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Hydroacoustic studies of the structure of the Baikal omul feeding stock in the Selenga shallows of Lake Baikal

Original Article
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ABSTRACT. A comparative analysis of hydroacoustic data from 2011 to 2024 allowed us to determine the distribution characteristics of Baikal omul in the spring in the water area of the Selenga shallows under a significant decrease in stocks. Test trawling provided analysis of the length-at-age data on Baikal omul, revealed an increase in the stock abundance owing to the 2019-2023 generations, and confirmed the possibility of the correct use of the length-weight relationship (*LWR*), $W = 10.9(SL_{dm})^{3.02}$, based on long-term data. The obtained data predict a growth of biomass, as a more inert indicator, in four-six years. To formulate a more accurate forecast, it is necessary to adjust the natural mortality rates.

Keywords: Baikal omul, hydroacoustic method, test trawling, length-at-age data, length-weight relationship, stock assessment, Lake Baikal

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1. Introduction

As the population grows, and exploitation of fish resources increases, the latter becomes a decisive factor in the population dynamics of many commercial fish species. The fishing intensity has a significant impact on the stocks of commercially important fish species with a long development cycle, such as whitefish (family Coregonidae). Whitefish stocks are a sought-after resource in the continental waters of the Northern Hemisphere (Fera et al., 2015; Winfield and Gerdeaux, 2015, Bourinet et al., 2024). In some regions, they are of great socio-economic importance, being an important component of the consumer market and food security. These species exhibit large stock fluctuations due to both fishing pressure and their high sensitivity to environmental conditions during reproduction and first-year development (Lukin et al., 2006; Straile et al.,2007; Anneville et al., 2009; Myers et al., 2015; Rook et al., 2022; Bourinet et al., 2024).

The decrease in Baikal omul *Coregonus migratorius* (Georgi, 1775) stocks and the subsequent introduction of a commercial fishing ban and recreational fishing restrictions in 2017 led to the decline in the living standard of a significant part of the local residents, whose income source was fishing. Initially, these measures were expected to help recover the stocks within five years. However, their effect can only be assessed 11-14 years after the ban introduction (Anoshko et al., 2020). Coregonid fishes, with their low reproduction capacity and slow growth, increase their population size in at least two generations (Lukin et al., 2006; Matkovsky, 2021). Taking into account the demographic crisis of the Baikal omul population in 2016-2018 (Materialy …, 2024) and the fact that the generations capable of providing a sufficient number of spawning stock need six-seven years to reach sexual maturity, their spawn will only be able to significantly increase the biomass of the commercial stock after five-seven years.

The Selenga shallows are one of the main fishing areas at Lake Baikal thanks to vast areas of shallow water with depths favorable for the habitation of Baikal omul. Based on previous estimates resulted from hydroacoustic studies (Melnik et al., 2009), this area concentrated a significant part (up to 50% or more) of the total stock of this species. The Selenga shallows form the basis of the commercial stock of the Selenga and Posolsk populations, which spawn in the Selenga River and the rivers of the Posolsky Sor Bay, respectively. With the decline in the Baikal omul stocks and fish-

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ing restrictions, the volume of test scientific research limited to fishing areas (Goncharov et al., 2022a; b, 2023a; b) is clearly insufficient. Nevertheless, data on hydroacoustic studies from 2011 to 2015 (Melnik et al., 2009; Makarov et al., 2012) allow us to conduct a comparative analysis of the distribution density of Baikal omul in the Selenga fishing area with our data obtained after the ban introduction. This study aims to conduct a comparative analysis of the structure of the feeding fish stock and change in the Baikal omul stocks in the Selenga shallows between 2011 and 2024.

2. Materials and methods

Hydroacoustic survey in the Selenga fishing area of Lake Baikal was conducted from 22 to 24 May 2024, onboard the research vessel "G.Yu. Vereshchagin" (Table 1). The work was carried out along the standard traverse mesh (Fig. 1) with depth ranges from 50 to 400 m and distance 370 km. An "Echo-Baikal" hydroacoustic complex was used in the survey, representing a software and hardware bundle of the modernized Furuno FCV-1100 fishing sonar (Japan) and the authoring software. The complex was configured for a dual-frequency mode with the following parameters: sounding signal frequencies 28 and 200 kHz, pulse duration 1.0 ms, and single target detection threshold -52 dB. The hydroacoustic complex was calibrated by the standard technique (Simrad, 2001) using a 60 mm diameter copper sphere with a calculated target strength (*TS*) of 33.61 dB. The hydroacoustic data, both modern (2020-2024) and archival (2011 and 2015), were processed in the Echoview software (Australia) with identical settings. The echo integration method was used to calculate surface densities along the survey traverses. The hydroacoustic traverses were divided into 500 m long sections. The *NASC* value (Nautical Area Scattering Coefficient) was obtained for each section as a result of data analysis in the software package. The vertical data analysis was limited to 8 m from the surface and 2 m from the bottom. Sections with multiple bottom reflection and sound-scattering layers not associated with fish accumulations, such as gas seepages, were excluded from the analysis. *TS* of Baikal omul was calculated via the equation $TS = 28.7 * Log(SL) - 76.4$ (Kudryavtsev et al., 2005) with a correction for the radiation frequency +0.77 dB. This equation provides less bias (underestimation) in the reconstruction of the sizes of small fish from the *TS* values with the average *SL* = 15-18 cm, which were recorded in trawl catches compared to the equations obtained for fish with *SL* = 21-38 cm (Goncharov et al., 2008) and *SL* = 24-27 cm (Makarov et al., 2018).

Test trawling (Table 1) was performed with a pelagic trawl (vertical opening 10 m and opening along the ground rope 17.5 and 26.0 m) after passing four-five traverses and detecting fish accumulations. The operation of the trawl gear (opening and movement trajectory relative to the bottom and fish accumulations) was monitored using synchronized depth recording devices installed on the trawl doors, head ropes, and ground ropes. The devices developed in Laboratory of Hydrology and Hydrophysics at Limnological Institute SB RAS consisted of a controller that recorded and saved data from the depth sensor in non-volatile memory as well as of a wireless communication interface of the Bluetooth standard. The devices installed on the trawl doors were additionally equipped with a three-axis acceleration sensor that can record their spatial orientation to monitor the main parameters of the trawl operation. The devices were calibrated before trawling by the cross-calibration method with an RBRduet3 T.D. two-channel submersible temperature and depth logger (Canada). After lifting the trawl on board, data was read via a wireless interface. Based on the test trawling data, the ratio of the trawl working depth to the length of the "veered" (wound from the trawl winch drums) warps, taking into account the operation of the main engine that ensures a vessel speed of 2.5-3.0 knots (4.5-5.5 km/h), was calculated.

The standard length (*SL*) of fish was measured with an accuracy of up to 1 cm during mass measurements and up to 1 mm during biological analysis. The weight (*W*) was measured with an accuracy of up to 1 g. The length-to-weight relationship $W_g = 10.9(SL_{dm})^{3.02}$ was used in the calculations, where W_g was the weight in grams and SL_{dm}–the standard length in decimeters (Anoshko et al., 2022) based on the long-term data analysis. The 2011 trawl catches were not used in this study because the selectivity of the size classes of the trawl fish differed significantly. Original hydroacoustic data for 2011 and 2023 from the archive of Laboratory of Ichthyology at Limnological Institute SB RAS were used for a comparative analysis of the distribution and assessment of Baikal omul stocks near the Selenga shallows (Table 1).

Table 1. Hydroacoustic survey data used in the analysis.

Year	Dates of survey, DD.MM – DD.MM	Traverse length, km	Number of test trawls, pcs	Number of analyzed fish, pcs
2011	30.05-01.06	311	10	1808
2015	29.05-31.05	307	-	-
2020	28.05-29.05	296	-	-
2021	26.05-28.05	450	-	-
2022	27.05-28.05	350	7	930
2023	23.05-26.05	217	8	1275
2024	22.05-24.05	370	6	523

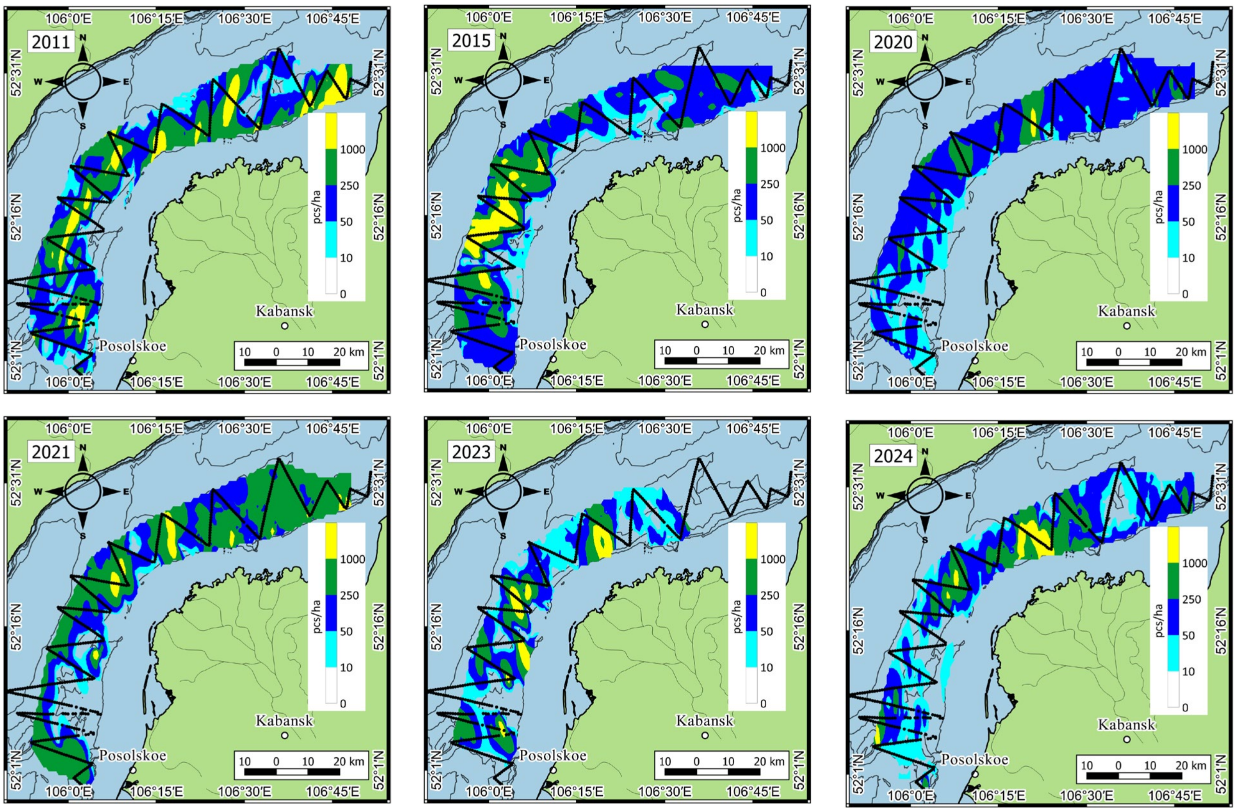

Fig.1. Distribution charts of Baikal omul in the Selenga shallows based on long-term data.

3. Results and discussion

The distribution characteristics of Baikal omul from 2011 to 2024 are shown in Fig. 1. In 2011, when Baikal omul stocks were assessed as satisfactory, accumulations of >1000 pcs ha^{-1} were recorded throughout the entire study area of the Selenga shallows, and in 2015, they were detected only in the southeastern part. In 2020, we recorded virtually no fish accumulations. As a rule, their concentrations were <250 pcs ha^{-1}, which is below average. In 2022, we recorded the concentrations of average density throughout the entire water area of the Selenga shallows. In 2023, there were large accumulations of Baikal omul in southwestern and central parts of the area, but they were relatively uneven and more dynamic (Anoshko et al., 2023). We observed their redistribution from south to north, probably due to the specific heating of the coastal-bay zone as well as to the influx of warmer waters of the Selenga River. In 2024, we recorded omul throughout the entire area of the shallows, and dense accumulations in its central part (Fig. 1).

Size data. The length-weight relationship (*LWR*) is an important characteristic used for calculations in test hydroacoustic studies. As a result of regression analysis based on the 2024 data, we obtained *LWR* $W = 9.6(SL_{dm})^{3.16}$ with a very high determination coefficient $R^2 = 0.99$ (Fig. 2). The average fish length (*SL*) was 17.6 cm, and the average weight–78 g. The use of our previous *LWR* based on long-term data, $W = 10.9(SL_{dm})^{3.02}$ (Anoshko et al., 2022), with such sizes, leads to an error in calculating the average weight of only 1.4% with a bias to the upside.

Based on trawl catches in different parts of the Selenga shallows, *SL* of fish from the feeding stock ranged from 9 to 35 cm between 2022 and 2024. Representative samples (Fig. 3) had a characteristic distribution of individuals by size with modes corresponding to age classes.

The distribution in *SL* frequency in 2022 indicates the presence of three modes: 10, 16, and 19 cm, that correspond to three generations of 2019, 2020, and 2021. The decrease in the proportion of fish longer than 21 cm was due to the demographic trough from 2016 to 2018 (Materialy …, 2024). In the subsequent 2023 and 2024, the number of large individuals increased due to the growth of fish of these generations. Moreover, the weight of fish in different size classes more clearly highlights the boundary between small and numerous generations. The size structure of Baikal omul in 2023 showed a relatively high number of individuals aged one year and their higher proportion compared to 2022 and 2024. On the contrary, individuals aged two years were slightly larger with a mode of 17 cm.

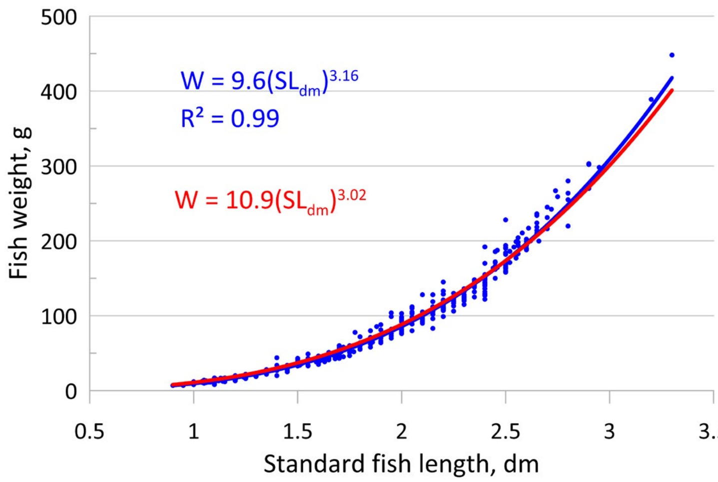

Fig.2. *LWR* of Baikal omul based on 2024 data and long-term data equation (Anoshko et al., 2022).

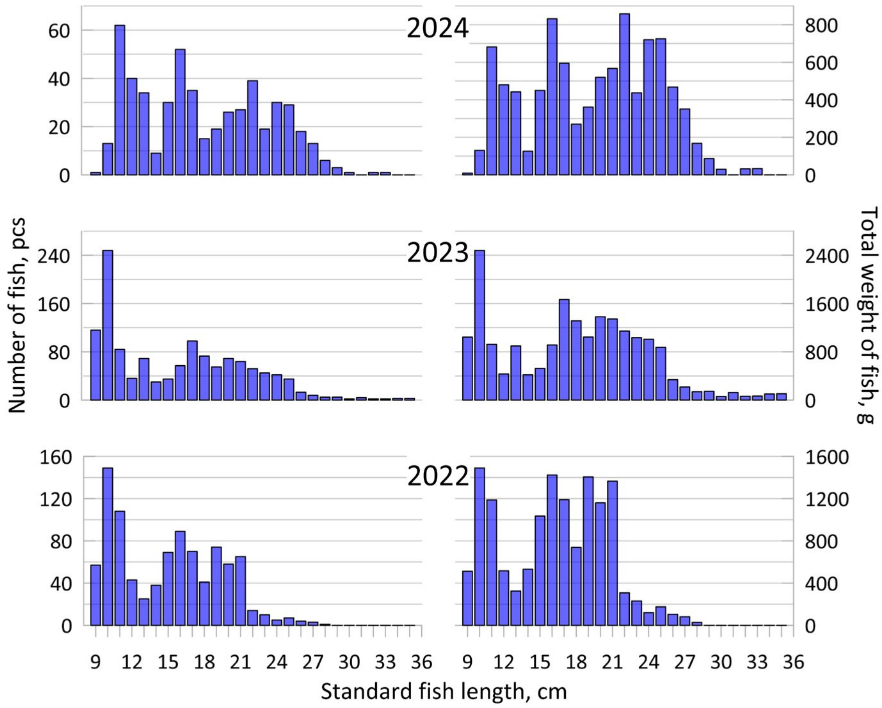

Fig.3. Distribution of Baikal omul individuals by size classes.

Due to the intersection of sizes of fish of different years, there was an additional peak between the peaks of the corresponding age classes, which can be considered as formed by a small generation (Anoshko et al., 2023). According to the official data, the larvae migration into the Selenga River in 2020 was 1186 million individuals, which is three times higher than the average for the period from 2014 to 2023 (Materialy …, 2024). At the same time, the entry of producers in 2019 was comparable with the entry in adjacent years (Materialy …, 2024). The size data from our catches were not correlated with this anomalous number of migrated larvae (Fig. 3). Fluctuations in fish sizes can be caused by interannual fluctuations of their growth rates in the first and second years of their life. Fluctuations in sizes of juveniles during the first year of life are expected because of their growth in the relatively dynamic conditions of the coastal-bay zone.

The age structure of Baikal omul depends on the feeding stock replenishment, natural and fishing mortality as well as migrations. The size structure of fish in the water area of the Selenga shallows allows us to conclude that, from 2022 to 2024, there were no significant changes in the replenishment level, which could affect the ratio of size and, hence, of age classes. From the second year of life, the mortality level during the feeding period practically does not depend on the pressure of predators. At depths greater than 50 m, omul juveniles are not accessible to predatory fish that inhabit the coastal-bay zone as well as to fish-eating birds.

The data for 2022 and 2024 allowed us to estimate the natural mortality level (Fig. 4) because commercial fishing of omul was banned, and the mortality of fish of this size due to recreational and poaching fishing can be excluded. The instantaneous rate of natural mortality of individuals aged one to three years in 2022, based on power exponential function, was 0.19, and those aged from one to four years in 2024 – 0.23. These results comply with the rates calculated for the corresponding ages of *Coregonus muksun* (Pallas, 1814) (Matkovskiy, 2023) having a long lifespan, like Baikal omul.

Stock dynamics. Comparative data analysis in retrospect indicated a fourfold decrease in stocks from 2007 (Melnik et al., 2009, Table 2) to 2020 in the Selenga shallows (145 122 ha). Subsequently, the number of juveniles increased owing to the 2019-2023 generations. Thus, compared to 2020, the abundance of fish doubled but reached only half of values calculated for 2011. Biomass is a more inert indicator, so, in the next four-six years, we expect its growth thanks to the 2019-2024 generations.

Stable state of the Baikal omul stocks in favorable period amounted to 20-26 thousand tones. According to the Total Allowable Catch (TAC) materials (Materialy …, 2017), which were a basis for the introduction of the ban on catching Baikal omul, its biomass in 2016 was 12.6 thousand tons. It was indicated

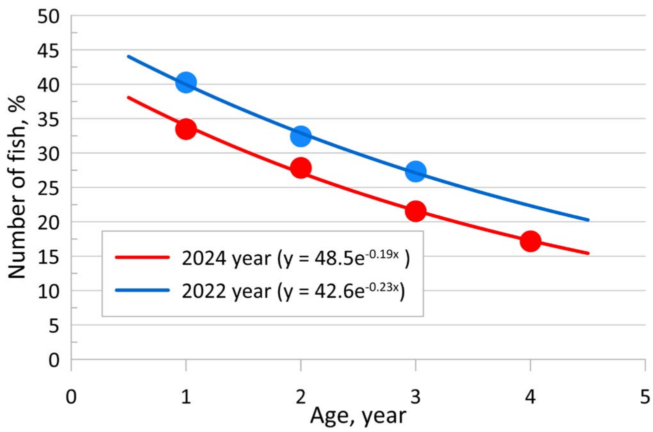

Fig.4. Ratio of age classes of Baikal omul based on trawl catches in 2022 and 2024.

Table 2. Estimation of biomass density and abundance of Baikal omul based on hydroacoustic data.

Year	NASC	Average weight, kg	Average length, cm	pcs ha^{-1}	kg ha^{-1}	Biomass, t
2007	229.3	104.0	21.1	367.2	38.2	5543
2011	194.2	85.5	19.8	363.1	31.1	4505
2015	172.2	104.0	21.1	305.6	31.8	4612
2020	52.6	72.0	18.7	128.7	9.3	1345
2021	106.1	46.5	16.2	205.0	9.5	1383
2023	89.6	71.5	18.6	224.7	16.1	2331
2024	83.9	78.8	19.3	195.3	15.4	2233

that the state of the stocks, compared to the 1990s, reached a critical level and was at a lower limit of the accepted reference estimates of stability. Even with these estimates, the stock of 6.8 thousand tons published in the TAC materials after the ban introduction seems inconsistent. According to these estimates, the stock decreased by 5.8 thousand tons. At the same time, according to the fishery statistical report, the catch was 0.6 thousand tons, and, taking into account expert estimates of IUU fishing (illegal, unreported, and unregulated fishing), the total catch was ~1.0 thousand tons. Even though we accept no replenishment during that period, there is still a difference in 4.8 thousand tons that, in our opinion, requires reasonable explanations.

Observations of the spawning stock abundance and stock assessment using hydroacoustic techniques conducted by Russian Federation Research Institute of Fisheries and Oceanography (VNIRO) since 2021 indicate that the omul biomass is much lower (7-8 thousand tons) than it was estimated before the ban was introduced (11-13 thousand tons) using virtual population models. Despite the increase in the number of juveniles, it remains at a consistently low level (Goncharov et al., 2023a; b). No comparative analysis of stock assessments of Baikal omul using virtual population models and hydroacoustic techniques was conducted. Therefore, the differences in the estimates likely result from the use of different methods, and not from the decrease in the biomass after the ban introduction. Notably, VNIRO studied the Baikal omul stocks only in the fishing areas where its main commercial aggregations form but account for <10% of the lake water area. Fish inhabiting the rest of the water area are not taken into account in these studies. In this regard, it is impossible to correctly compare the stock estimates before and after the ban introduction. Trawl-acoustic estimates for 1994, 1995 and 2003 (Melnik et al., 2009) – the period when this research method was developed – are not comparable. Nevertheless, hydroacoustic method is optimal for estimating the density and biomass of coregonid fish in large and deep lakes inhabited by their various ecomorphological forms (Schluter and McPhail, 1993; Harrod et al., 2010; Siwertsson et al., 2010; Malinen et al., 2014). However, unification of the survey according to the agreed traverses, as well as the *TS*(*SL*) and *LWR* dependencies, is advisable. If possible, it should be carried out in the dark. Dispersal and more even spatial distribution at night are typical of many whitefish species inhabiting relatively deep waters (Schluter and McPhail, 1993; Mehner et al., 2007; Girard et al., 2020). Thus, a significant proportion of fish is recorded in the form of single echo signals, facilitating more accurate estimates of their abundance and biomass. Modern scientific hydroacoustics hardware and software provide a non-lethal for fish and a cost-effective alternative for estimating abundance (Shin et al., 2005; Simmonds and MacLennan, 2008), which is especially important in the context of dramatically declining stocks. Furthermore, they offer a less selective method for determining size structure compared to fishing. In conditions of relatively low fishing pressure, stock assessment methods based on catch statistics are practically useless (Schluter and McPhail, 1993). At the same time, the construction of cohort models is necessary for forecasting and making administrative decisions on fisheries regulation.

Noteworthy is that coregonid fish inhabit mainly water bodies with dynamic environmental conditions typical of temperate and subarctic climate zones. Despite the ability to survive adverse environmental conditions, their stocks have experienced the periods of significant population decline over the past two decades (Myers et al., 2015; Zischke et al., 2017; Stewart et al., 2021; Bourinet et al., 2024) due to their irrational use as the habitat deteriorated. Significant polymorphism observed in coregonid fish (Smirnov et al., 2009; Zubova et al., 2022; 2024) is not only a way to expand the use of resources but also one of the adaptations to changing habitat conditions.

The main features of populations undergoing structural changes resulted from intensive long-term fishing pressure are as follows: a decrease in the number of age groups, an increase in the proportion of slow-growing individuals, reduction in lifespan, and early maturation with extremely small sizes for the species (Lukin et al., 2006). These features are not characteristic of the Baikal omul population in the Selenga shallows, except for a decrease in the number of older age groups, which is likely a consequence of low reproduction efficiency associated with high poaching pressure along spawning migration routes and high mortality in the first year of life. The discrepancy between the high number of spawning stocks in the autumn of 2015 and the subsequent small migration of larvae in the spring of 2016 (Materialy …, 2024) may be due to the high level of poaching along spawning migration routes. Meanwhile, from 1999 to 2013, rates of larval migration were high throughout Lake Baikal (Materialy …, 2024). This indicates that poaching in spawning rivers during that period did not affect the reproduction rate. Moreover, the Baikal omul generations of these years should have provided high biomass rates in the next seven years. Straile and coauthors (2007) hypothesized that a warm winter during the incubation period leads to earlier hatching of larvae of the common whitefish, *Coregonus lavaretus* (Linnaeus, 1758), under conditions of an undeveloped food supply (Straile et al., 2007). For Baikal omul, which spawns in rivers, early hatching of larvae in the river and their migration to the coastal-bay zone with unfavorable feeding conditions are possible during warm (arid) periods. Taking into account that the physicochemical conditions of the habitat did not significantly change in the spawning rivers, we cannot assume the influence of environmental factors on the mortality rate of eggs. High mortality rate in the coastal-bay zone, where juveniles feed, may be associated with high level of predation, including fish-eating birds. The reduction in the stocks of Baikal omul and fishes of the coastal-bay complex coincides with a catastrophic increase in the number of the great cormorant, *Phalacrocorax carbo* (Linnaeus, 1758). However, in the Selenga River delta, it invaded the colony of the great heron, *Ardea cinerea* (Linnaeus, 1758), only in 2014 (Pyzhyanov and Mokridina, 2023), and the number of nesting individuals reached 1000 only in 2020 (Elayev et al., 2021). Baikal omul juveniles 40-120 mm long are ~10% of its food spectrum (Yelayev et al., 2021). These are mainly individuals of the first year of life, which inhabit the coastal zone and are accessible to the great cormorant. On the other hand, its food spectrum includes fish species that can consume juvenile omul (Yelayev et al., 2021). Therefore, the predation of the great cormorant is probably partially compensated.

4. Conclusion

Analysis of long-term hydroacoustic data allowed us to determine the distribution characteristics of Baikal omul in the water area of the Selenga shallows under a significant reduction in the stock of the populations living here. Amidst the overall distribution heterogeneity, relatively dense fish aggregations were localized in one of its parts, rather than throughout the water area. Size data on Baikal omul in trawl catches confirmed the correctness of using the length-weight relationship, $W=10.9(SL_{dm})^{3.02}$, that we had obtained previously based on long-term data because it leads to an error in calculating the average weight of only 1.4% with a bias to the upside.

A comparative analysis of the data revealed a fourfold decrease in the Baikal omul stocks from 2007 to 2020. However, the increase in the number of juveniles owing to the 2019-2024 generations suggests a biomass growth in the next four-six years. Among the causes of the 2016-2018 demographic trough, the low-water period between 2015 and 2017 is one of the most likely. At the same time, its impact on the decrease in the replenishment of the Baikal omul stocks can result from several factors, such as accessibility to fish-eating birds, poaching during spawning migrations, and elevated mortality rate of juveniles due to migration to the coastal-bay zone with a low development of the food supply and/or their death being eaten by predators. To formulate a more accurate forecast, it is necessary to adjust the natural mortality rates.

The study of the distribution characteristics of fish, the feeding stock structure, and changes in abundance and biomass is important not only for regulating fisheries activities but also for understanding the functioning of ecosystems, including the reaction of populations to the stress effects of climate change and anthropogenic load.

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Conflict of interest

The authors declare no conflict of interest.

References

Anneville O., Souissi S., Molinero J.C. et al. 2009. Influences of human activity and climate on the stock-recruitment dynamics of whitefish, *Coregonus lavaretus*, in Lake Geneva. Fish Manag Ecol 16: 492-500. DOI: 10.1111/j.1365-2400.2009.00703.x

Anoshko P.N., Dzyuba E.V., Kucher K.M. et al. 2023. Acoustic-trawl studies of the *Coregonus migratorius* (Georgi, 1775) in the Selenga shallow water zone of Lake Baikal, 2023. Limnology and Freshwater Biology 6(4): 126-136. DOI: 10.31951/2658-3518-2023-A-4-126

Anoshko P.N., Makarov M.M., Ustarbekova D.A. et al. 2022. Ratio "lengh-weight" in the Baikal omul *Coregonus migratorius* in the fatting period of the Selenga shallow water zone of Lake Baikal. South of Russia: ecology, development 17(1): 17-23. DOI: 10.18470/1992-1098-2022-1-17-23

Anoshko P.N., Makarov M.M., Zorkaltsev V.I. et al. 2020. Limits for *Coregonus migratorius* (Georgi, 1775) catches and likely ecological effects. South of Russia: ecology, development 15(3): 132-143. DOI: 10.18470/1992-1098-2020-3-132-143

Bourinet F., Anneville O., Drouineau H. et al. 2024. Impact of fishing activities on the population dynamics of European whitefish in four peri-alpine lakes. International Journal of Limnology 60: 15. DOI: 10.1051/limn/2024015

Elayev E.N., Dorzhiev Ts.Z., Ananin A.A. et al. 2021. Nesting history and abundance dynamics of the Great cormorant (*Phalacrocorax carbo* L., 1758) in Baikal Siberia. Bulletin of Buryat State University. Biology, Geography 3: 21-32. DOI: 10.18101/2587-7143-2021-3-21-32

Fera S.A., Rennie M.D., Dunlop E.S. 2015. Cross-basin analysis of long-term trends in the growth of lake white fish in the Laurentian Great Lakes. J Gt Lakes Res 41: 1138-1149. DOI: 10.1016/j.jglr.2015.08.010

Girard M., Goulon C., Tessier A. et al. 2020. Comparisons of daytime and nighttime hydroacoustic surveys in temperate lakes. Aquatic Living Resources 33: 9. DOI: 10.1051/alr/2020011

Goncharov S.M., Popov S.B., Bondarenko V.M. et al. 2008. Measuring the target strength of the Baikal omul to improve the accuracy of estimating its reserve in Lake Baikal. Fisheries 3: 87-90.

Goncharov S.M., Popov S.B., Peterfeld V.A. et al. 2022. Results of test hydroacoustic surveys of the Baikal omul in the fishing waters of Lake Baikal in the spring-summer period of 2022. Trudy VNIRO 190: 186-192. DOI: 10.36038/2307-3497-2022-190-186-192

Goncharov S.M., Popov S.B., Peterfeld V.A. 2022. Results of hydroacoustic studies of the Baikal omul (*Coregonus migratorius*) in the fishing waters of Lake Baikal using domestic information developments. Fisheries 2: 54-58. DOI: 10.37663/0131-6184-2022-2-54-58

Goncharov S.M., Popov S.B., Peterfeld V.A. et al. 2023. Assessment the state of the omul stock *Coregonus migratorius* in the waters of Northen Baikal according to hydroacoustic investigations. Problems of Fisheries 24(4): 72-80. DOI: 10.36038/0234-2774-2023-24-4-72-80

Goncharov S.M., Popov S.B., Peterfeld V.A. et al. 2023. Hydroacoustic assessment of Baikal omul (*Coregonus migratorius*) reserves based on the results of two-year studies in the spring-summer period of 2021 and 2022. Fisheries 2: 73-79. DOI: 10.37663/0131-6184-2023-2-73-79

Harrod C., Mallela J., Kahilainen K.K. 2010. Phenotype-environment correlations in a putative whitefish adaptive radiation. Journal of Animal Ecology 79: 1057-1068. DOI: 10.1111/j.1365-2656.2010.01702.x

Kudryavtsev V.I., Dyogtev A.I., Sokolov A.V. 2005. About peculiarities of quantitative assessment of Baikal omul stock by hydroacoustic method. Fisheries 3: 66-69.

Lukin A.A., Sharova Y.N., Prishchepa B.F. 2006. The impact of fishery on the state of populations of the European whitefish *Coregonus lavaretus* in Lake Imandra. Journal of Ichthyology 46: 383-390. DOI: 10.1134/S0032945206050043

Makarov M.M., Degtev A.I., Khanaev I.V. et al. 2018. Experimental studies for measuring the target strength of the baikalian omul at the frequency of 200 kHz. International Journal of Applied and Fundamental Research 2: 142-146. DOI: 10.17513/mjpfi.12124

Makarov M.M., Degtev A.I., Kucher K.M. et al. 2012. Estimation of the abundance and biomass of the Baikalian omul by means of trawl-acoustic survey. Dokl Biol Sci 447: 363-366. DOI: 10.1134/S0012496612060051

Malinen T., Tuomaala A., Lehtonen H. et al. 2014. Hydroacoustic assessment of mono- and polymorphic *Coregonus* density and biomass in subarctic lakes. Ecology of Freshwater Fish 23: 424-437. DOI: 10.1111/eff.120

Materialy, obosnovyvayushchiye obshchedopustimyye ulovy vodnykh biologicheskikh resursov v ozere Baykal (s vpadayushchimi v nego rekami) na 2025 g. (s otsenkoy vozdeystviya na okruzhayushchuyu sredu) [Materials justifying the total allowable catches of aquatic biological resources in Lake Baikal (with the rivers flowing into it) for 2025 (with an assessment of the impact on the environment)]. 2024. URL: http://baikal.vniro.ru/images/материалы обосновывающие общие допустимые уловы вбр в озере байкал с впадающими в него реками на 2025 грdf.pdf (Accessed on 7 October 2024) (in Russian)

Materialy, obosnovyvayushchiye obshchiye dopustimyye ulovy vodnykh biologicheskikh resursov v ozere Baykal (s vpadayushchimi v nego rekami) na 2018 g. (s otsenkoy vozdeystviya na okruzhayushchuyu sredu) (dlya obshchestvennykh slushaniy). 2017. URL: http://ольхонский-район.рф/tinybrowser/files/novosti/odu-na-2018-god-dlya-obschestvennyh-slushaniy.pdf (Accessed on 7 October 2024) (in Russian)

Matkovskiy A.K. 2023. Study of the features of natural mortality in Muksun and Peled of the Ob River by constructing dependences of the number of their generations. Inland Water Biology 3: 407-419. DOI: 10.31857/S0320965223030154

Matkovsky A.K. 2021. Determination of the effectiveness of work on artificial reproduction of *Coregonus peled* in the Ob-Irtysh basin. Fisheries 4: 53-60. DOI: 10.37663/0131-6184-2021-4-53-60

Mehner T., Kasprzak P., Hölker F. 2007. Exploring ultimate hypotheses to predict diel vertical migrations in coregonid fish. Canadian Journal of Fisheries and Aquatic Sciences 64: 874-886. DOI: 10.1139/F07-067

Melnik N.G., Smirnova-Zalumi N.S., Smirnov V.V. et al. 2009. Hydroacoustic surveys of Baikal omul. Novosibirsk: Nauka (in Russian)

Myers J.T., Yule D.L., Jones M.L. et al. 2015. Spatial synchrony in cisco recruitment. Fish Res 165: 11-21. DOI: 10.1016/j.fishres.2014.12.014

Pyzhyanov S.V., Mokridina M.S. 2023. Reintroduktsiya baklana na Baykal: prichiny i posledstviya [Reintroduction of the cormorant to Lake Baikal: causes and consequences]. Proceedings of the All-Russian Scientific and Practical conf., dedicated. 30-th anniversary of the Baikal Museum SB RAS “Development of life in the process of abiotic changes on Earth”. Irkutsk. State University Publ. DOI: 10.24412/cl-34446-2023-4-31-35

Rook B.J., Lenart S.J., Caroffino D.C. et al. 2022. A 90-year record of lake whitefish *Coregonus clupeaformis* abundances in Michigan waters of the upper Laurentian Great Lakes. J Gt Lakes Res 48: 1618-1635. DOI: 10.1016/j.jglr.2022.08.013

Schluter D., McPhail J.D. 1993. Character displacement and replicate adaptive radiation. Trends in Ecology and Evolution 8: 197-200. DOI: 10.1016/0169-5347(93)90098-A

Shin Y.-J., Rochet M.-J., Jennings S. et al. 2005. Using size-based indicators to evaluate the ecosystem effects of fishing. ICES Journal of Marine Science 62: 384-396. DOI: 10.1016/j.icesjms.2005.01.004

Simmonds J., MacLennan D.N. 2008. Fisheries Acoustics Theory and Practice, 2nd ed.; John Wiley & Sons: New York, NY, USA.

Simrad. 2001. EK60 Scientific echo sounder instruction manual, Simrad Subsea A/S, Horten, Norway.

Siwertsson A., Knudsen R., Kahilainen K.K. et al. 2010. Sympatric diversification influenced by ecological opportunity and historical contingency in a young species lineage of whitefish. Evolutionary Ecology Research 12: 929-947.

Smirnov V.V., Smirnova-Zalumi N.S., Sukhanova L.V. 2009. Mikroevolyutsiya baikalskogo omulya: *Coregonus autumnalis migratorius* (Georgi) [Microevolution of Baikal omul *Coregonus autumnalis migratorius* (Georgi)]. Novosibirsk: Publishing House of the Siberian Branch of the Russian Academy of Sciences. (in Russian)

Stewart T.R., Mäkinen M., Goulon C. et al. 2021. Influence of warming temperatures on coregonine embryogenesis within and among species. Hydrobiologia 848: 4363-4385. DOI: 10.1007/s10750-021-04648-0

Straile D., Eckmann R., Jüngling T. et al. 2007. Influence of climate variability on whitefish (*Coregonus lavaretus*) year-class strength in a deep, warm monomictic lake. Oecologia 151: 521-529. DOI: 10.1007/s00442-006-0587-9

Winfield I.J., Gerdeaux D. 2015. Fisheries in the densely populated landscapes of Western Europe. In Freshwater Fisheries Ecology.John Wiley & Sons, Ltd, 181-190.

Yelayev E.N., Dorzhiev Ts.Z., Ananin A.A. et al. 2021. Feeding ecology and epizootological value of the Great cormorant (*Phalacrocorax carbo*) during the secondary expansion of the Baikal region. South of Russia: ecology, development 16(4): 47-55. DOI: 10.18470/1992-1098-2021-4-47-55

Zischke M.T., Bunnell D.B., Troy C.D. et al. 2017. Asynchrony in the inter-annual recruitment of lake whitefish *Coregonus clupeaformis* in the Great Lakes region. Journal of Great Lakes Research 43(2): 359-369. DOI: 10.1016/j.jglr.2017.01.007

Zubova E.M., Kashulin N.A., Terentyev P.M. et al. 2022. Morphoecological and genetic differentiation among sympatric forms of whitefish in Lake Kuetsjarvi (River Pasvik basin, Murmansk oblast) Biology Bulletin Reviews 142(5): 498-509. DOI: 10.31857/S0042132422050131

Zubova E.M., Terentyev P.M., Kashulin N.A. et al. 2024. European whitefish *Coregonus lavaretus* of the Nizhnetulomskoye Reservoir (Tuloma River basin, Murmansk region) and its habitat conditions. Limnology and Freshwater Biology 2024 (2): 58-97. DOI: 10.31951/2658-3518-2024-A-2-58