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Phytoplankton diversity in three lakes of South Ural, Russia

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Department of Chemistry, South Ural State University, 76 Lenin Prospect, 454080 Chelyabinsk, Russia. Tel./Fax. +7-351-2679517, ♥email: kostriukovaam@susu.ru, ♥♥email: krupnovatg@susu.ru, ♥♥♥email: mashkovaiv@susu.ru.

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Abstract. *Kostryukova AM, Krupnova TG, Mashkova IV, Gavrilkina SV, Nikita O. Egorov NO. 2018. Phytoplankton diversity in three lakes of South Ural, Russia. Biodiversitas 19: 1459-1467.* Preservation of water ecosystems in their natural state is of great significance. Phytoplankton is one of the biotic indicators of the lake trophic status and ecological state. This study deals with phytoplankton diversity of three lakes of South Ural, Russia. The studied lakes represented different trophic states: Lake Savelkul was oligo-mesotrophic, Lake Ilmenskoe was mesotrophic and Lake Argayash was eutrophic. The species composition of common phytoplankton was recorded in June-July months during 2015 and 2016. The Cyanophyta (blue-green algae) species were dominant in Lake Ilmenskoe(42-64%) and Lake Argayash(55-70%). The Bacillariophyta (diatom algae) species were dominant in the Lake Savelkul(40-66 %). The most common diversity indices namely the Shannon Index, Simpson Index and Margalef Index were determined and the data was also analysed using graphs. The graphs were constructed by the similarity calculating method on the basis of the Sorensen-Czekanowski coefficient. Diversity indices confirm the higher species richness of the microalgal community of Lake Ilmenskoe, classified as mesotrophic. It was shown that the lakes have sufficiently high biodiversity and high ecosystem resilience. Further, statistical analysis (CCA) revealed that orthophosphate-phosphorus, nitrite-nitrogen and pH were the most significant environmental factors influencing phytoplankton community of the lakes studied.

Keywords: Diversity indices, lake ecology, phytoplankton diversity, South Ural

INTRODUCTION

Water ecosystems are susceptible to numerous human activities (water supply, wastewater discharge, water transport, recreation, hydropower and many others) which have a negative impact on their ecological state (eutrophication). Eutrophication, which also occurs naturally, is the enrichment of surface waters with high concentration of nutrients, mostly nitrogen and phosphorus. It is one of the most widespread ecological problems of lakes and other open water sources. Under normal conditions, it takes thousands of years for the trophic state of water bodies to change. But human activity has rapidly increased eutrophication in water bodies.

Eutrophication is the process of change from oligotrophic or mesotrophic state to a higher trophic state (eutrophic). Eutrophication leads to increase in production and biomass of macrophytes and phytoplankton, oxygen depletion, reduced light penetration and extensive deterioration of water quality. Shallow lakes are especially vulnerable to eutrophication because of high level of phytoplankton biomass and significant nutrient input from sediments (Rao et al. 2018). Carlson's Trophic State Index (TSI) is one of the more commonly used trophic indices (Carlson 1977). The index can be calculated from any of several parameters, usually used ones are Secchi disk transparency, chlorophyll content and total phosphorus.

Phytoplankton dominate primary production in most freshwater ecosystems and they are often used as ecological indicators of freshwater lakes (Poot-Delgado and Okolodkov 2016; Jiang et al. 2014; Suda et al. 2016) and rivers (Vasiljević et al. 2017). They are relatively easy to detect, identify, and quantify; and they are sensitive to diverse environmental stressors. The differences in the dominant phytoplankton assemblage of lakes reflect their trophic levels (Barinova et al. 2006). So quantitative indicators of phytoplankton are widely used to assess the trophic state of water bodies (Wasmund et al. 2017; Wasmund 2017; Mangoni et al. 2017; Taş 2016; Liu 2014).

Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy was adopted in 2000 (Directive 2000). The directive's main objective is to ensure a good status of surface and groundwater. Phytoplankton is one of the five biological quality elements being recommended by the Directive to assess surface waters.

Since anthropogenic activities can lead to significant changes in the structure of phytoplankton community (Schuster et al. 2015), species richness is often used as the most convenient ecological indicator of water bodies. According to Barinova et al. (2006), information on the state of the first trophic level (algae) allows predicting the state of the entire biotic component of an aquatic ecosystem. Quite often, research also consists in identifying the most important environmental factors that have the greatest impact on the composition of a phytoplankton community (Jiang et al. 2014) by means of Canonical correspondence analysis.

There are more than 30 lakes with different trophic states located in the territory of the Ilmen State Reserve (South Ural, Russia). This paper deals with studies of the phytoplankton community of three lakes: Lake Savelkul (oligomesotrophic), Lake Ilmenskoe (mesotrophic state) and Lake Argayash (eutrophic state). The Ilmen Reserve is located in the central part of the Chelyabinsk Region near the city of Miass. Its area is 303.8 km². Lake Ilmenskoe is more studied than Lake Argayash and Lake Savelkul. There are several earlier reports on the phytoplankton of Lake Ilmenskoe, which explore its species composition, quantitative and eco-geographical characteristics (Krupnova et al. 2014, Krupnova et al. 2017, Kostryukova et al. 2016). There are also studies on the zooplankton communities, macrophytes and mollusks (Mashkova et al. 2015 a, b, Kostryukova et al. 2016). However, the phytoplankton diversity of Lake Argayash and Lake Savelkul is not studied.

MATERIALS AND METHODS

Study area

Three lakes have been studied, namely Lake Ilmenskoe, Lake Argayash and Lake Savelkul, in the South Urals, Russia. Sampling was carried out during the vegetation period in June-July of 2015 and 2016, in 5 stations distributed along the entire perimeter of Lake Ilmenskoe, 4 stations along the entire perimeter of Lake Argayash and 3 stations along the entire perimeter of Lake Savelkul (Figure 1, Table 2).

Lake Ilmenskoe

Lake Ilmenskoe is located on the south border of the Ilmen State Reserve and is between the Chashkovsky Mountains (south-western side), Mount Kosaya (eastern side) and Mount Ilmen . A motor road and railway runs along the northern shore of the lake, and also located buildings of Miass city. A recreational area is located on the western shore. A swamp is located in southern shore. The eastern shore of lake is located on the territory of the Ilmen State Reserve. Peat bogs surround Lake Ilmenskoe in the south and north-east. Water is accumulated from marshes in the southern and small rivers in the eastern and south-eastern part of the lak The bottom is mostly sandy or pebbly.e. Lake Ilmenskoe belongs to the flow-drain type of hydrological regime, it is characterized by low flowage and recharged mainly via groundwater seepage. The lake's flowage is periodic, which explains the fluctuation of the water level. Sufficient level of washing-out and leaching of the underlying rocks led to low mineralization of water. There is a predominance of hydrocarbonate ions (anionic composition), as well as ions of calcium, magnesium, alkali metals (cationic composition). Lake Ilmenskoe is poor in mineral compounds of iron, phosphorus, and nitrogen. Based on type of mineralization, Lake Ilmenskoe is a freshwater body of hydrocarbonate type HCO_3^- - Ca^{2+} - Mg^{2+}; the salt content is 79.3-164.7 mg/l (Andreeva 1973). By the trophic state, Lake Ilmenskoe is classified as mesotrophic (Mashkova et al. 2015 b).

Lake Argayash

Lake Argayash is entirely located on the territory of the Ilmen State Reserve, to the east of Lake Ilmenskoe. The bottom is mostly sandy, sometimes silty. The reservoir is located in an elongated depression of the relief. The coast is slightly rugged, and unlike Lake Ilmenskoe, the basin of Lake Argayash is shallow and level. Lake Argayash is located among the highlands formed by the spurs of Mount Kosaya. The banks are low, often swampy. Water is carried into the lake by a stream flowing into the lake from the west and a swamp in the southeast. A small river flows from Lake Argayash, passing through a swamp in the north. Only a small area in the center of the lake where the depths are maximal is free from macrophytic vegetation. By the trophic state, Lake Argayash is classified as eutrophic (Mashkova et al. 2015 b). It is natural eutrophication.

Lake Savelkul

Lake Savelkul is entirely located on the territory of the Ilmen State Reserve. This reservoir has a tectonic origin. The bottom is mostly silty. The banks are sand and rock, often flat. By the trophic state, Lake Savelkul is classified as oligomesotrophic. Lake is weakly flowing. The oxygen regime remains stable and favorable. Lake Savelkul, by the type of mineralization, is a freshwater body of hydrocarbonate type HCO_3^- - Ca^{2+} - Ca^{2+}; the salt content is 70.0-300.0 mg/l (Andreeva 1973). Table 1 summarises the main morphometric parameters of the three lakes studied.

Table 1. Main morphometric parameters of Lake Ilmenskoe, Lake Argayash, and Lake Savelkul, in the South Urals, Russia

Lake	Height above sea level, m	Surface area, km²	Depth, m	
			Maximum	Average
Lake Ilmenskoe	331.40	4.56	6.10	3.00
Lake Argayash	354.00	0.75	7.00	4.90
Lake Savelkul	314.90	0.51	8.00	5.00

Table 2. Coordinates of sites on lakes Ilmenskoe, Argayash and Savelkul, in the South Urals, Russia

Sites	Coordinates
Lake Ilmenskoe	
Site1	54°59'40.48" N, 60°9'44.35" E
Site 2	55°0'17.20" N, 60°9'56.03" E
Site 3	55°1'2.40" N, 60°8'53.64" E
Site 4	55°0'25.58" N, 60°8'6.05" E
Site 5	54°59'53.01" N, 60°8'29.97" E
Lake Argayash	
Site 6	54°59'22.93" N, 60°12'46.11" E
Site 7	54°59'4.33" N, 60°13'25.47" E
Site 8	54°59'18.41" N, 60°13'50.15" E
Site 9	54°59'57.64" N, 60°13'38.89" E
Lake Savelkul	
Site10	55°7'54.65" N, 60°18'40.33" E
Site 11	55°8'18.33" N, 60°18'17.00" E
Site 12	55°7'53.52" N, 60°18'21.34" E

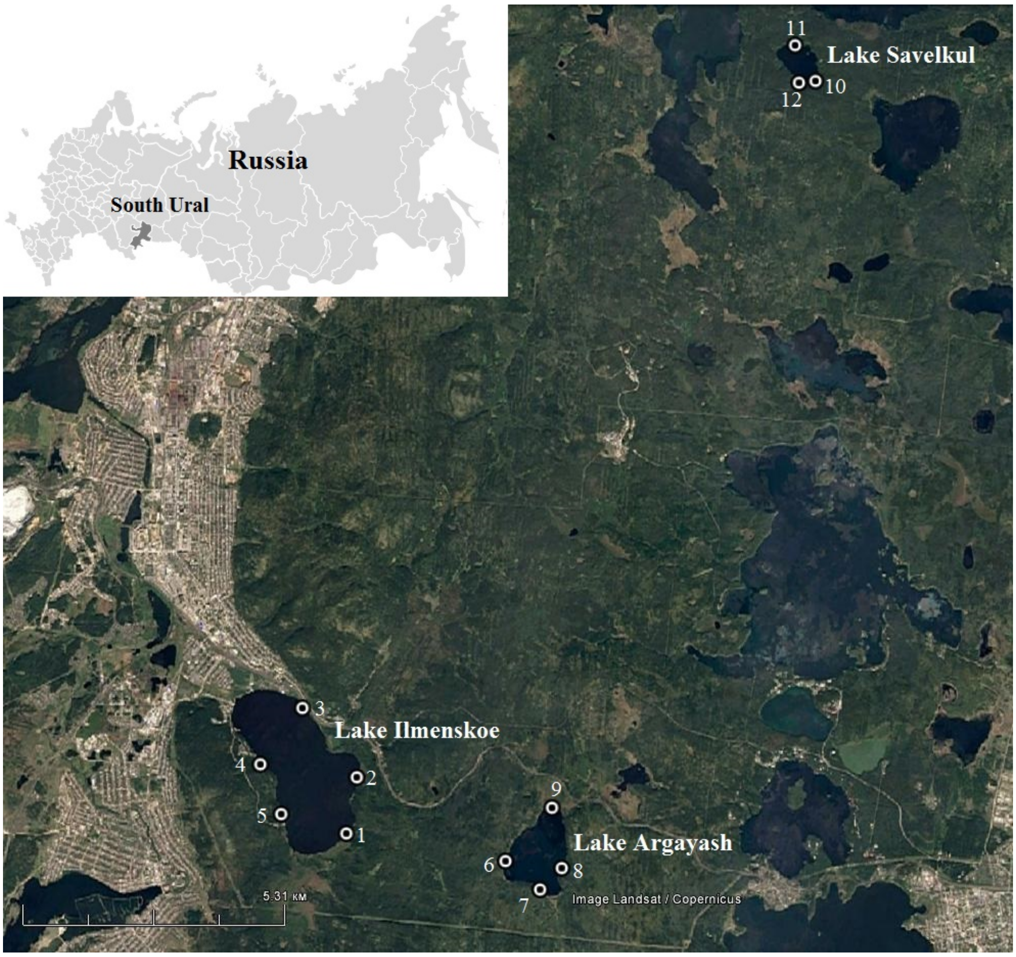

Figure 1. Map of lakes and location of the sampling stations, in the South Urals, Russia

Methodology

Identification of phytoplankton species

At each site, the samples were collected and then filtered through a plankton net (mesh size: 100 µm). The retained organisms were transferred into glass containers and the collected material was preserved in 5 % formalin. Non-diatom algae were analyzed using a magnification of 600× (Altami BIO 2T microscope, Altami Ltd, Russia, St. Petersburg.). Permanent diatom slides were prepared after oxidizing the organic material (by nitric acid and sulfuric acid) and a minimum of 300 valves were counted for each sample using an Altami BIO 2T microscope at 1000× under oil immersion. Species were identified using the handbooks by Sladecek (1973), Yarushina et al. (2004), Al-Kandari et al. (2009) and Guiry and Guiry (2018).

Water quality analysis

The following instream parameters including pH, dissolved oxygen (DO), and water temperature (WT) were measured *in situ* by a Portable Meter (Multitest IPL-513, Semico Ltd, Russia, Novosibirsk). Air temperature was determined with a mercury thermometer. Oxygen saturation (P, %) was calculated. At each site, water samples were also collected for further laboratory analysis including nitrate-nitrogen (NO_3^-), nitrite-nitrogen (NO_2^-), ammonium-nitrogen (NH_4^+), orthophosphate-phosphorus (PO_4^{3-}), common phosphorus (P_{com}), sulfate-sulfur (SO_4^{2-}), chlorides (Cl^-), alkalinity (Alk), total hardness (H), calcium hardness (Ca^{2+}), magnesium hardness (Mg^{2+}), bicarbonates (HCO_3^-). All these parameters were measured in the laboratory of the Department of Chemistry of South Ural State University, according to the standard methods (Mashkova et al. 2015b). Spectrophotometer KFK-3 was used for spectrophotometric analysis.

Data analysis

Diversity indexes have been created in order to empirically measure biodiversity. A diversity index is a quantitative measure that reflects how many different species there are in an ecosystem, and simultaneously takes into account how evenly the organism are distributed among those species. The Shannon index (Shannon-Weiner) is frequently used in the determination of phytoplankton diversity and consequently the pollution level (Setyono and Himawan 2018). Simpson's Diversity Index is often used to quantify the biodiversity in ecology. It takes into account the number of species present, as well as the relative abundance of each species. Also, the

Margalef index appears to be a good diversity indicator as well as a valuable parameter for the temporal data series analysis, from changing environments and for the conservation of natural environments.

The Shannon inhomogeneity index was used to assess the structure of the phytoplankton community (Motwani et al. 2014):

$$H' = -\sum_{i=1}^{N} p_i \cdot \ln p_i, \quad (1)$$

Where, $p_i = n_i / N$ is the share of the i-th species in the biotope, n_i is the number of the i-th species, N is the total number of organisms.

The Shannon index is a mathematical measure of species diversity in a community. Diversity indicators provide more information about the community composition than just species diversity (the number of species present). They also take into account the relative abundance of different species.

The data was analyzed using graphs. The graphs were constructed using a method for calculating the similarity on the basis of the Sorensen-Czekanowski coefficient as an index of community which takes into account the positive coincidences for cluster analysis. Graphs were calculated using a special program module "GRAPHS" (Nowakowski 2004).

$$I_s = \frac{2c}{a+b}, \quad (2)$$

Where: a is the number of species in one community; b is number of species in another community; c is the number of species common to the two communities. The limits of this coefficient are from 0 to 100 %, where 100 % means a complete similarity of communities (absolute coincidence of lists), and 0 means that they do not have any common species.

The Margalef index was calculated to assess the species richness (Motwani et al. 2014). It was estimated by the formula:

$$D_{Mr} = (S-1)/\ln N, \quad (3)$$

Where: S is the number of species, and N is the total number of individuals in the sample

As species richness and evenness increase, so diversity increases.

The Simpson index was used to estimate the species abundance:

$$C = \sum\left(\frac{n_i(n_i-1)}{N(N-1)}\right), \quad (4)$$

Where: n_i is the significance estimate of each species (abundance or biomass), N is the sum of significance estimates.

Berger and Parker indices is a simple dominance measure (Berger and Parker 1970):

$$d = N_{max}/N, \quad (5)$$

Where: N_{max} - the number of individuals in the most abundant species, N - the total number of individuals.

The relationship between the phytoplankton community and the environmental factors was analyzed using the Canonical Correspondence Analysis (CCA), as well as the «Graphs» suite. The Analysis of variance (ANOVA) was used to test for significant difference ($p < 0.05$) of the environmental parameters in the sites. Microsoft Excel 2013 and SPSS 24.0 software were used to organize and analyze the data.

RESULTS AND DISCUSSION

Phytoplankton community of the Lakes

The species composition of the phytoplankton community of the three lakes is provided as Table 3. The identified species belong to 7 algal classes namely Bacillariophyta, Cyanophyta, Chlorophyta, Chrysophyta, Euglenophyta, Dinophyta, and Xanthophyta.

The phytoplankton community of three lakes was represented 7 sub-divisions and11 classes. Number of taxa from order to species level resolution is provided in Figure 2. This is a common number of species for small freshwater lakes (Barinova et al. 2006). The phytoplankton community was more diverse in the mesotrophic Lake Ilmenskoe as compared to the oligomesotrophic Lake Savelkul and eutrophic Lake Argayash. Diatoms were the major phytoplankton group in the Lake Ilmenskoe (Figure 3), followed by blue-green and green algae. Diatoms were the major phytoplankton group in the Lake Savelkul also, but followed by green and blue-green algae (see Figure 3). Green algae were the major phytoplankton group in the Lake Argayash, followed by blue-green and diatom algae (see Figure 3). A few euglenoids, dinoflagellates, and yellow-green algae were found in all three lakes. The diversity of euglenoids was higher in lakes Argayash and Ilmenskoe than in Lake Savelkul (5, 5 and 3 species, respectively). This is consistent with Barinova et al. (2006), who showed that the biodiversity of euglenoids increased with the trophicity of the reservoir. 83 % of all the algae were widespread planktonic species. Their number was approximately the same across the studied lakes.

The Cyanophyta (blue-green algae) species were dominant in two water bodies (it was 42-64 % and 55-70 % for Lake Ilmenskoe and Lake Argayash, respectively). The proportion of diatoms and greens was between 14 and 36%. Usually, blue-green algae are dominant in mesotrophic and eutrophic lakes (Barinova et al. 2006).

The Bacillariophyta (diatom algae) species were dominant in the Lake Savelkul; it was 40-66 %. The proportion of blue-greens and greens was between 18 and 32 %.

Diversity indices

The different Diversity indices of the phytoplankton community (the Shannon, Simpson and Margalef Indexes) are given in Table 4.

Table 3. Comparison of phytoplankton composition of Lake Ilmenskoe, Lake Argayash and Lake Savelkul in the South Urals, Russia

Species	Lake Ilmenskoe	Lake Argayash	Lake Savelkul
Bacillariophyta			
Amphora ovalis (Kützing) Kützing	*	*	-
Asterionella formosa Hassall	*	*	*
Aulacoseira ambigua (Grunow) Simonsen	-	*	*
Aulacoseira granulata (Ehrenberg) Simonsen	*	*	*
Cocconeis placentula Ehrenberg	*	-	-
Cyclotella radiosa (Grunow) Lemmermann	*	-	*
Cyclotella meneghiniana Kützing	-	*	-
Cymbella cistula (Ehrenberg) O.Kirchner	*	-	*
Cymbella cymbiformis C.Agardh	*	*	*
Cymbella helvetica Kützing	*	*	*
Cymbella lanceolata (C.Agardh) C.Agardh	*	-	*
Cymbella parva (W.Smith) Kirchner	*	-	-
Diatoma elongatum (Lyngbye) C.Agardh	*	-	-
Diatoma vulgare Bory	*	*	*
Epithemia turgida var. turgida (Ehrenberg) Kützing	*	-	-
Eunotia meisteri Hustedt	*	-	-
Fragilaria acus (Kützing) Lange-Bertalot	*	-	*
Fragilaria crotonensis Kitton	*	*	*
Fragilariforma virescens (Ralfs) D.M.Williams & Round	*	*	-
Gomphonema acuminatum Ehrenberg	*	-	-
Gomphonema truncatum Ehrenberg	*	-	-
Melosira varians C.Agardh	-	*	-
Navicula gracilis Lauby	*	-	*
Navicula radiosa Kützing	*	*	*
Navicula rhynchocephala Kützing	*	-	-
Nitzschia sigmoidea (Nitzsch) W.Smith	*	-	*
Pinnularia alpina W.Smith	*	-	*
Pinnularia gentilis (Donkin) Cleve	*	-	-
Pinnularia viridis (Nitzsch) Ehrenberg	*	-	*
Rhoicosphenia abbreviata (C.Agardh) Lange-Bertalot	*	-	-
Rhopalodia gibba (Ehrenberg) Otto Müller	*	*	-
Stauroneis sp.	*	-	*
Surirella elegans Ehrenberg	*	-	*
Synedra berolinensis var. berolinensis Lemmermann	*	-	-
Synedra ulna var. acus Mayer	*	-	*
Synedra ulna var. ulna (Nitzsch) Ehrenberg	*	-	-
Tabellaria fenestrata (Lyngbye) Kützing	*	*	*
Cyanophyta			
Anathece clathrata (W.West & G.S.West) Komárek, Kastovsky & Jezberová	*	-	-
*Chroococcus tenax (*Kirchner) Hieronymus	*	-	*
Chroococcus turgidus (Kützing) Nägeli	*	*	-
Coelomoron pusillum (Van Goor) Komárek	-	*	*
Dolichospermum flosaquae (Brébisson ex Bornet & Flahault) P.Wacklin, L.Hoffmann & J.Komárek	*	*	*
*Dolichospermum circinale (*Rabenhorst ex Bornet & Flahault) P.Wacklin, L.Hoffmann & J.Komárek	*	*	*
Dolichospermum lemmermannii (Richter) P.Wacklin, L.Hoffmann & J.Komárek	*	*	*
Dolichospermum scheremetievii (Elenkin) Wacklin, L.Hoffmann & Komárek	*	*	*
Dolichospermum spiroides (Klebhan) Wacklin, L.Hoffmann & Komárek	*	-	-
Gloeocapsa sanguinea (C.Agardh) Kützing	*	-	-
Gloeotrichia echinulata P.G.Richter	*	*	*
Gloeotrichia pisum Thuret ex Bornet & Flahault	*	-	-
Jaaginema subtilissimum (Kützing ex Forti) Anagnostidis & Komárek	*	*	-
Merismopedia convoluta Brébisson ex Kützing	*	-	-
Microcystis aeruginosa (Kützing) Kützing	*	*	*
Microcystis viridis (A.Braun) Lemmermann	*	-	-
Microcystis pulverea (H.C.Wood) Forti	*	*	*
Microcystis wesenbergii (Komárek) Komárek ex Komárek	*	*	*
Oscillatoria limosa C.Agardh ex Gomont	*	*	*
Snowella lacustris (Chodat) Komárek & Hindák	*	-	*
Snowella rosea (J.W.Snow) Elenkin	*	*	*
Woronichinia naegeliana (Unger) Elenkin	*	*	*

Chlorophyta			
Botryococcus braunii Kützing	*	-	*
Closterium parvulum Nägeli	-	*	*
Closterium strigosum Brébisson	-	*	-
Coenococcus planctonicus Korshikov	*	-	*
Cosmarium baileyi Wolle	*	*	*
Dispora crucigenioides Printz	*	-	-
Eudorina elegans Ehrenberg	*	*	*
Monactinus simplex (Meyen) Corda	*	-	*
Mucidosphaerium pulchellum (H.C.Wood) C.Bock, Proschold & Krienitz	-	*	-
Neocystis ovalis (Korshikov) Hindák	*	*	*
Oocystis borgei J.W.Snow	*	*	*
Pediastrum duplex Meyen	*	*	*
Planktosphaeria gelatinosa G.M.Smith	*	*	-
Pseudopediastrum boryanum (Turpin) E.Hegewald	*	*	*
Radiococcus polycoccus (Korshikov) I.Kostikov, T.Darienko, A.Lukesová & L.Hoffmann	*	-	-
Scenedesmus quadricauda (Turpin) Brébisson	-	*	*
Sphaerocystis schroeteri Chodat	*	*	*
Spirogyra porticalis (O.F.Müller) Dumortier	*	*	-
Spirogyra sp.	*	-	*
Staurastrum gracile Ralfs ex Ralfs	*	*	*
Staurastrum paradoxum Meyen ex Ralfs	*	-	-
Ulothrix tenerrima (Kützing) Kützing	*	-	
Ulothrix zonata (F.Weber & Mohr) Kützing	*	-	-
Volvox aureus Ehrenberg	*	*	*
Volvox sp.	-	*	*
Chrysophyta			
Chrysococcus klebsianus Pascher	*	-	-
Dinobryon divergens O.E.Imhof	*	*	*
Dinobryon sociale var. americanum (Brunnthaler) Bachmann	*	-	*
Euglenophyta			
Euglenaformis proxima (Dangeard) M.S.Bennett & Triemer	*	-	-
Lepocinclis acus (O.F.Müller) Marin & Melkonian	*	*	*
Trachelomonas armata (Ehrenberg) F.Stein	-	*	-
Trachelomonas euchlora (Ehrenberg) Lemmermann	-	*	-
Trachelomonas hispida (Perty) F.Stein	-	*	-
Trachelomonas planctonica Svirenko	*	-	-
Trachelomonas pseudobulla Svirenko	*	*	*
Trachelomonas volvocina (Ehrenberg) Ehrenberg	*	-	*
Dinophyta			
Ceratium hirundinella (O.F.Müller) Dujardin	*	*	*
Peridinium cinctum (O.F.Müller) Ehrenberg	*	*	*
Xanthophyta			
Tribonema viride Pascher	*	*	*

Note: * = Present, - = Absent

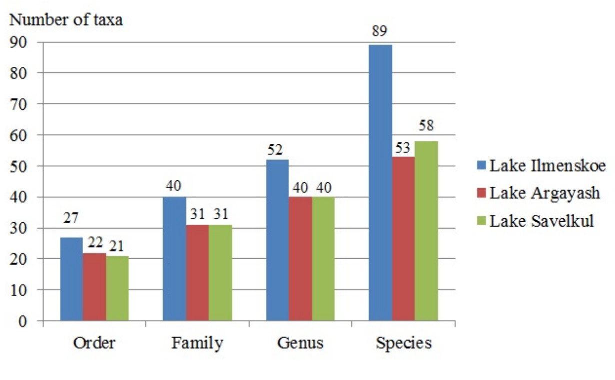

Figure 2. Number of taxa for each taxonomic resolution

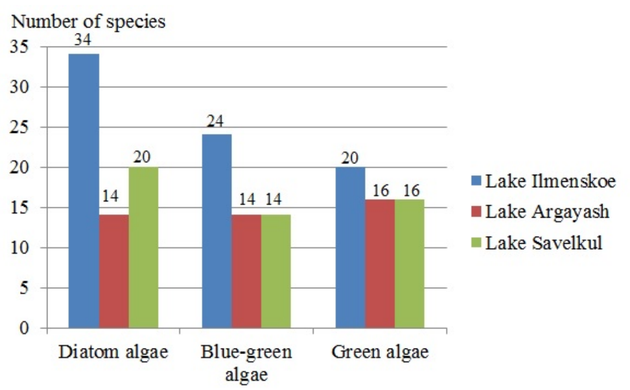

Figure 3. Number of species for diatoms, blue-green and green algae

Table 4. Biodiversity indices of the phytoplankton community of Lake Ilmenskoe, Lake Argayash, and Lake Savelkul.

Indexes	Lake Ilmenskoe					Lake Argayash				Lake Savelkul		
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11	Site 12
2015												
Shannon index	3.14	2.75	3.07	1.84	2.86	1.21	1.59	2.51	2.48	2.62	1.96	2.91
Margalef index	9.31	7.16	6.21	3.10	7.40	2.30	1.97	4.60	3.94	4.12	1.70	5.57
Simpson index	0.06	0.08	0.05	0.25	0.07	0.45	0.23	0.07	0.06	0.07	0.13	0.05
2016												
Shannon index	2.57	2.25	2.25	2.30	2.69	2.11	2.11	1.61	1.98	2.35	2.43	2.53
Margalef index	4.04	2.69	2.69	2.96	4.31	2.83	2.83	1.89	2.83	5.03	3.78	4.09
Simpson index	0.07	0.10	0.09	0.10	0.06	0.10	0.11	0.23	0.15	0.13	0.07	0.05

The Shannon index in Lake Ilmenskoe (annual average: 2.73 in 2015 and 2.41 in 2016), as well in Lake Savelkul (annual average: 2.50 in 2015 and 2.44 in 2016) was slightly higher than in Lake Argayash (annual average: 1.95 in 2015 and 2016). The values of the Shannon index over two years, reveals a medium diverse phytoplankton community. The phytoplankton diversity indicators are weak indicators of trophic state and may well characterize only the differences between complexes and associations (Rakocevic-Nedovic and Hollert 2005). Eutrophic and mesotrophic water bodies are characterized by high biodiversity indices. However, the low Shannon index values for the phytoplankton of Lake Argayash indicate a higher trophic state of the water body. The value of the Shannon index decreases with increasing trophic state. To better assess the trophic state of lakes, more detailed studies are required, including the determination of water quality, abundance, and biomass of plankton and the primary production of phytoplankton (Jekatierynczuk-Rudczyk et al. 2014).

Species similarity between the phytoplankton communities of the lakes was assessed using cluster analysis based on the Sorensen-Czekanowski coefficient (Figure 4). The species composition showed large similarity between sampling stations of Lake Ilmenskoe and Lake Argayash, while the taxonomic composition of algae of Lake Savelkul was highly specific, since it was characterized by low values of the Sorensen-Czekanowski similarity index.

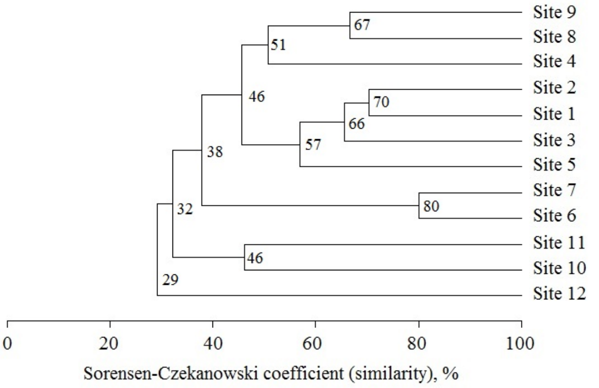

Figure 4. Sorensen-Czekanowski similarity of phytoplankton composition between different sampling stations in lakes

The Margalef index reflects the density of species over a certain area (the higher the index value, the greater the species richness over the study area). The average Margalef index value of Lake Ilmenskoe and Lake Savelkul was 6.64 and 3.80, respectively, in 2015, also 3.34 and 4.30, respectively, in 2016. The absolute index values ranged from 2.69 to 9.31 for Lake Ilmenskoe and from 1.70 to 5.57 for Lake Savelkul. For Lake Argayash, the average Margalef index value was 3.20 and 2.60, respectively, the absolute index values ranged from 1.89 to 4.60. Lake Argayash, being eutrophic, is characterized by lower species richness.

The Simpson index reflects the dominance of individual species in a community. An increase in their number means a decrease in diversity and an increase in the degree of dominance of one species. The average Simpson index value of lakes Ilmenskoe and Savelkul was 0.08-0.10 in 2015 and 2016. Of Lake Argayash it equaled 0.20 and 0.15, respectively. The obtained values indicate a uniform distribution of species without the predominance of any of them.

The dominant species were selected based on total abundance of species in all sampling stations of the three lakes. A species is considered dominant If its dominance value was greater than 0.05. Accordingly, there were 20 dominant species, including 5 species of Bacillariophyta (*Asterionella formosa*, *Diatoma vulgare*, *Fragilaria crotonensis*, *Fragilaria acus*, *Synedra ulna* var. *ulna*), 8 species of Cyanophyta (*Dolichospermum flosaquae*, *Dolichospermum circinale*, *Dolichospermum lemmermannii*, *Dolichospermum scheremetievii*, *Gloeotrichia echinulata*, *Microcystis aeruginosa*, *Microcystis wesenbergii, Oscillatoria limosa*), 6 species of Chlorophyta (*Neocystis ovalis, Coenococcus planctonicus, Eudorina elegans, Pediastrum duplex*, *Volvox aureus*, *Volvox sp*.) and one species of Dinophyta (*Ceratium hirundinella*).

Influence of environmental factors

To evaluate the relationship between the water quality indices and the number of observed phytoplankton dominant species, Canonical correlation analysis was conducted in each of the sites under study (Figure 5). Each environmental factor variable is represented by an arrow, which determines an axis. The projection of a species on this axis indicates the level of the factor where the species is most abundant.

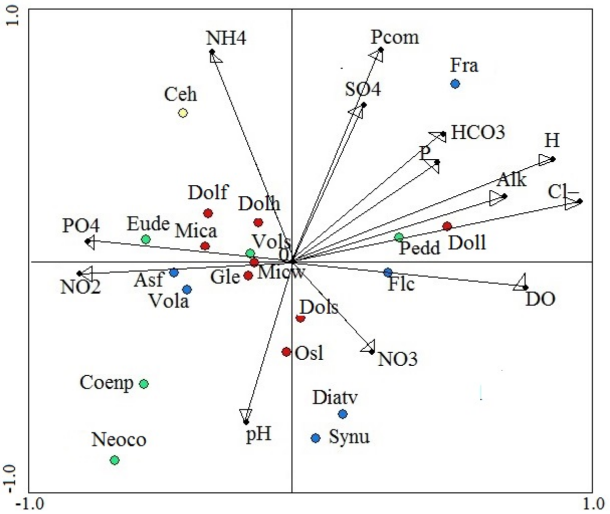

Figure 5. CCA biplot of phytoplankton and environmental factors in lakes. Asf: *Asterionella formosa*, Diatv: *Diatoma vulgare*, Flc: *Fragilaria crotonensis*, Fra: *Fragilaria acus*, Synu: *Synedra ulna var. ulna*, Dolf: *Dolichospermum flosaquae*, Dolh: *Dolichospermum circinale*, Doll: *Dolichospermum lemmermannii*, Dols: *Dolichospermum scheremetievii*, Gle: *Gloeotrichia echinulata*, Mica: *Microcystis aeruginosa*, Micw: *Microcystis wesenbergii,* Osl: *Oscillatoria limosa,* Neoco: *Neocystis ovalis,* Coenp*:* *Coenococcus planctonicus,* Eude: *Eudorina elegans,* Pedd*:* *Pediastrum duplex*, Vola: *Volvox aureus*, Vols: *Volvox sp*., Ceh: *Ceratium hirundinella*; blue Bacillariophyta, red Cyanophyta, green Chlorophyta, yellow Dinophyta.

The dominant species were mainly located in the second, third and fourth quadrants of bioplot, related to NH4, PO4, NO2, pH, NO3 and DO. Figure 5 shows that the dominant species clustered with the variables PO4, NO2, pH, and NO3. The species such as *Dolichospermum flosaquae*, *Microcystis aeruginosa*, and *Eudorina elegans*, showed a significantly positive correlation with PO4; *Asterionella formosa*, *Volvox aureus*, *Gloeotrichia echinulate* and *Microcystis wesenbergii* with NO2. The blue-green such as *Dolichospermum scheremetievii* and *Oscillatoria limosa* were positively correlated with pH.

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