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Article

Current ecological state of Lake Bannoye (Solovetsky settlement)

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Abstract. Hydrological, hydrochemical and hydrobiological features of shallow Lake Bannoye (Solovetsky settlement), characterized by high anthropogenic loads, are summarized for various hydrological periods of 2022–2024. In terms of quantitative and qualitative indicators of aquatic organisms, as well as biogenic elements, Lake Bannoye is classified as a β-, α-mesotrophic water body transitioning to eutrophic. According to the Goodnight-Watley Index (GW), the lake is a “polluted” reservoir. The content of mineral phosphorus is high in the lake, and ammonium ions in the bottom layer exceed the maximum permissible concentrations for fisheries. Hence, the lake, obviously, receives polluted waters discharged by residential buildings and municipal-industrial facilities. However, runoff from the lake does not have a noticeable impact on the waters of Blagopoluchiya Bay.

Keywords: Solovetsky Archipelago, eutrophication, biogenic elements, dissolved organic carbon, bacterioplankton, phytoplankton, zooplankton, zoobenthos

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Научная статья

Современное экологическое состояние озера Банное (п. Соловецкий)

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Аннотация. Обобщены гидрологические, гидрохимические и гидробиологические характеристики мелководного оз. Банное (п. Соловецкий), испытывающего на себе высокую антропогенную нагрузку, за различные гидрологические периоды 2022–2024 гг. По количественным и качественным показателям гидробионтов и содержанию биогенных элементов оз. Банное относится к β-, α-мезотрофному водоему, переходящему в эвтрофный. Значение индекса Гуднайт-Уотлея вод характеризует оз. Банное как загрязненный водоем. В озере выявлена высокая концентрация минерального фосфора, а также превышение ПДК для объектов рыбохозяйственного значения по содержанию ионов аммония в придонном горизонте. Таким образом, в озере, возможно, присутствует сброс загрязненной воды от жилых домов и коммунально-производственных объектов, однако сток с озера не оказывает ощутимого воздействия на воды Бухты Благополучия.

Ключевые слова: Соловецкий архипелаг, эвтрофирование, биогенные элементы, растворенный органический углерод, бактериопланктон, фитопланктон, зоопланктон, зообентос

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Introduction

The Solovetsky Archipelago natural complex is unique in having numerous freshwater lakes. According to Glitsevskaya et al. (1972), there are approximately 375 lakes on the archipelago, 337 of them are on Bolshoy Solovetsky Island. They are greatly diverse in location, bottom topography, watercolor, vegetation, area, genesis, depth, and basin shapes. The outlines and limnological characteristics of the lake include almost all lake shapes of the boreal zone described in the literature (Gritsevskaya et al., 1972; Shvartsman and Bolotov, 2007). The lakes are also distinguished by different anthropogenic impacts.

Lake Bannoye is located on the territory of Solovetsky settlement (Fig. 1), on Bolshoy Solovetsky Island. The lake is shallow and anthropogenically influenced by residential buildings and public utility facilities, i.e. a modern bathhouse (former boiler house building) and a car repair shop situated on its coast. Up the creek, flowing into the lake, there is a campground where tourists use its water in summer for household purposes. Buildings of the Beletskaya Bathhouse and the Solovetsky branch of the Arkhangelsk Experimental Algae Farm on the lakeshore are currently unused. Despite high flow rate of the lake, it undergoes intensive succession processes. A creek outflowing from the lake runs to Bukhta Blagopoluchiya Bay. The lake's runoff has no significant effect on the waters of the bay. Here, the tidal averages 1 m; during the tidal cycle, more than twice the volume of the lake passes through the bay at the creek mouth.

It is the opinion of local residents that Lake Bannoye was previously much deeper (approximately 4 m in the 1970s). According to A.A. Zakhvatkin (1927), the lake depth reached 5–6 m in 1927. Besides, fish kills in winters of the mentioned years are suggestive of longer water retention time in the lake in the past. Today, the creek inflowing to the lake are non-freezing. The dissolved oxygen content in its waters in late March of 2024 exceeded 13 mg/L.

Previously, one-time research of certain hydrological and hydrochemical parameters was conducted (Bespalaya et al., 2021; Titova et al., 2024). The aim of this article was to study the current state of the shallow lake, by the example of Lake Bannoye, as the ecosystem located on the isolated island at high latitudes and liable to anthropogenic pressure. We used the data on hydrological, hydrochemical and microbiological parameters obtained for the period of 2022–2024. The data on the quantitative and qualitative composition of phytoplankton, zooplankton and zoobenthos were also discussed in this work (Novikova et al., 2023; Novoselov et al., 2024a, b).

Fig. 1. Lake Bannoye.

Materials and methods

Sampling

Water samples for hydrochemical analysis were collected by a 5-L horizontal polycarbonate bathometer from the surface and bottom layers during the periods of maximum stratification in 2022–2024 (winter: late March – early April, summer: late July – early August). Additional sampling was implemented at the end of October 2023 before complete freezing. In winter and in summer of 2022, we conducted the reconnaissance works at one station (station 1). In 2023, the number of stations increased to three in order to assess spatial variability: station 1 – the deepest site (reference), station 2 – the site near the bathhouse, and station 3 – the site of the creek confluence. In 2024, the investigations were made in winter at four stations (station 4: the second creek confluence on the eastern side). Samples were also collected in the stream outflowing from the lake and falling into Blagopoluchiya Bay. Sampling sites are shown in Fig. 2.

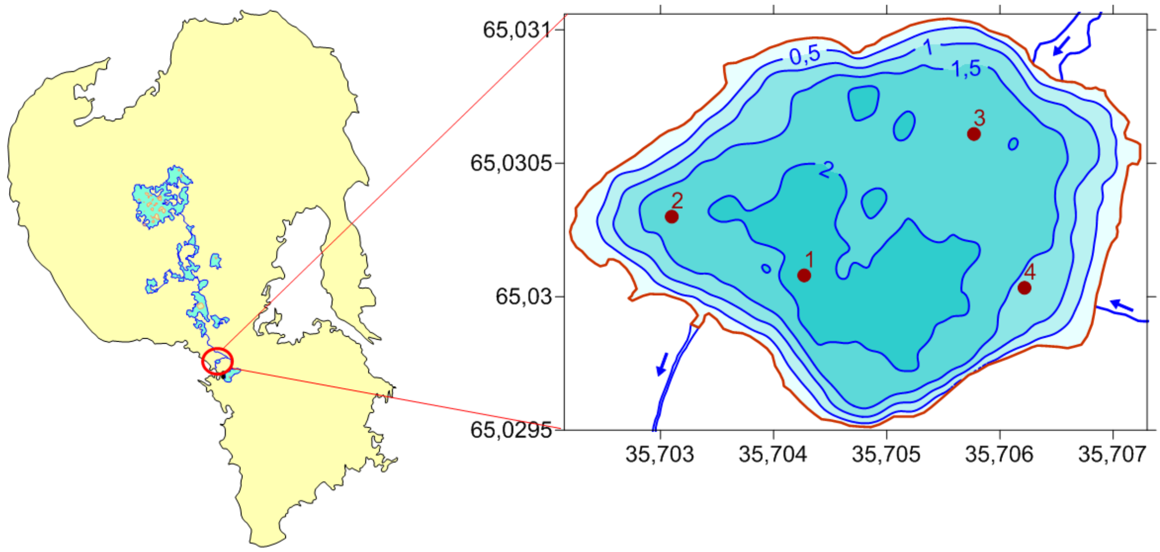

Fig. 2. Location and bathymetric map of Lake Bannoye. Red dots indicate sampling stations.

Research methods

The morphometric characteristics of the reservoir were obtained due to bathymetric surveys using a Humminbird Fishfinder 363 echosounder/chartplotter (USA). Vertical distribution of hydrological (temperature, electrical conductivity) and hydrochemical (pH, dissolved oxygen) parameters was defined in situ by a U-52G multiparameter water quality analyzer (Horiba, Japan) in winter and by a WTW Oxi 330i oximeter (Germany) with a DurOx 325 sensor (Germany) in summer. During summer sampling, we determined the hydrogen index (pH meters Expert 002 (Russia) and WTW ProfLine 3110 (Germany)) and specific electrical conductivity (conductivity meter WTW 3110 (Germany)).

Standard photometric methods were used to measure the concentration of biogenic elements in water samples: nitrite nitrogen $N\text{-}NO_2^-$, ammonium nitrogen $N\text{-}NH_4^+$, nitrate nitrogen $N\text{-}NO_3^-$, total nitrogen N_{tot}, phosphate ions $P\text{-}PO_4^{3-}$, total phosphorus P_{tot}, silicon Si (Sapozhnikov et al., 2003)[1]. To determine the dissolved carbon content in water samples, 0.22 μm filters were employed. The concentration of dissolved organic (DOC) and dissolved inorganic carbon (DIC) was defined using a Shimadzu TOC-Lscn total organic carbon analyzer (Japan). Spectral characteristics were obtained from a PE-5400UF scanning spectrophotometer (Russia). Color was measured photometrically by a chromium-cobalt scale[2].

Samples for total microbial counts were collected in sterile 15 ml vials and fixed with filtered bacteria-free glutaraldehyde (final concentration 2%). Total number of microorganisms was counted on a Luminex Guava® EasyCyte 12HT flow cytometer (USA) using DAPI staining and blue fluorescence detection (Blu-V (450/45) sensor).

Zoobenthos was taken by an Ekman-Burge bottom grab with a capture area of 0.04 m^2. Samples were washed through a no. 23 mesh with a cell side length of 0.333 mm. The selected zoobenthic material was fixed in a 4% formalin solution neutralized with sodium tetraborate for better preservation of benthic organisms with calcium skeletal elements. Then it was processed in the laboratory via applying the standard methods (Abakumov, 1992). Taxonomic identification of organisms was performed with the use of a MBS-12 stereoscopic microscope (Russia). Each group of organisms was weighed on a KERN EW electronic scale of 0.001-g accuracy (Germany). To identify benthic animals, we used generally accepted identification Keys (Chertoprud and Chertoprud, 2011; Tsalolikhin, 2016). Water quality class was established according to the "Comprehensive ecological classification of surface water quality."[3]

[1] PND F 14.1:2.2.4–95. Quantitative chemical analysis of waters. Methodology for measuring the mass concentration of nitrate Ions in natural and wastewater using a salicylic acid photometric method.

[2] GOST 31868-2012. Water. Methods for determining color.

[3] RD 52.24.309-2016. Organization and monitoring of state and pollution of surface waters on land.

To reveal statistically significant differences in the data on biogenic elements for different stations, the nonparametric Wilcoxon test for paired comparison to evaluate dependent samples was applied. Comparisons were made by seasons based on the normalized values of biogenic elements for the study period.

Physical and geographical features of Lake Bannoye

The lake is located in the northeastern part of Solovetsky settlement (N 65°01'49'' E 35°42'21'). According to the classification by P.V. Ivanov (Teoreticheskie voprosy..., 1993), it belongs to the category of very small lakes. Lake Bannoye is oval in shape, its maximum length – 240 m, width – 165 m, area – 25580 m^2, and volume – 38290 m^3. The reservoir is shallow; its average depth is 1.5 m. In the southern part of the lake, there is a small basin with a maximum depth of 2.3 m (Fig. 2). The shore is mostly high dry marshy in the northeast and bushy in the southeast. The lake's bed is saucer-shaped with a flat bottom relief. The bottom is sandy near the shore and silty in the center (Titova et al., 2023). Water transparency is poor (less than 1 m). In the northeast, a creek from Pityevoy Canal flows into the lake. In the east, another creek outflows from a small nameless overgrown lake located in the settlement. In the southwest, a stream outflows from the lake and in 250 m it falls into the White Sea.

Results and discussion

Hydrological conditions

In summer, the lake waters are well mixed due to winds, nighttime cooling, air temperature fluctuations, thermal radiation, and low cloudiness. In 2022, homothermy of water layers depended on convective mixing at nights preceding the measurements when temperature dropped from 18–19 °C to 10–13 °C in conditions of light cloudiness. Insolation induced temporary minor water stratification, as we observed in 2023. Vertical changes in specific electrical conductivity were insignificant, i.e. from 63–66 to 71–74 μS/cm.

In winter, the lake's hydrological regime depended on autumn weather conditions. The autumn of 2021 was characterized by frequent strong winds responsible for intensive mixing of waters. The winter of 2022 saw the lowest bottom temperature (0.40 °C) and electrical conductivity (92 μS/cm) (Figs. 3**A, B**). In the autumn of 2022, winds (before ice formation) were less strong. In the autumn of 2023, earlier ice formation provided greater heat reserves and high water mineralization in winters of the years 2023 and 2024. Bottom temperature and specific electrical conductivity made up 2.40 and 3.15 °C, 344 and 375 μS/cm, respectively. A sharp increase in electrical conductivity was observed from one meter layer to the bottom, with vertical gradients of 257 and 297 μS/cm/m. As soon as ice cover forms, the lake waters begin to warm from the bottom thereby increasing their density. Colder and less dense creek waters spread within the surface subglacial layer. Intensive decomposition of easily oxidizable sediments contributes to greater density stratification resulting in high mineralization of bottom waters and their relatively rapid isolation.

The pH of lake waters was generally slightly acidic; during the periods of increased photosynthetic activity, it became neutral and could reach 7.4. As compared to summer, the bottom pH in winter increases insignificantly, owing to abundant ammonium ions formed by organic matter mineralization in conditions of insufficient dissolved oxygen.

Oxygen

It is well known that dissolved oxygen is among factors influencing the hydrochemical and hydrobiological parameters. Lake Bannoye was characterized by favorable summer conditions (Figs. 4**A**, **B**, **C**). However, we noted a sharp reduction of oxygen content in the bottom layer in winter, with its minimum recorded at st. 1 in March 2023 and 2024 (Figs. 4 **A**, **B**).

At present, fish kills in the subglacial layer of the lake are hardly possible due to incoming saturated-with-oxygen (up to 13.6 mg/L, 95%) waters of the relatively powerful non-freezing creek. There was reason to think that this stream originated due to the degradation of Pityevoy Canal and water flow bifurcation. Part of this flow, through breakthrough, reached the drainage system near Solovetsky settlement, merged with the drainage canal and running along the main canal entered Lake (Zakharov, 2006). Sedimentation formed as a result of the canal erosion presumably caused the reservoir shoaling.

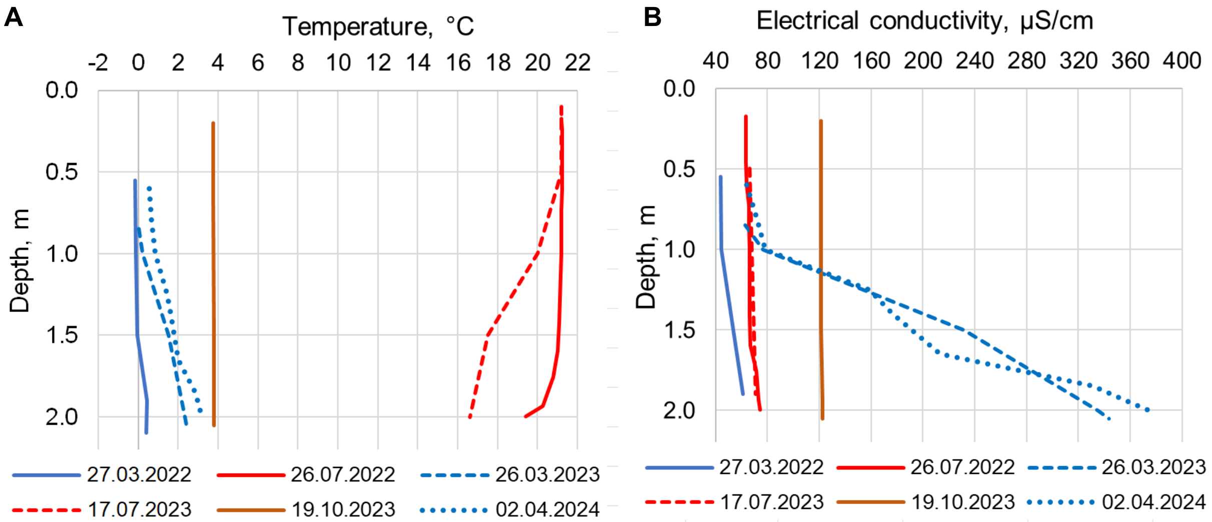

Fig. 3. Vertical distribution of temperature (**A**) and electrical conductivity (**B**) in Lake Bannoye in 2022–2024.

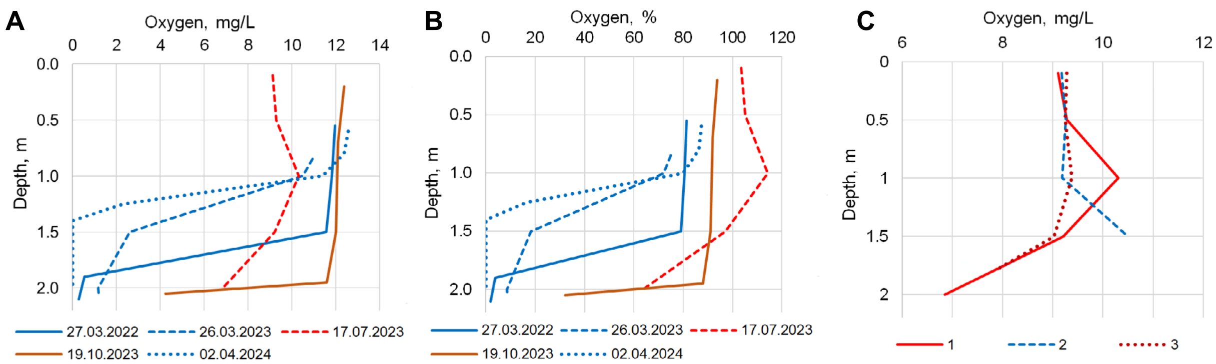

Fig. 4. Vertical distribution of dissolved oxygen in Lake Bannoye in mg/L (**A**) and in % (**B**) for different seasons at station 1 and at three stations in mg/L (**C**) in July 2023.

Despite the lake's small size, variations in vertical distribution of oxygen between stations is possible; July 2023 is a vivid example (Fig. 4**C**). The increased oxygen content at the bottom (st. 2) is obviously associated with powerful production processes since the photic layer reaches the bottom layers.

The established water quality standards for fishery bodies limit the dissolved oxygen content during winter (under-ice period) to 6 mg/L for Category 1 and 4 mg/L for Category 2[4]. Clearly, the microaerophilic conditions in the bottom layer of this reservoir in winter hamper the development of aerophilic aquatic organisms.

Biogenic elements

Vertical distribution of mineral phosphorus content varied during winters of 2022–2024 (Fig. 5). Its quantity was decreasing towards the bottom in 2022, but increasing in 2023 and 2024 due to more intense mineralization of organic phosphorus compounds. Vertical distribution of total phosphorus in winters of 2022–2024 was similar and increased with depth. Thus, at the end of winters of 2022–2024, complete mineralization processes were noted at the surface. In the bottom layer of the anaerobic zone,

[4] Order of the Ministry of Agriculture of Russia dated December 13, 2016, No. 552 "On approval of water quality standards for water bodies of fishery importance, including standards for maximum permissible concentrations of harmful substances in water bodies of fishery importance."

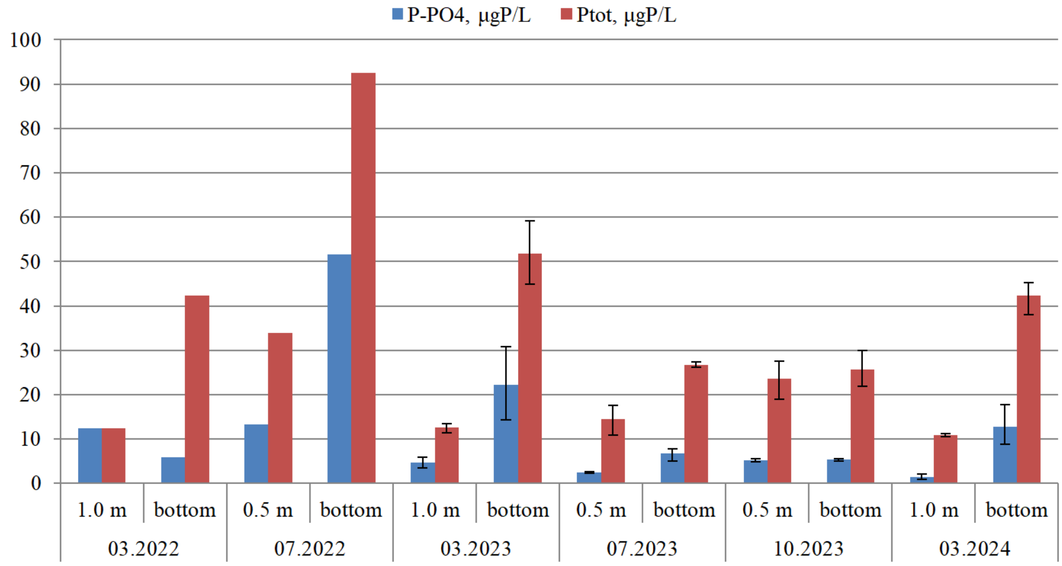

Fig. 5. Average content of mineral (P-PO_4^{3-}) and total (P_{tot}) phosphorus in Lake Bannoye in 2022–2024. "Mustaches" on the histogram indicate minimum and maximum values.

the greater accumulation of organic compounds was recorded in 2022, as compared to 2023 and 2024.

In summers of 2022 and 2023, the concentration of mineral and total phosphorus were higher towards the bottom. In 2022, the increased total and mineral phosphorus (2.7- and more than 4-fold rise, respectively) were recorded in the bottom layer. High vertical concentrations of phosphorus compounds in the reservoir were probably associated with weather conditions during this period. A few days before sampling, heavy rain (17 mm of precipitation, or one-third of the monthly norm) induced the increased influx of phosphorus compounds with surface runoff[5]. Furthermore, waters from the bottom layer containing organic matter (from phosphorus-rich planktonic detritus) could enter the bathometer (Baranov, 2014). Despite minor stratification, the summer of 2023 did not see such high values: mineral and total phosphorus concentrations were lower than in the summer of 2022.

During the period of autumn water mixing (2023), with-depth distribution of mineral and total phosphorus was uniform; the first was 4.5 times lower than the latter.

When assessing the spatial variability of phosphorus (inorganic and total) (Table 1), the differences between the stations were particularly noticeable in autumn ($p < 0.05$) and in winter ($p < 0.1$). The more detailed information on statistically significant differences in concentrations of biogenic elements by stations and seasons is given in Table 4.

In accordance with the MPC for fisheries[6], the phosphate ion content (converted to phosphorus) should not exceed 0.2 mg/L. During the study period, mineral phosphorus was within the MPC. At the same time, the secondary sources of phosphorus pollution appeared in winter (due to the constant oxygen deficiency at the bottom) and in summer, as evidenced from the 3- to 5-fold difference in mineral phosphorus concentrations of the surface and bottom layers. In creek waters, running to Blagopoluchiya Bay, the mineral phosphorus content in the winter of 2024 reached 1.74 µgP/L.

Nitrogen, as one of the most important biogenic elements, is present in water bodies in three main dissolved forms: ammonium, nitrite, and nitrate. Seasonal patterns in distribution of mineral nitrogen compounds were not established (Fig. 6).

In 2022, nitrate nitrogen predominated in Lake Bannoye both in winter and in summer. In the winter

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[5] Weather Archive in Solovetsky. Web page. URL: http://www.rp5.ru/Архив_походы_в_Соловецком (accessed: 20.03.2024).

[6] Order of the Russian Ministry of Agriculture dated December 13, 2016 No. 552 "On approval of water quality standards for water bodies of fishery importance, including standards for maximum permissible concentrations of harmful substances in the waters of water bodies of fishery importance."

Table 1. Spatial variability of mineral and total phosphorus (μgP/L) in the surface and bottom horizons of Lake Bannoye in 2023.

Date	Station 1		Station 2		Station 3	
	Surface	Bottom	Surface	Bottom	Surface	Bottom
			Inorganic phosphorus			
March 2023	4.85	30.78	3.44	14.26	5.81	21.64
July 2023	2.20	5.05	2.47	7.84	2.56	7.15
October 2023	5.57	5.56	4.82	5.58	5.04	5.02
			Total phosphorus			
March 2023	13.24	44.95	11.31	51.45	13.37	59.10
July 2023	14.76	26.29	17.63	27.44	10.84	26.16
October 2023	24.62	25.13	18.91	21.86	27.49	29.87

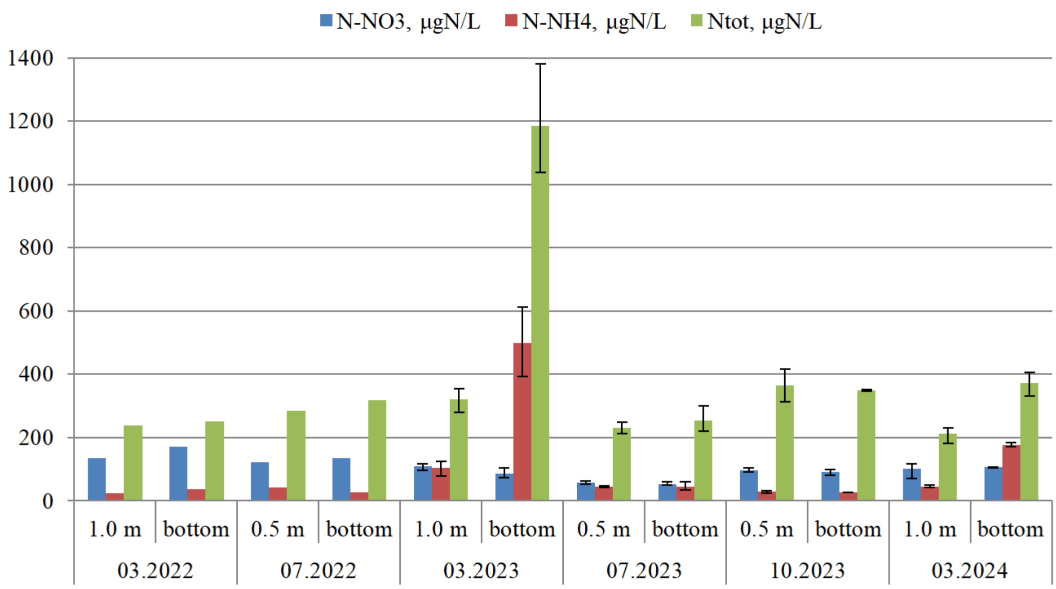

Fig. 6. Average content of nitrate (N-NO_3^-), ammonium (N-NH_4^+), and total nitrogen (N_{total}) in Lake Bannoye in 2022–2024. "Mustaches" on the histogram indicate minimum and maximum parameter values.

of 2023, nitrate and ammonium nitrogen concentrations were approximately equal at the surface. In the bottom layer, dissolved oxygen made up 1 mg/L; ammonium nitrogen was 4–7.5 times higher than nitrate nitrogen. This indicates the influx of large amounts of organic matter to the bottom that prevents ammonium (formed by mineralization under poor oxygen conditions) from being oxidized to nitrates. As mentioned above, the bottom layer exhibited the highest mineralization (specific conductivity: 340 µS/cm) and the relatively high phosphate ion content. In the winter of 2024, we observed a tendency towards the ammonium nitrogen predominance over nitrate nitrogen in the bottom layer.

In the summer of 2023, nitrate nitrogen was higher than ammonium nitrogen by 1.2–1.5 times and during the autumn mixing period by 2.9–3.8 due to sufficient vertical oxygen concentrations ensuring more complete oxidation of organic nitrogen compounds and resulting in lower ammonium and higher nitrate ion levels.

Nitrite nitrogen concentrations were very low (less than 6 µgN/L) in all studied seasons.

The total nitrogen distribution in winters of 2022–2024 was approximately the same; it increased towards the bottom at oxygen deficiency. In the winter of 2023, the total nitrogen in the bottom layer averaged 1185 µgN/L, apparently, because of the influx of large amounts of organic matter. Such concentrations were not recorded in the bottom layer in winters of 2022 and 2024.

In the summer of 2022, when concentrations of phosphorus compounds were high, the total nitrogen made up 285.4 µgN/L at the surface and 318.8 µgN/L in the bottom layer, respectively. At insignificant stratification in the summer of 2023, the total nitrogen content was 1.25 times lower than in the summer of 2022. This reduction implies the presence of easily utilized organic matter involved in the biological cycle after biochemical transformation. During the autumn mixing period when most biota dies off, subglacial mineralization begins and nutrients accumulate, approximately 1.5-fold increase in the total nitrogen is observed, compared to the summer of 2023.

When assessing the spatial variability of nitrogen compounds, the data on autumn ($p < 0.05$) and winter ($p < 0.1$) (Table 4) differ for various stations (Table 2).

In accordance with the MPC for fishery sites[7], nitrate ions concentrations should not exceed 9.0 mg/L, nitrite ions – 0.02 mg/L, and ammonium ions – 0.4 mg/L (all data converted to nitrogen**).** During the study period, ammonium nitrogen in the bottom layer exceeded the MPC (Table 2). In the stream flowing into Blagopoluchiya Bay, ammonium nitrogen amounted 46.5 µg N/L and nitrate nitrogen -114.6 µg N/L in the winter of 2024.

High concentrations of mineral phosphorus and ammonium ions exceeding MPC for fishery resources at a depth of 1.5–2 m (bottom layer) give an indication of polluted waters discharges from residential buildings and municipal production facilities into the lake.

The content of dissolved silicon compounds in Lake Bannoye depends on a hydrological season (Fig. 7). In winter periods of 2022–2024, this indicator was growing from the surface to the bottom during its accumulation owing to the die-off of most biota. Moreover, in the winter of 2023, silicon concentrations were greater than in winters of 2022 and 2024 despite the presence of little oxygen in the bottom layers during all three years of the study. Since water temperature in the bottom layer was 2 °C higher that time, high values of silicon in the winter of 2023 were related with more intensive processes of organic matter decomposition.

In summer, silicon was largely consumed by living organisms. Therefore, its summer concentration was lower than in winter. In 2023, during the autumn cooling and mixing of waters, the silicon content averaged 1904 µg/L.

Spatial variability of the silicon content is presented in Table 3.

In summer, statistically significant differences in the content of biogenic elements were not revealed between stations, except for st. 2 in autumn ($p < 0.05$) and winter ($p < 0.1$) (Table 4). This may be explained by the isolated zones' formation by circulation currents due to high flow rates of the lake, or by other causes that require further research.

[7] Order of the Russian Ministry of Agriculture dated December 13, 2016 No. 552 "On approval of water quality standards for water bodies of fishery importance, including standards for maximum permissible concentrations of harmful substances in the waters of water bodies of fishery importance."

Table 2. Spatial variability of nitrogen compounds (μgN/L) in Lake Bannoye in 2023.

Date	Station 1		Station 2		Station 3	
	Surface	Bottom	Surface	Bottom	Surface	Bottom
			Ammonium nitrogen			
March 2023	125.1	612.0	76.	393.0	108.0	488.2
July 2023	42.9	42.9	43.6	58.6	48.2	34.6
October 2023	24.4	25.1	32.0	26.1	27.8	26.6
			Nitrate nitrogen			
March 2023	116.5	81.1	97.0	103.0	112.7	71.9
July 2023	62.4	60.7	51.7	48.8	57.2	48.8
October 2023	96.8	94.4	91.6	79.5	103.0	99.2

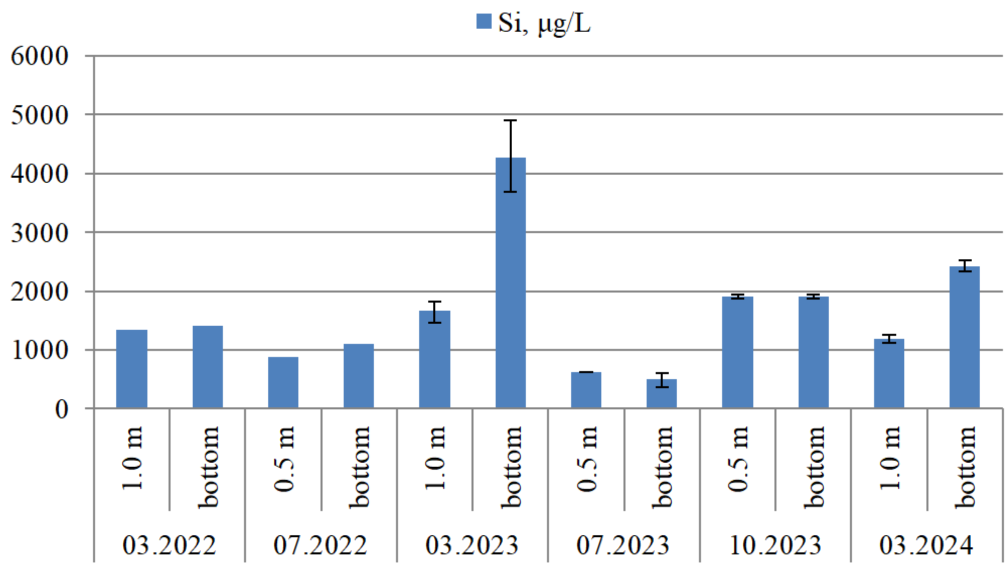

Fig. 7. Average content of silicon compounds (Si) in Lake Bannoye in 2022–2024. "Mustaches" on the histogram indicate minimum and maximum parameter values.

Table 3. Spatial variability of silicon (μg/L) in Lake Bannoye in 2023.

Date	Station 1		Station 2		Station 3	
	Surface	Bottom	Surface	Bottom	Surface	Bottom
March 2023	1820	4910	1462	3695	1743	4199
July 2023	620	607	622	358	618	565
October 2023	1905	1903	1870	1874	1938	1938

Table 4. Results of the analyzed samples by stations and seasons using the nonparametric Wilcoxon test for dependent samples, where N is the sample length, T the Wilcoxon statistics, Z – the criterion value, and p - the significance level of the criterion. Values $p < 0.1$ are given in italics.

Month	Stations of comparison	N	T	Z	p
March	1 и 2	10	10	1.78	**0.074**
	1 и 3	10	19	0.87	0.386
	2 и 3	10	9	1.89	**0.059**
July	1 и 2	10	23	0.46	0.646
	1 и 3	10	20	0.76	0.445
	2 и 3	10	27	0.05	0.959
October	1 и 2	10	8	1.99	**0.047**
	1 и 3	10	13	1.48	0.139
	2 и 3	10	8	1.99	**0.047**

DOC and DIC content

DOC and DIC content was determined only in March and October of 2023 at three stations. Their in-depth increase was observed during winter in all stations (Fig. 8). Towards the bottom layer, DOC and DIC concentrations increased on average by 1.6 and 4.36 times. In autumn, their distribution in the water column was uniform at all stations.

Thus, in winter and in autumn, DIC increased mainly toward the bottom thereby indicating the presence of the predominant mineralization of dissolved and suspended organic matter during these seasons. Maximum and minimum concentrations of DOC and DIC in winter were detected at st. 1 and st.2, respectively.

Dynamics of watercolor (W) and DOC in Lake Bannoye was similar (Fig. 8).In all stations, the color of the water increased with depth in winter; its distribution in autumn was uniform. In winter, it averaged 60.8° in the surface layer, being approximately 1.8 times higher in the bottom layer. With depth, this indicator in autumn was 80.4° on average.

Based on the optical characteristics (Figs. 9**A**, **B**, **C**) of Lake Bannoye, we examined the structure of dissolved organic matter (DOM). With autumn cooling of waters, the wavelength ratios D_{254}/D_{436}, D_{254}/D_{365} and $SUVA_{254}$ (Helms et al., 2008; Ilina et al., 2014; Weishaar et al., 2003) pointed to the influx of a labile (and potentially bioavailable) fraction of organic carbon appeared during plankton mortality alongside the decreased role of allochthonous organic matter. As a result, the role of condensed aromatic structures in the DOM composition decreased, and, consequently, the amount of high-molecular humic compounds reduced as well. During winter stratification, the proportion of allochthonous organic matter and active destruction processes in the bottom layers rises, and the role of condensed aromatic structures in the DOM composition also increases.

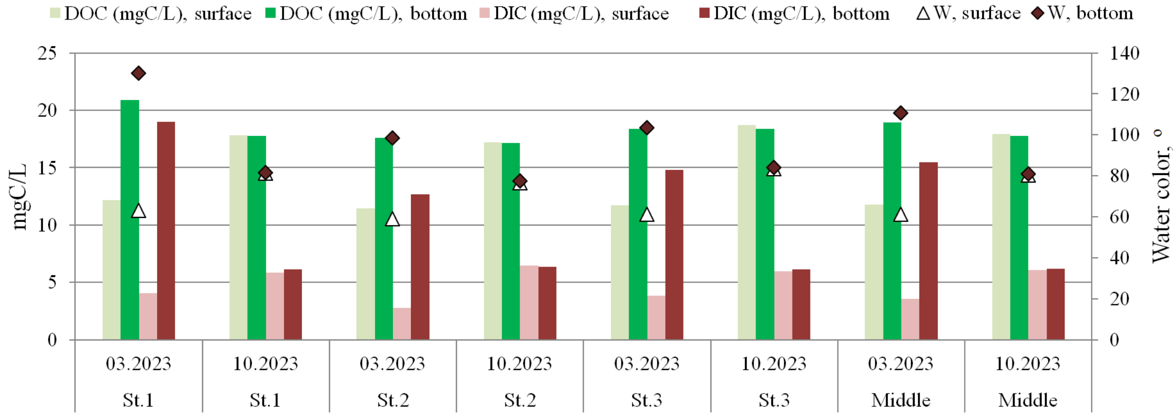

Fig. 8. DOC, DIC and watercolor index (W) for Lake Bannoye at stations 1, 2, and 3 in winter and autumn of 2023 (surface and bottom layers).

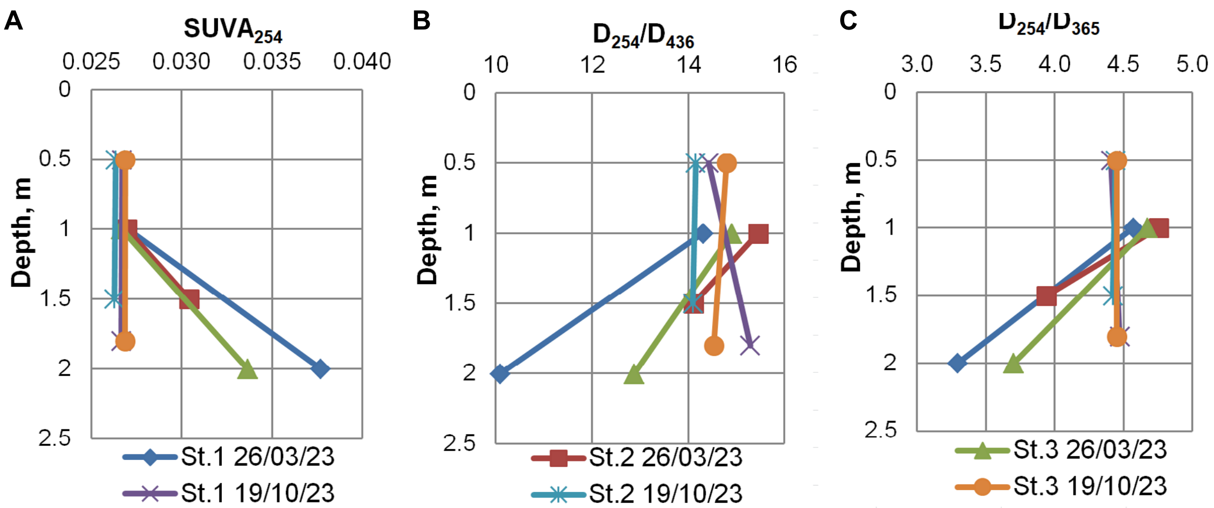

Fig. 9. Spectral characteristics of DOM: $SUVA_{254}$ (**A**), D_{254}/D_{436} (**B**), and D_{254}/D_{365} (**C**) wavelength ratios.

Bacterioplankton (BP)

During winter stratification, BP abundance in the surface layer was approximately 10 times lower than in the bottom (Table 5). Its high number in the bottom layer at stations 1 and 3 in the winter of 2023 is evidence of the occurrence of intensive destruction processes that is confirmed by $SUVA_{254}$ spectra (Fig. 9). In summer and autumn, BP was evenly distributed across sampling stations and layers. In July, its amount was virtually equal for all study sites. However, BP in the surface layer of the lake was higher in October than in July. In terms of microbiological parameters, the samples generally corresponded to "clean" waters, though in March the bottom layers were characterized as "polluted" (Abakumov, 1992).

Phytoplankton and zooplankton

In July 2022, taxonomic richness of the studied phytoplankton communities was poor. The structure and quantitative indicators of plankton demonstrated low stability of the community. High algal abundance and biomass indicated eutrophication of Lake Bannoye. The species composition of the lake phytoplankton was scarce (an average of 10 species), the average abundance – 12.3×10^{10} cells/m^3, the average biomass – 80.4 g/m^3. The largest share of the total number and biomass falls on green algae. Based on the analysis of indicator species and the saprobity index calculations, the lake waters belong

Table 5. Total number of BP (million µl/ml) in Lake Bannoye for 2023 (mean value with standard deviation). Dashes – data unavailable.

Date	Station 1		Station 2		Station 3	
	Surface	Bottom	Surface	Bottom	Surface	Bottom
March 2023	0.323 ± 0.010	5.552 ± 0.100	0.135 ± 0.003	2.297 ± 0.104	0.544 ± 0.000	4.890 ± 0.008
July 2023	0.216 ± 0.001	0.279 ± 0.002	0.220 ± 0.001	0.239 ± 0.004	0.202 ± 0.000	0.192 ± 0.010
October 2023	0.356 ± 0.001	–	0.368 ± 0.005	–	0.429 ± 0.007	–

to class II, i.e. "slightly polluted" (Novikova et al., 2023).

Zooplankton of Lake Bannoye in July 2022 was represented by a relatively small number of species (11) and characterized by weak quantitative development. Qualitatively and quantitatively, Cladocera was the basis of zooplankton. In the trophic structure, filter feeders getting food in the water column primary dominated. According to the fisheries classification (Pidgayko et al., 1968) and the level of zooplankton development, Lake Bannoye is the water body of low food capacity. During the study period, lake waters corresponded to the β-mesosaprobic level (Novoselov et al., 2024b).

Zoobenthos

The lake’s zoobenthos was studied at three sites in late March and mid-July of 2023; a total of six samples were collected. For analysis, we also used the findings of A.P. Novoselov et al. (2024a).

In the lake's benthic fauna, we identified four taxa of benthic invertebrates belonging to three phyla: Arthropoda, Annelida, and Mollusca (Table 6).

In July 2022 (Novoselov et al., 2024a), oligochaetes were most abundant, and aquatic chironomid larvae dominated by biomass. Chironomidae gen. sp. prevailed in March 2023, while Sphaeriidae gen. sp. in July 2023. Oligochaeta gen. sp. were detected only in winter and Ceratopogonidae gen. sp. solely in summer samples.

Overall, the average number and biomass of the benthic fauna of Lake Bannoye in March reached 400.00 ind./m^2 and 8.50 g/m^2, whereas in July – 825.00 ind./m^2 and 6.40 g/m^2, respectively. In terms of food capacity, this reservoir can be classified from the medium- up to high food source for benthophagous fish (Kitaev, 2007; Pidgayko et al., 1968). From the analysis of the Goodnight–Watley Index (GWI) for various biotopes, the assigned water quality class I and VI generally classify the lake as “polluted” in the summer of 2022 (Novoselov et al., 2024a). In March 2023, the GWI for the lake corresponded to class III (“polluted” reservoir). In July 2023, the GWI was not determined because of the absence of oligochaetes in the collected samples.

Determining the trophic status of the lake based on the composition of biogenic elements

The content of biogenic elements (total nitrogen and total phosphorus) in waters is a very effective indicator of the trophic status of a reservoir. The ratio of the main nutrients used by primary producers is of great importance (Bikbulatov and Stepanova, 2002; Bogdanovskaya, 2001; Redfield et al., 1963). From Table 7, which presents the average N_{tot}/P_{tot} ratios for the lake in summer and autumn, it follows that, depending on the year, the limiting element in the phytoplankton community development in the surface layer can be either phosphorus or nitrogen, in contrast to the bottom layer where only nitrogen acts as a limiting element. The studies suggest that by biogenic elements Lake Bannoye is classified as β- and α-mesotrophic transitioning to eutrophic (Kitaev, 2007).

Table 6. Taxonomic composition of zoobenthos and its quantitative indicators in Lake Bannoye for March and July of 2023. Dashes – data unavailable.

Taxonomic composition	March				uly			
	Number		Biomass		Number		Biomass	
	spec./m²	%	g/m²	%	spec./m²	%	g/m²	%
Arthropoda								
Chironomidae gen. sp.	200.00	50.00	8.20	96.30	100.00	12.12	4.00	62.19
Ceratopogonidae gen. sp.	–	–	–	–	125.00	15.15	0.50	8.02
Annelida								
Oligochaeta gen. sp.	125.00	31.25	0.10	1.60	–	–	–	–
Mollusca								
Sphaeriidae gen. sp.	75.00	18.75	0.20	2.10	600.00	72.70	1.90	29.79
In total	**400.00**	**100.00**	**8.50**	**100.00**	**825.00**	**100.00**	**6.40**	**100.00**
Goodnight–Watley Index (GWI)	50.00				–			

Table 7. Ratio of total nitrogen and total phosphorus (N_{tot}/P_{tot}) in Lake Bannoye.

Date	N_{tot}/P_{tot}	
	Surface layer	Bottom layer
July 2022	8.4	3.4
July2023	15.9	9.5
October 2023	15.4	13.6

Conclusion

The current ecological state of Lake Bannoye was assessed based on the results of the 2022–2024 studies. In summer, the lake waters were mixed well to the bottom. In winter, a sharp chemocline formed from one meter depth owing to oxidation of organic sediments carried by creeks. In summer and autumn of 2022–2023, the oxygen regime of the reservoir was favorable. In the ice-covered period, the oxygen content dropped to 0.5–1.0 mg/L in the bottom layer. During our study, the water reaction was generally slightly acidic transitioning to neutral. In terms of microbiological indicators, the lake waters were referred to the category "clean", except for March when the bottom waters were "polluted." By plankton development and concentrations of biogenic elements, the lake waters are β- and α-mesotrophic transitioning to eutrophic. The Goodnight-Watley Index classifies Lake Bannoye as a “polluted” water body.

High concentrations of mineral phosphorus and ammonium ion levels, exceeding the MPC for fisheries, were detected in the bottom layer. Obviously, the reservoir receives polluted waters discharged from the residential buildings and municipal-industrial facilities, however, the lake runoff impact on Blagopoluchiya Bay is insignificant. It is worth noting that the creek’s sediments are responsible for Lake Bannoye shallowing.

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