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Current state of bacterial community of Lake Ladoga

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Abstract: The data are presented on a quantitative assessment of the bacterioplankton community of Lake Ladoga and total bacterial numbers dynamic in the period from 2009 to 2019. The trophic state of the lake and water quality in different areas have been characterized by microbiological parameters. Maximum concentrations of microorganisms and highest water temperatures were commonly observed in the shallow coastal area (Volkhov Bay, up to 6.40 $\times 10^6$ cells ml^{-1}), and minimum – in the deepest part of the lake (ca. 0.45 $\times 10^6$ cells cm^{-3}). The bacterial abundances correlate with water temperatures both within each year of observations and over the whole study period. The trophic state of the lake expressed by the total bacterial numbers during summer seasons closely matches the state during the first decade of the 21st century. In the period of 2009-2019, the trophic state varied from oligo-mesotrophic in the hypolimnion of deep-water areas to mesotrophic-eutrophic in the shallow southern coastal area, which corresponds to the trophic state indicated by chlorophyll-a concentrations. Within the previous decade (2000-2008), the waters of Lake Ladoga were "clean" and "especially clean", while during the 2017-2019 period, water masses all over the lake can be identified as "especially clean". From 2017 to 2019 the coccoid forms of bacterial cells prevailed over rod-shaped cells comprising 57.6 ±5.1% (2017), 64.4 ±4.5% (2018), 61.1 ±4.6% (2019), which imply the high quality of the waters.

Key words: total bacterial abundance, trophic state, water temperature, saprophytic bacteria, water quality

Introduction

Lake Ladoga is the largest freshwater basin in Europe. The lake is an uncontested source of water supply for St. Petersburg and many other cities of the Leningrad Region and the Republic of Karelia (North-West of Russia).

Because of the wide range of adaptive capabilities and high growth rates, microorganisms present one of the most informative components of ecosystems, able to respond to the slightest changes in environmental conditions. During the last 60 years of studies, several stages have been distinguished in the development of the bacterial community of the lake:

In the early 60s (the beginning of the microbiological studies), according to the development of bacterioplankton, it was an oligotrophic water body (0.06-0.30 $\times 10^6$ cells cm^{-3}) with a uniform spatial distribution of microorganisms (Rodina and Kuzmitskaya 1963, 1968). The concentration of total phosphorus in water was about 10 µg P dm^{-3} (Raspletina 1982). Studies in the late 70s (1976-1980) revealed a significant increase in the total number of bacterioplankton (up to 3 $\times 10^6$ cells cm^{-3}) compared to previous observations and heterogeneous spatial distribution of bacterioplankton. Values of dark CO_2 –fixation and bacterial O_2 uptake varied from levels below the detection limit up to 11µg C dm^{-3} day^{-1} and 0.7 mg O_2 dm^{-3} day^{-1}, respectively. The concentration of microorganisms increased three times compared to 1960-1961 in the shallow southern part of the lake and almost twice in the deep part of the lake (Aleksandrova and Kapustina 1982). According to microbiological parameters in the late 70s, the state of the lake fluctuated from oligotrophic to mesotrophic, sometimes approaching eutrophic in the southern coastal region. The change of the state accompanied the sharp increase of the total phosphorus concentration, which reached 27 µg P dm^{-3} in 1976 (Raspletina 1982). Eutrophication of Lake Ladoga led to a continuous increase in the number of bacterioplankton and the intensity of dark carbon dioxide assimilation (up to 21 µg C

dm^{-3} day^{-1}) until the early 90s of the last century (Kapustina 1996).

A decrease of the anthropogenic load in the early 1990s resulted in the reduction of phosphorus concentration to 19-22 μg P dm^{-3} (Niinioja et al. 1997; Drabkova 1999; Viljanen et al. 2008). Since 1992, interannual fluctuations in bacterial abundance started while, until the early 90s the number of microorganisms raised almost continuously, both in the epi- and hypolimnion. The decrease in the phosphorus load caused a pronounced decline of the dark CO_2 fixation values in the period of 1992-1999 compared to the 80s. The average summer values of dark CO_2 assimilation for the periods 1981-1991 and 1992-1999 are 1.92 ±0.6 and 0.41 ±0.11 μg C dm^{-3} day^{-1}, respectively, i.e., they differ by almost five times (Kapustina 2003).

During the first decade of the 21st, the concentration of total phosphorus in the lake decreased to 11-13 μg P dm^{-3} and was kept at the same level after 2010. The highest concentrations of phosphorus were mostly observed in the coastal zone, which is directly influenced by tributaries (Petrova and Ignatieva 2013). Despite the natural interannual fluctuations caused by different reasons, during this period, there was a stabilization of the number of microorganisms in Lake Ladoga compared to previous years, especially in the hypolimnion. Spatial and temporal variations of bacterioplankton were nearly the same as in the 1990s and were mainly determined by the hydrophysical regime and the development of phytoplankton in Lake Ladoga (Kapustina 2013). The average values of microbiological parameters in the lake over this period do not exceed the values typical to mesotrophic reservoirs (Sorokin 1973; Drabkova 1981; Kopylov and Kosolapov 2007). The trophic state of the lake, according to bacterial abundances, varied from oligo-mesotrophic in the hypolimnion of deep-water areas to mesotrophic in the shallow southern coastal area.

The present study aims to quantify the development of the Lake Ladoga bacterial community, trace the interannual bacterioplankton variations in the lake over the last 10 years, and determine the water quality based on microbiological criteria.

Study area

Lake Ladoga is located at the boundary between the Precambrian Baltic Shield and the Russian Plain (e.g., Kalesnik 1968). The surface area of the lake is 17,890 km^2, the shoreline length excluding the island's coast is 1570 km (Raspopov 2009; Naumenko 2013), and the drainage area – 258,000 km^2. The mean depth is 48.3 m, the maximum depth 230 m, and the volume of water 847.8 km^3 (Naumenko 2020). The deepest areas are found in the northern part of the basin, where the fractured crystalline bedrock and glaciogenic landforms generate a variable topography. Water depth towards the south gradually decreases. The mean water exchange time is approximately 11 years (Naumenko 2002). The largest tributaries are the River Svir in the East (flows out from Lake Onega), River Volkhov from the South (flows out from Lake Ilmen), and River Vuoksa in the West (which flows out from Lake Saima, Finland). The only outlet is the River Neva, which flows out from the southwestern part of the lake (Petrokrepost Bay).

Considerable depth gradients in large lakes imply heterogeneity of hydrophysical, hydrochemical, and, consequently, hydrobiological properties. In Lake Ladoga, the following limnological zones have been distinguished: coastal (depth below 15 m), slope (depth 15-52 m), deep (depth 52-89 m), and extremely deep (depth > 89 m) (Terzhevik et al. 1987) which considerably determine temporal and spatial variations of bacterioplankton over the lake.

Methods

Bacterioplankton in Lake Ladoga has been mostly developed during the summer periods (Kapustina 2013) and hence, the data obtained in the summer seasons of 2009-2019 (except 2014) are presented. We consider the data obtained in July and August with maximum water temperatures and the presence of temperature stratification as the most representative of constraining the development of the bacterial community.

Samples were taken from the stations, which have been previously accepted for ecological monitoring (Fig. 1). They are located in the deep pelagic area, in the shallow southeastern region, in the northern archipelago, and on areas with a pronounced anthropogenic impact. In shallow areas (<15 m water depth) samples were taken from the surface and near-bottom layers, and in deeper areas - up to five levels were sampled depending on the depth.

Water was collected into sterile plastic containers and preserved with 40% formaldehyde (2% final concentration). The total numbers of bacterial cells were counted under luminescent microscopes LUMAM P 8 and MIKMED 26 at magnification ×1000 on dark nucleopore filters

(pore diameter 0.20 μm) colored by fluorochrome acridine orange (N,N,N',N'- Tetramethylacridine-3.6-diamine) (Hobbie et al. 1977; Kuznetsov and Dubinina 1989). In 2017-2019, the ratio of different morphological types of bacterial cells was determined. The trophic state of various regions of the lake was assessed according to the classification of freshwater reservoirs based on the values of bacterial abundance (Kopylov and Kosolapov 2007).

The numbers of saprophytic bacteria were obtained on nutrient agar for the cultivation of microorganisms (GRM) plates (Kyznetsov and Dubinina 1989) in formalin-free samples onboard the research vessel in 2009 and 2017-2018.

To assess the water quality, a quantitative ratio of saprophytic bacteria to the total bacterial number was calculated (Romanenko 1979; Abakumov 1982; Dzjuban et al. 2007).

Interannual (2009-2019) variations of the total bacterial numbers were quantified by the Kruskal-Wallis test, the most pronounced exceptions over the years – by the Tukey's range test.

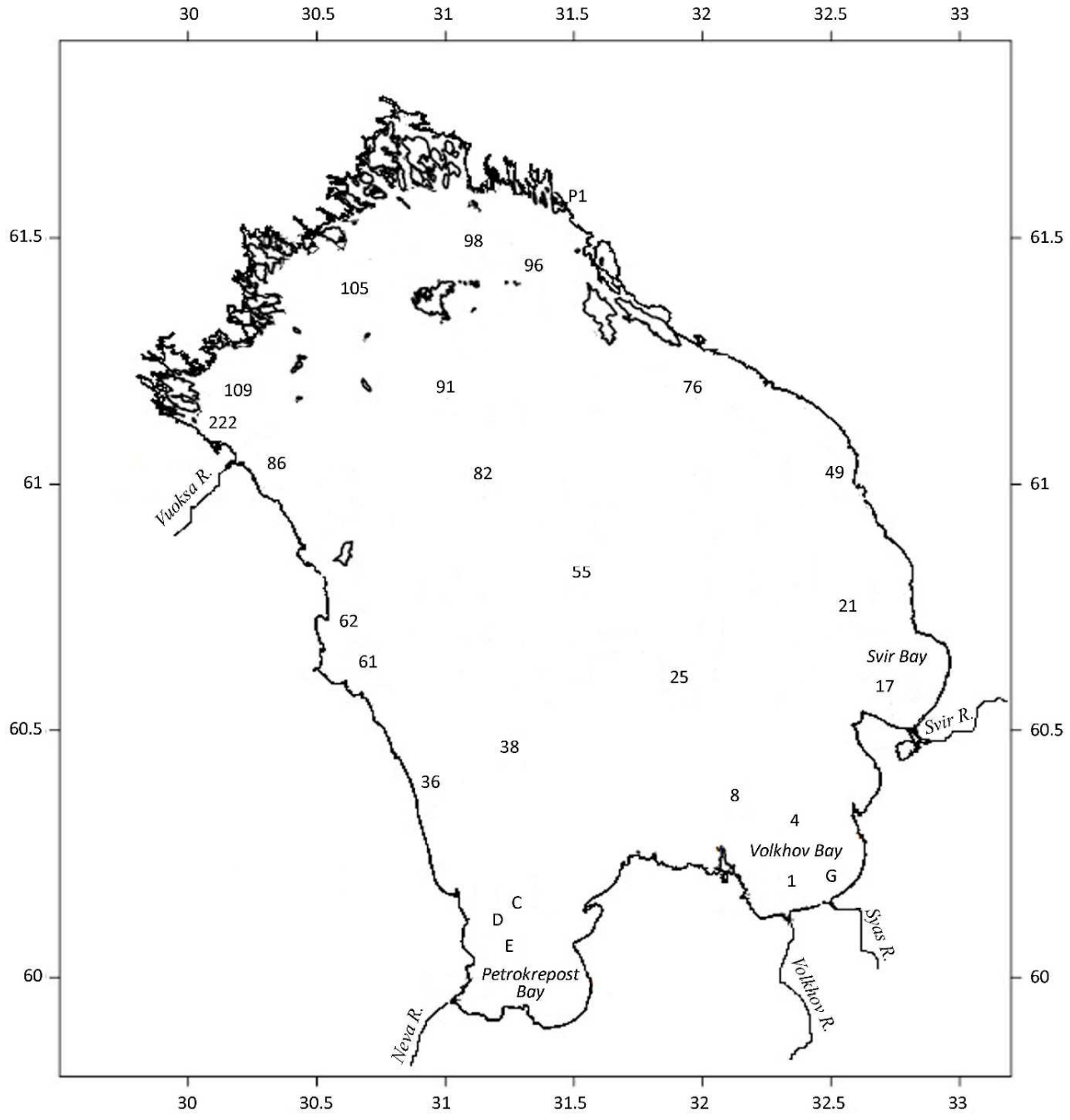


Fig. 1. Scheme of sampling stations

Results and discussion

Bacterial abundances for the period of investigations vary within the range of 0.45 x10^6 cells ml^{-1} in the hypolimnion of the deep-water part of the lake (near the bottom at depths exceeding 200 m) and 6.40 ×10^6 cells cm^{-3} in the shallow southern region (Volkhov Bay). Both minimum and maximum values of the bacterial abundances in hypolimnion were observed within the deep-water zone at depths exceeding 200 m. The minimum values were measured in 2019 (0.45 x10^6 cells ml^{-1}), and the maximum values – in 2018 (1.52 ×10^6 cells cm^{-3}). The minimum and maximum numbers of bacteria in epilimnion were found in 2011 (0.62 ×10^6 cells cm^{-3}, depth >100 m) and in 2013 (6.40 ×10^6 cells cm^{-3}, depth 10 m).

The total number of bacteria in the water is one of the indicators of water quality (Romanenko 1979; Abakumov 1982) and the trophic state of reservoirs (Kuznetsov 1952; Potaenko 1979; Romanenko 1979; Gak 1975; Lokk 1986; Tiphenbakh 1986; Dzyuban et al. 2007). The limits of fluctuations in bacterial numbers of water bodies with different trophic levels were previously evaluated (Sorokin 1973; Kopylov and Kosolapov 2007). These data are in good agreement with the results of studies on the relationship between the concentrations of bacterioplankton, chlorophyll-*a,* and the primary production in reservoirs of different regions (Bird and Kalff 1984; Currie 1990; Hakanson and Boulion 2003).

According to the bacterial abundancies over the past 10 years, Lake Ladoga generally kept the mesotrophic state, while the trophic level changed across different parts of the lake from oligo-mesotrophic in the hypolimnion of deep-water regions to typically mesotrophic in the shallow southern coastal area (Kopylov and Kosolapov 2007). The spatial-temporal distribution of microbiological parameters was stable over this period, being mainly determined by the hydrophysical regime and phytoplankton development. In summer seasons, maximum values of microbiological parameters were mostly observed in the shallow coastal area (especially in the zones of large tributaries influence) with the highest water temperatures, while the minimum values were commonly observed in the deepest part of the lake (Table 1). However, during some years characterized by high water temperatures and mass development of phytoplankton, the spatial distribution of microorganisms in the water area was more uniform (2015 and 2018), and sometimes the maximum values of bacterial abundance were observed in the extremely deep zone (2013 in Table 1).

During 2009-2019 large interannual fluctuations of the total bacterioplankton numbers were detected; the weighted average summer values vary up to 2.2 times in epilimnion and 2.7 times in hypolimnion (Fig. 2).

The interannual (2009–2019) variations of the total bacterial numbers checked by H-criterion (Kruskal-Wallis test) yield a significant difference ($\rho<0.05$, n=472). Tukey's range test revealed the most pronounced exceptions in 2009, 2011, 2013, and 2015. In 2009 and 2011, the minimum average annual values of the total number of bacterioplankton both in epi- and hypolimnion were observed during the study period, and in 2013, on the contrary, the maximum average annual concentrations of bacteria were found only in the epilimnion.

Table 1. Weighted averages of bacterial abundances (x10^6 cells ml^{-1}) in different regions of Lake Ladoga in summer 2009-2013 and 2015-2019

Year	Region			
	Coastal	Slope	Deep	Extremely deep
2009 (August)	1.45 ±0.49	1.22 ±0.47	1.13 ±0.73	0.94 ±0.40
2010 (August)	2.48 ±0.86	1.24 ±0.36	1.37 ±0.77	1.46 ±0.88
2011 (June)	2.05 ±0.50	1.03 ±0.33	0.87 ±0.14	0.64 ±0.08
2012 (August)	2.15 ±0.91	1.23 ±0.53	–	1.41 ±1.35
2013 (August, epilimnion)	3.60 ±1.20	3.00 ±0.80	3.10 ±1.00	4.10 ±0.81
2015 (August)	3.00 ±0.83	2.30 ±0.82	2.00 ±0.44	2.03 ±1.31
2016 (June)	2.57 ±0.62	2.20 ±0.43	1.70 ±0.54	1.60 ±0.95
2017 (August)	2.67 ±0.88	2.02 ±0.60	1.90 ±0.87	1.55 ±0.89
2018 (June)	3.18 ±1.36	2.21 ±0.70	2.27 ±1.29	1.77 ±0.64
2019 (August)	2.25 ±0.66	1.81 ±0.81	1.98 ±1.02	1.29 ±0.79

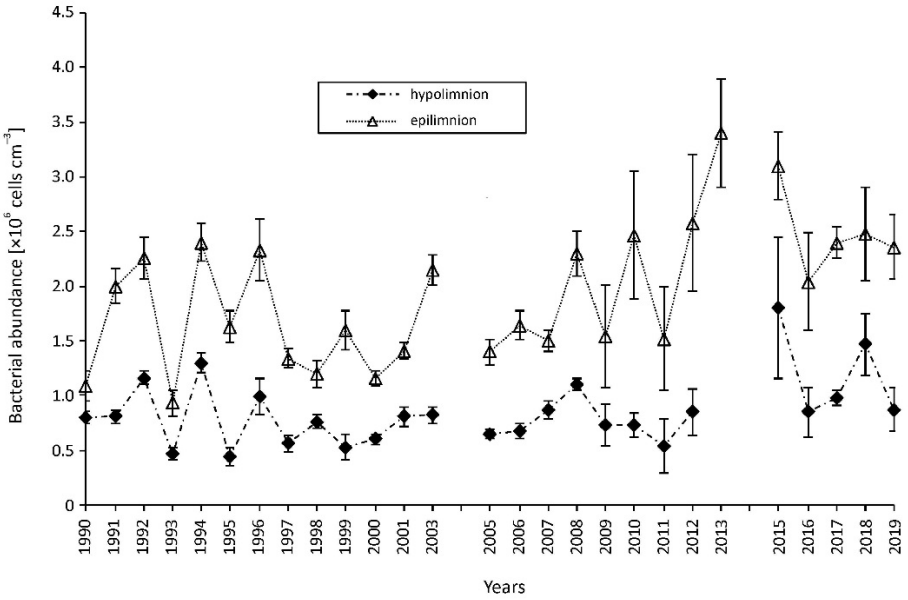


Fig. 2. Dynamic of the total bacterial numbers (average annual values, N) in the epi- and hypolimnion of Lake Ladoga during summer seasons

In 2015, high bacterial abundance was observed both in epi- and hypolimnion. The fluctuations were caused by several reasons, including water temperature, phytoplankton development, organic carbon concentration, lake water level, etc. However, in 2011, samples were taken at the beginning of the hydrological summer (early June) during the existence of the thermal bar (Tikhomirov 1982). In 2016, a pronounced decrease of the average summer total bacterial abundance in the epi- and hypolimnion compared to 2015 was indicated. Samples in 2016 were collected in June, while in 2015 – in August, the height of summer. Based on the results obtained, it is clear that the time of sampling is a very important factor affecting the interpretation of field observations.

The linear trend indicates a general increase in the bacterial number, despite the decrease in the average annual concentration of microorganisms for the lake in 2019, which is revealed by smoothing the data by averaging over the step of 3 years (Fig. 3).

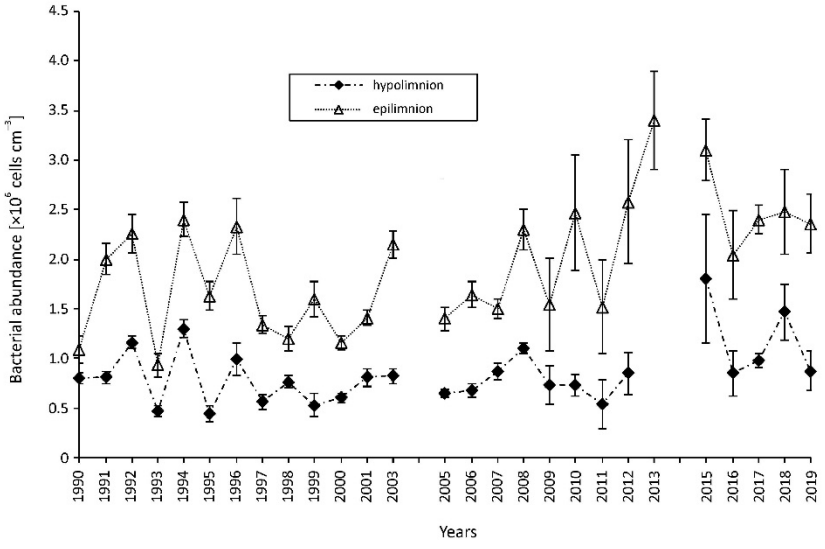


Fig. 3. Dynamic of the total bacterial numbers (weighted averages) in Lake Ladoga in the summer period

The water temperature usually affects the intensity of bacterioplankton development, especially in large cold-water bodies. The highest median concentrations of microorganisms in epilimnion during the study period corresponded to the maximum medians of water temperature (2010, 2013, 2015, and 2018, Table 2). The curve of the interannual dynamics of the hypolimnion microorganism concentration reflects that in the epilimnion; however, the correspondence of the median values of water temperatures and the number of bacteria over the years was not observed (Fig. 2, Table 2).

All summer data for each year separately as well as for the entire studied period indicate the positive correlation between the bacterial numbers and the water temperature from the surface to the bottom (epi- and hypolimnion) (Table 2). Hypolimnion depth was estimated by the vertical distribution of the monthly average water temperatures based on long-term observations (Naumenko 1994; Naumenko et al. 2015). With the exception of 2013 and 2019, total bacterial numbers in epilimnion correlate with water temperature (Table 2). During these years, samples were collected in August when the upper water level of the lake was warmed evenly (Table 2). Water temperatures are low in the hypolimnion, with small variations during stratification. The significant correlation between total bacterial numbers and temperature is found only in 2019.

The labile organic carbon concentration (LOC) is likely the main limiting factor for hypolimnion microorganisms adapted to low water temperatures. LOC is a fraction of total organic carbon (TOC) that is easily accessible to aquatic microorganisms and can be primarily used by bacteria in the process of biochemical oxidation. The source of this fraction in the pelagic part of the lake is mainly lysed phytoplankton cells, dying zooplankton, and extracellular phytoplankton secretions, which comprise from 10 to 80% of the primary production in different reservoirs (Fogg 1971; Boulion 1977; 1988; Sadchikov and Frenkel 1990). The share of labile carbon from the total carbon is usually higher in the surface layers of water and the shallow zones of the lake. Over the past decade, the concentration of labile organic matter in the lake varied in both epi- and hypolimnion, which could be among the reasons for significant fluctuations in the summer values of the bacterioplankton total number. Since 2013, the LOC variations decreased if compared to the period 2008-2012 (0.46-0.60 mg C dm^{-3} and 0.70-1.00 mg C dm^{-3}, respectively). During 2016-2019 the fluctuations became even smaller – 0.46-0.55 mg C dm^{-3} (Petrova 2019) along with a relative stabilization of the microorganism concentration, following significant rises during 2010, 2012-2013, and 2015 (Fig. 2).

Table 2. Medians of water temperatures (*T*, °C) and bacterial abundances (*N*, $\times 10^6$ cells cm^{-3}) in epi- and hypolimnion during summers 2009-2019

Year	*T*		*N*		Correlation		
	Epi	Hypo	Epi	Hypo	Epi	Hypo	Whole column
2009	15.7 ±2.24	4.67 ±0.79	1.30 ±0.52	0.70 ±0.21	**0.35**(34)	0.19(15)	**0.63**
2010	20.6 ±6.00	4.48 ±0.61	2.10 ±0.75	0.82 ±0.21	**0.48**(40)	0.41(20)	**0.77**
2011	9.0 ±5.28	3.79 ±0.60	1.03 ±0.67	0.65 ±0.15	**0.73**(33)	0.06(20)	**0.78**
2012	16.9 ±3.58	4.75 ±1.43	1.58 ±1.02	0.79 ±0.27	**0.56**(30)	0.07(12)	**0.62**
2013	19.9 ±1.57	–	3.75 ±1.24	–	0.21(32)	–	–
2015	16.6 ±3.50	4.40 ±0.56	3.00 ±0.81	1.30 ±0.47	**0.73**(33)	0.21(15)	**0.84**
2016	14.2 ±5.34	4.46 ±0.72	2.01 ±0.88	0.85 ±0.33	**0.71**(30)	0.12(14)	**0.82**
2017	16.2 ±2.78	4.17 ±0.71	2.40 ±0.62	1.15 ±0.44	**0.34**(36)	0.20(16)	**0.75**
2018	19.0 ±4.49	4.47 ±0.81	2.70 ±1.10	1.46 ±0.44	**0.39**(30)	0.27(14)	**0.61**
2019	15.5 ±1.87	4.53 ±1.06	2.44 ±0.59	0.93 ±0.28	0.03(30)	**0.51**(18)	**0.81**
Total							**0.71**(472)

Epi – in epilimnion, Hypo – in hypolimnion. In brackets the number of observations, significant (95%). Correlations are highlighted in bold

The spatial distribution of saprophytic bacteria adapted to relatively high concentrations of organic matter did not always coincide with that of the total number of bacterioplankton. The concentration of bacteria of this physiological group depends on the concentration of labile organic carbon and usually significantly decreases with depth because phytoplankton (as a source of LOC) in Lake Ladoga is concentrated within the upper 10-meter layer due to the low transparency of the water (Letanskaya and Protopopova 2012). The highest saprophytic bacterial numbers are commonly observed within the deep and extremely deep zones (Table 3). This implies the intensive phytoplankton development in the deep areas of the lake, characterized by the evolved water transparency compared to the shallow regions.

Bacterioplankton plays a major role in the mineralization of organic matter, being also an important link between detritus, dissolved organic matter, and higher trophic levels in the ecosystem of water bodies (Kuznetsov 1970; Pomeroy 1974; Cole et al. 1988; Currie 1990). Therefore, the values of microbiological parameters should be considered to assess water quality. The number of saprophytic bacteria related to the total bacterial number is commonly used to determine water quality. Depending on the value of this ratio, waters belong to one of the conditional groups: "extremely clean" (≤0.003), "clean" (0.003-0.30), "contaminated" (0.31-3.0), "especially dirty" (≥3.0). (Romanenko 1979; Abakumov 1982; Dzyuban et al. 2007). The estimated values of the ratio in different studied periods imply that the water masses in all the lake regions during summers belonged to the categories of "clean" and "extremely clean" (Table 4). During 1990-2000 and 2001-2010, waters of the zones with small and medium depths belong to "clean", and the deepest zones as "extremely clean" categories. During 2017-2018 water masses of the entire area were classified as "extremely clean" (Table 4).

Table 3. Weighted summer averages of bacterial numbers growing on GRM agar plates ($\times 10^3$ cells cm^{-3}) in different regions of Lake Ladoga

Region	2009	2010	2017*	2018
	end of August	early August	end of July / early August	July
Coastal	0.11 ±0.04	0.25 ±0.12	2.74 ±2.57	0.38 ±0.22
Slope	0.06 ±0.02	0.19 ±0.07	2.29 ±1.38	0.79 ±0.47
Deep	0.06 ±0.03	0.21 ±0.09	2.15 ±1.50	0.66 ±0.60
Extremely deep	0.13 ±0.06	0.27 ±0.11	1.26 ±1.15	0.78 ±0.32

*numbers of bacteria growing on GRM agar diluted 10 times. On this medium, more bacteria usually grow than on undiluted agar

Table 4. The ratio of the bacterial numbers growing on GRM agar plates to the bacterial abundances in different parts of Lake Ladoga during summers

Region	1990-2000	2001-2010	2017-2018
Coastal	0.005 ±0.002	0.004 ±0.002	0.0006 ±0.002
Slope	0.004 ±0.001	0.005 ±0.004	0.0008 ±0.003
Deep	0.004 ±0.001	0.003 ±0.002	0.0008 ±0.002
Extremely deep	0.003 ±0.001	0.003 ±0.002	0.0006 ±0.001

The water microflora is mainly represented by the rod-shaped and coccoid forms of bacteria. Azotobacter-like cells, filamentous forms, vibrions, and spirills occasionally occur in the southeastern coastal areas, in the zones influenced by the waters of the main tributaries of the lake (Volkhov and Svir Rivers). The ratio of different morphotypes of microorganisms can also serve as an indirect indicator of anthropogenic impact on the reservoir. The predominance of rod-shaped forms indicates a higher concentration and a lower degree of mineralization of organic matter in the water. When a reservoir is polluted with organic matter, the proportion of rod-shaped forms often increases (up to 80%), vibrions appear in significant numbers (10% or more), and the number of cocci decreases down to 10% or even less (Kozhova and Dutova 1989; Kireeva 2007).

Coccoid forms of microorganisms during 2017-2019 dominated at almost all stations. This reflects the relatively low content of total organic matter in Lake Ladoga and the very rapid mineralization of the easily oxidized organic matter of phytoplankton. The number of rods in the entire water area over the years changed from 26.4% at the outlet of Volkov Bay in 2018 to 52.5% in the slope zone near the western shore of the lake in 2017. The number of coccoid forms varied from 47.5 (2017, slope zone) to 71.0% (2019, Svir Bay). During 2017-2018, a relatively low amount of rod-shaped bacteria was observed in Volkhov Bay. Perhaps, at the periods of sampling in these years, the summer peak of phytoplankton in the southern coast region had already passed. In 2019 the number of rod-shaped bacterial cells in Volkhov Bay was not lower than at most other stations. Different ratios of bacterial cell morphotypes could reflect the variability of the state of the phytoplankton community, which is the main source of labile organic carbon for bacteria in large and deep reservoirs. The average amount of rods in different areas of the lake for 2017-2019

varied within a narrow range (32.8-44.4%). Variation of rod-shaped bacterial forms among years was rather low (42.4 ±5.10%, 35.6 ±4.50%, and 38.9 ±4.60% in 2017, 2018, and 2019, respectively). Slightly different annual ratios of various bacterial morphotypes were detected within the lake in summers during the previous decade – rod-shaped forms were 52.0-57.6%, coccoid – 42.1-47.8% (Kapustina 2013). As mentioned above, in 2012-2019, the average concentration of labile organic carbon in the lake during the open water period decreases compared to the previous research period (2000-2010) (Petrova, personal communication). This also could cause a decrease in rod-shaped forms in Lake Ladoga during the last decade. The spatial distribution of various morphotypes of microorganisms is often similar to that of saprophytic bacteria, which directly depends on the concentration of easily oxidized organic matter in water.

Conclusions

In the early 90s, there was a decrease in the anthropogenic load on Lake Ladoga, which continued until the end of the first decade of the 21st century and cause interannual fluctuations in the total number of bacterioplankton, both in epi- and hypolimnion, after the continuous increase in the concentration of microorganisms during 1980-1992. In the last decade, Lake Ladoga has experienced intensive interannual changes of the average summer values of the total number of bacterioplankton in the epilimnion with significant increases in 2010, 2012, and 2013, while the variations were less pronounced in the hypolimnion. In recent years (2016-2019), the concentration of bacterioplankton has stabilized at a higher level than in the previous decade. Positive relationships exist between water temperatures and the total number of bacteria, both for each year and the entire study period. Water temperature significantly influences both the level of quantitative development and the spatial distribution of bacterioplankton in the lake. The maximum concentrations of microorganisms, as well as the maximum water temperatures, were commonly observed in the shallow coastal area, and the minimum – in the deepest part of the lake. High water temperatures and intensive development of phytoplankton in the pelagic zone resulted, however, in a more uniform spatial distribution of microorganisms in the water area in 2015 and 2018, while during 2013 the maximum value of the total bacterial counts was observed in the deepest zone. The trophic state of the lake in terms of the total bacterioplankton numbers did not change in comparison with the first decade of the 21st and varied in 2009-2019, according to summer data, from oligo-mesotrophic in the hypolimnion of deep-water areas to typically mesotrophic in the shallow southern coastal area. In 1990-2010, the water masses of different zones of the lake in terms of the ratio of the number of saprophytic bacteria and the total number of microorganisms corresponded to the categories "clean" and "especially clean". In 2017-2019 water of all lake districts corresponded to the category of "especially clean", which indicated a consistently high quality of the water masses of Lake Ladoga. In 2017-2019, coccoid forms of bacterial cells prevailed over rod-shaped ones in the lake water – 57.6-64.4% and 35.6-57.6%, respectively, which indirectly also confirms the purity of lake water masses.

Acknowledgments

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