 1). The catches were carried out as part of the research activities of the reserve (Order of the Ministry of Natural Resources of Russia No. 431 dated 16.05.2003[2]).

Table 1. Size and weight parameters and Hg content in the muscles of perch from different groups of water bodies and watercourses. Above the line, the mean ± standard deviation is shown; below the line, the range of values is shown. Different letter indices indicate significantly different values at $p < 0.05$.

Water bodies and watercourses	n	Body length, cm	Body weight, g	Hg, mg/kg wet weight
Pra River	84	14.0 ± 0.5^{b} 5.4–23.4	75.4 ± 8.1^{b} 2.4–301.0	0.30 ± 0.02^{c} 0.02–0.68
Other rivers	31	13.1 ± 0.4^{ab} 9.8–18.0	44.7 ± 4.4^{a} 17.2–127.1	0.14 ± 0.01^{a} 0.06–0.29
Floodplain lakes	53	13.2 ± 0.6^{b} 7.0–23.0	65.6 ± 9.9^{ab} 6.3–288.0	0.23 ± 0.02^{b} 0.04–0.49
Non-floodplain lakes	32	13.1 ± 0.8^{ab} 8.6–23.5	56.3 ± 12.2^{ab} 10.2–279.0	0.17 ± 0.02^{a} 0.03–0.44
Drainage ditch	22	10.9 ± 0.9^{a} 4.6–17.0	35.6 ± 6.7^{a} 1.7–98.6	0.24 ± 0.03^{b} 0.04–0.45
All water bodies combined	222	13.2 ± 0.3 4.6–23.5	62.0 ± 4.4 1.7–301.0	0.24 ± 0.01 0.02–0.68

[2] Order of the Ministry of Natural Resources of the Russian Federation No. 431 of May 16, 2003 «On approval of the regulations on the federal state institution «Oka State Natural Biosphere Reserve» (as amended on March 17, 2005 and February 27, 2009).

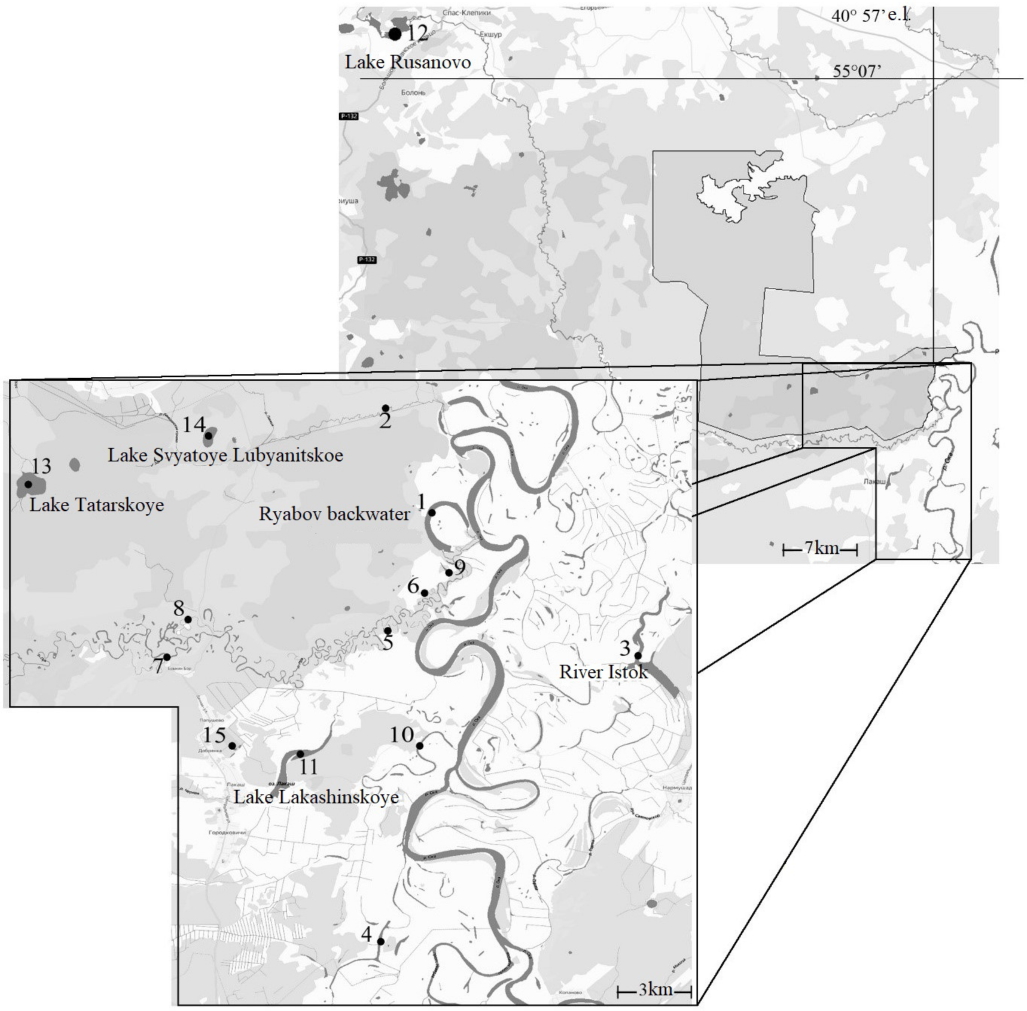


Fig. 1. Map of fish sampling stations (numbers correspond to those given in Table 1) on the territory of the Oka Nature Reserve and adjacent areas.

During a preliminary analysis, water bodies with different hydrological regimes were divided into five groups. The criteria for division were the type of water body and the hydrological connection with the Oka River. The first group consisted of stations located on the Pra River (Mirskaya Roshcha, Nefedovo, Brykin Bor, Aleshina Luka). The second group included all other rivers (Istok, Tolpega, Lamsha, Oka). The third and fourth groups comprised floodplain and non-floodplain lakes, respectively (floodplain lakes – Alekseevo, Shilishche, Lakashinskoe; non-floodplain lakes – Rusanovo, Tatarskoe, Svyatoe Lubyanitskoe). The fifth group was represented by a single water body – a reclamation ditch near the village of Papushevo, which flows into the Oka River.

The caught fish were placed in plastic bags, frozen (−4...−14 °C), and stored until Hg content determination. Thawed fish were placed in enameled cuvettes to prevent possible secondary Hg contamination, weighed, measured for length from the tip of the snout to the end of the scaled cover (Pravdin, 1966); sex was determined visually, and the ratio of males to females in the sample was approximately 1:1. From the left side of each perch, 2–4 g of skeletal muscle were excised from the dorsal fin to the beginning of the ribs (Haines et al., 1992). Mercury content in perch muscles was determined in 2–3 replicates using the atomic absorption method on a RA-915+ mercury analyzer with a PYRO attachment (Lumex) without preliminary sample preparation. The accuracy of the analytical measurement methods was controlled using certified biological reference materials DORM-2 and DOLM-2 (Institute of Environmental Chemistry, Ottawa, Canada). The differences between replicates averaged 4.7%.

The recording structures used for determining fish age and growth rates include scales and bones (operculum, otoliths, cleithrum, vertebrae, fin rays, pharyngeal teeth, etc.) (Sterligova, 2016). In our study, opercula (gill covers) cleaned of soft tissues were used. The age group of fish was determined by the number of complete years (Kamshilova et al., 2013). The opercula were scanned on a flatbed scanner at a resolution of 300 dots per inch, and the area (mm²) corresponding to the growth increment of each year of life was measured. Measurements were performed using the Image Tool computer software (version 1.91). Analysis of opercula was performed for all fish in which muscle Hg content was determined.

To compare these parameters in fish from different water bodies, linear regression equations were used according to the formula:

$$Y = a \times X,$$

where Y is body length or Hg concentration in muscles, a is the coefficient, X is age or body length. At the starting point, all parameters were taken as 0.

Correlation and regression analyses of the relationship between total Hg content in perch muscles and fish length and age were performed for the 5 groups of water bodies, and for the Pra River – also for samples of perch aged up to 3 years and older than 2 years (fish aged 3 years were included in the second group). Total Hg concentrations in perch muscles were normalized by logarithmic transformation. Significant differences between individual groups of water bodies and age groups from the Pra River were judged by the results of pairwise comparisons of the slope coefficients (SC) of the regression lines as indicators of Hg accumulation intensity (Backstrom et al., 2020; Gedig et al., 2023). The slope coefficients, as well as the p-values for significance of differences obtained from pairwise comparisons of the regression lines of the analyzed parameters, are presented once in the article as an example; in other cases, the results of the comparative analysis are reflected only in letter indices on the figures.

Back-calculation of growth was performed using the E. Lea (1910) formula, which allows determining the size of an individual at each year of life. Knowing the fish length at capture (L_n), its operculum area (S_n), and the annual ring area (S_x), the length of the individual at the time of this ring formation (L_x) can be determined from the proportion:

$$\frac{\mathrm{Ln}}{\mathrm{Sn}} = \frac{\mathrm{Lx}}{\mathrm{Sx}}$$

Determination of annual body length increment (G_i) was carried out according to the following formula (Ilmast, 2005; Mina and Klevezal, 1976):

$$G_i = L_x - L_{x-1}$$

Statistical data processing was performed using the software package Statgraphics 18 (Statgraphics Technologies, Inc., USA). One-way analysis of variance (ANOVA) and the LSD test procedure were applied at a significance level of $p < 0.05$.

Results

The body length of perch ranged from 4.6 to 23.5 cm, body weight – from 1.7 to 301 g, and Hg content in muscle tissue – from 0.02 to 0.83 mg/kg wet weight (Table 1).

The highest average body length of perch was recorded in the Pra River and floodplain lakes, while the lowest was recorded in the reclamation ditch (Table 1, Fig. 2). The highest average Hg content in muscles was found in perch from the Pra River, and the lowest in fish from the other rivers (Table 1, Fig. 3).

Perch age, length and body weight are strongly interrelated, while Hg concentration in muscles correlates with them to a lesser extent (Table 2). Further data analysis for fish samples from the studied groups of water bodies used body length as the main parameter. The most intensive growth was recorded in perch from the Pra River, floodplain lakes, and the reclamation ditch (Table 3, Fig. 4).

Normalized total Hg concentration in muscles significantly positively correlated with age in perch from the Pra River, other rivers of the reserve, and the reclamation ditch (Table 2). The most intensive increase in Hg concentration in muscles with age was observed in perch from the reclamation ditch (Table 2, Fig. 5).

The correlation between Hg concentrations in fish muscles and age across all studied groups of water bodies in the reserve, with respect to the Pra River, is described by a nonlinear relationship: $r = 0.59–0.91$, $R^2 = 35.6–82.4$, $p < 0.0000$ (Fig. 6**A**). Consequently, the intensity of metal accumulation in

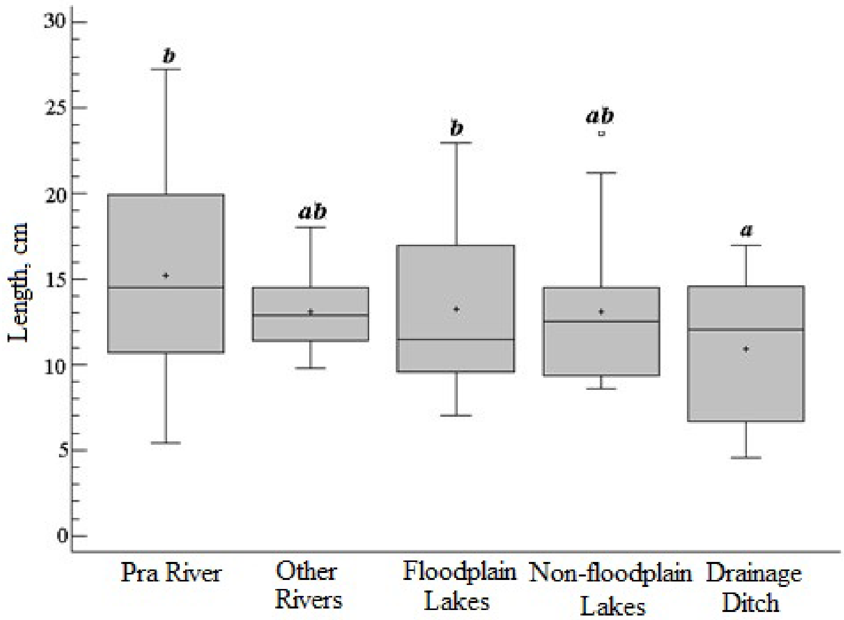


Fig. 2. Mean fish length from different groups of water bodies and streams. Here and elsewhere, different letter indices indicate significantly different values.

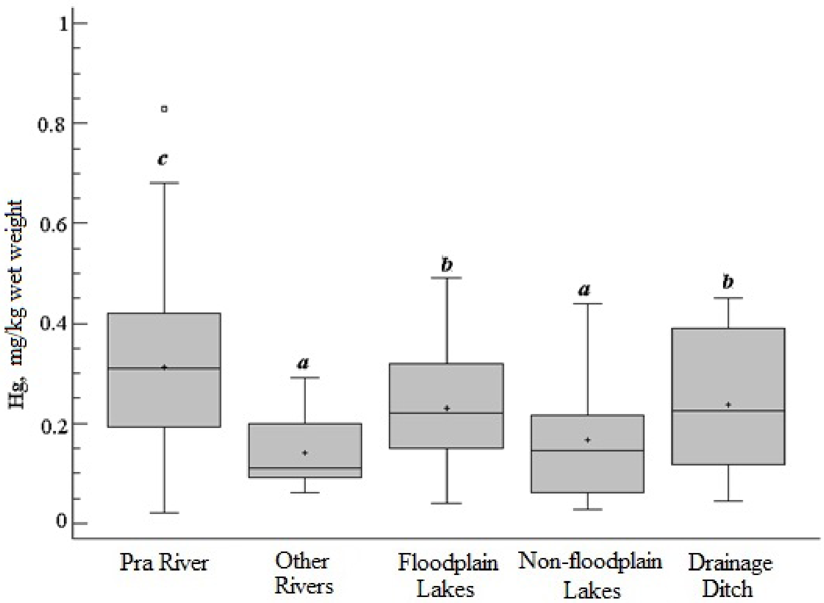


Fig. 3. Hg content in fish muscles from different groups of water bodies and streams.

Table 2. Correlation coefficients (r, R^2, p) between size-weight characteristics, age, and muscle Hg concentration in fish from different groups of water bodies and watercourses. A dash indicates comparison of a parameter with itself.

Water bodies and watercourses	n	Parameter	Body length	Body weight	Hg Content (log Hg)
Pra River	84	Age	0.87, 75.4, 0.000	0.78, 60.2, 0.000	0.28, 7.7, 0.01
Other rivers	31		0.60, 36.0, 0.000	0.59, 34.3, 0.000	0.64, 40.9, 0.000
Floodplain lakes	53		0.80, 64.7, 0.000	0.77, 59.6, 0.000	0.27, 7.1, 0.054
Non-floodplain lakes	32		0.69, 47.6, 0.000	0.54, 29.0, 0.000	0.09, 0.1, 0.60
Drainage ditch	22		0.92, 85.0, 0.000	0.87, 75.2, 0.000	0.80, 63.7, 0.000
Pra River	84	Body length	–	0.91, 82.2, 0.000	0.33, 10.8, 0.002
Other rivers	31		–	0.95, 91.1, 0,000	0.72, 51,4, 0.000
Floodplain lakes	53		–	0.95, 90,7, 0.000	0.29, 8.5, 0.03
Non-floodplain lakes	32		–	0.94, 89.2, 0.000	0.14, 2.0, 0.44
Drainage ditch	22		–	0.94, 90.5, 0.000	0.89, 79.2, 0.000
Pra River	84	Body weight	0.91, 82.2, 0.000	–	0.20, 3.9, 0.07
Other rivers	31		0.95, 91.1, 0,000	–	0.66, 44.1, 0.000
Floodplain lakes	53		0.95, 90,7, 0.000	–	0.37, 13.5, 0.007
Non-floodplain lakes	32		0.94, 89.2, 0.000	–	0.10, 1.1, 0.57
Drainage ditch	22		0.94, 90.5, 0.000	–	0.80, 64.1, 0.000

Table 3. Slope coefficients of regression lines and p-values for significance of differences obtained from pairwise comparisons of fish length–age relationships across individual groups of water bodies. Statistically significant values are shown in bold.

Group of water bodies	Кн	Pra River	Other rivers	Floodplain lakes	Non-floodplain lakes	Drainage ditch
Pra River	2.99923	–	**0.0001**	0.4735	0.1016	0.9305
Other rivers	1.1999	–	–	0.0020	0.0567	**0.0000**
Floodplain lakes	2.76078	–	–	–	0.3658	0.2677
Non-floodplain lakes	2.30049	–	–	–	–	0.0966
Drainage ditch	3.36839	–	–	–	–	–

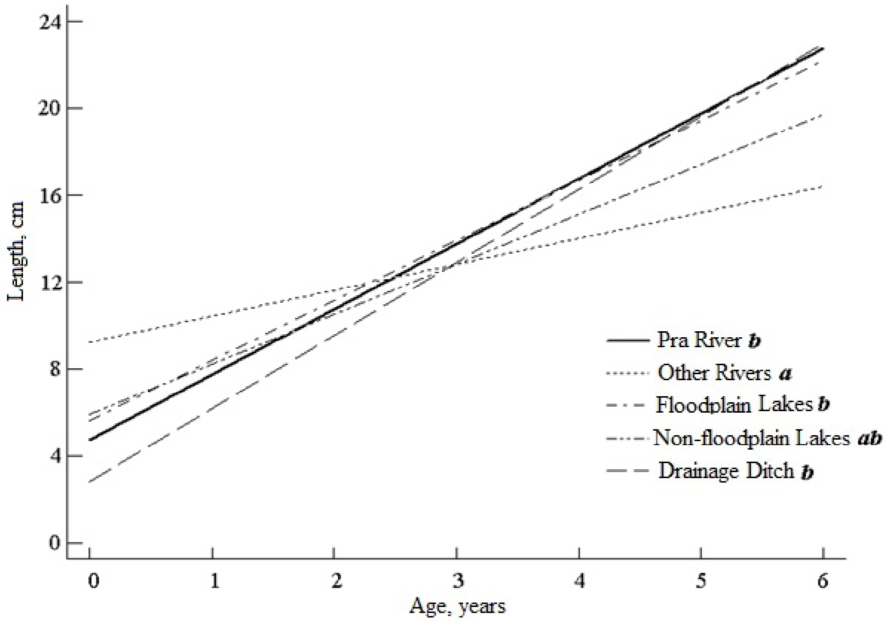


Fig. 4. Regression lines of fish length on age for different groups of water bodies in the reserve.

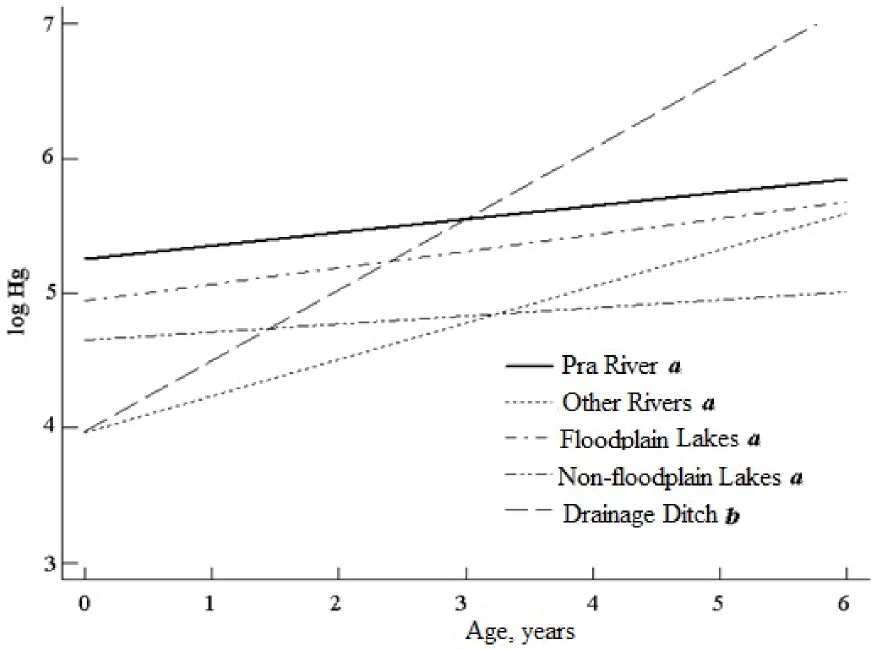


Fig. 5. Regression lines of total Hg concentration in perch muscles (mg/kg wet weight) on fish age for different groups of water bodies and streams.

perch aged up to and including 2 years (mean length 12–13 cm) is higher than in older fish (> 2 years and length > 12–13 cm). For fish from the Pra River, other rivers of the reserve, and the reclamation ditch, a relationship between Hg concentrations and body length was also found: $r = 0.34–0.91$, $R^2 = 11.9–82.4$, $p < 0.0000$. Significant differences in the intensity of Hg accumulation were revealed between different age groups of fish from the Pra River (the largest sample) (Fig. 6**B**). In the age group up to 3 years, the highest and most significant increase in Hg concentrations with fish growth was found in the Pra River and the reclamation ditch, and the lowest (negative) in the group of floodplain lakes (Fig. 7**A**). In the age group older than 2 years, the relationship was reversed: in the Pra River – low increase in Hg in perch muscles, in other rivers and floodplain lakes – high and significant (higher in other rivers) (Fig. 7**B**).

Analysis of back-calculated growth showed that the most intensive increase in body length occurs in the first two years of life, except for perch from the reclamation ditch (Fig. 8). Then growth rates slow down. Fish from the rivers (excluding the Pra River) are characterized by the lowest growth rates in different years (Table 4). For the other groups of water bodies, no differences in perch growth rates were found.

The highest increase in Hg concentration per unit body length in perch from different water bodies of the reserve was recorded in the first two years of life (Fig. 9**A**), whereas the increase in body mass per unit length increment was, conversely, found in individuals older than 2 years (Fig. 9**B**). This pattern is clearly seen in the example of fish from the Pra River (Fig. 9**C**)

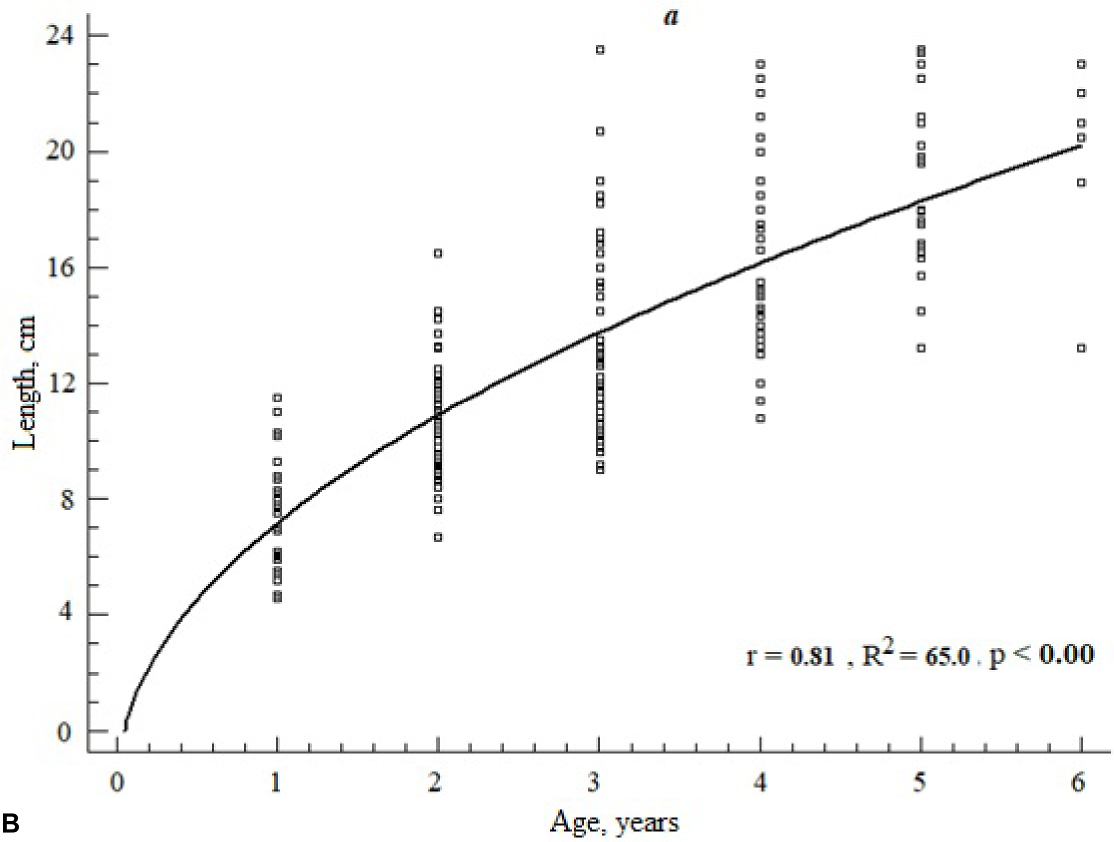
Discussion

Habitat conditions for European perch vary significantly across different parts of its extensive range, which inevitably affects its growth rates (Popova et al., 1993). In small, low-food water bodies, one-year-old perch reach about 5 cm in length, and by six years – 20 cm, whereas in large lakes and reservoirs, as well as in deltas of large rivers, yearling fish can reach 12 cm, and five-year-old fish – 35 cm (Popova, 1971, 1979). Perch from the rivers and lakes of the Oka Nature Reserve show accelerated growth in the first three years of life, similar to fish from lakes in Karelia (Reshetnikov et al., 1982) and the Uglich Reservoir (Makarova, 1979). In subsequent years, fish growth rates in all the aforementioned water bodies of the European part of Russia slow down, which may be associated with changes in the structure of the food supply and increased intraspecific competition.

The most important factor determining the growth rate of adult individuals is the availability of accessible and high-calorie fish prey, which allows for an early shift to a piscivorous diet (Popova et al., 1993). It is known that in rivers with fast currents and in shallow artificial water bodies (similar to the reclamation ditch), perch often switch to piscivory as early as the first or second year of life (Popova, 1971, 1979). This is confirmed by our data: the highest Hg concentrations in juveniles from the Pra River and the ditch coincide with the period of the presumed transition to a fish-based diet, which leads to accelerated biomagnification of the metal. As predator size increases, the preferred prey size also increases, contributing to more efficient energy assimilation and accelerated growth. Under conditions of insufficient suitable food, fish growth rates slow down (Dgebuadze, 2001). In the study of perch from the Oka Nature Reserve, it was found that after the second year of life, despite potential dietary improvement, the annual increase in body length slows down, while body mass increment increases. This indicates a transition from intensive linear growth to mass accumulation, characteristic of mature individuals directing energy towards reproductive functions (Wootton, 1998).

The Hg content in fish muscle tissue depends on several abiotic and biotic factors: water pH and organic matter content, the presence of swamps and waterlogged forests in the catchment area, the trophic status of the water body, fish size (age), and feeding habits (Driscoll et al., 2013; Lavoie et al., 2013; Ullrich et al., 2001). Average Hg concentrations in perch muscles from acidic ($pH < 5$) lakes of Vologda Oblast (Darwin Nature Reserve) are significantly higher than in fish from moderately acidified ($6.5 > pH \geq 5$) lakes of Karelia, Novgorod and Pskov Oblasts (Rdeysky and Polistovsky Nature Reserves), as well as in water bodies with neutral pH values (Kamshilova et al., 2011; Komov et al., 2009). At the same time, Hg content in fish muscles from moderately acidified and neutral lakes does not differ significantly. In the studied water bodies of the Oka Nature Reserve, pH ranges from 6.6 to 8.9 (Table 5), and the metal content in perch muscles ranges from 0.02 to 0.68 mg/kg wet weight. Such wide variability in Hg concentrations is also observed in other regions. For example, in distant Canadian lakes with neutral water pH values ($7.0 > pH \geq 8.5$), Hg concentrations in piscivorous fish muscles varied from 0.07 to 2.5 mg/kg wet weight (Gantner et al., 2010), and in water bodies of the Amazon basin (pH 4.5–6.5), Hg content in different fish species ranged from 0.05 to 0.69 mg/kg wet weight (Belger and Forsberg, 2006). A similar range of values was observed in lakes of Vologda Oblast, where mercury

A



B

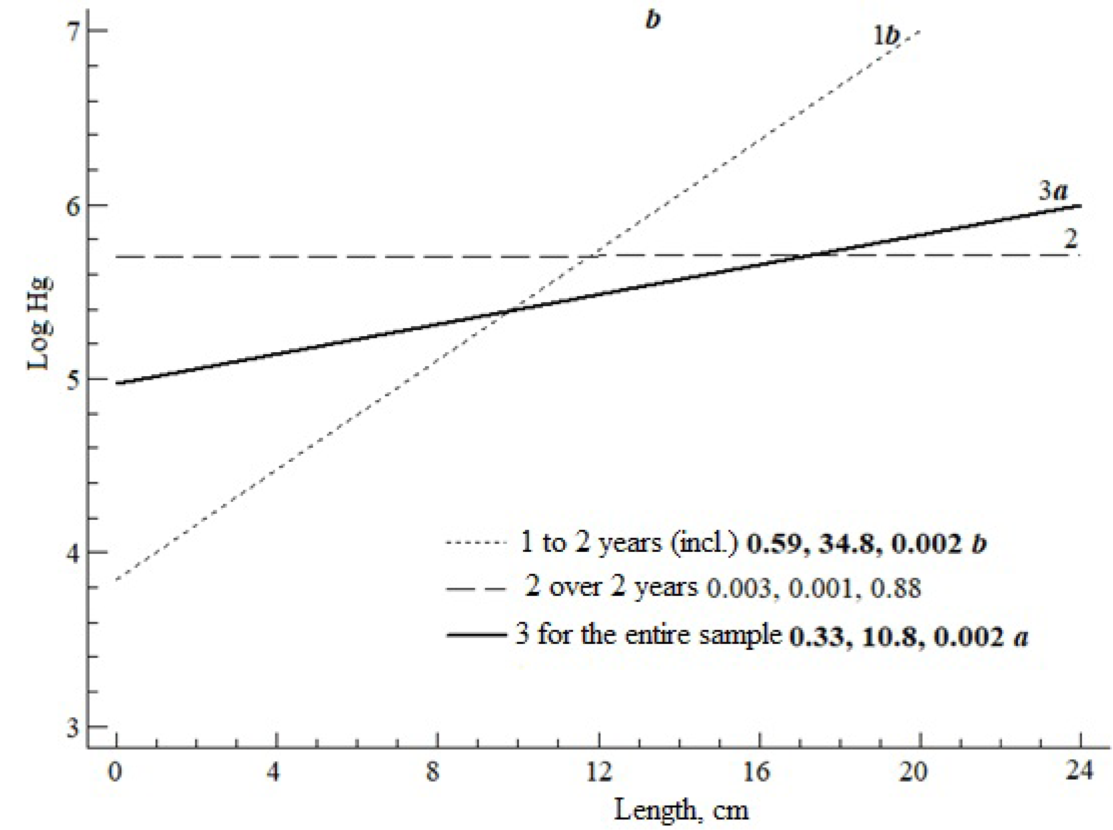


Fig. 6. Relationship between body length and age of fish from the Pra River (**A**); linear approximation of the relationship between Hg concentrations in fish muscles and length by different age groups and for the whole sample (**B**).

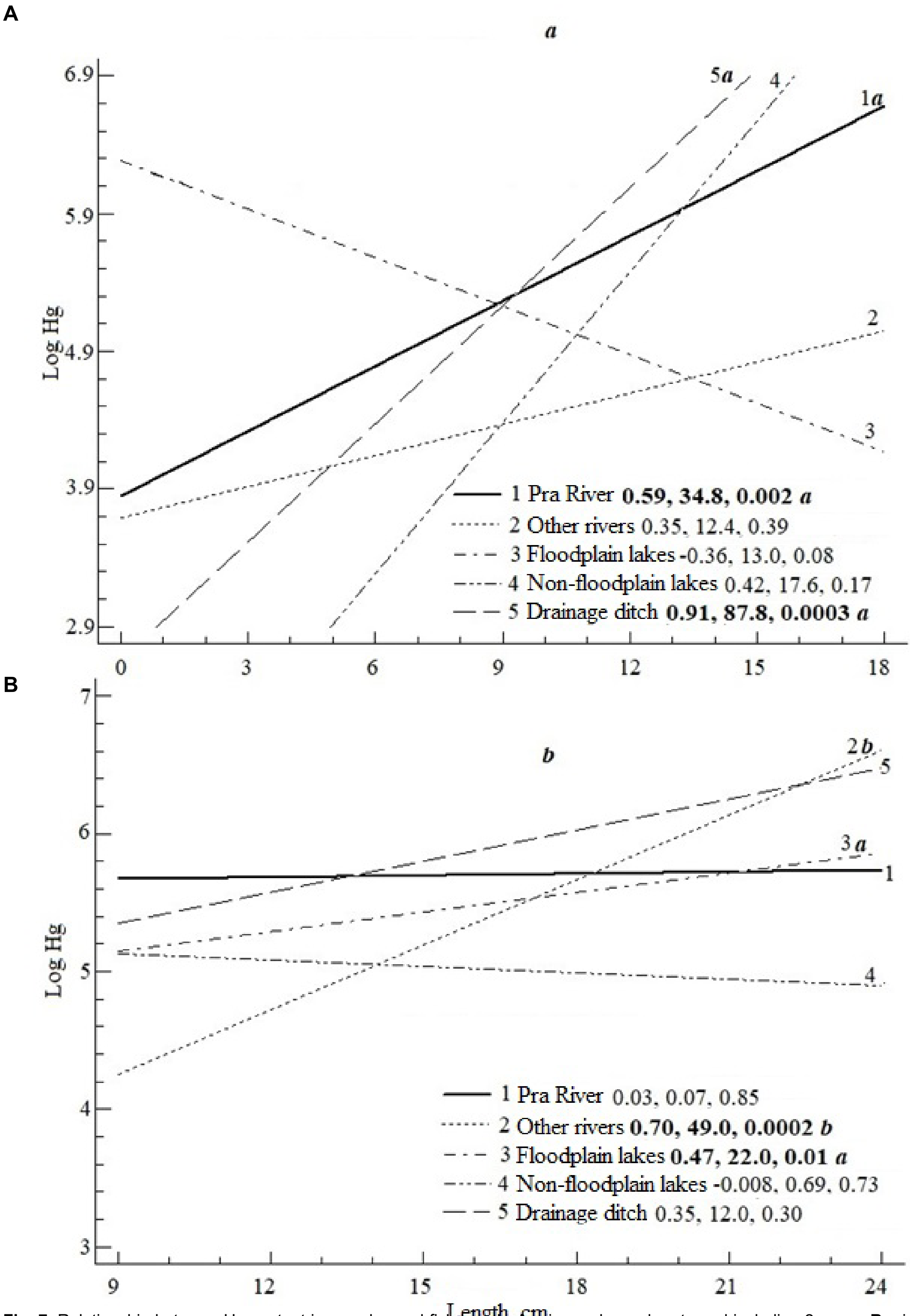


Fig. 7. Relationship between Hg content in muscles and fish length. **A** – in perch aged up to and including 2 years; **B** – in perch older than 2 years.

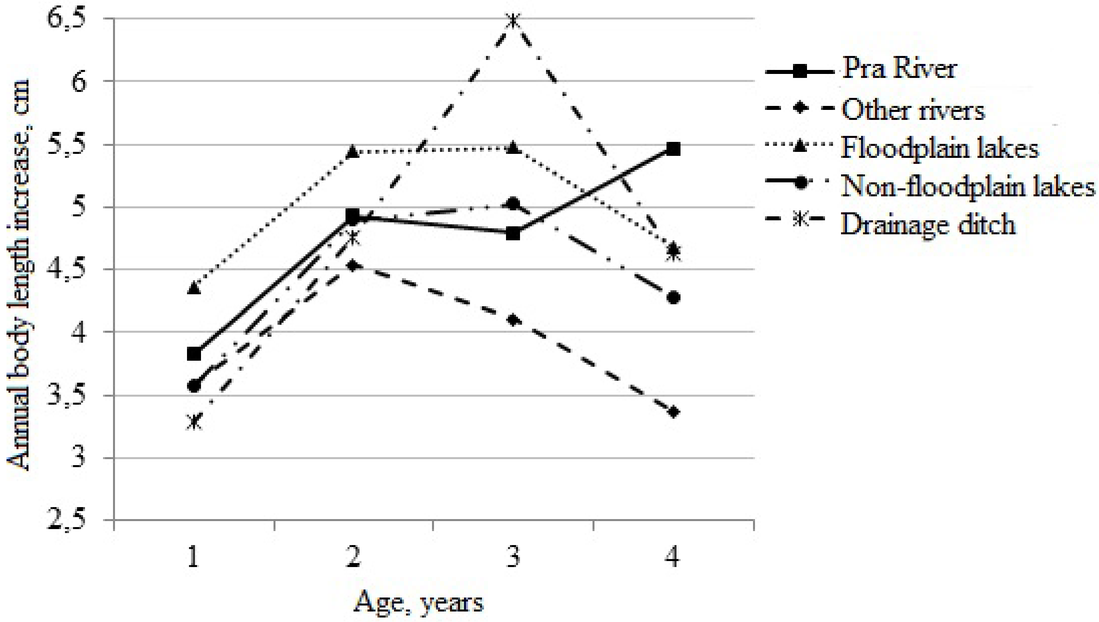
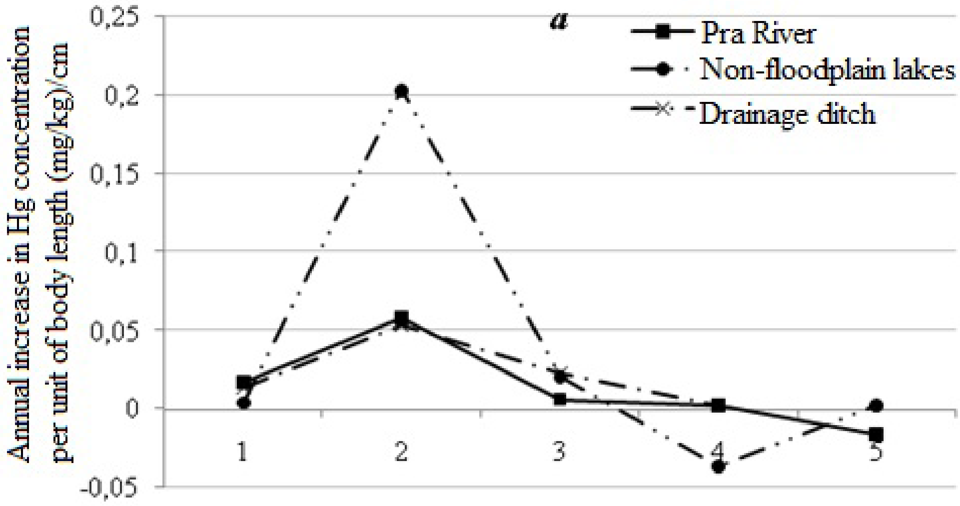


Fig. 8. Annual increase in body length of fish from different water bodies and streams (based on back-calculated growth data).

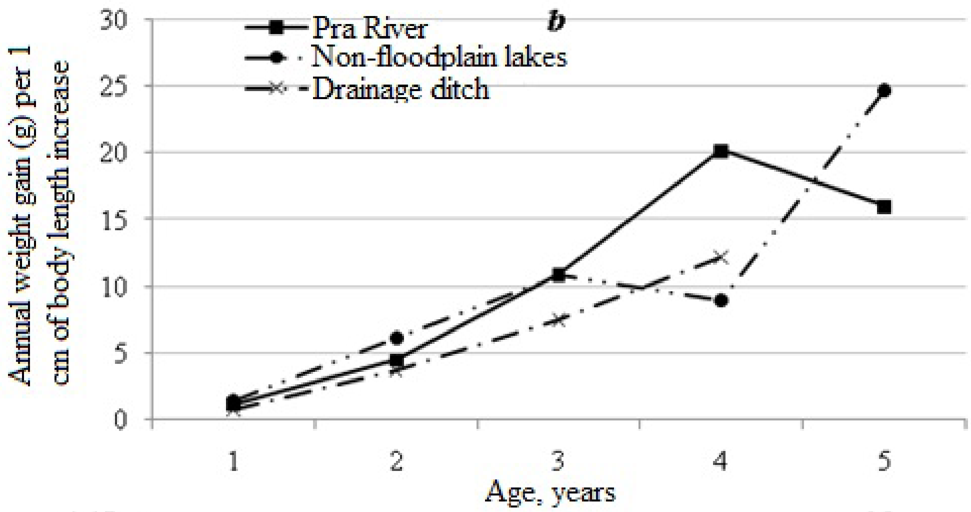
Table 4. Letter indices indicating the statistical significance of differences in length increment of different-aged fish across water bodies and watercourses.

Water bodies and watercourses	Indices			
	1 year	2 year	3 year	4 year
Pra River	a	ab	ab	b
Other rivers	a	a	a	a
Floodplain lakes	a	b	abc	ab
Non-floodplain lakes	a	ab	bc	ab
Drainage ditch	a	ab	c	ab

A



B



C

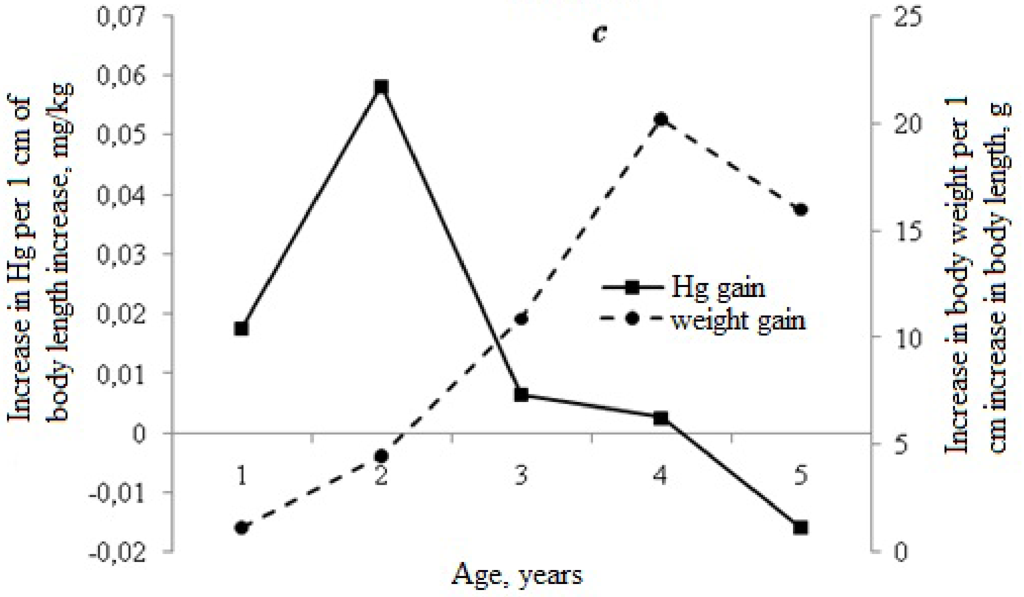


Fig. 9. Dynamics of age-related changes in mass and Hg concentrations in perch muscles from different water bodies and streams: **A** – annual increase in Hg concentrations; **B** – annual increase in fish body mass; **C** – annual increase in Hg concentrations and body mass in perch from the Pra River.

Table 5. Physicochemical parameters of water bodies and watercourses in the OSNBR and its surroundings (Gremyachikh et al, 2012). An em dash (–) indicates missing data.

Station no.	River/lake (station)	Surface area, km^2	pH	Color index, degrees	Watercourse length, km	Catchment area, thousand km^2
			Rivers and bays			
1	Oka River (Ryabov Backwater))	11.68	–	–	1500	245
2	Lamsha River	–	–	–	25	0.28
3	Istok River	–	–	–	17	0.027
4	Tolpega River	–	7.9	–	15	–
5	Pra River (Mirskaya Roshcha)	0.02	6.6	–	–	–
6	Pra River (Nefedovo)	0.03	6.9	70	–	–
7	Pra River (Brykin Bor)	–	–	–	–	–
8	Pra River (Alyoshina Luka)	–	7	540	–	–
			Floodplain lakes			
9	Alexeevo	0.03	6.7	440	–	–
10	Shilishche	–	–	–	–	–
11	Lakashinskoye	0.85	8.9	–	–	–
			Non-floodplain lakes			
12	Rusanovo	–	–	–	–	–
13	Tatarskoye	0.62	8.8	220	–	–
14	Svyatoye Lubyanitskoye	0.24	7.9	40	–	–
			Artificial water bodies			
15	Drainage ditch (Papushevo)	–	7.0	–	8.5	–

concentrations in perch varied from 0.01 to 1.51 mg/kg (Tropin et al., 2019). Moreover, a large-scale meta-analysis showed that even within a single water body and in the absence of local anthropogenic load, Hg concentrations in fish can vary significantly, differing by 2–3 orders of magnitude (e.g., from 0.005 to 0.5 mg/kg) (Lavoie et al., 2018).

Traditionally, growth rate is considered one of the key biological factors influencing Hg accumulation: it is assumed that slow-growing fish accumulate more metal due to a longer exposure period (Verta, 1990). However, our data refine this hypothesis. In the Pra River and the reclamation ditch, both intensive perch growth and the highest average Hg concentrations in muscles were recorded compared to fish inhabiting other water bodies of the reserve. This does not so much contradict the "growth dilution" model, according to which rapid somatic growth should reduce Hg concentration in tissues (Jardine et al., 2006; Karimi et al., 2007b), but rather indicates that the relationship between linear growth and body mass changes with age; this, in turn, affects the dynamics of Hg accumulation: during the period of active growth (first two years), the mercury concentration increases faster than during mass gain (Lester et al., 2004). The high Hg levels in fish muscles from the Pra River and the reclamation ditch may be associated with specific properties of their humic aquatic environment (acidic pH, high water color, low dissolved oxygen content) and increased natural content of organic matter and nutrients (a consequence of the swampiness of the river valley) (Grobova, 2008), as well as with an earlier and more widespread shift of perch in these water bodies to a piscivorous diet. Hg accumulation levels in biota are also influenced by biocenosis structure (species diversity and abundance of hydrobionts at different trophic levels), which determines the length and complexity of the food web (Poste et al., 2022). The species composition of the ichthyofauna in the studied water bodies of the reserve comprises five or more species, while elevated mercury concentrations in fish muscles were recorded in water bodies where there were no more than two species (Ivancheva et al., 2023). Perch in spawning aggregations and catches generally has the status "common," is encountered frequently, but usually does not dominate. Perhaps this is why the influence of fish species diversity on the levels of Hg accumulated by perch is small.

The most intensive metal accumulation occurs in the first two years of perch life, which coincides with the shift to piscivory (Gremyachikh et al., 2024). In the Oka Nature Reserve, the maximum intensity of Hg accumulation was recorded in juveniles (up to and including 2 years) from the Pra River and the reclamation ditch, and in fish older than 2 years from other rivers and floodplain lakes. In perch from the Pra River, non-floodplain lakes, and the reclamation ditch, the initially high annual increase in Hg concentrations in muscles decreases over time, apparently as a result of slowed linear growth and increased fish body mass. It is likely that in floodplain lakes, hydrophysical and hydrochemical habitat conditions (stagnation phenomena, high organic matter content in the water) contribute to the gradual accumulation of Hg, which becomes more pronounced with age. It can be assumed that the more efficient trophic transfer of mercury in floodplain lakes is due to ecosystem stability, longer nutrient retention time, and consequently, increased activity of methylating microorganisms in bottom sediments (Chételat et al., 2020).

The average Hg content in the muscles of river fish from the reserve (especially the Pra River) was higher than that in floodplain lakes, despite the hydrological connection between rivers and lakes during spring floods. This can be explained by the higher productivity and intensity of the Hg biogeochemical cycle in river ecosystems, as well as the input of metal from the waterlogged swampy headwaters of the streams, where natural biogeochemical processes favor mercury methylation (Driscoll et al., 2013).

Perch from the reclamation ditch recorded one of the highest Hg concentrations despite the small size of the fish. This is probably related to the functioning features of the artificial water body's ecosystem: limited space can lead to high population density and, as a consequence, intensifies intraspecific competition for food resources. Under such conditions, fish are forced to broaden their diet spectrum and begin consuming not so much preferred prey as available food, including small piscivores, benthophages, or detritophages that have already accumulated Hg (Amundsen et al., 2008; Eckley et al., 2020). A study in the Sacramento-San Joaquin Delta (California, USA) showed that the combination of a relatively high trophic level (e.g., in omnivorous species) and increased Hg bioavailability can lead to enhanced biomagnification of the metal within the small fish community (Eagles-Smith et al., 2009). Thus, even in small anthropogenically modified water bodies, under certain ecological conditions, large amounts of pollutants can accumulate.

In the Russian Federation, the maximum permissible levels of mercury for freshwater fish are 0.3 mg/kg wet weight (SanPiN 2.3.2.1078-01[3]). Thus, the average metal content in fish from the Pra River (0.30 mg/kg) is at the permissible level; however, the concentrations in individual specimens may exceed the standard. This indicates a potential risk to the health of people regularly consuming fish from these water bodies, especially from the Pra River, and the need for further monitoring.

The identified patterns require further study of the sources and pathways of Hg input into aquatic ecosystems, as well as monitoring the state of the ichthyofauna as a bioindicator of the ecological health of water bodies, especially in specially protected natural areas.

Conclusion

The conducted study revealed significant spatial and age-related variability in mercury content in the muscles of European perch from water bodies and streams of the Oka State Natural Biosphere Reserve. This is due to the fact that a substantial role in the processes of metal bioaccumulation is played not only by the amounts of Hg entering the reserve's territory via atmospheric transport but also by the biogeochemical characteristics of the aquatic ecosystems, as well as their trophic status.

The highest metal content was recorded in perch from the Pra River and the reclamation ditch. In the Pra River, this is associated with catchment swampiness, high water color, a shift in pH to the slightly acidic side (6.6–7.0), and, as a consequence, increased Hg bioavailability. In the reclamation ditch, despite neutral pH (7.0), high population density and limited space intensify intraspecific competition and force fish to consume available but already contaminated food. A key role in the increased Hg bioavailability in the studied water bodies is played by the high content of organic matter in the water and bottom sediments, as well as by the features of the biocenosis structure that determine the efficiency of trophic transfer of the pollutant. The rate of Hg biomagnification is influenced by the structure of the specific biocenosis, which determines the complexity and length of the food chain. Thus, the observed differences in Hg accumulation are caused by the combined impact of biotic and abiotic components of the ecosystem, and in simpler and shorter food chains, mercury concentration occurs rather than dilution, leading to its accumulation in top predators, including perch.

Fish growth rates vary among the groups of water bodies, as does the intensity of their Hg accumulation. The highest annual increase in perch body length (based on back-calculated length) was recorded in the Pra River, while the lowest was in the other rivers of the reserve. Perch from floodplain and non-floodplain lakes and the reclamation ditch occupy an intermediate position in this indicator. The intensity of Hg accumulation in fish muscles depends not only on the characteristics of specific water bodies and streams but also on age. The most intensive metal accumulation occurs in the first two years of life, after which the process slows down, which may be due to a "dilution effect" from accelerated somatic growth of the fish, increasing length and body mass. Differences were revealed in the dynamics of mercury accumulation in the muscles of fish of different ages inhabiting the studied water bodies. In juveniles (up to and including 2 years old), the maximum increase in Hg content per unit increase in body length was noted in the Pra River and non-floodplain lakes, whereas in adult individuals (older than 2 years), it was in floodplain lakes. In the reclamation ditch, despite the small size of the fish, intensive Hg accumulation was recorded, probably due to specific habitat conditions (high population density, limited space), including anaerobic conditions in the bottom layers favorable for mercury methylation.

The obtained mercury concentrations in individual perch from the Pra River exceed the permissible level, which requires attention from the perspective of fish consumption safety and necessitates further monitoring.

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