www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

POLISH POLAR RESEARCH
vol. 42 no. 4, pp. 249–268, 2021 DOI: 10.24425/ppr.2021.137147

Diatom assemblages in surface sediments of Lake Imandra (Russia, Murmansk region)

Sofiya VOKUEVA[1*] and Dmitrii DENISOV[1]

[1] *Institute of the North Industrial Ecology Problems, Federal Research Center "Kola Science Center of RAS", 8a Akademgorodok Street, 184209, Apatity, Murmansk region, Russia.*

* *Corresponding author: s.vokueva@ksc.ru*

Abstract: In this article we investigate diatom assemblages in surface sediments of the subarctic Lake Imandra. We examine taxonomic composition and ecological structure and describe spatial variations of diatoms over the lake area. The diatom flora described here are characterized by abundance of planktonic centric species. The habitats of diatoms in the different stretches of Lake Imandra reflect local environmental conditions and are determined by the type and intensity of the anthropogenic impact. *Stephanodiscus minutulus, S. alpinus, Aulacoseira islandica* are the most abundant species in the area of the lake affected by industrial effluents and eutrophication, while *Pantocsekiella comensis* is most typical in the background sites of the lake. Diatoms taxonomic diversity is high in shallow bays where aquatic vegetation is common. Abundance of diatoms in areas affected by anthropogenic eutrophication reflects the high intensity of plankton primary production. Differences in the ecological structure of the diatom assemblages in different parts of Lake Imandra are caused by significant hydrochemical heterogeneity of the water quality.

Keywords: Arctic, biodiversity, bioindication, water quality, subarctic freshwater ecosystems.

Introduction

Subarctic freshwater ecosystems are particularly sensitive to environmental changes caused by both natural fluctuations and human activity. The northern lakes are characterised by low resistance to anthropogenic pressure and their ability to combine all the negative impacts occurring in their watersheds (Kashulin *et al.* 2012). Nowadays a rapid degradation of aquatic ecosystems is observed in the industrially developed regions of the Arctic, leading to a reduction in high-quality freshwater and hydrobiological resources (Kashulin *et al.* 2017). Maintaining water quality and protecting aquatic habitats is a priority strategy for ensuring environmental safety in the Arctic. For this reason an adequate freshwater-quality assessment and analysis of changes in the ecosystem is an urgent scientific task. Lake Imandra, in the Murmansk region, is one of the largest Arctic water bodies with major socioeconomic importance (Fig. 1).

There are large industries enterprises — mining, metallurgical, mineral processing, and chemical — in the Lake Imandra catchment. The lake is used as a cooling reservoir for a nuclear power plant, and as a supply of potable and non-potable water. As a result of long-term industrial pollution, the environment has changed. This change has led to deviations of hydrochemical parameters in anthropogenic-transformed areas compared with 'background' values from areas of Lake Imandra without direct pollution which affected the biota (Dauvalter *et al.* 1999, 2000; Moiseenko *et al.* 2002, 2009a,b; Moiseenko and Sharov 2010, 2019; Dolgonosov and Moiseenko 2007; Denisov 2007; Dauvalter and Kashulin 2018). The undergoing drastic changes in the algae-species composition and abundance are most typical for zones of intense anthropogenic pollution and eutrophication. Algae bioindicators are proven tools for capturing the effects of environmental interactions and pollution as well as of abrupt water-quality changes (Kagan 2001; Sharov and Denisov 2021). They also are the most informative markers of ecosystem stability. Diatoms in Lake Imandra are the dominant algae group in terms of abundance, biomass and taxonomic diversity (Denisov and Genkal 2018; Sharov 2008; Sharov and Denisov 2021).

Diatoms are successfully used in integrated environmental monitoring of water bodies. It is especially important to clarify the taxonomic composition and environmental tolerance of diatoms. Diatom diversity and adaptive capabilities in the Arctic regions have been widely investigated (Agustil *et al.* 2020; Stoof-Leichsenring *et al.* 2020).

The use of modern phytoplankton communities as bioindicators is associated with number of difficulties. Thus, a short 'hydrobiological summer' in the Arctic region is characterized by a sharp change in temperature and hydrological regimes and causes a significant variability in the qualitative and quantitative parameters of phytoplankton over several days. At the same time, the organization of sampling in a short time on large water bodies for a comparative analysis is a complex and resource-intensive task. Diatom assemblages (DA) of surface sediments contain integrated information on the species composition and cenosis structure over recent years, which allows us to conduct accurate aquatic-environment assessments in different parts of the lake.

The aim of this study is to analyse the DA taxonomic composition and their ecological structure in the surface sediments from the different parts of Lake Imandra to identify differences in habitat conditions because DA of different compositions are observed in different parts of the lake. Previously, phytoplankton communities or sediment cores from several sampling points were mainly studied for these purposes (Kagan 2001). Here we carried out for the first time a detailed study of diatom communities of surface sediments.

Materials and methods

Hydrochemical heterogeneity of different parts of Lake Imandra is largely determined by anthropogenic impact. The sources of this impact include sewage released into Moncheguba Bay from the non-ferrous metallurgy enterprise PJSC 'MMC 'Norilsk Nickel" and the town of Monchegorsk, and sewage released into Belaya Bay from the apatite company, Kirovsk Branch of Apatite JSC 'PhosAgro' and from the towns of Kirovsk and Apatity (Fig 1).

The average sedimentation rate in Lake Imandra is 1–3 millimeters (mm) per year (Moiseenko *et al.* 2002). Considering the high content of organic matter, the low solidity of sediments and the influence of rivers flowing into the lake on the sedimentation processes of some stations, it can be assumed that the sedimentation period of the studied interval could be less than 3–4 years. Accordingly, DA of these sediments integrate information on the current taxonomic composition of diatoms in the lake.

Our sampling was conducted from 2013 to 2018. The sediment cores from the deepest areas were collected with open gravity-type corers (inner diameter of 44 and 85 mm) with an automatically closing diaphragm made from plexiglass (Skogheim 1979). Cores were stored intact and upright at the Institute of the North Industrial Ecology Problems (INEP) until extrusion. Cores were sectioned at 1 cm intervals using a vertical extruder, and the uppermost layers (0–1 cm) from each sampling point were used for DA analysis. One slide was done from the one layer, and all parameters were calculated on one slide for each sampling point separately.

We took water samples from the surface and the bottom layers of the lake with a 2L plastic bathometer, from which we poured the samples into 1L plastic bottles from Nalgene®, the material of which does not have absorbing properties (Sandimirov *et al.* 2019). When water was sampled, we rinsed the bottles twice with lake water, then placed bottles in dark containers and refrigerated them (~+4°C) in the laboratory. We filtrated the water samples in the laboratory during discharge at the Millipore phase-separation unit from high-density polypropylene through glass and polycarbonate membrane filters of Millipore HVLPO 4700, Schleicher and Schuell ME 25/21 ST, Whatman GF/A with a pore size of 0.45µm.

We determined the following parameters in unfiltered samples: pH, NH^{4+}, NO^{3-}, $PO4^{3+}$, metals (after acidification with concentrated nitric acid). In the filtered samples, we determined phosphorus content. Water chemistry was

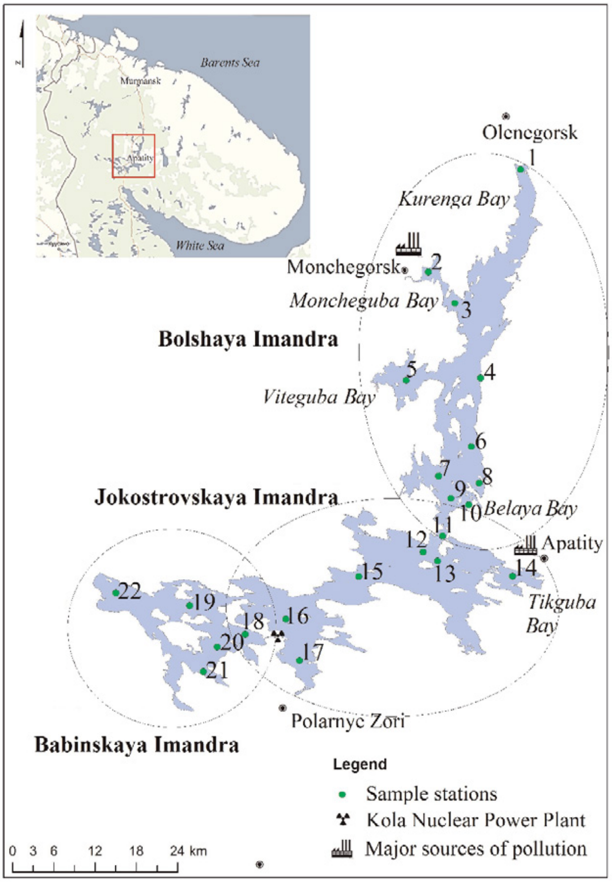

Fig. 1. Lake Imandra and the sampling station locations.

determined at the resource-sharing centre of INEP Kola Science Centre RAS using the same methods described in Rand *et al.* (1975). For the quality control of the measurements of pH and concentrations of alkali and alkaline-earth metals, we used the specialized ALPEFORM software suite, including an assessment of ion balance, and we measured and calculated electrical conductivity (Denisov *et al.* 2020).

We prepared diatom samples according to the standard method (Juse *et al.* 1949; Davydova 1985; Battarbee 1986; Battarbee *et al.* 2001), with some modifications developed at INEP (Sandimirov *et al.* 2019). The modifications of this method included successive stages of oven-drying and combustion samples in a muffle at a temperature of 550°C. Then samples were mixed with strong oxidizer (HNO_3) and kept in Teflon (fluoroplastic) lined autoclaves at a temperature of 140°C for 5 hours. As a result of preparation, the organic matter was almost completely removed from the sample. Permanent preparations were made from samples washed with distilled water. Elyashev aniline–

formaldehyde resin with refraction indices n = 1.67–1.68 was used as a mountant in slide preparation.

We identified diatoms' taxa at 1000 × magnification using Leitz BIOMED and Motic BA 300 microscopes and phase contrast under oil immersion. We identified diatoms to the lowest taxonomic-level possible according to specialized keys (Krammer 2000, 2002, 2003; Lange-Bertalot 2001; Krammer and Lange-Bertalot 1986, 1988, 1991a,b, etc.). We examined the dominant species using a VEGA II LSH scanning electron microscope (SEM) at the Analytical Centre of the Institute of Geology, Karelian Research Centre of the Russian Academy of Sciences in Petrozavodsk; previously SEM was used to identify centric species (Denisov and Genkal 2018). We assigned names of the diatom taxa in accordance with the internationally updated electronic database (Guiry and Guiry 2020).

Further analysis included our calculation of the relative abundance (by percentage) of identified taxa in the DA, the identification of dominant species (more than 15%) and subdominant species (5–15%), the study of total diatom abundance per 1 gram of dry sediment mass (N_o, million ind./g) (Davydova 1985). We took the autecological data of the species from a database (Barinova *et al.* 2006; Van Dam *et al.* 1994).

We analysed ecological groups of diatoms and their proportions in sediments to reconstruct the conditions in the lake. According to their preferred habitat, we divided diatoms into epibionts, planktic, benthic, and plankto-benthic forms. We also considered relationship to water salinity (chloride concentration) and identified halophob (growth is inhibited by salinity), indifferent (tolerates different salinities), oligohalob (tolerates some salinity), halophilic (growth is stimulated by salinity) and mesohalob (grows in water with medium salinity) groups. We identified diatoms in relation to pH values: neutrophilic (developmental optimum at pH 7.0), indifferent (capable of developing in a relatively wide range of pH around 7), alkaliphilic (preferring pH>7.0), alkalibiont (preferring pH 7.6 and above), and acidophilic (preferring pH<7.0). We formed the last ecological group according to biogeographical association (cosmopolitan, arctic-alpine, boreal, holarctic) (Dauvalter and Denisov 2015).

We estimated taxonomic diversity in each site based on selected indices: Shannon-Weaver (H'), Simpson (1/D), Margalef, Menhinick and Berger–Parker (Washington 1984; Berger and Parker 1970). We estimated the comparative floristics of the DA by the Sørensen–Chekanovsky coefficient (Czekanowski 1909; Sörensen 1948), using the GRAPHS software module (Novakovsky 2014).

Results

Hydrochemical characteristics. — According to hydrochemical composition in general, the waters of the lake can be assigned to the hydrocarbonate class and the calcium group, with a low content of nutrients and low mineralization (the total salt content ranges from 25 to 60 mg/l) (Moiseenko *et al.* 2002). The average pH of the water is close to neutral: 7.3, but the maximum values are observed in the Bolshaya Imandra stretch (Bol.I): up to 7.62 (Table 1). Based on the parameters in Table 1, the hydrochemical heterogeneity of Lake Imandra can be observed. Thus, the maximum values of both biogenic (N, P) and toxic (Cu, Ni) elements are typical for the northern part of the lake. The average content of the elements also decreases from Bol.I to Babinskaya Imandra (B.I).

Table 1

Hydrochemical parameters of the Lake Imandra: average values and ranges.

	Bol.I	Y.I	B.I
pH	7.36 (7.1–7.62)	7.35 (7.29–7.42)	7.32 (7.23–7.43)
N (mkgN/l)	392 (152–3530)	188 (63–758)	154 (66–218)
P (mkgP/l)	54 (13–617)	13 (5–116)	6 (4–22)
NH_4 (mkgN/l)	20 (0–593)	9 (0–156)	6 (0–22)
NO_3 (mkgN/l)	164 (1–2950)	2 (0–324)	22 (0–118)
PO_4 (mkgP/l)	8 (0–470)	1 (0–20)	2 (0–3)
Cu (mkg/l)	4.57 (3.65–7.1)	3.21 (2.3–3.95)	3 (2.45–3.85)
Ni (mkg/l)	8.7 (6.35–16.2)	5.19 (2.2–7.85)	1.95 (1.55–2.37)
Mn (mkg/l)	28.52 (7.9–135)	23.88 (2.6–76)	2.4 (1.7–3.7)
Al (mkg/l)	46.75 (8–94.5)	36 (19–55)	21.29 (17.5–24.25)

(Bol.I — Bolshaya Imandra stretch, J.I — Jokostrovskaya Imandra, B.I. — Babinskaya Imandra)

Diversity of diatoms. — We have identified 378 diatom species belonging to 78 genera in the surface sediments of 22 sampling sites of Lake Imandra. Genera with the largest number of species are *Eunotia* – 30; *Pinnularia* – 25; *Navicula* – 18; *Fragilaria* – 15; *Gomphonema* –15; *Nitzschia* – 15; *Epithemia* – 11; *Psammothidium* – 11, and *Cymbopleura* – 10 (Fig. 2).

Taxonomic richness (the number of taxa, N_t) and values of biodiversity indices of the DA along the Lake Imandra aquatory are represented in Table 2. The greatest N_t variability between the sampling stations is in the Bol.I, as an indicator of the environmental differences for diatoms cenoses. The highest taxonomic richness is in the stations (st.) 2, 3, 5 (Moncheguba and Viteguba). The

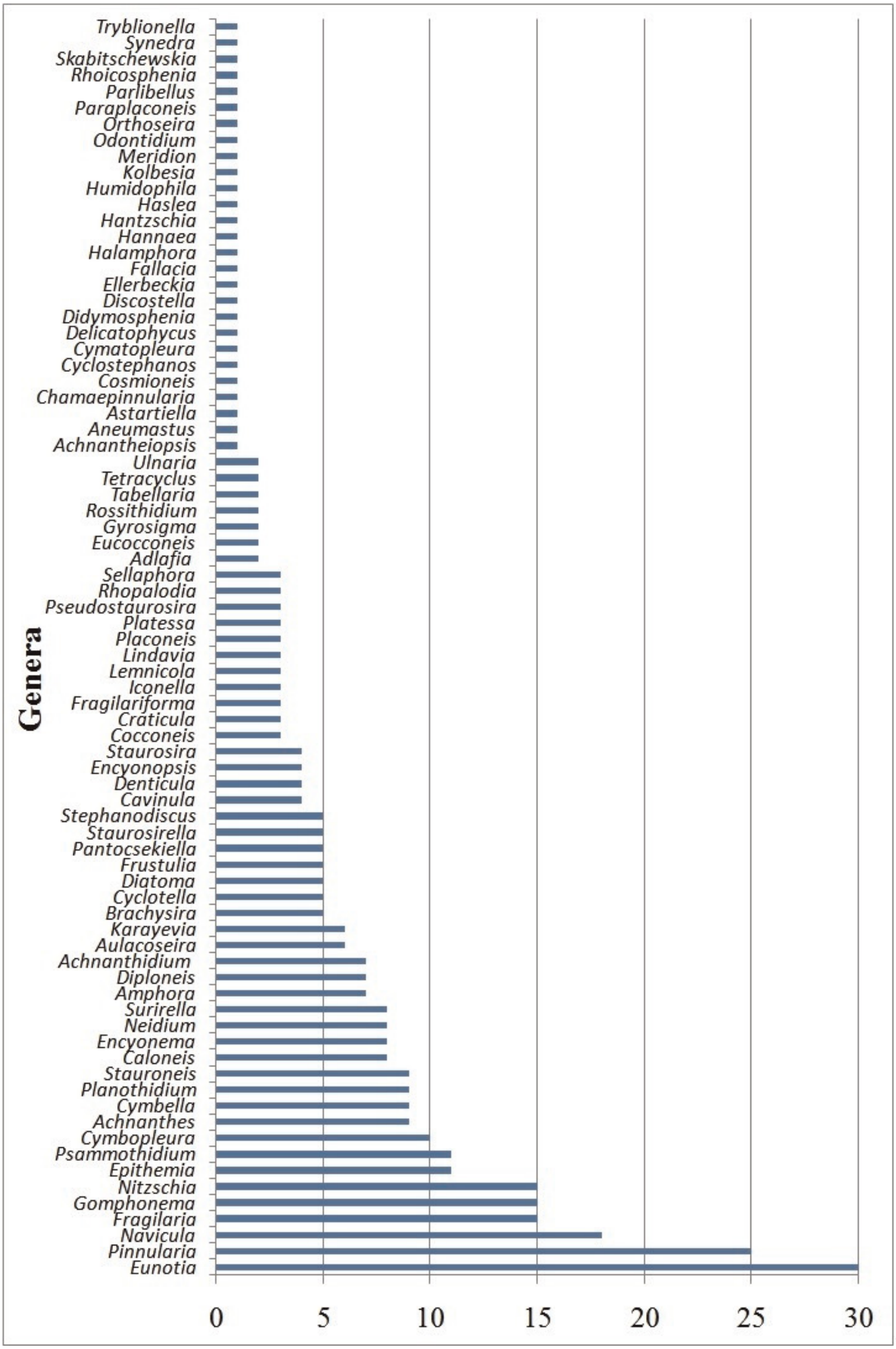

Fig. 2. Distribution of the identified diatom species by genera.

distribution of the H' values confirms the significant differences in the environmental conditions for the diatoms' growth in the lake (Fig. 3a). The highest H' is fixed in bays: Kurenga, Moncheguba, Viteguba and Tikguba (st. 1, 2, 5, 14). In southern Bol.I and especially in Belaya Bay (st. 8) the value of H' is minimal — 2.5 bit/ind. along with an abundance of *Stephanodiscus minutulus* (Kütz.) Cleve *et* Möller. The analysis of the Simpson polydominance index (1/D) shows a similar distribution of values (Table 2). Maximum 1/D values are found for Kurenga, Viteguba and Tikguba (st. 1, 5, 14). The minimum values of 1/D are found in the southern Bol.I and northern Jokostrovskaya Imandra (J.I), especially in Belaya Bay. Spatial distribution of the inverse Berger–Parker index values is similar. Margalef and Menchinik biodiversity indices as well as H' are the highest at Moncheguba and Viteguba Bays (Table 2, Fig. 3a).

The values of diatom abundance in the sediments (N_o) in the Bol.I and the northern part of J.I stretches are characterized by high variability for different sampling points: from 24.8 to 884.6 million ind./g (Fig. 3b). The highest N_o is confined to the southern Bol.I (st. 9), and the minimal N_o is in the Kurenga Bay (st. 1). In contrast, in the B.I and the western part of the J.I areas have insignificant differences (from 182 to 235 million ind./g) (Fig. 3b).

Qualitative and quantitative structure of diatom assemblages and their autecology. — Planktonic centric diatoms are the most common and abundant at all stations (Figs. 4, 5, 6). At the same time, the species composition and dominant taxa are different in three main stretches of Lake Imandra (Table 3). Species that dominate in DA of the Bol.I include *Stephanodiscus minutulus* (Kütz.) Cleve *et* Möller, *S. alpinus* Hust., *Aulacoseira islandica* (O. Müller) Simonsen, as well as *Cyclostephanos dubius* (Hust.) Round, *Tabellaria*

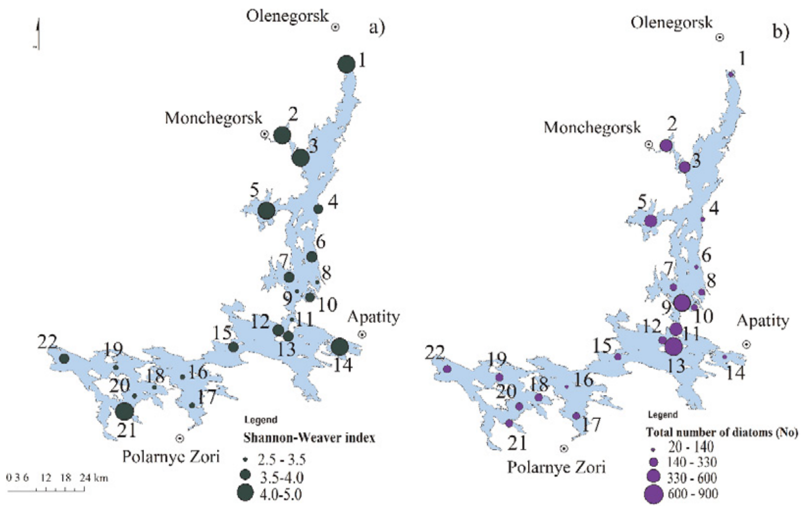

Fig. 3. Spatial distribution of the calculated values of: a) – the Shannon-Weaver H' index, bit/ind. b) – the total diatoms abundance, mln.ind./g (dry weight).

Table 2

Diatom assemblages diversity and species richness indices in sampling stations of Lake Imandra.

Sampling stations, №		Number of taxa	Margalef index	Menhinick index	Inverse Simpson index (1/D)	Inverse Berger-Parker index
Bol.I	1	46	7.58	2.37	29.10	10.00
	2	127	21.23	6.53	18.59	5.88
	3	133	22.24	6.84	16.07	5.56
	4	73	12.13	3.75	13.73	5.00
	5	168	27.97	8.59	29.69	6.67
	6	64	10.62	3.29	12.99	4.55
	7	75	12.47	3.86	11.27	4.35
	8	61	10.11	3.14	3.51	1.89
	9	93	15.50	4.78	4.74	2.22
	10	72	11.79	3.65	7.74	3.03
J.I	11	75	12.47	3.86	7.11	3.57
	12	69	11.46	3.55	15.11	6.67
	13	81	13.48	4.17	11.38	3.85
	14	72	11.96	3.70	50.17	12.50
	15	68	11.29	3.50	8.93	3.13
	16	56	9.27	2.88	4.43	2.13
	17	86	14.32	4.42	6.13	2.50
B.I	18	81	13.48	4.17	4.02	2.04
	19	77	12.81	3.96	6.58	2.70
	20	84	13.99	4.32	5.08	2.33
	21	85	14.15	4.37	12.28	4.00
	22	83	13.82	4.27	8.06	3.03

(Bol.I — Bolshaya Imandra stretch, J.I — Jokostrovskaya Imandra, B.I. — Babinskaya Imandra)

flocculosa (Roth) Kütz, *Aulacoseira granulata* (Ehrenberg) Simonsen and *Stephanodiscus neoastraea* Håk. *et* Hickel. The SEM pictures of some of the dominant species are shown in Fig. 5.

The great taxonomic differences from the main aquatory have been identified in station 1 (Kurenga Bay), where *Cyclotella radiosa* (Grun.) Lemm., *Aulacoseira alpigena* (Grun.) Kramm., *Pantocsekiella schumannii* (Grun.) K.T. Kiss *et* E. Ács and *Tabellaria flocculosa* have large relative percentage abundance, and station 5 (Viteguba Bay), where *S. minutulus* is nearly absent, while this species is the common dominant for other stations of the Bol.I.

The dominant complex in the northern part of J.I includes *Stephanodiscus minutulus, S. alpinus,* and *Pantocsekiella comensis* (Grun.) K.T. Kiss *et* E. Ács. *Pantocsekiella comensis* also prevails in the central and western part of J.I. Taxonomic differences have been observed in station 14 (Tikguba Bay), with high relative percentage abundances of benthic and plankto-benthic species. *Tabellaria flocculosa, Pantocsekiella comensis, Stephanodiscus alpinus* and *S. minutulus* are the most abundant diatoms for this station.

DA taxonomic composition of the B.I is almost the same for all stations. *Pantocsekiella comensis, Aulacoseira alpigena, Pantocsekiella rossii* (H.Håk.) K.T.Kiss *et* E.Ács, *P. schumannii, P. kuetzingiana* (Thwaites) K.T.Kiss *et* E.Ács, *Tabellaria flocculosa* and *Cyclotella radiosa* prevail in all examined stations of B.I. The SEM pictures of some dominant species are shown in Fig. 6.

As a result of a floristic comparison of DA species composition, the Lake Imandra ecosystem can be divided into several groups. One closely related cluster in diatom diversity and structure includes B.I (st. 18–22) and the western part of J.I (st. 15–17) (Fig. 7). A separate, relatively heterogeneous group is formed with the Bol.I sampling stations. The greatest floristic similarity is revealed in the southern part of the Bol.I (st. 6–10) together with northern stations of the J.I (st. 11–13). Moncheguba and Viteguba Bays stations (2, 3, 5) form a separate floristic cluster. According to DA floristic analysis, some bays seem to have a different environment and water quality from the main Lake Imandra

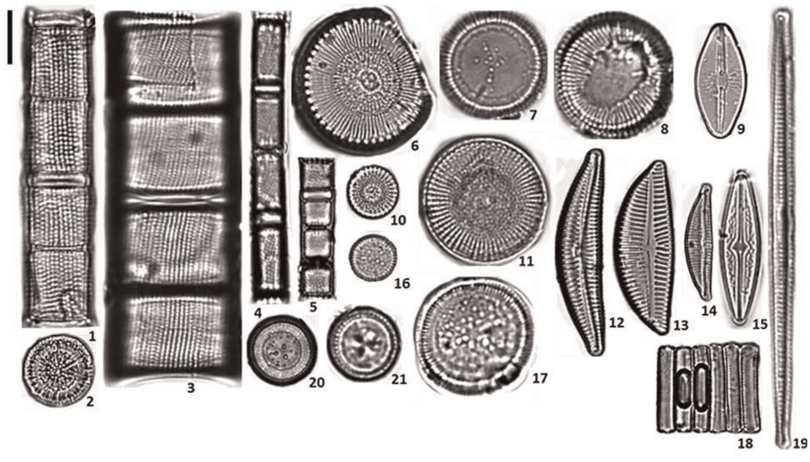

Fig. 4. The most common diatom species in the sediments of Lake Imandra: 1 – *Aulacoseira granulata*, 2 – *Cyclotella radiosa*, 3 – *Aulacoseira islandica*, 4 – *A. subarctica f. recta* (O. Müller) E.Y. Haworth, 5 – *A. alpigena,* 6 – *Cyclotella bodanica var. lemanica* (O. Müller ex Schroter) Bachmann, 7 – *Pantocsekiella rossii,* 8 – *P. schumannii,* 9 – *Cavinula cocconeiformis* (W. Gregory ex Greville) D.G. Mann *et* A.J. Stickle, 10 – *Stephanodiscus minutulus*, 11 – *S. alpinus,* 12 – *Cymbella affinis* Kützing, 13 – *Encyonema cespitosum* Kützing, 14 – *E. silesiacum* (Bleisch) D.G. Mann, 15 – *Brachysira brebissonii* R. Ross, 16 – *Pantocsekiella comensis*, 17 – *P. kuetzingiana*, 18 – *Staurosira construens* Ehrenberg, 19 – *Fragilaria crotonensis* Kitton, 20, 21 – *Pantocsekiella ocellata* (Pantocsek) K.T. Kiss *et* Ács (scale 10 mkm).

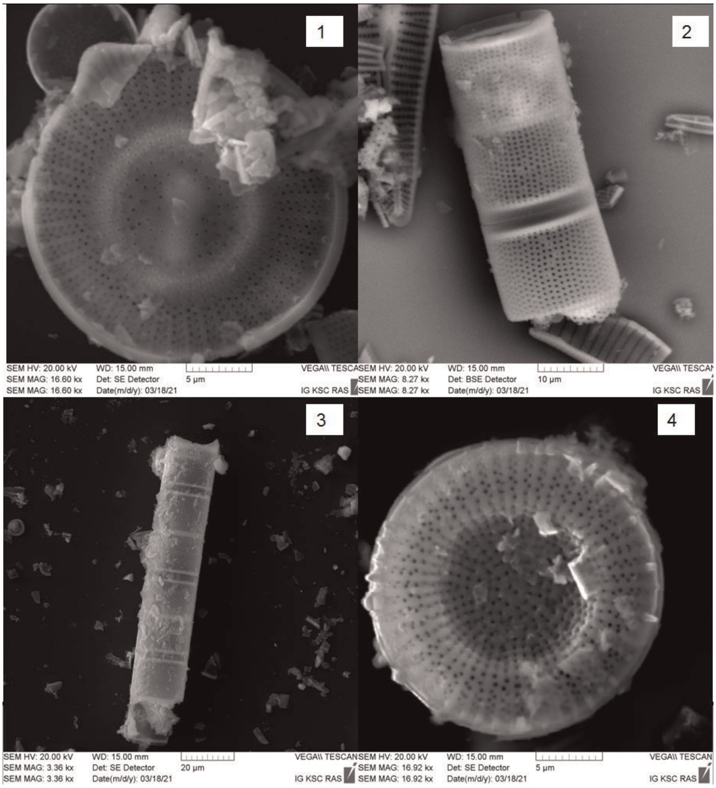

Fig. 5. Electron microphotos of valves (SEM) in polluted areas of Lake Imandra: 1 – *Stephanodiscus alpinus,* 2, 3 – *Aulacoseira islandica,* 4 – *Cyclostephanos dubius*.

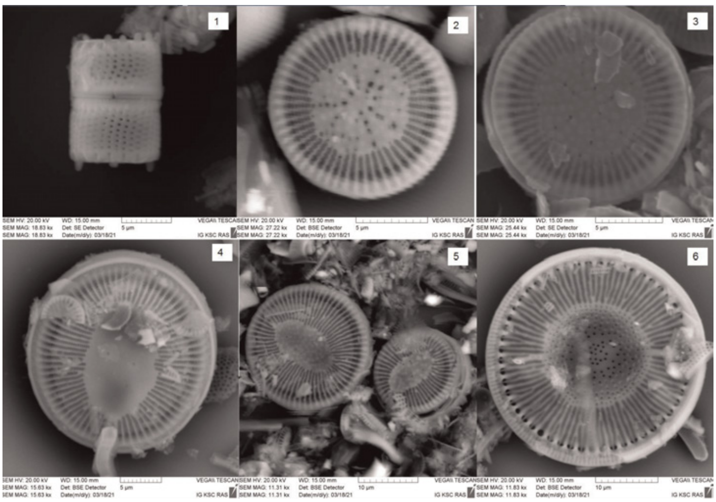

Fig. 6. Electron microphotos of valves (SEM) in areas of Lake Imandra undisturbed by direct human activities: 1 – *Aulacoseira alpigena,* 2, 3 – *Pantocsekiella rossii,* 4, 5 – *Pantocsekiella schumannii,* 6 – *Cyclotella bodanica var. lemanica*.

Table 3

Taxonomic differences in diatom assemblages of Lake Imandra stretches

Lake area	Bol.I	J.I north	J.I central-west	B.I.
Sampling stations, №	1–10	11–14	15–17	18–22
Dominant taxa (>15 %)	*Stephanodiscus minutulus; S. alpinus; Aulacoseira islandica*	*Stephanodiscus minutulus; S. alpinus*	*Pantocsekiella comensis*	*Pantocsekiella comensis*
Subdominat taxa (5–15 %)	*Cyclostephanos dubius; Tabellaria flocculosa; Aulacoseira granulata; Stephanodiscus neoastraea*	*Pantocsekiella comensis; Tabellaria flocculosa; Aulacoseira islandica*	*Pantocsekiella rossii; Cyclotella radiosa; Tabellaria flocculosa; Aulacoseira alpigena*	*Aulacoseira alpigena; Pantocsekiella rossii; Tabellaria flocculosa; Pantocsekiella schumannii; Pantocsekiella kuetzingiana; Cyclotella radiosa*

(Bol.I — Bolshaya Imandra stretch, J.I — Jokostrovskaya Imandra, B.I. — Babinskaya Imandra)

aquatory. We discovered that the minimal Sørensen–Chekanovsky coefficients were 46 (bay Kurenga, st. 1) and 49 (bay Tikguba, st. 14) (Fig. 7).

The ecological structure of the DA confirms the heterogeneity of the environmental conditions and water quality in different parts of Lake Imandra. Freshwater diatoms (oligohalobes) dominate in DA of the sediments in all investigated stations (Fig. 8a). Plankton diatoms strongly prevail in most of the examined stations. Benthic and plankto-benthic inhabitants maintain a large abundance in the relatively shallow bays (Tikguba, Moncheguba, Viteguba and Kurenga — st. 14, 2, 5, 1) (Fig. 8b).

Relative abundance of boreal species in the DA of the central and western parts of the J.I stretch is high in comparison with Bol.I, where cosmopolitan diatoms are dominant (Fig. 9a). In general, the diatom flora retains the subarctic features: the presence of Arctic-alpine and holarctic species is revealed in all the examined stations, but their abundance is very small. Significant differences between the DA of the sampling stations are revealed in the ratio of diatoms to the acidity degree (pH) of ecological groups (Fig. 9b). The results of the pH bioindication show that most stations of the Bol.I and the northern part of J.I are rich in alkaliphile species. Alkaliphiles represent up to 80% of pH-indicator species in Belaya Bay (st. 8). In other parts of the Lake Imandra aquatory, pH indicator group of indifferents is dominant.

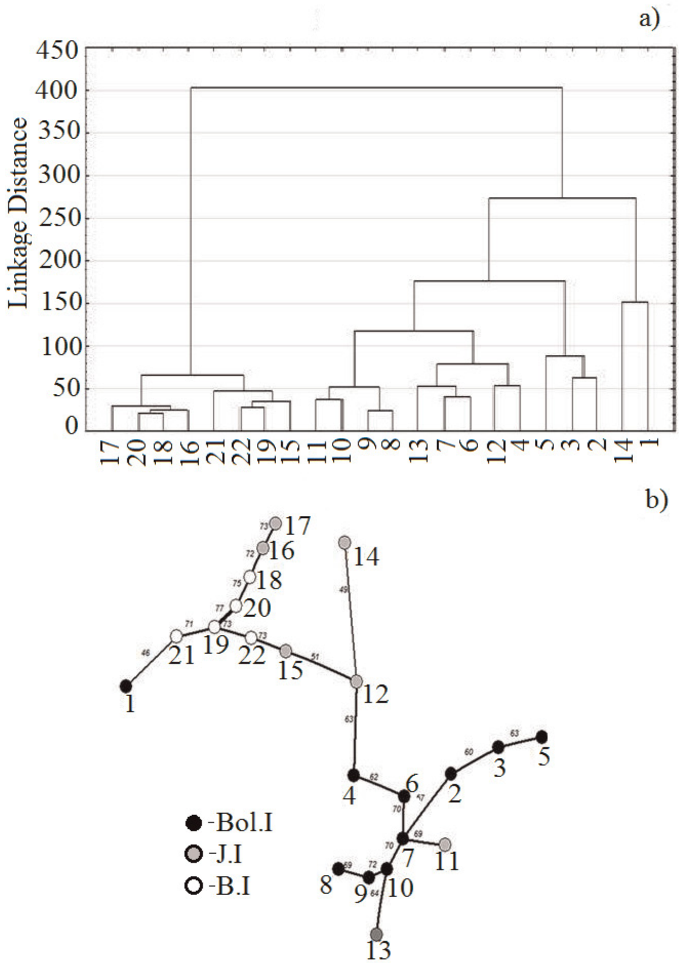

Fig. 7. Dendrograms of taxonomic composition and structure similarity of Lake's Imandra diatom assemblages: a, on the relative number of each taxon (Ward's method and city-block (Manhattan) distances); b, by the quantitative coefficient of Sørensen-Chekanovsky.

Discussion

As a result of our study, the diatom species list of Lake Imandra has been expanded by 148 taxa and 19 genera compared to previous studies (Denisov and Kosova 2017). Our taxonomic data have been included in the patented database 'Algae of the Euro-Arctic region' and in the herbarium of INEP (Borovichov *et al.* 2018).

Our analyses indicate differences in the areas of Lake Imandra in terms of ecological conditions, finding zones both disturbed by human activity and those that have preserved their natural subarctic status (Kagan 2001; Moiseenko *et al.* 2002, 2009a,b).

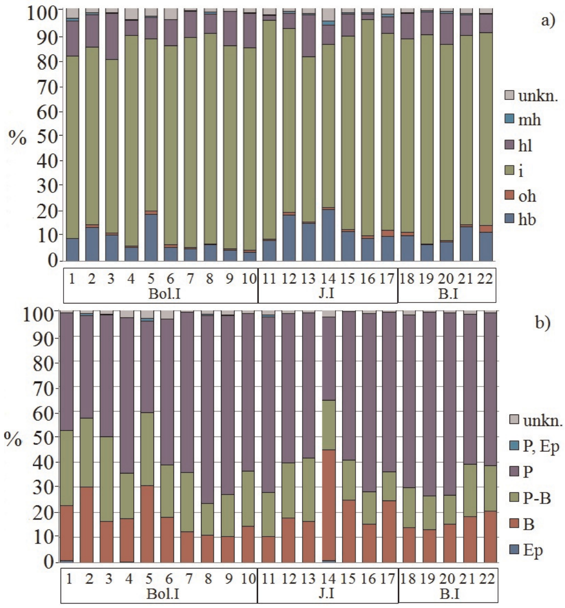

Fig. 8. Distribution of indicator diatoms in the ecological groups: a – salinity tolerance, and b – habitat. Hb – halophobes, oh – oligohalobes, i – indifferents, hl – halophiles, mh – mesohalobes; Ep – epibionts, B – benthic, P–B – plankto-benthic, P – planktic; unkn. species with unknown ecological characteristics.

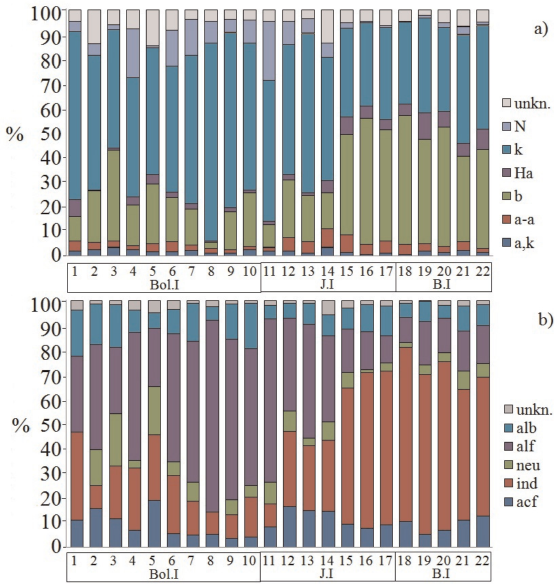

Fig. 9. Distribution of indicator diatoms in the ecological groups. a – biogeographical; b – pH. A,k – arctic-alpine, cosmopolitan, a-a – arctic-alpine, b – boreal, Ha – Holarctic, k – cosmopolitan, N – North; acf – acidophilic, ind – indifferent, neu – neutrophilic, alf – alkaliphilic, alb – alkalibionts; unkn. – species with unknown ecological characteristics.

The distribution of taxonomic richness and the Shannon–Weaver index allows us to conclude that there are significant differences in the conditions for the development of diatoms. For example, large species diversity (3.45–4.04 bit/ind.) in bays (Kurenga, Moncheguba, Viteguba and Tikguba) is a result of relatively shallow depth with substantial growth of vegetation, which could be a substrate for diatoms. Also, rivers are enriching the waters in the Kurenga and Viteguba Bays by rheophilic diatoms (Sharov and Denisov 2021). The greatest taxonomic richness is also in the parts of the lake that are affected by the combined effects of non-ferrous metallurgy, sewage, and anthropogenic eutrophication (Moncheguba and Viteguba) (Moiseenko and Sharov 2019). For diatom communities of Moncheguba Bay, apparently, the most important factor is water pollution by toxic heavy metals, which to some extent inhibits the eutrophication processes (Denisov *et al.* 2020). Thus, different types of impact have combined to lead to high biodiversity (value of H'). A sensitive indicator of the dominant species' abundance is the Simpson polydominance index (1/D). This index confirms the presence of high species diversity in Kurenga, Viteguba and Tikguba Bays. The minimum values of 1/D in the southern Bol.I and northern J.I, especially in Belaya Bay, indicate the dominance of one or a few species that are most abundant relative to others.

Values of species diversity at the studied stations are often inversely proportional to total diatom abundance. The high diatom abundance in the sediments (N_o) is mainly confined to the areas of Lake Imandra with anthropogenic eutrophication processes and reflects primary-production intensity. To a certain extent, the spatial variations of the N_o also indicate the sedimentation conditions in various parts of the lake. Obviously, the most stable sedimentation processes are in the B.I and the western part of the J.I stretches. Despite the high average nutrient content in water, diatom abundance is not so high in Belaya Bay (st. 8) by comparison to the southern Bol.I. The cause could be the high sedimentation rate, accompanied by large amounts of mineral suspension that 'dilute' the diatom valves' concentration in the sediments (Denisov 2007). The minimal N_o is in the Kurenga Bay (st. 1), possibly due to the flow of the river into the bay, which demolishes the deposited material, changing the sedimentation processes.

All of above parameters (including hydrochemical) and the floristic analysis of the diatom-species abundance distribution allowed us to conditionally divide the lake into two parts: (1) the Bol.I and northern part of the J.I, where *Stephanodiscus minutulus*, *Aulacoseira islandica*, *Stephanodiscus alpinus*, *Cyclostephanos dubius*, *Aulacoseira granulata* and *Stephanodiscus neoastraea* are dominant; and (2) central and western part of the J.I and the B.I, with the most abundant diatoms: *Pantocsekiella comensis*, *Aulacoseira alpigena*, *Pantocsekiella rossii*, *Pantocsekiella schumannii* and *Cyclotella radiosa*. Different species composition reflects various environmental conditions. Thus, the Bol.I is the most polluted by anthropogenic activity (Table 1), and the dominant species in this part are indicators of pollution. In addition, the Bol.I stretch is not floristically homogeneous. Basic floristic similarity here is revealed in the southern part of the Bol.I together with northern stations of the J.I. Water quality in this area is influenced by the apatite-industry sewage. Specific DA have been formed in sediments affected by non-ferrous metallurgy (Moncheguba and Viteguba Bays). *Aulacoseira islandica* dominates the DA at these sites and is an indicator of P load and eutrophication, which is described in many studies (Sharov 2008; Shaw Chraïbi *et al.* 2014; Ludikova 2021). In addition, this species is described as toxic resistant, that is, it dominates with high environmental toxicity (Dolgonosov and Moiseenko 2007), and this proves the dual anthropogenic load in the Moncheguba Bay (eutrophication and toxicity). While diatom species typical of subarctic lakes undisturbed by human activities are common in the B.I and part of the J.I.

Autecological structure of the DA confirms the leading role of anthropogenic factors in the formation of the diatoms environment in various parts of Lake Imandra. Typically, freshwater species, predominantly planktonic, are represented in the DA of the lake; the relative abundance of benthic and epiphytes is high only in shallow bays. In the polluted and eutrophicated area, biogeographic cosmopolitan diatoms dominate; the abundance of boreal diatoms is high in conditionally background zones of the lake, which are not directly changed by anthropogenic factors (B.I and western part of J.I). The long-term alkaline sewage impact from industrial enterprises and municipal waters has led to high abundance of alkaliphiles and alkalibiontes in the DA of the Bol.I and northern J.I. The largest number of alkaliphile species is represented in the Belaya Bay, where alkaline sewage of the apatite industry and municipal waters of the towns of Kirovsk and Apatity are discharged (Denisov 2007). Besides, species indifferent to pH dominate in the southern parts of Lake Imandra.

Conclusions

In the course of this study, we identified 378 diatom taxa (lower than the genus, namely species and subspecies) in the DA of Lake Imandra surface sediments. The greatest numbers of species were found within the *Eunotia* and *Pinnularia* genera. Freshwater species were typically the most abundant: planktonic-centric diatoms, predominantly cosmopolitan and boreal species. The floristic features, autecology and the structure of the DA of the studied stations reflect the environmental differences in the studied parts of the lake. Diatom habitats in the lake were determined mainly by the type and power of anthropogenic impact. Based on floristic-similarity analysis and distribution of dominant species, the lake is divided into two large areas with radically different species composition, reflecting various environmental conditions: (1) Bol.I stretch and the northern part of J.I, and (2) the central and western part of J.I and the B.I stretch. In addition, the Bol.I stretch is not floristically homogeneous. Specific DA have formed in sediments affected by the impact of non-ferrous metallurgy and apatite industries' sewage. The long-term alkaline sewage impact from industrial enterprises and municipal waters has led to an increased abundance of alkaliphiles and alkalibiontes in the DA of the Bol.I and northern J.I. Besides, species indifferent to pH dominated in the southern parts of Lake Imandra. High diatom diversity (by Shannon index) was noted for shallow bays with higher aquatic vegetation. The highest diatom abundance (N_o) in DA was found in areas under anthropogenic eutrophication. Thus, the most stable conditions of sedimentation were obviously in the B.I stretch, where the spatial variations of N_o were comparatively low.

Thus, modern DA in various parts of the lake confirm the significant hydrochemical heterogeneity of the environmental habitats and water quality. The main factor determining the modern diatoms' taxonomic composition and structure should be considered the anthropogenic impact. Significant natural environmental factors are water depth, presence of aquatic vegetation and the action of rivers flowing into some bays. DA in the surface sediments can be used for an integrated water-quality assessment of the Lake Imandra ecosystem in recent years. This method would avoid the drawbacks associated with the use of modern phytoplankton, which is too vulnerable to sharp seasonal fluctuations, and it could solve the problem of synchronizing sampling on large lakes.

Acknowledgments. — This research was funded by research project 0226-2019-0045 (results generalization) and partially supported by the RFBR grant 18-05-60125 Arctic (large lakes algae study) and RSF grant 19-77-10007 (hydrochemical analysis and fieldwork). We thank three anonymous Reviewers whose comments helped to improve this manuscript.

References

Agustí S., Krause J.W., Marquez I.A., Wassmann P., Kristiansen S. and Duarte C.M. 2020. Arctic (Svalbard islands) active and exported diatom stocks and cell health status. *Biogeosciences* 17: 35–45.

Barinova S.S., Medvedeva L.A. and Anisimova O.V. 2006. *Diversity of Algal indicators in Environmental Assessment*. Pilies Studio, Tel Aviv (in Russian).

Battarbee R.W. 1986. Diatom analysis. *In:* B.E. Berglund (ed.) *Handbook of Holocene palaeoecology and palaeohydrology*. Wiley, Chichester: 527–570.

Battarbee R.W., Jones V., Flower R., Cameron N., Bennion H., Carvalho L. and Juggins S. 2001. Diatoms. *In*: J. Smol, H.J.B. Birks and M. Last (eds) *Tracking environmental change using lake sediments. Vol. 3: Terrestrial, Algal, and Siliceous Indicators.* Dordrecht, Kluwer: 155–202.

BERGER W.H. and PARKER F.L. 1970. Diversity of planktonic *Foraminifera* in deep-sea sediments. *Science* 168: 1345–1347.

BOROVICHOV YE.A., DENISOV D.B., KORNEYKOVA M.V., ISAEVA L.G., RAZUMOVSKAYA A.V., KHIMICH YU.R., MELEKHIN A.V. and KOSOVA A.L. 2018. Herbarium of INEP KSC RAS. *Trudy Kolskogo Nauchnogo Tsentra RAN* 9: 179–186 (in Russian).

CZEKANOWSKI J. 1909. Zur differential Diagnose der Neandertalgruppe. *Korrespondenzblatt der deutschen Gesellschaft für Anthropologie, Ethnologie und Urgeschichte* 40: 44–47.

DAUVALTER V.A., MOISEENKO T.I. and RODYUSHKIN I.V. 1999. Geochemistry of Rare Earth Elements in Imandra Lake, Murmansk Area. *Geochemistry International* 37: 325–331.

DAUVALTER V.A., MOISEENKO T.I., KUDRYAVTSEVA L.P. and SANDIMIROV S.S. 2000. Accumulation of heavy metals in Lake Imandra because of its pollution with industrial waste. *Water Resources* 27: 279–287.

DAUVALTER V.A. and DENISOV D.B. 2015. Sediments and Paleolimnology. Chapter 4: Evaluation and development of the lake monitoring network. *In:* J. Ylikörkkö, G.N. Christensen, N. Kashulin, D. Denisov, H.J. Andersen and E. Jelkänen (eds) *Environmental Challenges in the Joint Border Area of Norway, Finland and Russia. Reports 41/2015.* Centre for Economic Development, Transport and the Environment for Lapland, Finland: 116–131.

DAUVALTER V.A. and KASHULIN N.A. 2018. Mercury pollution of Lake Imandra Sediments, the Murmansk region, Russia. *International Journal of Environmental Research* 12: 939–953.

DAVYDOVA N.N. 1985. *Diatoms-indicators of ecological conditions of reservoirs in the Holocene.* Nauka, Leningrad (in Russian).

DENISOV D.B. 2007. Changes in the hydrochemical composition and diatomic flora of bottom sediments in the zone of influence of metal mining production (Kola Peninsula). *Water Resources* 34: 682–692.

DENISOV D.B. and KOSOVA A.L. 2017. Diversity of diatoms (*Bacillariophyta*) of Lake Imandra (Kola Peninsula). *Proceedings of the scientific session, GI KSC RAS:* 448–450 (in Russian).

DENISOV D.B. and GENKAL S.I. 2018. Centric diatom of Lake Imandra (Kola Peninsula, Russia). *International Journal on Algae* 20: 27–36.

DENISOV D.B., TERENTJEV P.M., VALKOVA S.A. and KUDRYAVTZEVA L.P. 2020. Small Lakes Ecosystems under the Impact of Non-Ferrous Metallurgy (Russia, Murmansk Region). *Environments* 7: 42–55.

DOLGONOSOV B.M. and MOISEENKO T.I. 2007. Modeling the succession of diatomic complex under growing industrial load on an aquatic ecosystem. *Water Resources* 34: 301–313.

GUIRY M.D. and GUIRY G.M. 2020. *AlgaeBase*, World-wide electronic publication. National University of Ireland, Galway.

JUSE A.P., PROSHKINA-LAVRENKO A.I. and SHESHUKOVA V.S. 1949. *Diatomic analysis. 1.* State publishing house of geological, Moscow – Leningrad (in Russian).

KAGAN L.YA. 2001. Human-induced changes in the diatom communities of Lake Imandra. *Water Resources* 28: 297–306.

KASHULIN N.A., DENISOV D.B., VALKOVA S.A., VANDYSH O.I. and TERENTIEV P.M. 2012. Current trends in freshwater ecosystems of the Euro-Arctic region. *Proceedings of Kola Science Center RAS* 1: 6–53 (in Russian).

KASHULIN N.A., DAUVALTER V.A., DENISOV D.B., VALKOVA S.A., VANDYSH O.I., TERENTJEV P.M. and KASHULIN A.N. 2017. Selected aspects of the current state of freshwater resources in the Murmansk region, Russia. *Journal of Environmental Science and Health. Part A: Toxic/Hazardous Substances and Environmental Engineering* 52: 921–929.

KRAMMER T. and LANGE-BERTALOT H. 1986. *Bacillariophyceae (Naviculaceae). 2(1). Süsswasserflora von Mitteleuropa*. Gustav Fisher Verlag, Stuttgart.

KRAMMER T. and LANGE-BERTALOT H. 1988. *Bacillariophyceae (Bacillariaceae, Epithemiaceae, Surirellaceae). 2(2). Süsswasserflora von Mitteleuropa*. Gustav Fisher Verlag, Stuttgart.

KRAMMER T. and LANGE-BERTALOT H. 1991a. *Bacillariophyceae (Centrales, Fragilariaceae, Eunotiaceae). 2(3). Süsswasserflora von Mitteleuropa.* Gustav Fisher Verlag, Stuttgart.

KRAMMER T. and LANGE-BERTALOT H. 1991b. *Bacillariophyceae (Achnanthaceae, Kritische Erganzungen zu Navicula (Lineolate) und Gomphonema Gesamtliteraturverzeichnis). 2(4). Süsswasserflora von Mitteleuropa*. Gustav Fisher Verlag, Stuttgart.

KRAMMER K. 2000. *Diatoms of Europe. Diatoms of the European Inland Waters and Comparable Habitats. Vol. 1. The genus Pinnularia*. A.R.G. Gantner Verlag K.G, Ruggell.

KRAMMER K. 2002. *Diatoms of Europe. Diatoms of the European Inland Waters and Comparable Habitats. Vol. 3. Cymbella.* A.R.G. Gantner Verlag K.G, Ruggell.

KRAMMER K. 2003. *Diatoms of Europe. Diatoms of the European Inland Waters and Comparable Habitats. Vol. 4. Cymbopleura, Delicata, Navicymbula, Gomphocymbellopsis, Afrocymbella.* A.R.G. Gantner Verlag K.G, Ruggell.

LANGE-BERTALOT H. 2001. *Diatoms of Europe. Diatoms of the European Inland Waters and Comparable Habitats. Vol. 2. Navicula sensu stricto. 10 Genera Separated from Navicula sensu lato. Frustulia.* A.R.G. Gantner Verlag K.G, Ruggell.

LUDIKOVA A.V. 2021. Long-term studies of surface-sediment diatom assemblages in assessing the ecological state of Lake Ladoga, the largest European Lake. *Geography, Environment, Sustainability* 14: 251–262.

MOISEENKO T.I., DAUVALTER V.A., LUKIN A.A., KUDRYAVTSEVA L.P., ILYASHCHUK B.P., ILYASHCHUK L.I., SANDIMIROV S.S., KAGAN L.YA., VANDYSH O.M., SHAROVA YU.N., KOROLEVA I.N. and SHAROV A.N. 2002. *Anthropogenic changes in the ecosystem of the Lake Imandra.* Nauka, Moscow (in Russian).

MOISEENKO T.I., GASHKINA N.A., SHAROV A.N., VANDYSH O.I. and KUDRYAVTSEVA L.P. 2009a. Anthropogenic transformations of the Arctic ecosystem of Lake Imandra: tendencies for recovery after a long period of pollution. *Water Resources* 36: 290–303.

MOISEENKO T.I., SHAROV A.N., VANDYSH O.I., KUDRYAVTSEVA L.P., GASHKINA N.A. and ROSE C. 2009b. Long-term modification of Arctic Lake ecosystems: Reference condition, degradation under toxic impacts and recovery (case study Imandra Lakes, Russia). *Limnologica* 39: 1–13.

MOISEENKO T.I. and SHAROV A.N. 2010. The retrospective analysis of aquatic ecosystem modification of Russian large lakes under antropogenic impacts. *Ecotoxicology around the Globe* 12: 1–17.

MOISEENKO T.I. and SHAROV A.N. 2019. Large Russian Lakes Ladoga, Onega, and Imandra under strong pollution and in the period of revitalization: a review. *Geosciences* 9: 1–16.

NOVAKOVSKIY A.B. 2014. Presentation of the Module "Graphs" for Analyzing Geobotanical Data. *Journal of Earth Science and Engineering* 4: 88–93.

RAND M.C., GREENBERG A.E. and TARAS M. J. 1975. *Standard method for examination of water and wastewater.* American Water Works Association, Denver, CO, USA.

SANDIMIROV S.S., KUDRYAVCEVA L.P., DAUVALTER V.A., DENISOV D.B. and KOSOVA A.L. 2019. *Methods of ecological research of Arctic water bodies.* Izd. MSTU, Murmansk (in Russian).

SHAROV A.N. 2008. Phytoplankton as an indicator in estimating long-term changes in the water quality of large lakes. *Water Resources* 35: 668–663.

SHAROV A.N. and DENISOV D.B. 2021. Algae of Lakes in the European North of Russia. Chapter 7. *In:* O.S. Pokrovsky, Y. Bespalaya, L.S. Shirokova and T.Y. Vorobyeva (eds) *Lake water: properties and uses (Case studies of Hydrochemistry and Hydrobiology of Lakes in Northwest Russia)*. Nova Science Publishers, New York: 153–191.

SHAV CHRAÏBI V.L., KIRETA A.R., REAVIE E.D., CAI M. and BROWN T.N. 2014. A paleolimnological assessment of human impacts on Lake Superior. *Journal of Great Lakes Research* 40: 886–897.

SKOGHEIM O.K. 1979. *Rapport fra Arungenprosjectet. No 2*. As-NLN, Oslo.

SÖRENSEN T. 1948. A method of establishing groups of equal amplitude in plant sociology based on similarity of species content. *Kongelige Danske Videnskabernes Selskab. Biologiske Skrifter*. 5: 1–34.

STOOF-LEICHSENRING K.R., PESTRYAKOVA L.A., EPP L.S. and HERZSCHUH U. 2020. Phylogenetic diversity and environment form assembly rules for Arctic diatom genera – a study on recent and ancient sedimentary DNA. *Journal of Biogeography* 47: 1166–1179.

VAN DAM H., MERTENS A. and SINKELDAM J. 1994. A coded checklist and ecological indicators values of freshwater diatoms from the Netherlands. *Netherlands Journal of Aquatic Ecology* 28: 117–133.

WASHINGTON H.G. 1984. Diversity, biotic and similarity indices: a review with special relevance to aquatic ecosystems. *Water Research* 18: 653–694.

Received 12 February 2021
Accepted 31 July 2021