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Article

Study of the ultra-fresh meromictic lake on Bolshoy Solovetsky Island

A.A. Chupakova*, T.Ya. Vorobyeva, S.I. Klimov, N.S. Prilutskaya, E.I. Sobko, O.Yu. Moreva, S.D. Prasolov, T.I. Lovdina, K.V. Titova, A.V. Chupakov

N.P. Laverov Federal Research Center for Comprehensive Study of the Arctic, the Ural Branch of the Russian Academy of Sciences, Nikolsky prospect 20, Arkhangelsk, 163020 Russia

**anna.a.ershova@gmail.com*

Abstract. The article deals with the study results of Lake Svetlenkoye located in the heart of Bolshoy Solovetsky Island. Hydrological, hydrochemical and hydrobiological characteristics of the reservoir, proving its meromictic status, are presented. A bathymetric distribution of specific electrical conductivity, temperature, dissolved oxygen, pH, biogenic elements (nitrogen, phosphorus, silicon), iron, basic ionic composition, dissolved organic carbon, methane, carbon dioxide, total number of microorganisms, pigment characteristics of phytoplankton reflects the occurrence of mixolimnion and monimolimnion layers, as well as a transition zone (chemocline). Such a stable structure is recorded in all major hydrological periods, including autumn when convective mixing of waters in limnic ecosystems takes place. The lake is distinguished by low mineralization even in the monimolimnion horizons and, accordingly, by its ultra-fresh status. The high content of ferrous iron in the anaerobic zone indicate that Lake Svetlenkoye is a meromictic water body with a ferruginous anoxia.

Keywords: meromixis, ferruginous anoxia, Solovetsky Islands, hydrochemistry, zooplankton, total number of microorganisms

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ORCID:
A.A. Chupakova, https://orcid.org/0000-0001-8234-3514
T.Ya. Vorobyeva, https://orcid.org/0000-0002-3410-0240

N.S. Prilutskaya, https://orcid.org/0009-0008-2985-8373
E.I. Sobko, https://orcid.org/0000-0003-3153-899X
O.Yu. Moreva, https://orcid.org/0000-0002-5114-8481
S.D. Prasolov, https://orcid.org/0009-0007-6826-9048
T.I. Lovdina, https://orcid.org/0000-0003-2713-559X
K.V. Titova, https://orcid.org/0000-0001-7664-7706
A.V. Chupakov, https://orcid.org/0000-0001-6424-5582

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Научная статья

Исследование ультрапресного меромиктического водоема на Большом Соловецком острове

А.А. Чупакова*, Т.Я. Воробьева, С.И. Климов, Н.С. Прилуцкая, Е.И. Собко, О.Ю. Морева, С.Д. Прасолов, Т.И. Ловдина, К.В. Титова, А.В. Чупаков

Федеральный исследовательский центр комплексного изучения Арктики имени академика Н.П. Лаверова УрО РАН, 163020, Россия, г. Архангельск, Никольский проспект, д. 20

**anna.a.ershova@gmail.com*

Аннотация. В статье приводятся результаты исследования озера Светленького, расположенного в центре острова Большой Соловецкий. Представлены гидролого-гидрохимические и гидробиологические характеристики водоема, доказывающие его меромиктический статус. Распределение по глубине значений удельной электропроводности, температуры, растворенного кислорода, pH, биогенных элементов (азот, фосфор, кремний), железа, основного ионного состава, растворенного органического углерода, метана, углекислого газа, общей численности микроорганизмов, пигментных характеристик фитопланктона отражают наличие слоев миксолимниона, монимолимниона и переходной зоны (хемоклина). Данная структура стабильна и зафиксирована во все основные гидрологические периоды, в том числе и осенний, когда в лимнических экосистемах происходит конвективное перемешивание вод. Особенностью озера является его низкая минерализация даже в горизонтах монимолимниона и, соответственно, ультрапресный статус. Высокое содержание двухвалентного железа в анаэробной зоне позволяет оценить озеро Светленькое как меромиктический водоем с ферругинозной аноксией.

Ключевые слова: меромиксия, ферругинозная аноксия, Соловецкие острова, гидрохимия, зоопланктон, общая численность микроорганизмов

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ORCID:
А.А. Чупакова, https://orcid.org/0000-0001-8234-3514
Т.Я. Воробьева, https://orcid.org/0000-0002-3410-0240
Н.С. Прилуцкая, https://orcid.org/0009-0008-2985-8373
Е.И. Собко, https://orcid.org/0000-0003-3153-899X
О.Ю. Морева, https://orcid.org/0000-0002-5114-8481
С.Д. Прасолов, https://orcid.org/0009-0007-6826-9048
Т.И. Ловдина, https://orcid.org/0000-0003-2713-559X
К.В. Титова, https://orcid.org/0000-0001-7664-7706
А.В. Чупаков, https://orcid.org/0000-0001-6424-5582

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Introduction

Being specific objects, meromictic lakes characterized by the absence of complete mixing as the distinctive feature form the depth structure consisting of the following layers (Ecology of meromictic lakes, 2017; Lampert and Sommer, 2007):

1) the mixolimnion - an aerobic zone where water circulates;

2) the monimolimnion – an anaerobic zone, a non-mixing and not contacting with the atmosphere layer where decomposition of organic matter is in progress;

3) the chemocline – a transition zone where a jump in hydrological and hydrochemical parameters occurs at the boundary of both layers, and a complex microbial community is formed.

In the relatively small chemocline layer, various intensive biogeochemical processes take place. The presence of sharp gradients of oxidation-reduction conditions and chemical composition in the water column, the absence of contact between low water layers and the atmosphere, etc. make them unique objects of study in terms of hydrochemistry, microbiology, paleolimnology, etc. (Stewart et al., 2009).

K. Walker and G. Likens (1975) identified two classes of meromixis:

• class A – exogenous, caused by external factors;

• class B – endogenous, primarily associated with internal factors.

Within class A, the authors described three types of meromixis:

I – the layered structure of the reservoir is formed by a salt water influx to a freshwater lake or, conversely, a fresh water influx to a salt reserve (Ia – continental lakes, Ib – coastal lakes);

II – the differences in water density emerge due to the surface inflow of waters with a high content of suspended solids (for example, after clearing a forest catchment);

III – the density stratification of water mass is formed due to the underground influx of fresh or salt water.

Two types were referred to class B:

IV – the meromixis is caused by morphometric features of the lake basin shape and a surrounding relief (usually in small deep reservoirs);

V – the density stratification is associated with accumulation of salts deposited to the bottom layer as a result of freezing during ice formation.

Being very sensitive to environmental changes, freshwater meromictic lakes are of interest to researchers in the climatic context. In low-mineralized waters, the density gradient of the mixolimnion and monimolimnion is insignificant that makes the lake structure less stable and more vulnerable to external effects. Inter-annual (with depth) variations in the chemocline can serve as an integral characteristics of autumn temperature and wind regime, acting as a marker of climate change. In small lakes, the mechanism of water mixing can be affected by local factors, which in larger reservoirs are masked by the influence of other circumstances.

Meromictic lake ecosystems are unique for understanding both modern and ancient aquatic ecosystems. They should be protected as the objects distinguished by specific hydrological, hydrochemical and hydrobiological conditions.

Meromictic lakes are the rare type of water bodies. Most of them are explored in North America and Europe since these two regions are best studied (Ecology of meromictic lakes, 2017). In works of E.D. Krasnova (2021a, b) devoted to the ecology of meromictic lakes in Russia, the related available scientific data are presented. As of 2020, 54 meromictic water bodies were identified in Russia: 31 coastal water bodies of marine origin, 12 karst lakes, 5 glacial ones, 4 endorheic salt meromictic reservoirs, an artificial pond and the Black Sea – the world largest meromictic reservoir. However, the actual number of such water bodies remains unknown because of poor study of the majority of lakes.

Bolshoy Solovetsky Island is situated in the Onega Bay of the White Sea. On the territory of the Solovetsky Archipelago, there are about 370 (Shvartsman and Bolotov, 2007) primarily small lakes; 90% of them are located on Bolshoy Solovetsky Island (lake content – 11.63%). This indicator is quite high for the Northwestern Russia (Izmailova, 2018).

Natural complexes of the North, including the Solovetsky Archipelago, undergo significant transformations under the influence of climatic and anthropogenic factors. Among the most important and vulnerable natural components of the Solovetsky Archipelago are its freshwater ecosystems, which largely determine the nature uniqueness of these islands, as well as the possibility of living and carrying out economic activities there.

On the Solovetsky Archipelago, the only meromictic lake of exogenous type (Class A, type Ib) was previously studied (Krasnova, 2021a). S.I. Klimov and T.Ya. Vorobyeva (2025) identified presumably 19 meromictic water bodies (including Lake Svetlenkoye) based on the design characteristics. Due to remoteness from the Solovetsky settlements and its inaccessibility, Lake Svetlenkoye is not subject to direct anthropogenic impacts that enables to consider it as a natural laboratory for studying complex hydrochemical and hydrobiological relationships under the unique chemocline and monimolimnion conditions.

The aim of this work is to prove the meromictic status of Lake Svetlenkoye on Bolshoy Solovetsky Island and to describe its primary hydrological, hydrochemical and hydrobiological characteristics.

Objects and methods of study

The object of our study is Lake Svetlenkoye (N 65.0915° E 35.6795°) located on Bolshoy Solovetsky Island (Fig. 1).

We measured the reservoir parameters in summer, winter and autumn of 2022–2024. The main hydrological characteristics of the lake are presented in Table 1.

According to the classification of P.V. Ivanov (Smirnov, 1993), in terms of the surface area, Lake Svetlenkoye is a small, deep and slightly open waterbody with high transparency (Kitaev, 2007) reaching 6 m by the Secchi disk in summer. Fig. 2 shows the bathymetric map of Lake Svetlenkoye.

The morphometric features of the lake basin were established based on the results of a bathymetric survey with the use of an echo sounder and chart plotter. Vertical profiles of distribution of temperature, specific electrical conductivity, hydrogen index (pH), oxidation-reduction potential (ORP), and dissolved oxygen were measured using a U-52G multiparameter water quality analyzer (Horiba, Japan). Some temperature profiles were obtained together with oxygen content data from a WTW Oxi 330i probe-oximeter (Germany) equipped with a DurOx 325 sensor (Germany).

Water sampling for hydrochemical and microbiological analyses was implemented in the deepest point of the lake, in the discrete horizons from the surface to the bottom using a pre-cleaned polycarbonate horizontal bathometer (Aquatic Research Co, ID, USA). When sampling, we preserved water with zinc acetate to measure the hydrogen sulfide content and then made photometric determination with N,N-dimethyl-paraphenylenediamine[1]. To find the concentration of methane (CH_4) and carbon dioxide (CO_2), the samples were collected in the 60 ml vials according to the method described by S.A. Zabelina et al. (Zabelina et al., 2021), followed by adding 0.2 ml of a saturated $HgCl_2$ solution. Concentrations of CH_4 and CO_2 were determined on a gas chromatograph "Chromatec-Crystal 5000" (Russia) with a flame ionization detector and a methanator for CO_2 evaluation. The concentration in the liquid phase was calculated from the data on specific solubility (Weiss, 1974; Yamamoto et al., 1976).

The content of dissolved organic carbon (DOC) was estimated on a Shimadzu total organic carbon analyzer (Japan) of the TOC-Lcsn series by means of the catalytic oxidation method at 680 °C. When sampling, the water was passed through a 0.22 µm filter. The ionic composition (concentrations of sulfate ions (SO_4^{2-}), chloride ions (Cl^-), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}) cations) was found by HPLC on a Shimadzu LC-20 Prominence chromatograph (Japan) with a conductometric detector[2]. The content of hydrocarbonate ions (HCO_3^-) was evaluated via two-point potentiometric titration (Lozovik et al., 2017). When collecting water samples to estimate dissolved iron (Fe^{2+} and Fe_{total}), we minimized their contact with atmospheric oxygen, preserved the samples with the concentrated hydrochloric acid and photometrically analyzed their content in water using a ferrozine modified with ascorbic acid (Kononets et al., 2002; Titova and Kokryatskaya, 2013). Concentrations of major biogenic elements (nitrogen, phosphorus, silicon) were measured by standard photometric methods (Lozovik et al., 2017).

Pigment characteristics of phytoplankton were obtained according to GOST 17.1.04.02-90[3].

To count the total number of microorganisms, the samples were collected in sterile 15 ml vials and fixed with filtered bacteria-free glutaraldehyde (final concentration of 2%). The total number of microorganisms was determined due to a Luminex Guava® EasyCyte 12HT flow cytometer (USA) with DAPI fluorochrome staining and blue spectrum fluorescence detection (Blu-V (450/45) sensor).

The taxonomic diversity of microorganisms was identified via using molecular genetic methods. For studying microbial communities, water samples were collected in sterile containers and transported to the laboratory where microbial cells were concentrated on membrane filters with a pore diameter of 0.22 µm (GSWP, Millipore) using pre-sterilized Sartorius polycarbonate filtration units. Isolation of the total DNA from lake water was implemented by the Genomic Technologies and Cell Biology Collective Use Center of the All-Russian Research Institute of Agricultural Microbiology of the Russian Academy of Agricultural Sciences (Pushkin) through applying a modified CTAB method (Rahimah et al., 2006). A Precellys 24 homogenizer (Bertin Technologies, France) was used for cell disruption, run twice at

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[1] Guidance document 52.24.450-2010. Mass concentration of hydrogen sulfide and sulfides in waters. Measurement procedure via using photometric method with N,N-dimethyl-p-phenylenediamine.

[2] Environmental Regulations of RF 14.1:2:4.132-98. Quantitative chemical analysis of waters. Measurement procedure of mass concentration of anions: nitrite, nitrate, chloride, fluoride, sulfate and phosphate in samples of natural, drinking and waste waters using ion chromatography.

[3] GOST 17.1.04.02-90. Water. Method of spectrophotometric determination of chlorophyll *a*.

Fig. 1. Schematic map of Bolshoy Solovetsky Island and its photographs for assessing the lake content. Location of Lake Svetlenkoye is indicated as a red dot.

Table 1. Main hydrological characteristics of Lake Svetlenkoye.

Characteristic	Lake Svetlenkoye
Area, km^2	0.01643
Volume, km^3	0.0001667
Length, m	210
Maximum width, m	120
Maximum depth, m	22.0
Average depth, m	10.1
Parameter of relative depth, α	40.9
Z (relative depth), %	15.8
Catchment area,km^2	0.07073
Coefficient of conditional water exchange, year $^{-1}$	0.11
Water residence time, year	8.5

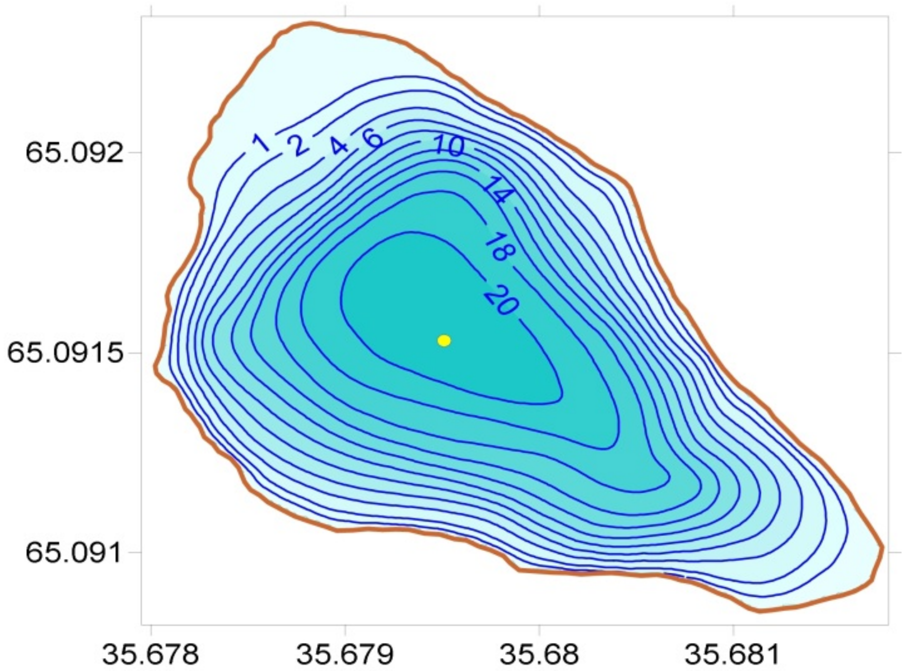

Fig. 2. Bathymetric map of Lake Svetlenkoye.

a speed of 6000 rpm for 30 s. Universal PCR primer (F515/R806) sets were employed for targeting the 16S pRNA-v4 gene variable region in bacteria and archaea (GTGCCAGCMGCCGCGGTAA / GGACTACVSGGGTATCTAAT) (Bates et al., 2010). PCR products were purified by AMPureXP in accordance with the Illumina method (Beckman Coulter, USA). Libraries were sequenced in Illumina MiSeq using the MiSeq® Reagent Kit v3 (600-cycle) with two-sided reading (2x300 N) (Illumina, Inc., USA).The obtained data were processed following T.N. Melnichuk et al. (2019).

Samples for determination of the qualitative and quantitative composition of zooplankton were collected by a Juday plankton net with a cutter (entrance diameter 18 cm, mesh size 74 μm) in the mixolimnion (0–2.5 m, 2.5–5 m, 5–14 m), chemocline (14–16 m) and monimolimnion (16–20 m) layers. Additionally, we pulled the net from the bottom to the surface. Samples were fixed with a 4% formaldehyde solution and processed using MBS-10 (Russia) and Altami LUM 1 (Russia) microscopes. We identified the zooplankton species in accordance with V.R. Alekseev (2010) and calculated wet biomass of zooplankton from the equation for the relationship between body length/wet mass (Balushkina and Vinberg, 1979; Ruttner-Kolisko, 1977).

Results and discussion

Hydrological and hydrochemical characteristics

In summer and winter, direct and reverse temperature stratification in the mixolimnion structure of Lake Svetlenkoy with characteristic layers, i.e. epilimnion and metalimnion, was noted. In summer, the epilimnion developed to depths of 2.5 to 3.0 m, metalimnion – up to 7 m (Fig. 3). In 2022 and 2023, the maximum vertical temperature gradients reached 10.5 °C/m at 3.0–3.5 m and 7.2 °C/m at a depth of 3.5–4.0 m, respectively. In the summer-autumn period, water temperature gradually dropped with depth, up to the chemocline zone. In winter, a subglacial thermocline was formed at depths of 3.0–3.5 m with water temperature of 3.4–4.2 °C, followed by the gradual temperature rise towards the bottom. During the observation period, water temperature fluctuations beneath 12 m did not exceed 0.5 °C, and bottom temperature varied from 4.0 to 4.4 °C.

In the surface layer, the specific electrical conductivity made up 42–49 and 46–50 μS/cm above the chemocline, while in the monimolimnion it was 73–96 μS/cm at a depth of 18–20 m (Fig. 3). The chemocline characteristics are given in Table 2.

Depending on seasons, a permanent anaerobic zone in the reservoir was located below 15–16 m (Fig. 3).

In the water column, the structure of the hydrogen vertical profile in the mixolimnion – from 5.6 to 7.8, in the chemocline – a slight decrease of pH followed by its increase towards the bottom (Fig. 3).

Measurements of the oxidation-reduction potential carried out in March and October 2023 suggest positive values from the surface to the 17 m depth, whereas negative – in deeper layers, reaching −100 mV in the bottom horizon. A sharp reduction in ORP starts from the 15 m chemocline layer.

Thus, the obtained data are evidence of the structure characteristic of a meromictic reservoir where mixolimnion, monimolimnion and chemocline zones are present. In the latter, we also observe pH changes related, obviously, with functioning of the microbial community.

Both, in the mixolimnion and monimolimnion layers of Lake Svetlenkoye, waters are classified as ultra-fresh and very soft (mineralization < 100 mg/l, hardness < 1.5 mmol/l). In the mixolimnion, chloride and sodium ions dominate because of the influence of marine aerosols. Hence, the mixolimnion waters may belong to a chloride sodium type. In the water sampled from the lake's monimolinion, hydrocarbonate ion and sodium cation predominate among macrocomponents. Concentrations of magnesium, sodium, potassium and chloride ions slightly vary with depth, while the content of sulfate ions drops. A sharp decrease in concentrations of sulfate ions, along with an insignificant variation in the content of chloride ions, are indicative of the occurrence of sulfate reduction and hydrogen sulfide generation (Fig. 4).

According to the Kurlov formula (Lozovik, 2017), the hydrochemical composition of the studied layers looks as:

$$\text{mixolimnion: M 23.86 H 0.1 } \frac{\text{Cl 64 SO}_4\text{24 HCO}_3\text{12}}{\text{Na66 Mg22 Ca12}} \text{ pH 6.35,}$$

$$\text{monimolinion: M 44.45 H 0.2 } \frac{\text{HCO}_3\text{57 Cl41}}{\text{Na35 Ca13 Mg13}} \text{ pH 6.40,}$$

where M is mineralization, mg/l; H – hardness, mmol/l.

The meromictic structure of the lake is also manifested in distribution of biogenic elements (nitrogen, phosphorus and silicon compounds). The accumulation of these elements in the bottom horizons is induced, on the one hand, by anaerobic destruction of sedimentary material, and on the other by their inflow from the bottom sediments (Fig. 5).

In the anoxic zone of the lake, the concentration of total dissolved iron is constantly high. In the anaerobic zone, this element is mostly represented by a bivalent form (up to 98%) (Fig. 6). Predominance of iron concentrations over hydrogen sulfide and biogenic elements is recorded in the monimolimnion zone.

The meromictic structure is also traced in distribution of carbon cycle indicators. Anaerobic mineralization of organic matter and, apparently, methanogenesis occur in the monimolimnion.

Vertical distribution of DOC tends to increase in concentrations from the surface to the bottom horizons with its abrupt rise in the chemocline zone. In the lake mixolimnion, the concentration of CH_4 declines from the surface towards the chemocline (from 7.41 µl/l to 1.36 µl/l), while in the monimolimnion, on the contrary, it grows with depth. The concentration of CO_2 in water also increases with depth, i.e. from the surface to the bottom (Fig. 7).

Hydrobiological characteristics

The pigment characteristics of phytoplankton were determined in July 2022. The recorded concentrations of chlorophyll *a* in the mixolimnion made up < 1 µg/l, being generally typical of oligotrophic reservoirs (Kitaev, 2007). It is hardly possible to clearly differentiate the phytoplankton community by specific chlorophylls (Chl *b* and Chl *c*), as well as to assess its state by pigment indices. There are no data on pigment characteristics in the chemocline zone.

The study of species diversity of the prokaryotic communities showed that in addition to bacteria, archaea were also present in the chemocline and monolimnion (about 5% of identified prokaryotes). At a depth of 13.5 m, archaea were detected in small quantities. However, this indicator was several times higher in the bottom layer at a depth of 20 m. From the surface up to the 13m layer, the total number of bacterioplankton was constant in all seasons, varying from 0.054 ± 0.003 to 0.144 ± 0.004 million cells/ml (Fig. 8). With depth, prokaryotes demonstrated a sharply 8-fold increase in number: from 0.167 ± 0.004 (at a depth of 16 m) to 1.351 ± 0.058 million cells/ml (18 m). However, deeper in the monimolimnion (20 m), their total number was almost 2 times lower (0.764 ± 0.003 million cells/ml). A similar trend was observed in October. The upper boundary of the chemocline in this season was at a depth of 15 m. An abrupt 4-fold increase in bacterioplankton abundance occurred at depths of 15–17 m, amounting

Table 2. Position of the chemocline and the layer with maximum vertical gradient of specific conductivity in Lake Svetlenkoye.

Date	30.03.22	21.07.22	30.03.23	23.07.23	21.10.23	30.03.24
Chemocline depth, m	13.5–16.0	14.0–16.0	15.5–17.0	15.5–17.0	15.0–17.5	15.0–17.5
Gradient of specific conductivity, μS/cm/m	8.9	11.3	14.7	17.3	12.1	10.7
Layer of the maximum gradient, μS/cm	14.5–15.0	14.0–14.5	16.5–17.0	16.0–16.5	16.0–16.5	16.5–17.0
Maximum gradient of specific conductivity, μS/cm /m	28.0	37.4	45.7	58.0	36.9	29.7

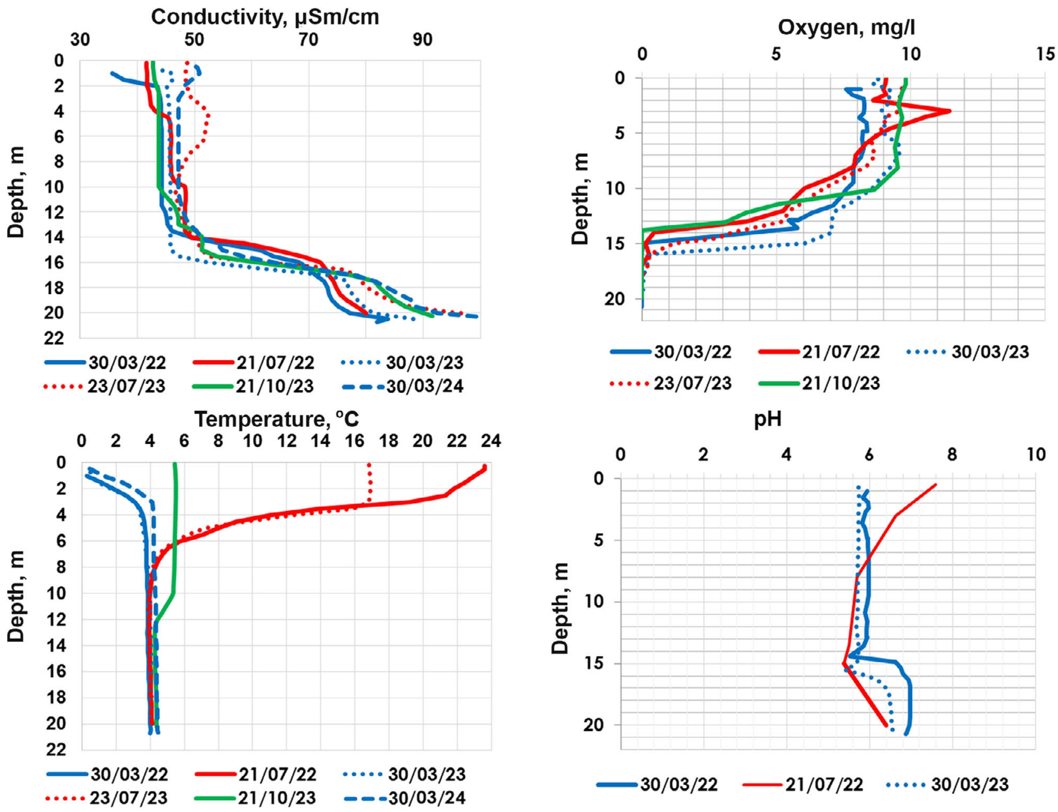

Fig. 3. Vertical distribution of specific conductivity, oxygen content, temperature and pH in Lake Svetlenkoye.

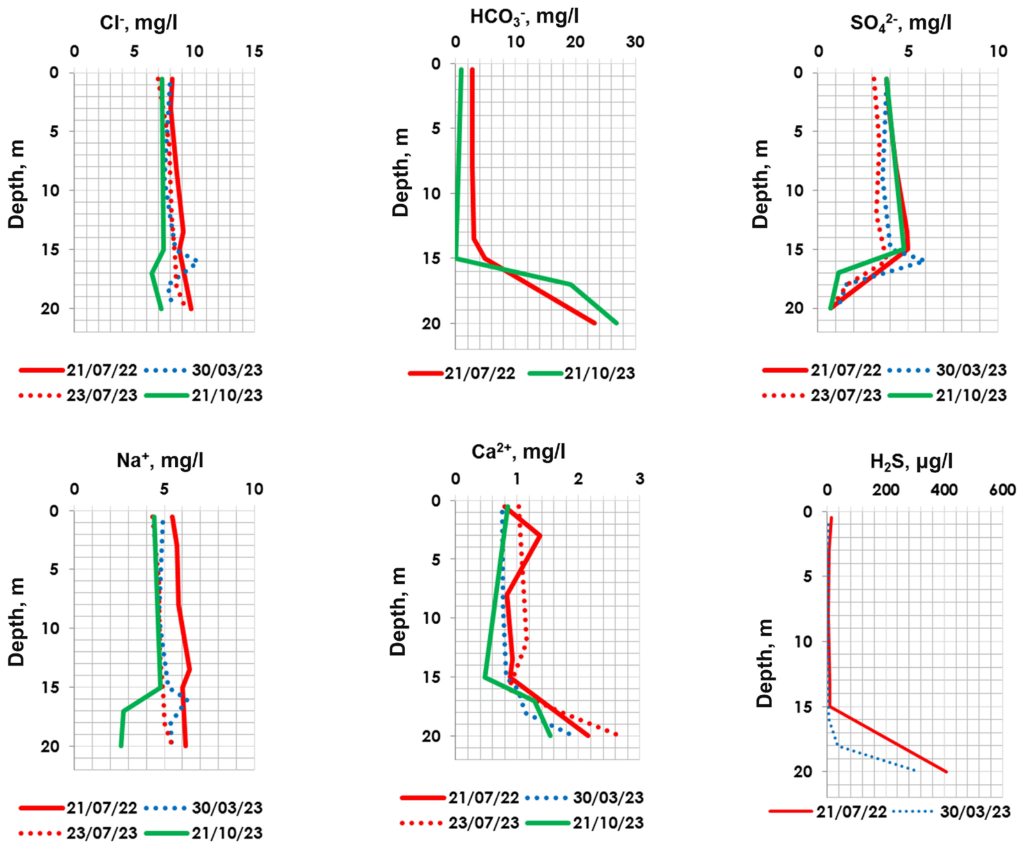

Fig. 4. Vertical distribution of chloride ions Cl^-, hydrocarbonate ions HCO_3^-, sulfate ions SO_4^{2-}, sodium cations Na^+, calcium Ca^{2+}, hydrogen sulfide H_2S.

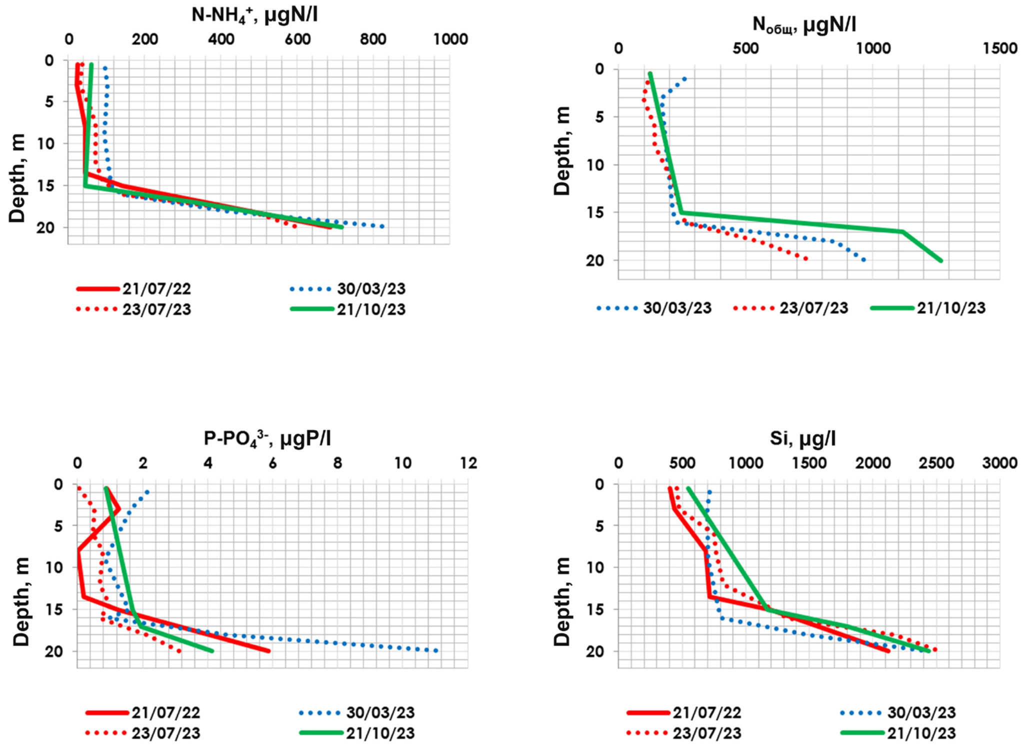

Fig. 5. Vertical distribution of ammonium nitrogen ($N\text{-}NH_4$+), total nitrogen (N_{total}), phosphates ($P\text{-}PO_4^{3-}$), silicon (Si).

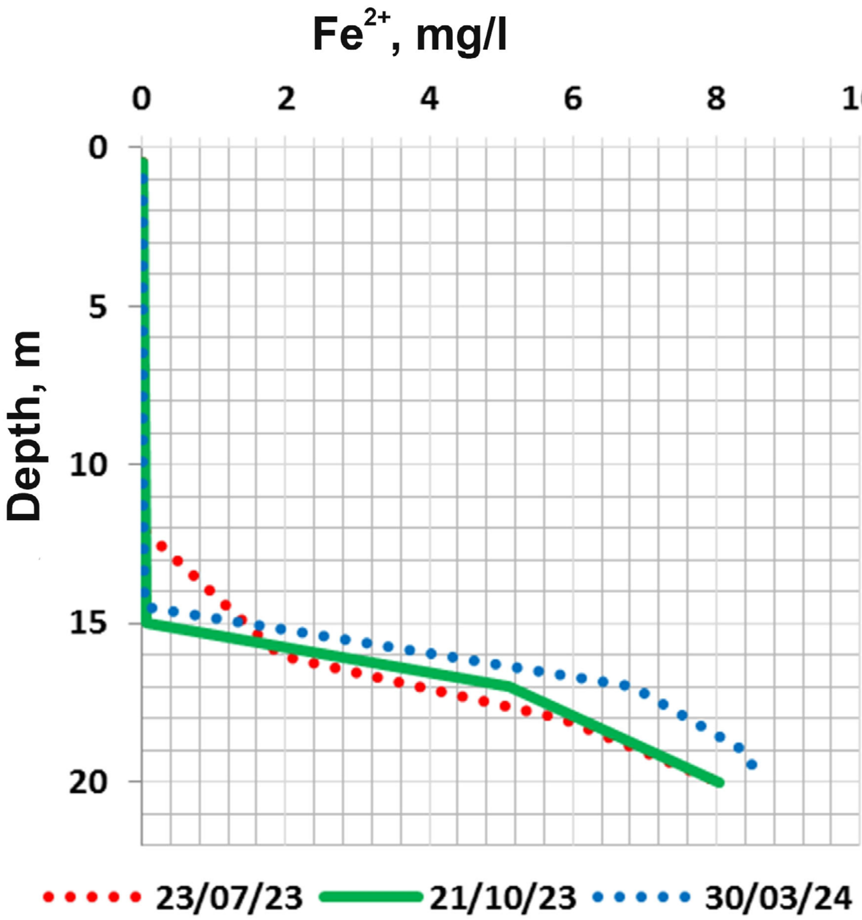

Fig. 6. Vertical distribution of dissolved iron Fe^{2+}.

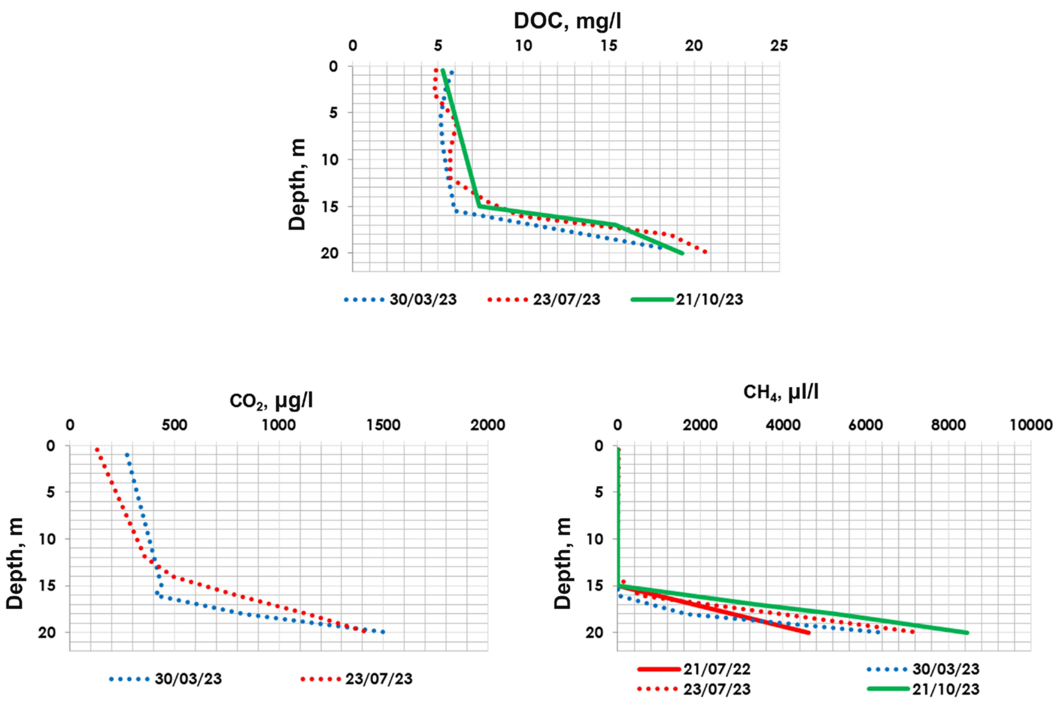

Fig. 7. Vertical distribution of dissolved organic carbon (DOC), carbon dioxide (CO_2) and methane (CH_4).

to 0.286 ± 0.006 and 1.086 ± 0.004 million cells/ml, respectively. As in March, this indicator sharply decreased in the monolimnion, being 0.903 ± 0.008 million cells/ml at a depth of 20 m. In July, the upper boundary of the chemocline corresponded to the 15 m level, where the total number of bacterioplankton made up 0.805 ± 0.003 million cells/ml that was 4 times higher than at the 13 m horizon.

The zooplankton community of the reservoir was represented mainly by palearctic and holarctic species. In the lake zooplankton, we identified 14 species of invertebrates: 7 species of Cladocera, 3 – Copepoda and 4 – Rotifera. The structure-forming complex consisted of 5 species: *Kellicottia longispina* (Kellicott, 1879), *Polyarthra dolichoptera* Idelson, 1925, *Keratella cochlearis* (Gosse, 1851), *Mesocyclops leuckarti* (Claus, 1857), *Bosmina longirostris* (O.F. Muller, 1785).

In zoocenosis, rotifers dominated in number (63%), while copepods in biomass (60%). A significant contribution to the total number was made by the species *K. longispina* – 36–56%, *M. leuckarti* – 10–26%, *P. dolichoptera* – 10–18%.

Biomass was mainly composed of *M. leuckarti* (47–58%), *Diaphanosoma brachyurum* (Lievin, 1848) (11–25%), *B. longirostris (*11–18%). The average number and biomass of zooplankton during the study period reached 28,300 specimens/m^3 and 0.3 g/m^3, respectively.

Vertical distribution of zooplankton depended on temperature and oxygen conditions. Abundance of hydrobionts was maximum in the upper well-oxygenated layers of the mixolimnion, as well as in the thermocline (2–9 m). Here, zooplankton number amounted 73.9 ± 23 thousand specimens/m^3 and its biomass 0.3 ± 0.09 g/m^3, respectively. The number and biomass of zooplankton declined with depth. Uneven vertical distribution of different groups of zooplankton was registered. The highest number of rotifers turned out to be in the mixolimnion at a depth of 3–5 m. Deeper, their number reduced. Copepods were most abundant in the layers of 16–20 m. Cladocera prevailed above the boundary of aerobic and anaerobic zones (13 m).

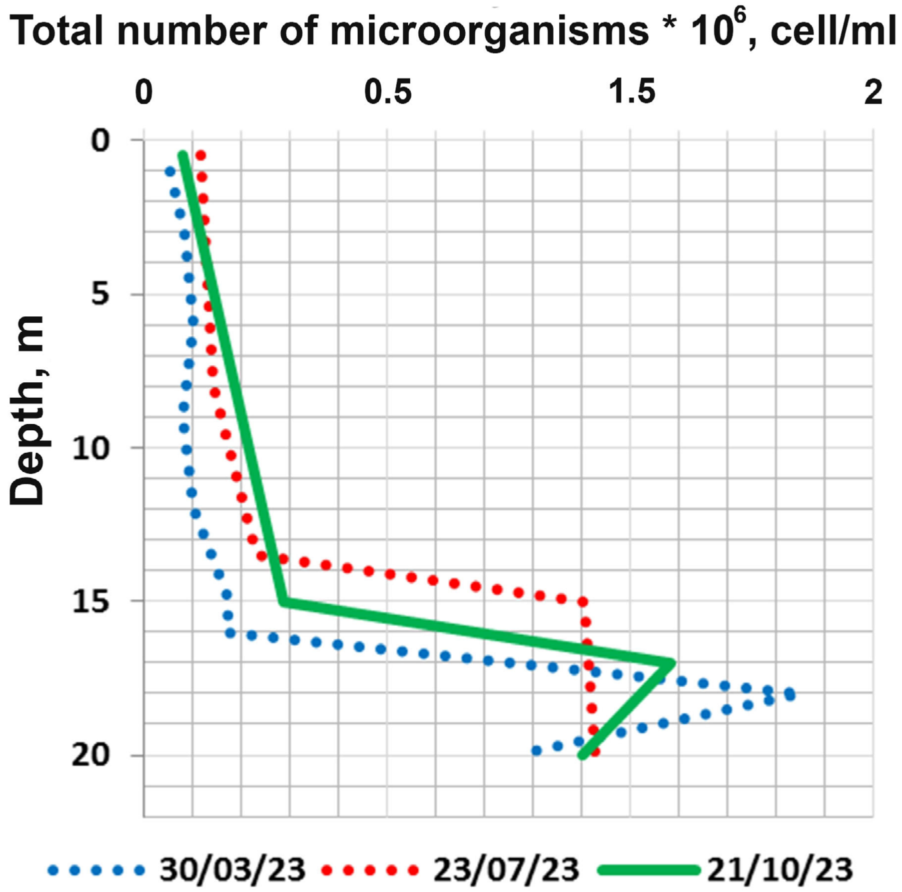

Fig. 8. Vertical distribution of the total number of microorganisms.

Conclusion

Identification and investigation of the unique natural objects – the meromictic lakes on Bolshoy Solovetsky Island, are topical for studying both the local evolution of the Solovetsky Archipelago ecosystems and global climate change in the past and present.

Lake Svetlenkoye has a stable stratification with water layers characteristic of meromictic reservoirs. In the very beginning of the chemocline anaerobic zone, a sharp increase in the specific electrical conductivity is recorded. The hydrochemical composition of water in the monimolimnion is indicative of occurring anaerobic mineralization of organic matter, sulfate reduction and methanogenesis. Depth distribution of biogenic elements (sharply increasing concentrations in the chemocline zone) also corresponds to the meromictic structure of the reservoir. Growing (with depth) iron content and its predominance over hydrogen sulphide and biogenic elements in the monimolimnion are evidence of a ferruginous ("iron") type of anoxia. Despite the meromictic status and close location to the sea, Lake Svetlenkoye is the ultra-fresh reservoir with mineralization under 50 mg/l. Thus, the lake belongs to endogenous meromictic reservoirs of type IV (Walker and Likens, 1975).

Since Lake Svetlenkoye is difficult to access for tourists and local residents, it can serve as a background object for monitoring water bodies of Bolshoy Solovetsky Island and as a “natural laboratory” for studying the ongoing processes in the chemocline and monimolimnion zone of meromictic water bodies with a ferruginous type of meromixis.

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