RESEARCH PAPER

CHANGES IN THE CHEMICAL COMPOSITION OF WATER IN THE SMALL LAKE VENDYURSKOE (SOUTHERN KARELIA, RUSSIA) OVER 50 YEARS DUE TO CLIMATE CHANGE AND ANTROPOGENIC IMPACT

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ABSTRACT. Studies of changes in the chemical composition of lake water due to climate variability and human impact are highly relevant for Karelia, which has more than 60,000 lakes. Lake Vendyurskoe, a typical small lake in Karelia, has been used for growing rainbow trout since 2009. In the 1970–90s, drainage and logging were practiced in the catchment of this lake. A change in the composition of major ions in the lake's water and an increase in the labile component of organic matter were observed between 1971 and 2023. In 2021–2023, the concentration of sulfate ions decreased fourfold compared to 1971–1985, which may be due to both the cessation of drainage operations and a reduction in the concentration of sulfates in precipitation. Chloride ion concentrations were reduced by half. The 50-year decrease in bicarbonate concentrations was likely associated with increased precipitation. Total phosphorus concentrations in the lake water showed an upward trend over the 50 years (in both surface and bottom layers), indicating increased anthropogenic impact on the lake. During the summer stratification period, hypoxia develops in the deep-water parts of the lake and near trout cages, and phosphate concentrations in the bottom layers are quite high (up to 36 µg/L). The mobilization of phosphorus from bottom sediments under anoxic conditions creates a secondary phosphorus load, which may be the reason for the increased bioproductivity. A direct correlation was found between the duration of near-bottom hypoxia in summer and the average air temperature over the three summer months (R^2 = 0.51), suggesting deteriorating oxygen conditions in the lake during the open-water period as regional climate warming continues. The greatest oxygen depletion in the lake occurs in winters with early freeze-up and late ice-breaking. The inverse correlation of the duration of winter hypoxia with the November air temperature of the previous year (R^2 = 0.39) and the May air temperature of the current year (R^2 = 0.41), which influence the timing of ice formation and breakup, suggests the oxygen conditions in the lake during the winter have improved, with a shorter freeze-up period due to warming in the fall and spring. The observed changes in the water chemical composition provide reasoning for reducing the trout farming volumes.

KEYWORDS: small lake, human impact, climate change, major ions, nutrients, oxygen

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INTRODUCTION

Lakes are vulnerable to anthropogenic impacts and climate change (Adrian et al. 2009; Maberly et al. 2020; Saros et al. 2023; Woolway et al. 2025). Shifts in water temperature (O'Reilly et al. 2015), ice phenology (Sharma et al. 2019), oxygen content (Jansen et al. 2024), mixing patterns (Woolway and Merchant 2019), and biogeochemical cycles (Hobbie et al. 1999; Bush et al. 2017; Joung et al. 2017; Quinlan et al. 2021; Wu et al. 2022; Zhu et al. 2025) have been detected in lakes around the world in response to global warming and growing nutrient loading. In small lakes, due to their small volume, changes occur very quickly (Wik et al. 2016; Wu et al. 2022), which raises the relevance of studying changes in the chemical composition of such lakes under the influence of climate change and human impact.

There are more than 60 thousand lakes in Karelia, most of which are small (Lakes… 2013). In recent decades, Karelia has experienced a steady increase in air temperature (the rate of increase in average annual air temperature was +0.5–0.6 °C/

decade (Nazarova et al. 2022) in 1976–2021) and a change in precipitation (20–70 mm surplus in annual precipitation relative to the 1961–1990 baseline (Nazarova 2015)). Coupled with intensive economic use of the catchments, this contributes to changes in the input of organic matter (OM) and nutrients to lakes (Sabylina et al. 2010). The impact of trout farms on lake ecosystems (Galakhina and Zobkov 2022) is the most acute problem for Karelia, since fish production volumes are constantly growing.

Lake Vendyurskoe is a small lake in southern Karelia, located 50–100 km away from large industrial areas but affected by fish farming since 2009. There are no farmlands in the Lake Vendyurskoe catchment. Logging and drainage between 1971 and 1986 have significantly altered the landscape in the catchment. Drainage caused lake water enrichment with OM, inorganic substances, and nutrients, but the operations ceased after 1991.

Previously, the chemical composition of the lake water was studied in the summers of 1971, 1972, 1978, 1983, 1986, 1991, 1992 and seasonally in 1979–1990 (excluding 1982, 1983, 1986). Lake Vendyurskoe was a model for studying the acidifying effect of polluted precipitation in 1981–1986 (Kharkevich and Kryukova 1981; Freindling and Kharkevich 1982; Martynova 1982). After 1992, the sampling frequency was sharply reduced for a number of reasons (lack of funding, change in the Institute's research topics), and hydrochemical studies were carried out at intervals of 9–10 years in 2001, 2011/2012 and 2021–2023. The chemical composition of water in tributaries to Lake Vendyurskoe was studied in 1976–1985 and 2001.

The purpose of this study is to assess changes in the chemical composition of Lake Vendyurskoe water over 50 years, which occurred as a result of the economic activities in its catchment area, fish farming inside the lake, and regional climate variability.

MATERIALS AND METHODS

Lake Vendyurskoe is located in southern Karelia (62°10´–62°20´ N, 33°10´–33°20 E) and belongs to the basin of the Suna River, a tributary of Lake Onego (Fig. 1a, b). The lake is of glacial origin, with an area of 10.1 km^2 and water volume of 0.0609 km^3 (Lakes… 2013). The catchment is ~15% paludal. The Rindozerka River and several streams empty into the lake, while the Kulapdegi River originates from it. The total average annual runoff into the lake (according to V.A. Freindling and N.S. Kharkevich, archival records of the Northern Water Problems Institute) is 22.2×10^6 m^3, with the Rindozerka River accounting for about 43%. Atmospheric precipitation over the lake surface is 6.5×10^6 m^3 (Lakes… 2013). The lake is ice-covered for 5–6 months, from November or the first half of December to late April–early May. In the summer, the surface water layers warm up to 20–25°C and the bottom layers to 15–17°C. During the open water period, the lake becomes completely mixed 3–7 times (Smirnov et al. 2024), and so it classifies as polymictic.

Water sampling in Lake Vendyurskoe was carried out in the summers of 1971, 1972, 1978 and seasonally in 1979–1980, 1983–1985, 1987, 1990-1992, 2001, 2011–2012, 2021–2023 at the same stations (Fig. 1c).

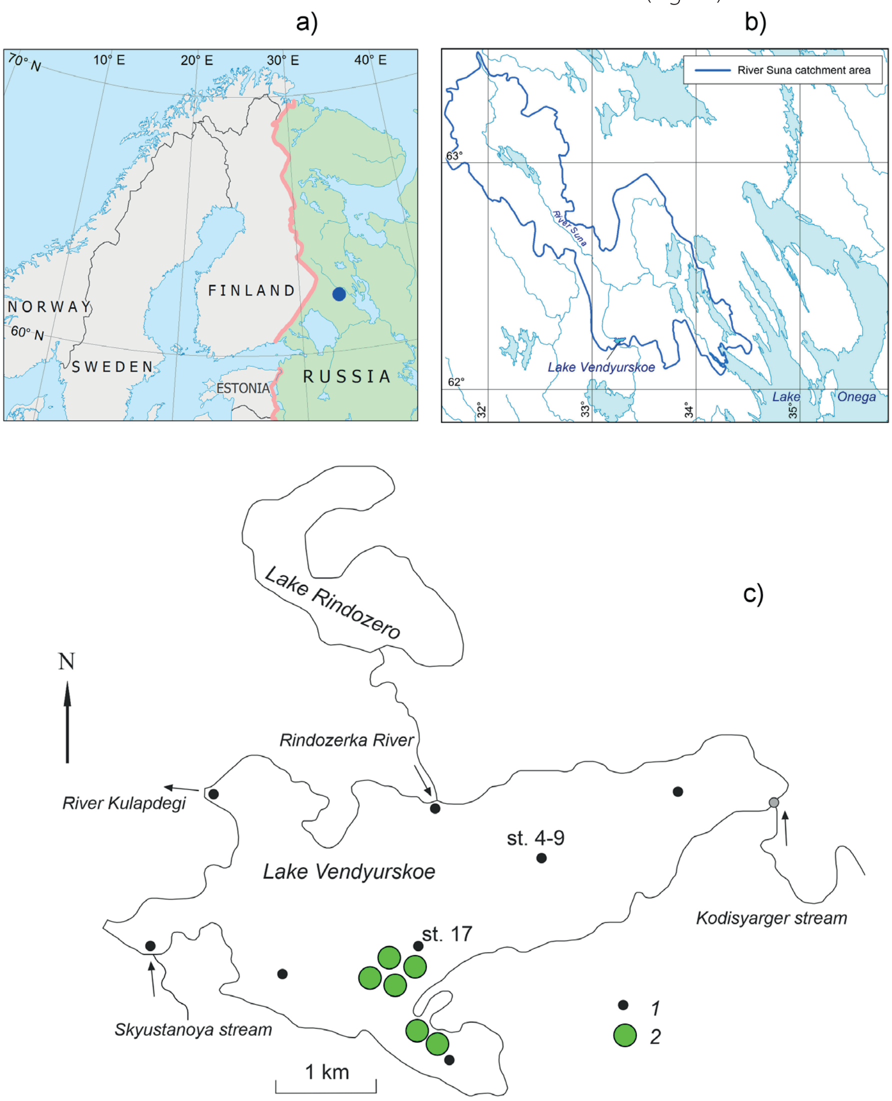

Fig. 1. (a) Location of Lake Vendyurskoe (blue circle). (b) Lake Vendyurskoe in the Suna River catchment area. (c) Measurement stations (1) and trout cages (2)

Water sampling in tributaries to Lake Vendyurskoe was carried out in 1976–1985 and 2021–2023 on Kodisyarger and Skyustanoya Brooks and in 1971–1991, 2001, and 2021–2023 on the Rindozerka River. Water samples were collected by Niskin bottles from the surface and bottom layers. The samples for total phosphorus and iron (250 mL) were acidified with H_2SO_4 solution immediately after sampling. Water from the lake and its tributaries was tested for total dissolved solids (TDS) and concentrations of major ions and nutrients (nitrogen, phosphorus, iron, silicium). Also, pH, OM proxies (color, permanganate (COD_{Mn}) and bichromate (COD_{Cr}) chemical oxygen demand, five-day biological oxygen demand BOD_5, ratio of COD_{Mn} to COD_{Cr}), and concentrations of oxygen and carbon dioxide were determined in the lake water. Chemical analyses were performed in the Laboratory of Hydrochemistry and Hydrogeology of the Northern Water Problems Institute using equipment of the Core Facility of the Karelian Research Centre RAS. Standard laboratory analysis methods were used throughout the study period (Lozovik 1994; Analytical… 2017). It should be noted that iron (Fe_{tot}) determination methods varied during the 50-year period. In the 1970s, iron determination was performed with ammonium rhodanide; in the 1980s – with ortho-phenanthroline; and lately – by atomic absorption spectrometry. The results obtained by the last two methods showed good convergence (Lozovik et al. 2006).

The exogenous load of total phosphorus *(Lp)* on the lake is calculated from the weighted average concentration of total phosphorus (P*pr*) using the Eq. (1) (Gusakov 1987):

$$\left[P\ pr\right] = \frac{Lp}{\bar{z}S} \quad (1)$$

where $\bar{z}$ is the average depth, m; *S* is the residence time, year $^{-1}$; the values for Lake Vendyurskoe are $\bar{z} = 5.3$ m and $S = 0.44$ year $^{-1}$.

To identify changes in the chemical composition of water in Lake Vendyurskoe and its tributaries over a long time period, we employed the following approach. Taking into account the heterogeneity of the data series (changes in the sampling frequency, large gaps in the data series), it was decided to compare two base periods that corresponded to the “past” (1971–1992 for the lake and 1979–1985 for the tributaries) and “current” (2021–2023 both for the lake and the tributaries) conditions.

Sofa Statistics 1.4.6 software was used for statistical data processing. The chemical analysis data (P_{tot}, P_{min}) followed a normal distribution. The number of samples analyzed was n = 28 (1971–2001 and 2021–2023). Spearman’s test was used to determine statistically significant differences in the content of P_{tot} and P_{min} between the survey periods. The paired t-test was used to identify statistically significant differences in the studied components (COD_{Cr}, COD_{Mn}, pH, BOD_5, HCO_3^-, Cl^-, SO_4^{2-}, CO_2) in different periods (1971–1990 and 2021–2023).

Additional valuable information about the oxygen regime of the lake was obtained by analyzing records from an autonomous measurement station – a chain with temperature and dissolved oxygen (DO) sensors (RBR Ltd., Canada), which was deployed in the central deep-water part of Lake Vendyurskoe (St. 4–9, see Fig. 1b) in July 2007 and has been operating year-round since then. This article summarizes the data from 2007 to 2023. Records were collected from 10-15 temperature sensors (0.002 ºC accuracy) and 4–5 DO sensors (0–150% oxygen range, 1% accuracy) distributed evenly throughout the water column, taking measurements at one-minute intervals. The oxygen sensor located at 0.5–0.7 m above the bottom was used to determine hypoxia periods (DO below 2 mg/L).

Data on the weather conditions were taken from the Petrozavodsk Weather Station (Bulygina et al. 2025). The air temperature and precipitation were analyzed for each year, and the precipitation volumes were calculated per decade (1970–1979, 1980–1989, etc.). The average precipitation amounts from November of the previous year to July of the current year were calculated to determine the effect of lake water volume fluctuations across years on the concentration of bicarbonates in the lake water. The relationship between the duration of hypoxia (< 2 mg/L) at the bottom of the central basin of the lake and the average air temperature of the three summer months was analyzed. For the winter period, we analyzed the relationships between hypoxia duration and air temperatures in November and May as factors that can determine the ice-on and ice-off dates and, consequently, the duration of the winter hypoxia.

RESULTS and discussion

Chemical composition of water in the lake’s tributaries

Over the long-term period, the annual average TDS in the Rindozerka River and the brooks decreased, presumably due to regional climate change and alteration of the landscape structure in the catchment area (deforestation and drainage). According to seasonal data for 1979–1985 and for 2021–2023, the annual average TDS in the Rindozerka River, Kodisyarger, and Skyustanoya Brooks was 19.4, 24.2, and 30.2 mg/L, and 13.7, 16.4, and 20.3 mg/L, respectively.

From 1975 to 1983, hydrological engineering was implemented in the northern and northeastern parts of Lake Vendyurskoe catchment (79.8 km^2) to reclaim wetlands, which covered ~15% of the area. Forest drainage was the most intensive in the catchment of Lake Rindozero (32.9 km^2), which is within Lake Vendyurskoe catchment. The proportion of drained land in its northern and north-eastern parts amounted to 20% of Lake Vendyurskoe catchment area. Monthly hydrochemical observations were carried out from October 1978 to June 1981 in two main canals draining fens and transitional mires with peat deposits up to 2 m thick (Kharkevich et al. 1982). The TDS content of water in the drains was closely correlated with the water regime: the average values during low-water periods were 47.5 mg/L (in summer) and 66.3 mg/L (in winter). The water was of the calcium-rich hydrocarbonate type. Sulfate ion concentrations in summer and winter were 4.6 and 5.9 mg/L, respectively. During the high-water period, TDS decreased to 24.3 mg/L, the value during freshets being 36.5 mg/L. During this time, the water class changed from the bicarbonate to the sulfate type. The sulfate content during the flood period rose to 12.9–13.9 mg/L (8.6 on average). The average concentration of inorganic phosphorus (P_{min}) in the canal water was at maximum (42 µg/L) in 1979 and decreased to 10–15 µg/L by 1981. In the summer of 1979, there was also an elevated content of ammonium nitrogen, up to 0.81 mg/L (average annual 0.28 mg/L). In 1981, the average annual content of ammonium nitrogen dropped to 0.20 mg/L. The average annual concentration of nitrate nitrogen was an order of magnitude lower.

Drainage-induced ecosystem transformation in the taiga zone of northern European Russia is most intensive during the first 3–4 years and ends after 10 years. The anthropogenic load of total nitrogen and phosphorus from forestry areas in the catchments of southern Karelia in the first years after drainage accounts for 11% and 10% of river flow, respectively (Karpechko 2004). In subsequent years, the effect of forest drainage on the flow of chemicals from drained land to the stream is insignificant. After that, the formation of the hydrological and chemical runoff in the drained wetlands is the same as in the rest of the forest area.

The current reduction in water mineralization in the tributaries is primarily due to a decrease in the concentrations of sulfate and chloride ions. In 1979–1985, the average annual content of sulfate and chloride ions was 4.6 and 1.2 mg/L, respectively. In 2021–2023, the concentration of sulfate ions dropped 4.5-fold and that of chloride ions 1.7-fold. In the past, the increased content of sulfate and chloride ions in the lake was due to the influx of water from drained lands and precipitation. In the early 1990s, ameliorative operations in Lake Rindozero catchment were terminated. The average annual concentration of sulfate ions in atmospheric precipitation in Lake Vendyurskoe catchment in 1981–1984 was 2.1 mg/L (Kharkevich and Kryukova 1981; Kharkevich et al. 1982; Sabylina and Basov 2003) and in 2021–2023 it was 0.9 mg/L.

Nutrients in the water of the tributaries have exhibited little change. For example, the average annual concentration of total phosphorus in the water of the Rindozerka River and the Kodisyarger Brook in the early 1980s was 22 and 39 µg/L, respectively, while by 2021–2023 it had increased 1.3-fold. The weighted average concentration of total phosphorus in the lake's tributaries in 2021–2023 was 30 µg/L; the exogenous load of total phosphorus *(Lp)* on the lake was 0.07 g/(m^2·year). These levels correspond to oligotrophic conditions (Dillon and Rigler 1974).

The average annual concentration of ammonium and nitrate nitrogen in the water of the Rindozerka River in the past (0.04 mg/L) was close to the current level (0.05 mg/L). Within-year fluctuations also remained the same: ammonium nitrogen is the highest in the spring (0.11 mg/L) and nitrate in the winter (0.08 mg/L). Organic nitrogen (0.35 mg/L) contributes 54% to the total nitrogen. The average annual concentration of total nitrogen in the tributaries is 0.67 mg/L. The current exogenous load of total nitrogen is low and amounts to 1.6 g/(m^2·year), which corresponds to an oligotrophic state.

The average annual silicon content in the Rindozerka River during earlier studies was 2.9 mg/L, and the current content is close to that level – 2.6 mg/L.

The total iron concentration in the water of the Rindozerka River and the Kodisyarger Brook has changed little over time, being 0.80 and 3.0 mg/L, respectively.

OM proxy indicators in the tributary water varied widely in 2021–2023: color from 28 to 194 degrees, and COD_{Mn} from 7.1 to 23.4 mgO/L. The values were the lowest for the Rindozerka River.

The water pH in the tributaries is low (6.33–6.85), with little variation over time.

Chemical composition of Lake Vendyurskoe water

The chemical composition of water in Lake Vendyurskoe is mainly shaped by the river runoff – Rindozerka River, Kodisyarger, and Skyustanoya Brooks, as well as by precipitation, baseflow, and anthropogenic impact.

Due to the natural characteristics of the catchment area, especially the fluvioglacial genesis and edaphic conditions, the content of total dissolved solids in Lake Vendyurskoe water is low (TDS < 50 mg/L). The average annual TDS currently is 15.7 mg/L, while in 1971–1992 it was up to 21.1 mg/L (Table 1). Studies show (Tables 1 and 2) that there have been no noticeable changes in the cationic composition of the water. In the anionic composition, the content of bicarbonates, sulfate and chloride ions has changed over the 50 years. The concentration of chloride ions has dropped by half from the 1970s to the present (Table 1). A statistically significant difference in chloride content ($p << 0.001$ (1.852 e^{-6})) and bicarbonates ($p << 0.001$ (3.656 e^{-5})) was confirmed for the two study periods (1971–1992 and 2021–2023) using a paired t-test. In the summer seasons of 1971–1984, the proportion of sulfates in the anion composition remained quite constant (4.86 mg/L on average) (Table 3), but starting from 1985, their concentration has been declining, with a 4-fold reduction by 2021–2023 (paired t-test; $p << 0.001$ (3.265 e^{-20})) (see Tables 1 and 3, Fig. 2a). The decrease in the concentration of sulfates in lake water is a consequence of their reduction in atmospheric precipitation due to a decrease in economic activity in the region and in the catchment area (Lozovik and Potapova 2006). Lake acidification was observed throughout Northern Europe and North America in the mid-20th century, resulting from the precipitation of sulfates from atmospheric emissions. However, regulatory measures adopted in the 1980s (Grennfelt et al. 2020) led to a general decline in sulfate concentrations in lakes. A large-scale study of changes in the chemical composition of Finnish (Forsius et al. 2003) and Canadian (Mazoyer and Houle 2025) lakes found that sulfate concentrations decreased in recent decades, indicating a clear response to reduced sulfate emissions.

The proportion of hydrocarbonates in the anion composition throughout the research period varied from 8.3 to 15.2 mg/L (Table 3, Fig. 2). Based on the available measurement data for different years, an inverse correlation was found between the hydrocarbonate concentration and the precipitation amount from November of the previous year to July of the current year (Fig. 2b), with the determination coefficient $R^2 = 0.36$ (excluding the data for 1983 with the maximum HCO_3^- value). It is unclear what caused the extremely high hydrocarbonate concentration in the summer of 1983 (15.2 mg/L), given the rather high precipitation amount from November to July (428 mm). A significant increase in precipitation (by 65–80 mm between November to July over the past 50 years (Fig. 2a)) may be one of the reasons for the decrease in the lake's HCO_3^- in summer at present versus 1971–1987.

During the low-water periods of 2021–2023, TDS in the lake exhibited minor vertical heterogeneity. The maximum was observed at the bottom in late March and early August, with an increased role of groundwater recharge (the TDS gradient between the surface and bottom layers during these periods was 2–3 mg/L) (see Table 2).

Table 1. Average annual content of total dissolved solids (TDS) (mg/L) and concentrations of major ions (mg/L) in Lake Vendyurskoe water in 1971–1990 and 2021–2023

Years	Ca^{2+}	Mg^{2+}	K^+	Na^+	HCO_3^-	SO_4^{2-}	Cl^-	TDS
1971–1990	2.3	0.9	0.5	1.3	11.6	3.2	1.3	21.1
2021–2023	1.9	0.7	0.6	1.5	9.1	1.0	0.7	15.6

Table 2. Total dissolved solids (TDS) and concentrations of major ions in the surface and bottom layers of Lake Vendyurskoe water in 2021–2023 (above the line – mg/L, below the line – %-eq.)

Season	Layer	Ca^{2+}	Mg^{2+}	K^+	Na^+	HCO_3^-	SO_4^{2-}	Cl^-	TDS
Winter	surface	1.8/41.7	0.6/22.8	0.6/7.2	1.4/28.3	8.5/78.4	0.9/10.5	0.7/11.1	14.5
	near-bottom	1.8/41.7	0.6/22.8	0.6/7.2	1.4/28.3	8.5/74.9	1.3/14.6	0.7/10.6	14.9
Spring	surface	1.8/38.7	0.7/24.7	0.6/6.6	1.6/30.0	9.5/80.2	0.9/9.6	0.7/10.1	15.8
	near-bottom	1.9/39.3	0.7/23.8	0.6/6.4	1.7/30.6	10.3/80.3	0.9/8.9	0.8/10.8	16.9
Summer	surface	2.0/42.6	0.6/21.0	0.6/6.6	1.6/29.7	8.8/76.0	1.1/12.1	0.8/11.9	15.5
	near-bottom	2.0/43.5	0.6/21.4	0.6/6.7	1.5/28.4	9.3/79.0	1.0/10.8	0.7/10.2	15.7
Autumn	surface	1.9/39.5	0.7/23.9	0.7/7.5	1.6/29.0	8.3/78.0	0.9/10.7	0.7/11.3	14.9
	near-bottom	2.2/43.5	0.7/22.8	0.6/6.1	1.6/27.6	9.6/78.4	1.0/10.4	0.8/11.3	16.4

Table 3. Average hydrocarbonate and sulfate ion levels in Lake Vendyurskoe in summer in different years

Year	HCO_3^-, mg/L	SO_4^{2-}, mg/L
1971	9.8	4.7
1972	13.3	4.0
1978	9.8	4.7
1979	13.6	4.7
1980	9.1	4.2
1983	15.2	4.9
1984	11.0	4.5
1985	12.8	3.2
1987	10.8	3.4
1990	9.6	2.7
1991	10.3	2.6
2001	10.1	2.3
2011	9.3	1.3
2012	9.0	1.5
2021	9.7	1.3
2022	8.9	1.2
2023	8.3	1.3

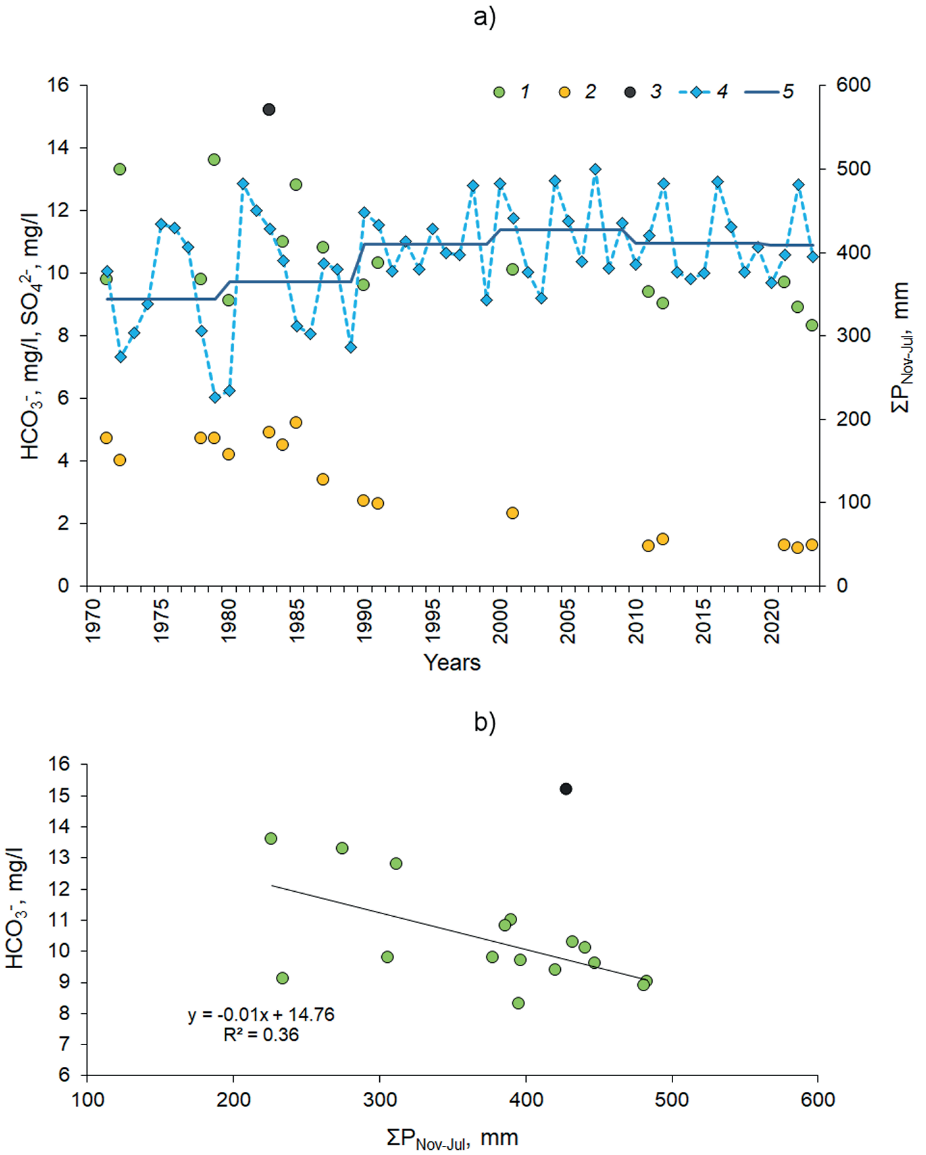

Fig. 2. (a) Concentrations of HCO_3^- (1) and SO_4^{2-} (2) in Lake Vendyurskoe water in summer in different years; HCO_3^- in the summer of 1983 (3); $\Sigma P_{Nov-Jul}$ – total precipitation from November of the previous year to July of the current year (4); $\Sigma P_{Nov-Jul}$ averaged per decade (5). (b) Relationship between HCO_3^- and $\Sigma P_{Nov-Jul}$

Thus, according to the classification of Alekin (1970), water in Lake Vendyurskoe belongs to the calcium group of the hydrocarbonate class.

In 2021–2023, pH fluctuated slightly within a year: the minimum in winter was 6.20–6.40, the maximum in summer was 6.60–7.03 (surface layer), and the annual average was 6.64. The pH gradient in the water column was also small: pH in the bottom water layers was lower than in the surface layers by only 0.3–0.7 units. In 1971–1992, pH varied from 6.0 to 7.4 (6.76 on average). Thus, no significant decrease in pH was observed between the two study periods ($p > 0.001(0.015)$).

Organic matter (OM). Large-scale studies of OM dynamics in the lake in 1971–1992 showed that the water color varied from 15 to 55 mg Pt-Co/L (40 mg Pt-Co/L on average), COD_{Mn} – from 4.6 to 8.9 mgO/L (7.4 mgO/L on average), and COD_{Cr} – from 9.3 to 20.5 mgO/L (16.8 mgO/L on average) (Table 4). Fluctuations of these indicators across the lake area and between the upper and bottom water layers were insignificant, with a slight rise in the area influenced by humus-rich water of the Rindozerka River (Freindling and Kharkevich 1982; Sabylina and Basov 2003).

A statistically significant difference in the content of COD_{Mn} (paired t-test; $p << 0.001$ ($1.383\ e^{-3}$)) and COD_{Cr} (paired t-test; $p << 0.001$ ($2.125\ e^{-8}$)) for the two study periods was confirmed. According to the test, the content of OM (COD_{Cr} and COD_{Mn}) is now 1.2 times higher. For BOD_5, no statistically significant difference between the two study periods was detected ($p > 0.001$ (0.6778)).

During both study periods, BOD_5 values in the lake were the highest in the autumn and the lowest in the winter (Table 4). As reported by Slastina et al. (2022), the bulk of the lake's phytoplankton biomass in the autumn is formed by diatoms, both in the central part of the lake (83–99%) and near the trout farm (96–99%). The contribution of other algal groups is insignificant. The concentration of labile OM in the summer, characterized by the ratio of BOD_5 to COD_{Cr}, has been the same in the past and in the current period (6-7%), but with a rise to 12% around trout cages.

The main driver of bioproductivity in Lake Vendyurskoe is trout farming, as there are no other significant sources of nutrients: there is no farmland in the catchment area, and the village on the shore has only a few houses and is populated only in the summer. Meanwhile, studies conducted on other lakes with operating trout farms in Karelia prove the facilities release nutrients into water (Mikhailenko and Sterligova 2021; Galakhina and Zobkov 2022).

Table 4. **Average content of OM proxies in the water of Lake Vendyurskoe in 1971–1992 (I) and 2021–2023 (II)**

Period	Season	Layer	Color mg Pt-Co/L	COD_{Mn}, mgO/L	COD_{Cr}, mgO/L	BOD_5, mgO_2/L	COD_{Mn}/COD_{Cr}, %
I	Winter	surface	46	8.0	18.2	1.2	44
		near-bottom	51	7.8	17.0	1.3	46
	Spring	surface	50	8.4	17.7	1.5	47
		near-bottom	51	7.8	17.1	1.2	46
	Summer	surface	33	7.4	16.9	1.2	44
		near-bottom	34	6.7	16.6	1.1	40
	Autumn	surface	28	6.6	15.6	1.3	42
		near-bottom	27	6.8	15.8	1.3	43
II	Winter	surface	35	6.8	16.8	0.8	39
		near-bottom	46	8.0	18.4	0.6	43
	Spring	surface	49	8.1	21.6	1.1	37
		near-bottom	50	7.5	20.5	0.8	36
	Summer	surface	27	8.0	24.8	1.5	37
		near-bottom	39	6.9	20.9	1.2	33
	Autumn	surface	30	8.2	22.1	1.6	37
		near-bottom	31	6.9	19.0	1.4	36

Gas conditions and the hydrogen index. In 1971–1992, the oxygen concentration in the surface layers of Lake Vendyurskoe varied within the range of 6.7–12.0 mg/L. Currently, it remains close to this level, at 6.9–11.8 mg/L.

Data for 2007–2023 from the autonomous measurement station indicate that the bottom layers of the central, deep-water basin developed hypoxia (oxygen concentration below 2 mg/L) every winter and summer, with increased stratification. During the open-water period, hypoxia duration varies across years from 1–2 weeks to 46 days (18 days on average). A direct correlation was found between the average air temperature of the three summer months and the duration of oxygen deficiency (2007–2023), with the determination coefficient R^2 = 0.51 (Fig. 3a). Hypoxia lasted the longest in the warm summer seasons of 2010, 2013, 2016, 2021, and 2022, when the average air temperature of the three summer months was 16-17 ºC (with a baseline of 14.5 ºC), stratification of the water column was more pronounced and persisted longer (Smirnov et al. 2024). In the cooler summers of 2007, 2012, 2015, 2017, 2019, and 2020, with an average air temperature of the three summer months close to or slightly above the baseline (14.4–15.6 ºC), the water column of the lake was periodically mixed, the bottom layers were aerated, and hypoxia time was shorter. The duration of hypoxia in winter was 47–167 days in different years (96 on average). The poorest oxygen conditions were observed in the winters of 2007/08, 2016/17, 2021/22, which were characterized by a cold pre-freeze period (November temperature −3–4 ºC, i.e. 0.5–1.5 ºC below the baseline) and early ice-on and a cool spring period (May temperature +º5+7 ºC, i.e. 1.5–3.5 ºC below the baseline) with late ice-off. An inverse correlation was found between the duration of hypoxia in winter and the air temperature in November of the previous year and May of the current year, with the determination coefficients R^2 = 0.39 (Fig. 3b) and R^2 = 0.41 (Fig. 3c). The series of observations at the autonomous station is too short (15 years) to identify a statistically significant trend in the duration of bottom hypoxia. However, judging by the revealed correlations, the ongoing regional warming (increase in air temperature in the summer months) will negatively affect the oxygen conditions in the lake in summer. At the same time, an increase in air temperature in autumn and spring will result in a later ice-on and an earlier ice-melt, so the period of bottom-layer hypoxia in winter will be reduced.

The spring overturn occurs at low water temperatures (4-10°C). The oxygen saturation of the water mass is fairly uniform – 89% on average. By the time the summer stratification is established, the lake has a good supply of oxygen. The oxygen content in the surface layers of water in summer does not exceed 90–95%, which indicates a low activity of phytoplanktic photosynthesis. The oxygen content in the bottom layer of the lake's deep-water parts does not exceed 10–20%, and the concentration of carbon dioxide increases to 4.9–5.3 mg/L versus 2.2–2.8 mg/L in the surface layer. The water pH values decrease from 6.94–7.01 in the surface layers to 6.69–6.89 in the bottom layers of water. The oxygen conditions around trout cages (the southern part of the lake) at the beginning of the summer of 2022 were the following: the oxygen content was 8.8 mg/L (84% saturation) in the surface layer and 5.4 mg/L (48% saturation) in the bottom layer. During the autumn overturn, the deep water layers are involved in the

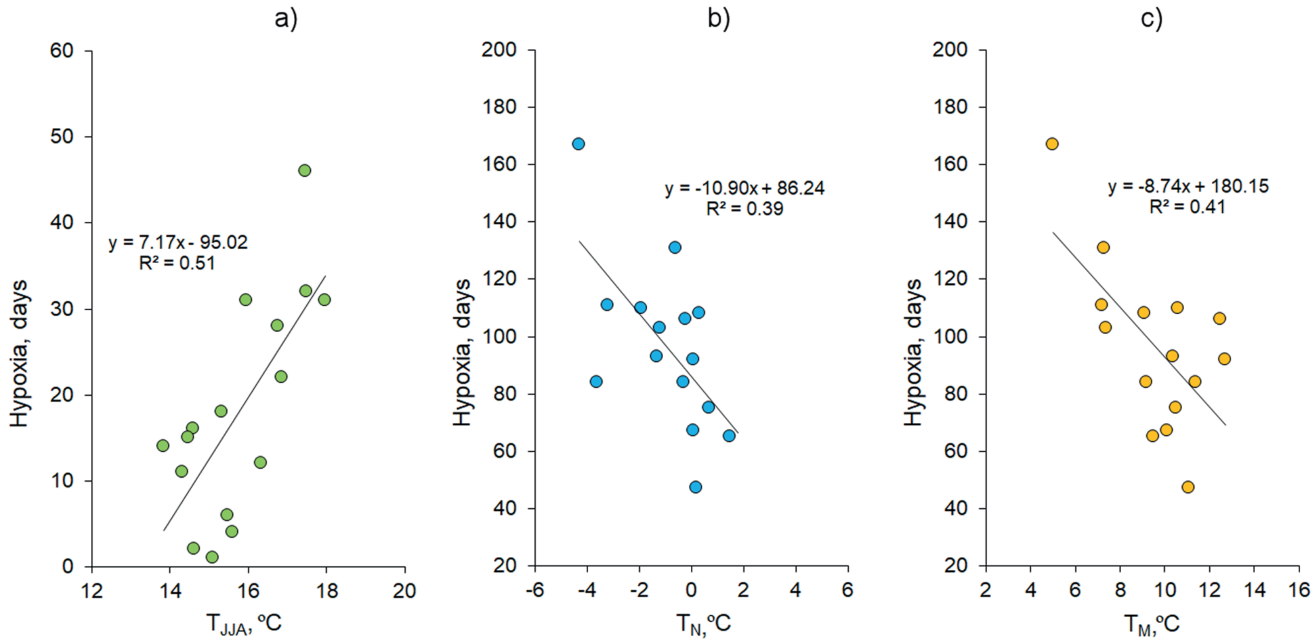

Fig. 3. Duration of hypoxia in Lake Vendyurskoe in 2007–2023 in summer (a) and winter (b, c) depending on the average air temperature in the summer months (a), in November of the previous year (b), and in May of the current year (c)

convection, and the entire water column is enriched with oxygen. Its average concentration in the lake is 10.5 mg/L.

The content of carbon dioxide in the surface and bottom layers of water in Lake Vendyurskoe varied in 2021–2023 from 2.1 to 2.9 and from 1.8 to 6.9 mg/L, respectively. The highest concentrations of CO_2 were noted in winter and the lowest – in spring and autumn. No statistically significant difference in the content of CO_2 in the two study periods (1971–1992 and 2021–2023) was detected (paired t-test; $p > 0.001$ (0.7603)). The mean CO_2 value in the past was 4.27, while at present it is 4.06 mg/L. Thus, the carbon dioxide content in the lake water has not changed significantly over the 50-year period.

Nutrients. To assess the current trophic status of the lake and to identify long-term trends, it is important to have information about the content and patterns of nutrients, first of all phosphorus. In Lake Vendyurskoe, measurements of inorganic (P_{min}) and total phosphorus (P_{tot}) began in 1971. The P_{min} concentration in 1971–1991 and 2001 varied from 3 to 8 μg/L, with an annual average of 3 μg/L. Season-wise, their concentrations were the highest in winter. In summer, the concentration of P_{min} did not exceed 3 μg/L, with the highest concentrations in October and November – 5–8 μg/L. The P_{tot} content varied within 13–25 μg/L (18 μg/L on average). The seasonal variation of P_{tot} concentrations was similar to that of P_{min} (Freindling and Kharkevich 1982; Sabylina and Basov 2003). The influx of inorganic and total phosphorus into Lake Vendyurskoe from the catchment area exhibited a minor change over the study period. At the same time, the direct input increased due to trout farming.

The wintertime concentration of P_{min} in the near-bottom water layers averaged 7–8 μg/L in the earlier years, while in 2021-2023 it increased to 11 μg/L in the central, deep-water part of the lake and to 17 μg/L near the trout cages (Tables 5, 6).

At the current stage, vertical differentiation of P_{min} has become clearly expressed in the deep-water area (st. 4–9) during the summer stratification. The difference between its concentration in the surface and near-bottom layers of water is up to 9 μg/L. In summer, the consumption of P_{min} by phytoplankton in the surface layers leads to below-detection levels throughout the lake.

The concentration of phosphates during the summer stratification averages 8 μg/L in the hypolimnion of the deep-water region of the lake (at 5 and 10 m depths) and near trout cages (5 m). This is due to the fact that the environmental conditions (pH, Eh) now forming in the hypolimnion induce a mobilization of $P\text{-}PO_4$ from bottom sediments into the water. Let us consider this process through the case study of a station located in the pelagic area of the lake and near the trout farm (Table 7). The water in the lake is enriched with humic substances (water color 40–56 mg Pt-Co/L, COD_{Mn} – 7–8 mgO/L) and total iron (summer concentration 0.34–0.45 mg/L), and is very soft (average water hardness is 0.41 mg-mol/L). Due to this, $P\text{-}PO_4$ is mobilized from bottom sediments into the water. Sorption of $P\text{-}PO_4$ on humates occurs by their binding with iron. Oxygen depletion in the bottom layers of water (to 48–52%) triggers reduction processes (Table 7). The concentration of ammonium ions in the near-bottom layers is 2 times higher than in the surface layers. Ammonification processes prevail at the bottom. Ammonium concentration rises to 49–114 μg/L. As Fe^{3+} is reduced to Fe^{2+}, the sorbed $P\text{-}PO_4$ is released into the water. The concentration of phosphates in the bottom layers increases to 9–36 μg/L. The content of ferrous iron increases by 1.5 times. The processes of phosphorus mobilization under reducing conditions in oxygen-depleted near-bottom water have been described for a number of lakes (Nürnberg et al. 2013; Joung et al. 2017).

Thus, during the summer stratification, phosphorus in the deep-water area of the lake and near the trout cages is mobilized from sediments, creating additional (endogenous) phosphorus load. This could stimulate further growth of phytoplankton in the lake, regardless of the amount of phosphorus coming from the catchment area, and contribute to the transition of the lake to a mesotrophic state. In autumn, due to active mixing and a decrease in phosphate consumption by algae, the phosphate concentration is equalized across the water area and depth (see Tables 5, 6). In 2021–2023, P_{tot} concentration in the lake varied from 11 to 68 μg/L. Its average annual concentration was 23 μg/L. Average annual P_{min} was 16% of the total, and its share in winter was 50–90%.

Total phosphorus content showed an upward trend over the 50-year period in both the surface ($p = 2.665\ e^{-4}$, $R = 0.65$) and near-bottom ($p = 1.367e^{-5}$, $R = 0.73$) layers (Spearman test; $p << 0.05$; number of samples $(n) = 28$). The increase in P_{min} content in the near-bottom layer has been

Table 5. Average content of nutrients in the water of Lake Vendyurskoe (excluding the station near the trout farm) in 2021–2023

Season	Layer	N, mg/L				P, µg/L		Fe_{tot}, mg/L	Si, mg/L
		NH_4^+	NO_3^-	N_{org}	TN	P_{min}	P_{tot}		
Winter	surface	0.05	0.05	0.28	0.38	5	13	0.18	0.8
	near-bottom	0.05	0.11	0.23	0.39	11	16	0.37	1.5
Spring	surface	0.06	0.04	0.22	0.32	3	19	0.42	1.6
	near-bottom	0.10	0.04	0.27	0.41	4	19	0.47	1.6
Summer	surface	0.06	<0.01	0.51	0.58	1	28	0.34	1.8
	near-bottom	0.10	<0.01	0.46	0.57	4	30	0.49	1.9
Autumn	surface	0.06	<0.01	0.32	0.39	4	25	0.25	0.1
	near-bottom	0.06	<0.01	0.26	0.32	4	26	0.30	0.1

Table 6. Nutrients around trout cages (St. 17) in Lake Vendyurskoe in 2021–2023

Season	Layer	N, mg/L				P, µg/L		Fe_{tot}, mg/L	Si, mg/L
		NH_4^+	NO_3^-	N_{org}	TN	P_{min}	P_{tot}		
Winter	surface	0.04	0.06	0.28	0.38	7	17	0.18	0.8
	near-bottom	0.02	0.10	0.30	0.42	17	28	0.35	1.3
Spring	surface	0.11	0.03	0.27	0.41	4	22	0.42	1.6
	near-bottom	0.09	0.04	0.27	0.39	3	24	0.43	1.6
Summer	surface	0.09	<0.01	0.35	0.44	1	25	0.34	1.8
	near-bottom	0.03	<0.01	0.36	0.39	8	47	0.52	1.7
Autumn	surface	0.07	<0.01	0.37	0.44		31	0.24	0.1
	near-bottom	0.09	0.01	0.28	0.37	4	27	0.26	0.1

Table 7. The content of some components of the chemical composition of water in Lake Vendyurskoe at the early summer (June 22, 2022)

Station	Depth, m	pH	Eh, mV	(O_2,mg/l)/(%)	P_{min}, µg/L	NH_4–N, µg/L	Fe, mg/L	
							Fe^{2+}	Fe^{3+}
St. 4-9	0.5	7.01	220	8.9/88	1	54	0.028	0.35
	11.0	6.45	215	5.6/52	9	61	0.034	0.55
St. 17	0.5	7.10	235	8.8/84	2	49	0.032	0.34
	8.0	6.42	225	5.4/48	36	114	0.048	0.71

minor ($p < 0.05$, $R = 0.327$), and no statistically significant difference was found in the surface layer over a long-term period.

The second component affecting primary productivity is nitrogen. Nitrate nitrogen enters the lake with river runoff, atmospheric precipitation, and as a result of bacterial transformation of nitrogen compounds during the destruction and mineralization of autochthonous and allochthonous OM.

The concentration of NO_3–N in 1971–1992 and 2001 varied from < 0.01 to 0.17 mg/L, with an average annual value of 0.10 mg/L. Maximum concentrations of 0.05–0.17 mg/L were observed in winter, when nitrification processes prevail, and minimum – in the spring-summer period of phytoplankton development: < 0.01–0.09 mg/L in spring (0.05 mg/L on average) and < 0.01–0.05 mg/L in summer (0.02 mg/L on average).

The concentration of NO_3–N in 2021–2023 varied from < 0.01 to 0.19 mg/L. Its assimilation by phytoplankton now increased in the summer-autumn period, while previously it tended to rise in the spring-summer period. In winter, the NO_3–N concentration reached its highest values of the year – up to 0.19 mg/L, with an average of 0.11 mg/L, because during this time of the year, nitrification processes prevail throughout the water column. The exception is the bottom layers of water near trout cages, where in the winter of 2021 low concentrations of nitrates (0.02 mg/L), elevated concentrations of nitrites (< 0.01 mg/L), hypoxia (40%) and an increase in phosphate concentrations to 17 µg/L were observed.

In spring, nitrate ions begin to be actively assimilated by growing phytoplankton, and their concentration decreases to the lake's average value of 0.04 mg/L.

During the summer stratification, the NO_3–N content decreased to < 0.01. NH_4–N was constantly present in the water at 0.06–0.10 mg/L (see Tables 5, 6). This means that where the oxygen saturation in the water column is 90–102%, a decrease in NO_3–N concentration to zero does not indicate its total disappearance, but only a lag in the rate of nitrification from the rate of its assimilation by plankton.

Surveys in the relatively warm autumn of 2021 also recorded an absence of NO_3–N in the lake water, with the exception of the area around trout cages (see Tables 5, 6). The concentration of NH_4–N in the lake in 1971–1992 and 2001 varied from 0.01 to 0.13 mg/L (0.05 mg/L on average).

In winter, ammonium ions did not accumulate in the lake because of active ammonium nitrogen oxidation by nitrifying bacteria taking place in parallel with the ammonification process. The environmental conditions (O_2 content 9–11 mg/L, pH ≈ 7) promoted the oxidation of ammonium ions to nitrites. During the growing season, the level of ammonium ions in the lake was mainly controlled by the ratio of several processes: ammonification, assimilation, nitrification, and denitrification. In spring, the river and stream mouth areas and areas around trout cages were richer in NH_{4+} ions (up to 0.12 mg/L) than the central lake areas, where they were actively consumed by the growing spring phytoplankton.

During the summer, ammonification processes predominated in the lake. Ammonium nitrogen was formed as a result of the destruction and mineralization of autochthonous OM. Its maximum in summer was up to 0.10 mg/L.

The distribution of ammonium ions by depth in summer and winter was uneven. Their maximum was found near the bottom in the deep-water parts of the lake, where hypoxia was detected, and their diffusion from bottom sediments was underway.

The predominant form of nitrogen in Lake Vendyurskoe throughout the year is organic nitrogen (see Table 5). Its concentration in water in 2021–2023 fluctuated within 0.12–0.51 mg/L (0.29 mg/L on average). Organic nitrogen during the periods of spring and autumn overturn was 67 and 80%, in the winter and summer – 65 and 87% of the total nitrogen. During the phytoplankton bloom, the surface layers of water got enriched with organic nitrogen (up to 0.5 mg/L). The average annual concentration of N_{org} in the lake water was 0.42 mg/L.

The features of the intra-annual circulation of nitrogen compounds ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^- \rightarrow N_{org}$) in Lake Vendyurskoe are consistent with the patterns established for the water bodies of Northwest Russia. In particular, the reported turnover time for nitrogen compounds in the summer in lakes of Karelia is 1.8 days (Ryzhakov et al. 2010; Ryzhakov 2020).

Iron enters the lake with river runoff, mainly in the form of organo-mineral compounds, and with groundwater discharge. In 1971–1992 and 2001, the average concentration of total iron in water was 0.15–0.17 mg/L, rising to 0.36–0.38 mg/L during freshets. In the recent study period, total iron content in the lake water varied from 0.11–0.45 mg/L (0.34 mg/L on average). A slight increase in the concentration of iron in the lake water may be due to the different methods of Fe (III) analysis as well as to an increase in the nutrient load on the lake.

The main source of dissolved silicon for the lake is river runoff. The content of dissolved silicon in the lake water in 1971–1992 and 2001 ranged from 1.5 to 2.3 mg/L (an average of 2.0 mg/L) (Kharkevich and Kryukova 1981; Ryzhakov et al. 2010). In 2021–2023, the concentration of dissolved silicon varied within 0.1–1.9 mg/L, with its highest level found in the mouth of the Rindozerka River. Its average annual content in 2021–2023 was 1.2 mg/L, and the autumn average was 0.1 mg/L, which is 10 times lower than in the past. Field and experimental studies have demonstrated that silicon consumption by algae depends on the supply of phosphorus compounds in the water body (Dillon and Rigler 1974; Raspletina and Susareva 2002). In autumn, when silicon in Lake Vendyurskoe is actively consumed by diatoms and removed from the cycle, the river runoff cannot replenish the reserves. The decrease in silicon concentration in the lake water over the 50-year period has been due not to a decrease in exogenous input, but to the intensification of biological processes in the lake. The trophic status of the lake based on the phytoplankton development criterion has changed from oligotrophic in 1973–1984 to mesotrophic in 2007–2020 (Sabylina and Basov 2003; Ilmast et al. 2008; Slastina et al. 2022). Consequently, the decrease in silicon content in the lake water can be considered as one of the consequences of eutrophication.

CONCLUSIONS

The ecosystem of Lake Vendyurskoe, formed as a result of the interaction of multiple natural processes in the aquatic environment and in the catchment area (forest drainage in 1971–1986), is currently impacted by trout farming and changes in the regional climate of Karelia. The lake water exhibits low mineralization (15.6 mg/L on average). Noticeable changes over the 50-year period have occurred in the ionic composition of the water: in 2021–2023, the content of sulfate ions dropped by 4 times compared to 1971–1985, which may be due both to cessation of amelioration and a reduction in the concentration of sulfates in precipitation. Chloride ions have decreased by half. An inverse correlation was revealed between the concentration of bicarbonates in the lake water in summer and the amount of atmospheric precipitation in the preceding winter-spring period. In the past 50 years, the amount of precipitation in southern Karelia has increased (by 65-80 mm from November of the previous year to July of the current year), creating the preconditions for a reduction in the concentration of bicarbonates in the lake water in the summer.

The lake water contains significant amounts of organic matter. The water color is 40 mg Pt-Co/L. The COD_{Mn} value is high (7.5 mgO/L on average).

The seasonal dynamics of nutrients in the lake have changed significantly, which is an indicator of an increased anthropogenic impact on the lake. A tendency towards an increase in the total phosphorus content in the lake's water over the 50 years (both in the surface and bottom layers) was revealed. During the summer stratification in the deep-water parts of the lake and near trout cages, inorganic phosphorus is mobilized from bottom sediments into the water under hypoxia conditions, and an endogenous phosphorus load builds up. This can stimulate an increase in biological productivity regardless of the amount of mineral phosphorus arriving from the catchment area.

The effect of air temperature on the duration of hypoxia at the bottom was revealed. The longest periods of hypoxia typically occurred in hot summer months (up to 30–46 days) and long winters (110–167 days) with early ice-on and late ice-off. The correlation between the duration of hypoxia in summer and air temperature in summer months suggests that the ongoing warming of the regional climate will deteriorate the oxygen conditions in the lake in summer. Longer hypoxia will be a factor for increased mobilization of mineral phosphorus and elevation of the phosphorus load. A rise in air temperature in autumn and spring, on the contrary, will help improve the oxygen conditions, as the period of hypoxia in winter will be reduced due to later ice-on and earlier ice-off.

The observed climatic variability and constant exposure to anthropogenic impact may affect the quality of the lake water in the near future. Having identified changes in the water's chemical composition, we managed to identify the zones of greatest risk in the lake (trout farm, deep-water areas). The findings can serve as reasoning for reducing trout farming volumes.

REFERENCES

Adrian R., O'Reilly C. M., Zagarese H., Baines S. B., Hessen D. O., Keller W., Livingstone D. M., Sommaruga R., Straile D., Van Donk E., Weyhenmeyer G. A., and Winder M. (2009). Lakes as sentinels of climate change. Limnol Oceanogr., 54(6), 2283-2297. DOI: 10.4319/lo.2009.54.6_part_2.2283.

Alekin O. A. (1970). Fundamentals of hydrochemistry. L.: Gidrometeoizdat. 442 p. (in Russian).

Analytical, kinetic and calculation methods in hydrochemical practice. (2017). Ed. by P. A. Lozovik, N. A. Efremenko. St. Petersburg: Nestor-History. 272 p. (in Russian).

Bulygina O. N., Veselov V. M., Razuvaev V. N., and Aleksandrova T. M. (2025). Description of the array of urgent data on the main meteorological parameters at stations in Russia. Certificate of state registration of the database No. 2014620549 (in Russian).

Bush T., Diao M., Allen R.J., Sinnige R., Muyzer G., and Huisman J. (2017). Oxic-anoxic regime shifts mediated by feedbacks between biogeochemical processes and microbial community dynamics. Nat Commun., 8, 789 DOI:10.1038/s41467-017-00912-x

Dillon P. I. and Rigler F. N. (1974). A test of a simple nutrients budget model predicting the phosphorus concentrations in lake water. J. Fish. Res. Board Can., 31(11), 1771-1778, DOI: 10.1139/f74-225

Forsius M., Vuorenmaa J., Mannio J., and Syri S. (2003) Recovery from acidification of Finnish lakes: regional patterns and relations to emission reduction policy. Science of The Total Environment, 310(1–3), 121-132, DOI: 10.1016/S0048-9697(02)00628-9.

Freindling V. A. and Kharkevich N. S. (1982). Complex studies of the conditions for the formation of the regime of a number of small reservoirs in southern Karelia. Petrozavodsk. 28-31. (in Russian).

Galakhina N. E. and Zobkov M. B. (2022). Hydrochemical studies of the trout farming area in Kondopoga Bay of Lake Onego in the winter of 2022. Transactions of the Karelian Research Centre RAS, 6, 76–87. DOI: 10.17076/lim1599, (in Russian with English summary).

Grennfelt P., Engleryd A., Forsius M., Hov Ø., Rodhe H., and Cowling E. (2020). Acid rain and air pollution: 50 years of progress in environmental science and policy. Ambio, 49, 849–864. DOI:10.1007/s13280-019-01244-4

Gusakov B. L. (1987). Critical concentration of phosphorus in a lake tributary and its relationship with the trophic level of a reservoir. Coll. scientific. works. USSR Academy of Sciences, Institute of Limnology. Elements of the phosphorus cycle in reservoirs. Leningrad: Nauka, 1987. 7-17. (in Russian).

Hobbie J. E., Peterson B. J., Bettez N., Deegan L., O'Brien W. J., Kling G. W., Kipphut G. W., Bowden W. B., and Hershey A. E. (1999). Impact of global change on the biogeochemistry and ecology of an Arctic freshwater system. Polar Research. 18(2): 207–214. https://doi.org/10.3402/polar.v18i2.6576

Ilmast N. V., Kitaev S. P., Kuchko Ia. A., and Pavlovsky S.A. (2008). Hydroecology of lakes of different types in southern Karelia. Petrozavodsk, KarRC RAS, 2008. 92 p. (in Russian).

Jansen J., Simpson G. L., Weyhenmeyer G. A., Härkönen L. H., Paterson A. M., del Giorgio P. A., and Prairie Y. T. (2024). Climate-driven deoxygenation of northern lakes. Nat. Clim. Chang., 14, 832–838 DOI:10.1038/s41558-024-02058-3

Joung D., Leduc M., Ramcharitar B., Xu Y., Isles P. D. F., Stockwell J. D., Druschel G. K., Manley T., and Schroth A. W. (2017) Winter weather and lake-watershed physical configuration drive phosphorus, iron, and magnese dynamics in water and sediment of ice-covered lakes. Limnol. Oceanogr., 62(4), 1620-1635. DOI:10.1002/lno.10521

Karpechko Yu.V. (2004). Hydrological assessment of anthropogenic impact on watersheds in the taiga zone of the European North of Russia. Abstract of a diss. Doctor of Sciences in Geography. Petrozavodsk. 49 p. (in Russian).

Kharkevich N. S. and Kryukova P. V. (1981). Seasonal dynamics of mineralization and ionic composition of water in lakes of the Vendyurskoe-Vokhtozero group. In: Study and use of water resources. Petrozavodsk: Karelian branch of the USSR Academy of Sciences, 1981. 25-29. (in Russian).

Kharkevich N.S., Mitina I.F., and Kryukova P.V. (1982). On the hydrochemical regime of melioration canals in the catchment area of Lake Rindozero. In.: Studies of lake-river systems of Karelia. Operational information materials. Karelian branch of the USSR Academy of Sciences. p. 33-36. (in Russian).

Lakes of Karelia. Handbook. (2013). Ed. by N.N. Filatov, V.I. Kukharev. – Petrozavodsk: Karelian Research Center of the Russian Academy of Sciences. 464 p. (in Russian).

Lozovik P. (1994). Methods of water analysis in the hydrochemical laboratory of Northern Water Problems Institute, Petrozavodsk, Russian Karelia. Mimeogr., November 1994, 6 pp. (in Russian).

Lozovik P.A. (2006). Hydrogeochemical criteria for the state of surface waters in the humid zone and their resistance to anthropogenic impact. Abstract of a diss. Doctor of Sciences in Chemistry. Petrozavodsk: Karelian Research Center of the Russian Academy of Sciences, 2006. 56 p. (in Russian).

Lozovik P.A. and Potapova I.Yu. (2006) Input of chemical substances with atmospheric precipitation onto the territory of Karelia. Water Resources, 33(1), 104-111. DOI: 10.1134/S009780780601012X

Lozovik P.A., Efremenko N.A., and Basov S.V. (2006) Development of methods for chemical analysis of natural and polluted waters. In: Water resources of the European North of Russia: results and prospects of research. Proc. of the jubilee conference devoted to the 15th anniversary of NWPI. 92-110. (in Russian).

Maberly S.C., O'Donnell R.A., Woolway R.I., Cutler M. E. J., Gong M., Jones I. D., Merchant Ch. J., Miller C. A., Politi E., Scott E. M., Thackeray S. J., and Tyler A. N. (2020). Global lake thermal regions shift under climate change. Nat. Commun., 11, 1232, DOI:10.1038/s41467-020-15108-z

Martynova N.N. (1982). Chemical composition of atmospheric precipitation in the territory of the Syamozero basin of Karelia. In: Comprehensive study of water resources of Karelia. Petrozavodsk: Karelian branch of the USSR Academy of Sciences p. 33-35. (in Russian).

Mazoyer F. and Houle D. (2025) Long-term temporal response of eastern canadian lakes chemistry along a large spatial gradient of atmospheric sulfate deposition. Environmental Pollution, 366, 125498, DOI: 10.1016/j.envpol.2024.125498.

Mikhailenko V.G. and Sterligova O.P. (2021). Some ecological aspects of cage farming of rainbow trout. Proceedings of the Karelian Research Center of the Russian Academy of Sciences. Series: Ecological Research, 12, 82-90. DOI: 10.17076/eco1509 (in Russian).

Nazarova L.E. (2015). Precipitation over the territory of Karelia. Transactions of the Karelian Research Centre RAS, 9, 114-120. (in Russian with English summary).

Nazarova L.E., Isakova K.V., Kalinkina N.M., and Balaganskii A.F. (2022). The Climate Warming Influence on the Shuya River Winter Runoff and the Consequences for The Zoobenthos of the Onego Lake. Bulletin of the Russian Geographical Society, 154(1), 28-36. (in Russian with English summary).

Nürnberg G. K., Lazerte B. D., Loh P. S., and Molot L. A. (2013). Quantification of internal phosphorus load in large, partially polymictic and mesotrophic Lake Simcoe, Ontario. J. Great Lakes Res., 39, 271–279. DOI:10.1016/j.jglr.2013.03.017

O'Reilly C.M., Sharma S., Gray D.K., Hampton S. E., Read J. S., Rowley R. J., Schneider Ph., Lenters J. D., McIntyre P. B., Kraemer B. M., Weyhenmeyer G. A., Straile D., Dong B., Adrian R., Allan M. G., Anneville O., Arvola L., Austin J., Bailey J. L., Baron J. S., Brookes J. D., de Eyto E., Dokulil M. T., Hamilton D. P., Havens K., Hetherington A. L., Higgins S. N., Hook S., Izmest'eva L. R., Joehnk K. D., Kangur K., Kasprzak P., Kumagai M., Kuusisto E., Leshkevich G., Livingstone D. M., MacIntyre S., May L., Melack J. M., Mueller-Navarra D. C., Naumenko M., Noges P., Noges T., North R. P., Plisnier P.-D., Rigosi A., Rimmer A., Rogora M., Rudstam L. G., Rusak J. A., Salmaso N., Samal N. R., Schindler D. E., Schladow S. G., Schmid M., Schmidt S. R., Silow E., Soylu M. E., Teubner K., Verburg P., Voutilainen A., Watkinson A., Williamson C. E., and Zhang G. (2015). Rapid and highly variable warming of lake surface waters around the globe. Geophysical Research Letters, 42(24), 10,773-10,781 DOI:10.1002/2015GL066235.

Quinlan R., Filazzola A., Mahdiyan O., Shuvo A., Blagrave K., Ewins C., Moslenko L., Gray D. K., O'Reilly C. M., and Sharma S. (2021). Relationships of total phosphorus and chlorophyll in lakes worldwide. Limnol. Oceanogr. 66, 392–404, DOI:10.1002/lno.11611

Raspletina G.F. and Susareva O.M. (2002). Biogenic elements. In: Lake Ladoga – past, present, future. St. Petersburg: Nauka. p. 77-86. (in Russian).

Ryzhakov A.V., Kukkonen N.A., and Lozovik P.A. (2010). Determination of the rate of ammonification and nitrification in natural water by kinetic method. Water Resources, 37(1), 70-74. DOI: 10.1134/S0097807810010069

Ryzhakov A.V. (2020). Temperature dependence and activation parameters of ammonification and nitrification reactions in the water of Lake Onega. Ecological chemistry, 29(2), 65-70. (in Russian).

Sabylina A.V. and Basov M.I. (2003). Abiotic environmental factors, primary production and destruction of organic matter in Karelian water bodies. In: Hydroecological problems of Karelia and use of water resources. Petrozavodsk: Karelian Research Center of the Russian Academy of Sciences, p.72-91. (in Russian).

Sabylina A.V., Lozovik P.A., and Zobkov M.B. (2010). Water chemistry in Onega Lake and its tributaries. Water Resources, 37(6), 842-853, DOI: 10.1134/S0097807810060102.

Saros Ja.E., Arp Ch.D., Bouchard F., Comte J., Couture R.-M., Dean J. F., Lafrenière M., MacIntyre S., McGowan S., Rautio M., Prater C., Tank S. E., Walvoord M., Wickland K. P., Antoniades D., Ayala-Borda P., Canario J., Drake T. W., Folhas D., Hazuková V., Kivilä H., Klanten Y., Lamoureux S., Laurion I., Pilla R. M., Vonk J. E., Zolkos S., and Vincent W. F. (2023) Sentinel responses of Arctic freshwater system to climate: linkages, evidence, and a roadmap for future research. Arctic Science. 9(2), 356-392. DOI: 10.1139/as-2022-0021

Sharma S., Blagrave K., Magnuson J.J., O'Reilly C. M., Oliver S., Batt R. D., Magee M. R., Straile D., Weyhenmeyer G. A., Winslow L., and Woolway R. I. (2019). Widespread loss of lake ice around the Northern Hemisphere in a warming world. Nature Climate Change, 9 (3), 227-231, DOI: 10.1038/s41558-018-0393-5

Slastina Yu. L., Zdorovennova G. E., and Smirnova V. S. (2022). Structural and functional characteristics of phytoplankton of Lake Vendyurskoe affected by trout farm. Vestnik of Astrakhan State Technical University. Series: Fishing Industry, 1:22-31, DOI:10.24143/2073-5529-2022-1-22-31. (In Russian)

Smirnov S.I., Zdorovennov R.E., Efremova T.V., Palshin N. I., Smirnovsky A. A., Bogdanov S. R., Terzhevik A. Yu., and Zdorovennova G. E. (2024) Parameters of Water Column Stability in a Small Polymictic Lake in Years of Different Weather Conditions. Water Resources, 51, 299–313, DOI:10.1134/S0097807824700817.

Wik M., Varner R., Anthony K., MacIntyre S., and Bastviken D. (2016). Climate-sensitive northern lakes and ponds are critical components of methane release. Nature Geosci , 9, 99-105, DOI:10.1038/ngeo2578

Woolway R.I. and Merchant C.J. (2019). Worldwide alteration of lake mixing regimes in response to climate change. Nat. Geosci., 12, 271–276 DOI:10.1038/s41561-019-0322-x

Woolway R.I., Zhang Y., Jennings E., Zohary T., Jane S. F., Jansen J., Weyhenmeyer G. A., Long D., Fleischmann A., Feng L., Qin B., Shi K., Shi H., Wang W., Tong Y., Zhang G., Zscheischler J., Ren Z., and Jeppesen E. (2025). Extreme and compound events in lakes. Nat Rev Earth Environ 6, 593–611. DOI:10.1038/s43017-025-00710-w

Wu Z., Li J., Sun Y., Peñuelas J., Huang J., Sardans J., Jiang Q., Finlay J. C., Britten G. L., Follows M. J., Gao W., Qin B., Ni J., Huo S., and Liu Y. (2022). Imbalance of global nutrient cycles exacerbated by the greater retention of phosphorus over nitrogen in lakes. Nat. Geosci., 15, 464–468 DOI:10.1038/s41561-022-00958-7

Zhu L., Ju J., Qiao B., Liu C., Wang J., Yang R., Ma Q., Guo L., and Pang S. (2025). Physical and biogeochemical responses of Tibetan Plateau lakes to climate change. Nat Rev Earth Environ., 6, 284–298, DOI:10.1038/s43017-025-00650-5