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Assessment of contamination of recent sediments of a large reservoir in the catchment area of Arctic Ocean, Northern Europe

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Abstract: The chemical composition of recent sediments of the Vygozero Reservoir, located in the North of Europe, in the Republic of Karelia (the catchment of Arctic Ocean), has been analysed. The level of enrichment and depletion of chemical elements, including trace elements, of the sediments relative to the Clarke numbers for the continental crust has been estimated. Elevated levels of Sb, Pb, Sn, Bi, W, Cu, and other elements in the sediments of the Vygozero Reservoir have been revealed in comparison with the concentrations of these elements in the background layers of the reservoir's sediments and their content in the sediments of small lakes of the south of the Republic of Karelia. It has been established that the main factor in the accumulation of these metals in the lake is the long-distance transport of pollutants from local anthropogenic sources located in Karelia, and from sources in neighbouring regions. In the vicinity of the town of Segezha, elevated V and Ni contents were revealed in the cores of the studied sediments, which indicates the impact on the reservoir of emissions from the fuel-oil thermal power plant. Based on the calculation of the geoaccumulation index (I_{geo}) and pollution load index (PLI), the level of pollution of the Vygozero Reservoir in the study areas was estimated. It was found that the northern part of the waterbody, where the settlements Segezha and Nadvoitsy and industrial enterprises associated with these towns are located, are subject to the greatest load.

Keywords: Arctic, Vygozero Reservoir, freshwater sediments, trace elements, long-range transport of pollutants.

Introduction

The analysis of the chemical composition of water and recent sediments of the largest waterbodies in Europe is a significant component in assessing their current ecological state (Davydova *et al.* 1999; Flerov *et al.* 2000; Wihlborg and Danielsson 2006; Virkutyte *et al.* 2008; Strakhovenko *et al.* 2018). This is of great importance for both the fundamental science and the practical application of the knowledge gained, given that most of the large lakes are actively used for economic and recreational purposes, and serve as sources of drinking water for settlements. The above-mentioned analysis is most relevant for studies of environmental pollutant behaviour. There are trace elements that can be dangerous for living organisms. Nowadays, these categories include elements such as Pb, Cd, Hg, As, Tl, V, Ni, Cu, Zn, Co, Cr, Bi, W, Sb, and Sn. At the same time, some of these elements have pronounced useful qualities; however, in high concentrations in water and sediments of waterbodies, they all can exhibit toxic properties. Moreover, they tend to accumulate in various components of aquatic ecosystems, including living organisms themselves, causing irreversible changes and even death (Gashkina *et al.* 2020).

Thus, it is extremely important to have an insight into the level of accumulation of trace elements in an environment containing the biotic constituent. The most informative studies of lakes concern recent sediments, because their geochemistry can simultaneously help to establish the current state of the reservoirs and reconstruct the historical dynamics of the accumulation of certain elements, including environmental pollutants (Kuwae *et al.* 2013; Smal *et al.* 2015; Fang *et al.* 2019; Sałata *et al.* 2019). Emissions from industrial enterprises and transport play the leading role in the formation of geochemical anomalies of hazardous trace elements in recently accumulated sediments in waterbodies (Dauvalter 2012; Kuwae *et al.* 2013). At the same time, given the large airborne migration potential of metals, increased accumulation of pollutants at the bottom of waterbodies can be recorded even at a large distance (up to thousands of kilometres) from direct sources of anthropogenic emissions (Krachler *et al.* 2006; Vinogradova *et al.* 2017).

The Republic of Karelia (a federal subject of the Russian Federation) is rich in water resources. The largest freshwater reservoirs of the region are the Ladoga and Onega lakes. The third-largest reservoir in Karelia, the tenth-largest in Europe, is the Vygozero Reservoir (or Vygozero) (Filatov and Kukharev 2013). The Vygozero Reservoir is the largest body of water in the White Sea basin (the catchment of Arctic Ocean), and belongs to the catchment area of the Vyg River (Fig. 1). In its natural state in the form of a lake, the reservoir existed until the early 1930s; its water surface area reached 561 km^2 (Aleksandrov *et al.* 1959). In the process of economic use, the original lake has twice undergone dramatic hydrotechnical transformations (Litvinenko *et al.* 2014). The first change was associated with the construction of the White Sea-Baltic Canal and the creation of

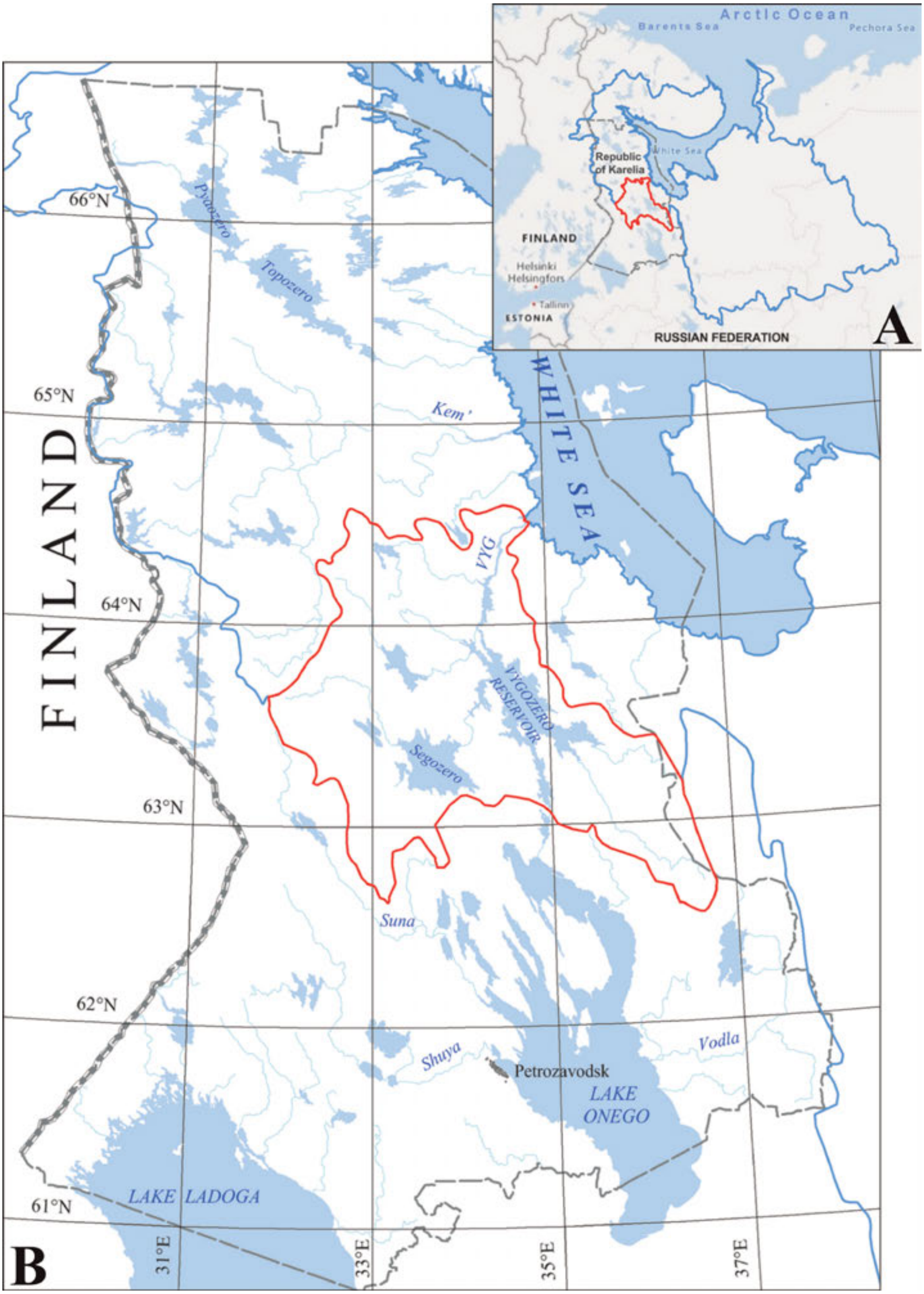

Fig. 1. Geographical position of the Vygozero Reservoir (A) and its catchment (B). The red line is the catchment of Vygozero, the blue line on the top part of the figure is the catchment of the White Sea.

the Vygozero Reservoir (1933). The construction of the Nadvoitskaya regulating dam raised the level of the reservoir by 6 m, more than doubling its area (Table 1) and making the Vygozero Reservoir part of the White Sea-Baltic Canal. The second transformation was associated with the hydropower development of the Vyg River basin and the creation of the Vygozero-Onda Reservoir (1957). However, now this name is no longer used – the current official name of the waterbody is Vygozero Reservoir. After the construction of the self-regulating Maygubsky canal changed the river's direction, the canal pound of the Ondskaya hydroelectric power station and the Vygozero Reservoir were connected. As a result, during the spring flood, excess water from the Onda River began to flow into the Vygozero Reservoir and accumulate in it. During the dry period, water from the reservoir began to be supplied to the Ondskaya hydroelectric power plant.

Table 1

The main morphometric characteristics of the Vygozero Reservoir in different periods of operation (Litvinenko *et al.* 2014).

Name of waterbody		Lake Vygozero	Vygozero Reservoir	Vygozero-Onda Reservoir
Period		until 1932	1934–1955	1957–1974
Height above sea level, m		82.7	88.8	89.1
Area, km^2		561	1196	1270
Depth, m	average	6.1	7.2	7.1
	max	18.0	25.0	25.0
Volume, km^3		3.4	8.7	9.1

The Vygozero Reservoir is a navigable waterbody through which ships regularly pass from Lake Onega to the White Sea and in the opposite direction. On the shore of the reservoir is located the town of Segezha (population of 26,000), with the Segezha Pulp and Paper Mill, operating since 1939, and a combined heat and thermal power plant that uses fuel oil. In addition, in the immediate vicinity of the Vygozero Reservoir coastline is located the settlement of Nadvoitsy (population of 7,500) with its aluminium plant, which has been operating since 1954. In this regard, the northern part of the reservoir is the most polluted in comparison with other areas of the reservoir (Filatov and Kukharev 2013). Despite the fact that the ecological condition of the Vygozero Reservoir has been monitored for a long time, detailed studies of the accumulation of trace elements in the sediments of the lake have not yet been carried out. Thus, the purpose of this work is to assess the level of accumulation of trace elements in the recent layers of sediments of the Vygozero Reservoir and the ecological interpretation of the obtained geochemical data.

Materials and methods

The sediment sampling was carried out from the research vessel "Ecolog", during expeditions in the summer of 2017 and 2018. The surface sediment samples were taken using the Limnos sampler (made in Finland). To select deeper (background) layers of recent sediments, the GOIN sampler (manufactured in Russia) was used. A detailed litho-stratigraphic description of the sediment cores and their photographs were conducted directly on shipboard. The sediment cores sampled by the Limnos sampler were divided into 2 cm layers. A total of five sediment cores were sampled at the stations indicated in Figure 2 with the core thickness ranging from 22 to 42 cm. Note that all these collected

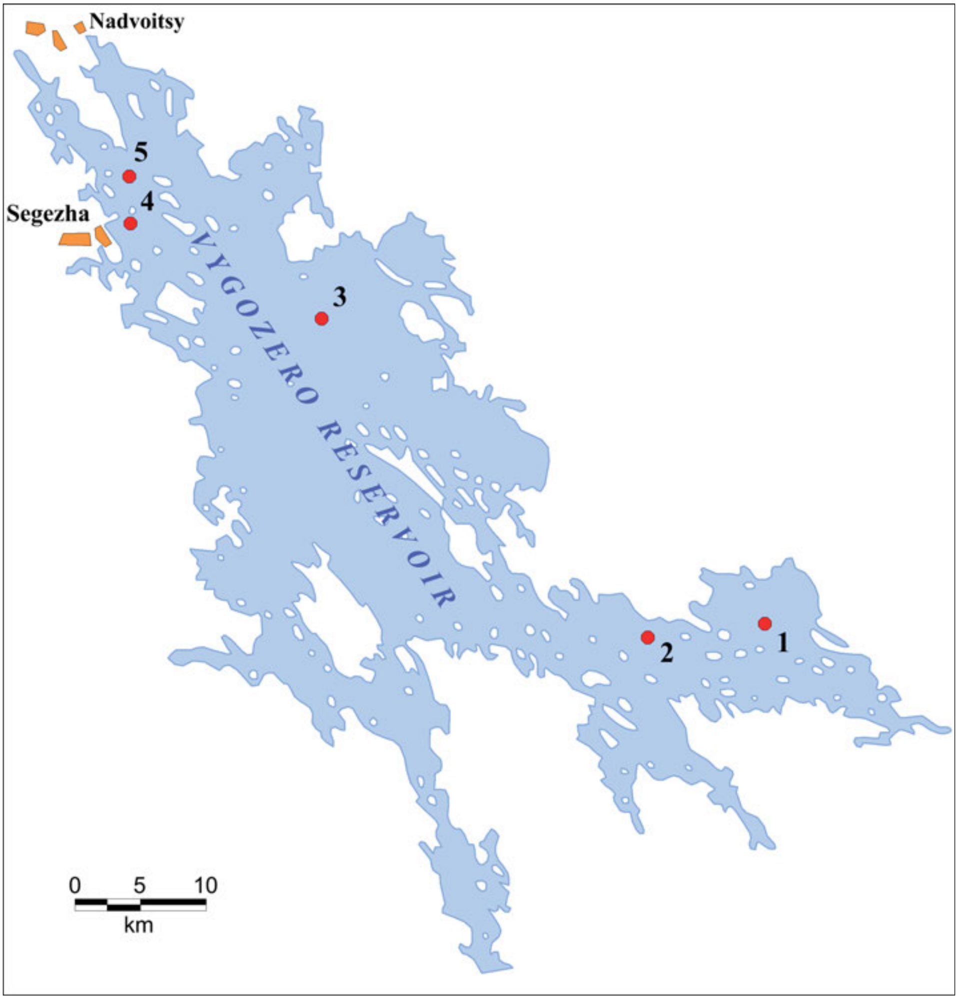

Fig. 2. Sediment sampling stations (filled circles).

sediments were formed after the water level in the lake rose and it became a reservoir. In addition, sediments corresponding to the natural state of the Vygozero Reservoir (Lake Vygozero) were sampled at one of the stations for background purposes.

Next, samples were delivered to the laboratory and placed in a refrigerator, where they were stored at a temperature of about 4°C. Before the analysis, sediment samples were dried to an air-dried state at room temperature, and to an absolutely dry state – in an oven at a temperature of about 110°C. The analytical work was carried out under laboratory conditions at the Institute of Geology of the Karelian Research Centre of RAS and the Northern Water Problems Institute of the Karelian Research Centre of RAS.

The granulometric composition of sediments was determined using a multi-purpose particle analyser LS13 320 series (Beckman Coulter). According to the ISO 13320-1 standard, the technical features of the device allow the analysis of particles ranging in size from 0.04 μm to 2.0 mm. Due to the fact that the accuracy of determining the particle size distribution directly depends on the preparation of the material for analysis, the selection of weighed portions included careful averaging of the material by the quartering method. Loss of ignition (LOI) was determined in accordance with GOST (State Standard) P 57065-216 by the weight method after heating a sample of air-dried samples at a temperature of 550°C to constant weight.

To assess the total concentrations of trace elements, including hazardous ones, open acid decomposition of samples was carried out using HF, HNO_3, and HCl. For analysis, we used analytical samples of weight 0.1 g. As a blank sample, we used a mixture of decomposition acids that underwent the same sample preparation procedure as studied samples and one standard sample (the chemical composition of the bottom silt of the Lake Baikal BIL-1 GSO 7126-94). The determination of trace element concentrations, including metals (Li, Ti, V, Cr, Co, Ni, Cu, Zn, Rb, Sr, Zr, Nb, Mo, Cd, Sn, Sb, Cs, Ba, rare earth elements [REE], Hf, W, Tl, Pb, Bi, Th, U), was performed using the mass spectrometric method on an XSeries-2 ICP-MS instrument. This technique is described in detail in a previously published article (Slukovskii 2020) that also provides the definition of measurement errors for each chemical element.

The concentrations of chemical elements in the sediments of lakes in Karelia and the Murmansk region were normalized using data on the average content of elements in the continental crust (Wedepohl 1995), and in sediments from small lakes in the southern part of the Republic of Karelia (accepted for background) (Slukovskii 2020).

Data processing was performed using Microsoft Excel 2007. Factor analysis and Pearson's correlation analysis were performed using Statistica 10. Inkscape 0.48.4 was used to illustrate the results graphically.

The environmental interpretation of geochemical data was based on the calculation of the pollution load index (PLI) (Tomlinson *et al.* 1980; Suresh *et al.* 2011):

$$PLI = (CF_1 * CF_2 * ... CF_n)^{1/n},$$

where CF is the concentration coefficient (the ratio of the concentration of the metal to the background concentration of this element) and n is the number of analysed elements. Depending on the value of the PLI index, the level of contamination can be estimated as low (PLI < 1), moderate (1 < PLI < 2), high (2 < PLI < 3), or extremely high (3 < PLI).

The geoaccumulation index (I_{geo}) of metals in the sediments of each lake was calculated with the formula

$$I_{geo} = \log_2 \left(\frac{C}{1.5 \text{ x } B}\right),$$

where C is the concentration of elements in the studied sediment layer and B is the background concentration of the element, determined in the lowest layer of the sediment core (Müller 1979). The following scale can be used to estimate the level of metal pollution in a lake: unpolluted ($I_{geo} \leq 0$), unpolluted to moderately polluted ($0 < I_{geo} < 1$), moderately polluted ($1 < I_{geo} < 2$), moderately to strongly polluted ($2 < I_{geo} < 3$), strongly polluted ($3 < I_{geo} < 4$), strongly to extremely polluted ($4 < I_{geo} < 5$) and extremely polluted ($I_{geo} > 5$).

Results and Discussion

Fractions from 0.01 to 0.25 mm prevail in the granulometric composition of the investigated recent sediments (Table 2). Particles of the indicated sizes account from 73 to 81% of the sediments. Particles from 0.25 to 2.00 mm make

Table 2

Average contents of granulometric fractions in the recent sediments of the Vygozero Reservoir.

Fractions, mm	Stations			
	#1	#2	#3	#5
2.0–1.0	1.6	0.0	1.5	0.0
1.0–0.5	8.7	1.1	6.1	2.0
0.5–0.25	11.9	15.0	12.5	12.4
0.25–0.1	30.4	36.0	29.2	27.0
0.1–0.05	21.2	19.6	19.5	21.1
0.05–0.01	22.8	25.2	24.3	31.9
0.01–0.005	3.6	3.9	4.2	4.9
<0.005	0.2	0.2	0.2	0.2

up from 14 to 22% of the sediments. The finest fractions (<0.01 mm) play the least significant role for studied sediments.

The investigated recent sediments of the Vygozero Reservoir are characterized by the content of organic matter (according to LOI) from 22% to 50%. The median organic matter content for all sampling stations is 36.9%. The highest accumulation of organic matter (38–50%) was noted in the upper layers of the core of recent sediments at station #4, which is the closest to the town of Segezha (Fig. 1). In the same core, in the lower layers, the amount of organic matter is significantly reduced to 25%. This tendency was found for all the studied sediment cores (in the northern, central, and southern parts of the Vygozero Reservoir) (Fig. 3). Similar patterns can be observed in the surface layers of sediments of other large waterbodies of northwestern Russia, also located on the territory of the White Sea catchment, for example, in the sediments of Lake Onega in Karelia and Lake Imandra in the Murmansk region (Dauvalter 2012; Belkina 2017). The pulp and paper, and woodworking industries are the main anthropogenic source of organic pollution in the northern part of the Vygozero Reservoir, affecting the enrichment of sediments in this area with organic matter. It explains well the maximum level of organic matter at station #4, given that the town-forming enterprise of Segezha is the pulp and paper mill.

The vicinity of the plant also affected the colour of sediments sampled at stations #5 and #4. In the studied sediment cores, the upper layers are composed of black silts, the formation of which is associated with the commissioning of a biological treatment plant and a diffuse discharge of the plant's wastewater, and (as a result) the transfer and accumulation of fine suspended matter along the bottom depressions along the path of wastewater distribution (Potakhin *et al.* 2018). Toward the bottom of the cores, brown silts have been formed after the transformation of the waterbody into a reservoir in 1933. This means that all the studied sediments are no more than 85 years old, and that the uppermost layers

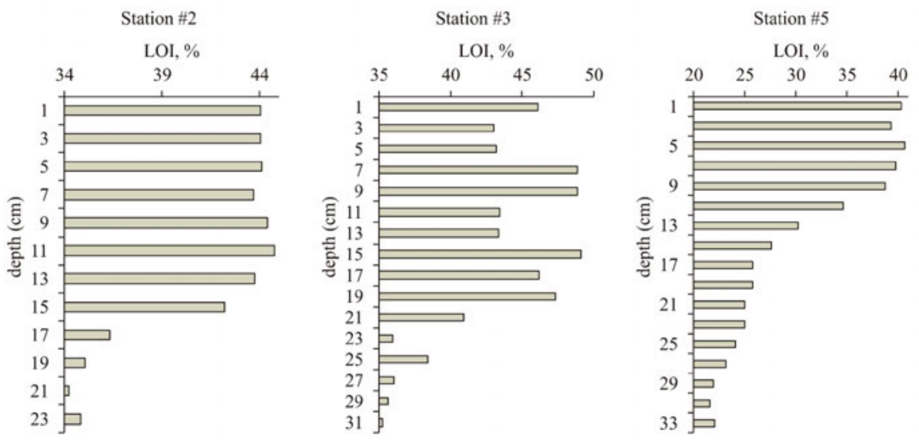

Fig. 3. Vertical distribution of organic matter in the sediment cores of the Vygozero Reservoir.

were probably formed in the last 30–40 years (Potakhin *et al.* 2018). At the same time, the layers of sediments formed before the transformation of the lake into a reservoir are green or greenish brown in colour and contain a significantly smaller amount of organic matter. The content of organic matter in green and brownish-green silts is two or three times lower than in the brown and black sediments of the Vygozero Reservoir (Potakhin *et al.* 2018).

A comparison of the concentrations of all chemical elements in the studied sediments of the Vygozero Reservoir with the composition of the continental crust (Wedepohl 1995) (Fig. 4) showed excessive accumulation of Zn, Mo, Cd, Sb, Pb and Bi in the recent sediments of all stations. At the same time, in the conditional background layer of the Vygozero Reservoir sediments, a noticeably lower content of Sb, Pb, and Bi, as well as Sn and W, was observed in comparison with more recent sediments. Similarly, in comparison with the continental crust, there is an enrichment of recent sediments of small lakes in the south of the Arkhangelsk region (also the catchment area of the White Sea) in such elements as Pb, Sb, Cd, and Bi (Starodymova *et al.* 2016). This is due to the influence of long-range atmospheric transport (Krachler *et al.* 2006; McConnell *et al.* 2019), which traditionally enriches the landscapes of the Republic of Karelia and neighbouring regions (Vinogradova *et al.* 2017; Slukovskii *et al.* 2020c). Increased accumulation of Cd, Zn, and Mo was noted in both the recent and the background sediments, which may be associated with the peculiarities of the natural level of these metals in the territory of Karelia, because earlier their increased concentrations were noted in the sediments of small lakes in this region and in the sediments of Lake Onega (Strakhovenko *et al.* 2018; Slukovskii 2020; Slukovskii and Dauvalter2020). At the same time, it should be borne in mind that Cd is also an agent for the long-range transport of pollutants, and that its increased accumulation in the recent layers of sediments of lakes in northern Europe largely depends on this process.

Interestingly, the background layer of the Vygozero Reservoir has a slightly higher content of Co, Zr, Hf, and rare earth elements (REE) (Fig. 4), which may be due to the significant presence of these metals in the terrigenous fraction of the sediments, given that the conditional background layers of the lake sediments are more enriched in them. For example, studies of the sediments of small lakes in Siberia revealed that the content of lanthanides is much higher in terrigenous-carbonate and organo-terrigenous sediments than in organic sediments (Strakhovenko 2011). Similarly, significantly fewer lanthanides are accumulated in organogenic sediments of small lakes in Karelia than in clays or clay-silty sediments (Strakhovenko *et al.* 2018). One should also note that, in the studied cores of sediments from Vygozero Reservoir, with a decrease in the content of organic matter in the sediments and, consequently, an increase in the terrigenous component, an increase in the concentrations of rare earth elements occurs. The value of the correlation coefficient between the LOI and the value of REE in the studied sediment samples was $r = -0.84$ ($p < 0.01$).

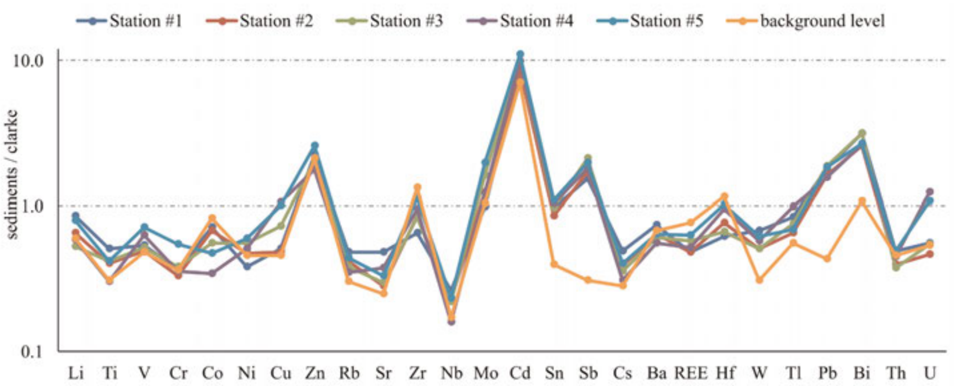

Fig. 4. Normalization of the concentrations of elements in the surface layer of sediments of Vygozero Reservoir by the average of the composition of the continental crust (Wedepohl 1995).

In relation to the background content of various chemical elements in the sediments of small lakes in the southern part of Karelia (Slukovskii 2020), the sediments of the Vygozero Reservoir are noticeably enriched in Li, Ti, Cr, Co, Rb, Sr, Zr, Nb, Sn, Cs, Hf, Tl, Pb, and Bi. Amid these metals, alkali and alkaline earth metals are especially distinguished. Their increased content can be associated with the terrigenous fraction, which is present in a significantly smaller amount in organogenic and organo-silicate sediments of small forest and bog waterbodies (Strakhovenko 2011). In order to reveal the influence of technogenic factors on the formation of geochemical features of recent sediments of the Vygozero Reservoir, the median concentrations of various elements in the sediment cores were normalized using the reservoir's own background (Fig. 5). At almost all stations, the sediments were enriched in Sb, Pb, Bi, and Sn, and in some parts of the Vygozero Reservoir, the sediments were enriched in Cu, W, and U. The latter facts may be associated with natural factors; at least in the territory of the Precambrian shield, natural anomalies of some of these metals

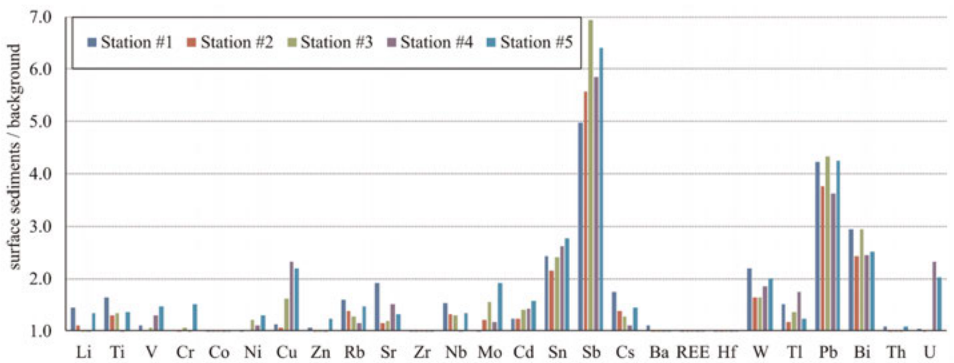

Fig. 5. Normalization of the concentrations of elements in the studied lake sediments in comparison with the background level (the south of Karelia; Slukovskii 2020).

may occur in modern sediments of lakes and swamps (Vodyanitskii *et al.* 2019; Slukovskii *et al.* 2020d).

The nature of the impact of anthropogenic emissions on the investigated waterbody is also illustrated by the vertical distribution of trace elements in the cores of the Vygozero Reservoir sediments (Fig. 6). The obtained charts clearly show an increase in the concentrations of Pb, Sn, Sb, Cd, and Bi from the lowest layers of the cores to the uppermost. It is these five noted elements that have the greatest excess over the lake background in the studied sediment cores. For example, for Bi and Sn, the excess reaches 4 times, whereas for Pb and Sb – 5 and 12 times respectively (Fig. 5). Despite the studied sediments are the result of the accumulation of sedimentary matter in the reservoir over the past approximately 30–50 years, the geochemical data was compared them with similar studies in small lakes, where there was a continuous sedimentation of last 100–150 years.

It has been revealed that similar trends in the behaviour of Pb, Sb, Cd, and other environmental pollutants in the Vygozero Reservoir and in small lakes of the South Karelia (Slukovskii *et al.* 2020b; Slukovskii and Dauvalter 2020), Lake Onega (Belkina *et al.* 2016; Belkina and Kulik 2020), Lake Ladoga (Davydova *et al.* 1999) still speak of a continuous process of the supply of these metals to water environments as a result of atmospheric transport, as evidenced by the studies of the last 10–15 years (Vinogradova and Ivanova 2013; Vinogradova *et al.* 2017).

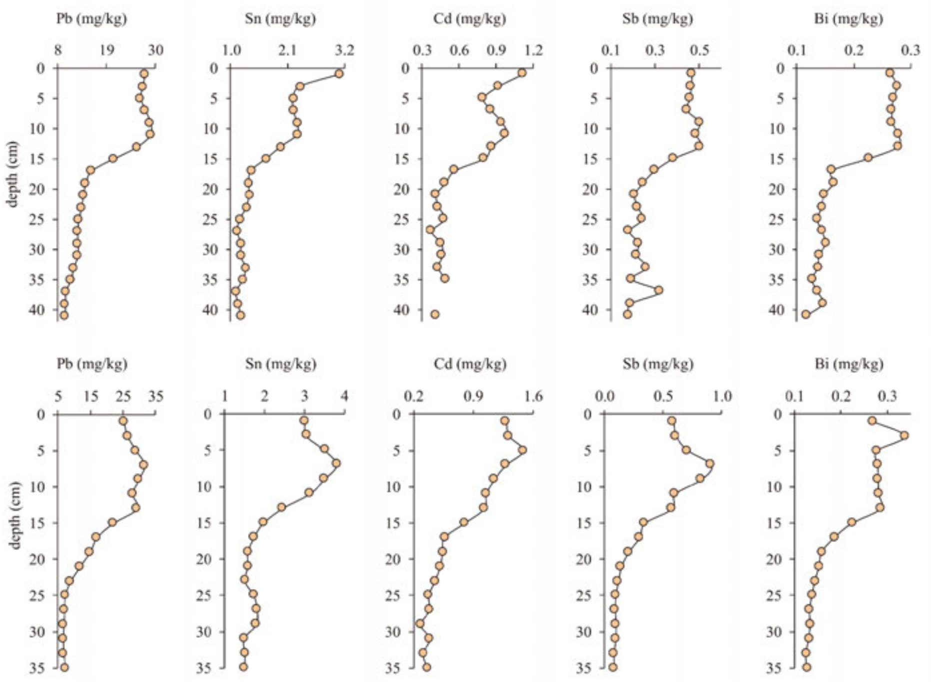

Fig. 6. The vertical distribution of Pb, Sn, Cd, Sb and Bi concentrations in the sediment cores of the Vygozero Reservoir at the stations #5 – top row and #1 – bottom row.

In particular, these works note the great role of Pb and Cd in the environmental pollution of the Republic of Karelia. The main directions of the supply of metals to the territory of the region are north from the direction of the Murmansk region and southwest from the direction of the Leningrad Oblast, St. Petersburg, and European countries. Results of studies of lakes from the Murmansk Region, which are included in the north part of the White Sea catchment, strongly suggest it. A similar situation exists in the case of sediments from the Lake Imandra, the largest waterbody of the Murmansk Region (Dauvalter 2012; Dauvalter and Kashulin 2018; Dauvalter 2020).

The correlation analysis revealed close relationships between the concentrations of the metals indicated in Figures 4 and 5 (Table 3). In particular, a close relationship is noted in the pairs Pb–Bi (0.88), Pb–Cd (0.88), Pb–Sn (0.85), Bi–Sn (0.74), and Bi–Cd (0.87). Lead is also closely related to Sb (r = 0.70), which was previously noted for sediments of small lakes in the southern part of Karelia (Slukovskii *et al.* 2020c; Slukovskii and Dauvalter 2020). To a large extent, the relationship of these metals is dictated by the combustion of furnace coal at industrial enterprises around the world (Krachler *et al.* 2006; Pacyna *et al.* 2007; McConnell *et al.* 2019), given that both Pb and Sb are part of coal (Yudovich and Ketris 2005). Cadmium and bismuth are also components of coal, so both elements have tendencies to accumulate, like Pb and Sb in recent sediments of the Vygozero Reservoir. In addition, until the early 2000s, Pb continued to be released into the atmosphere, and then – into terrestrial and aquatic ecosystems

Table 3

Results of Pearson's paired correlation analysis between trace elements in the sediments of the Vygozero Reservoir ($n = 61$, $r_{crit.} = 0.327$ [$\alpha = 0.01$], $r_{crit.} = 0.252$ [$\alpha = 0.05$]).

	LOI	V	Cr	Co	Ni	Cu	Zn	Mo	Cd	Sn	Sb	W	Tl	Pb
V	0.22													
Cr	0.04	0.21												
Co	0.07	-0.13	0.05											
Ni	0.38	0.81	0.46	0.21										
Cu	0.23	0.63	0.75	-0.21	0.73									
Zn	0.16	0.34	0.51	0.50	0.63	0.52								
Mo	-0.37	0.07	0.36	0.35	0.31	0.23	0.44							
Cd	0.65	0.42	0.38	0.43	0.73	0.53	0.74	0.20						
Sn	0.68	0.38	0.54	0.20	0.67	0.67	0.61	0.04	0.85	1.00				
Sb	0.57	0.11	0.31	0.19	0.43	0.39	0.35	0.19	0.68	0.69				
W	0.44	0.32	0.38	-0.03	0.51	0.45	0.23	0.26	0.47	0.47	0.54			
Tl	0.22	0.44	0.41	0.26	0.55	0.51	0.35	0.17	0.54	0.49	0.25	0.37		
Pb	0.75	0.18	0.32	0.38	0.50	0.39	0.61	0.08	0.88	0.85	0.70	0.40	0.35	
Bi	0.75	0.22	0.15	0.46	0.56	0.28	0.49	0.15	0.87	0.74	0.68	0.46	0.45	0.88

around the world, through exhaust emissions from road transport, owing to the tetraethyl lead added to gasoline to improve the quality of motor fuel (Escobar *et al.* 2013; Hosono *et al.* 2016). This metal accumulated and accumulates most intensively in soils and sediments of waterbodies of urban areas, which, for example, is typical of the territory of the Republic of Karelia, and for the neighbouring Murmansk region (Slukovskii *et al.* 2020b; Slukovskii and Dauvalter 2020). The obtained correlation matrix also shows a close relationship between the V and Ni concentrations (r = 0.81), which is obviously associated with emissions from the thermal power plant of Segezha, where fuel oil is used. This type of fuel has long been known for its negative impact on the environment, primarily throughout the S, Fe, V, and Ni contained in the fly ash (Hernandez and Rodriguez 2002; Mejia *et al.* 2007; Slukovskii *et al.* 2020a). Since the fuel-oil thermal power plant in the city of Segezha was commissioned relatively recently, the V and Ni concentrations that are higher than the background are observed only in the uppermost layers of the Vygozero Reservoir sediment cores. This applies mainly to stations #4 and #5 located in the northern part of the studied waterbody (Fig. 7). In the sediments of the stations of the central and southern parts of the Vygozero Reservoir, this tendency is not manifested so clearly, which additionally indicates the influence of the thermal power plant as a local source of anthropogenic emissions.

The patterns described above are reflected in the results of the factor analysis of the available geochemical data (Fig. 8). The analysis found that the dominant factors are the first two, which describe 53% of the total data variance. The first factor is closely related to Pb, Sb, Bi, Sn, and Cd, which are agents of long-range transport of pollutants in northern Europe. Consequently, it once again confirms the thesis about the significant influence on the formation of the chemical composition of sediments of emissions from industrial enterprises and transport located far from the reservoir. The factor analysis results also showed that the amount of organic matter in the sediments of the Vygozero Reservoir is closely correlated with the obtained association of elements. The second factor is most closely related to V and Ni, which enter the reservoir as a result of the thermal power plant activity. Thus, the second factor includes pollutants coming from local sources of anthropogenic emissions. At the same time, Cu and Tl are also connected with this factor. However, it is difficult to reliably establish the reason for this connection. Possibly, these elements are related to the influence of the urban environment and industrial enterprises of Segezha and Nadvoitsy on the geochemical features of the sediments of the Vygozero Reservoir and, simultaneously with the emissions from the thermal power station, enter the reservoir. This hypothesis should be tested in further studies.

According to the PLI integral index (14 elements were considered), the Vygozero Reservoir is characterized by a high level of anthropogenic load in the northern and central parts of the waterbody (Figure 9). At the same time, at stations #4 and #5, the highest index values were found for the upper layers of

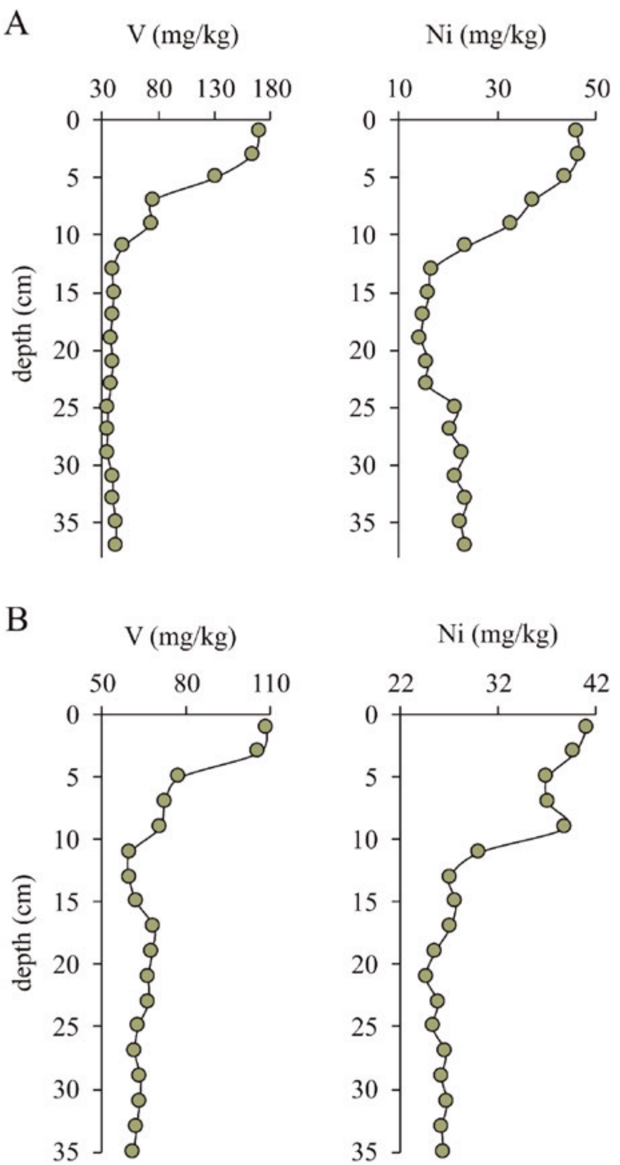

Fig. 7. The vertical distribution of V and Ni concentrations in the sediment cores of the Vygozero Reservoir on the stations #4 (A) and #5 (B).

sediments (0–10 cm), and at station #3, the highest PLI values were found in the lower layers (25–28 cm) of the studied sediments. In both cases, Sb, Pb, V, and Ni made the largest contribution to lake pollution. However, on average at all stations of the Vygozero Reservoir according to PLI, the reservoir is characterized by a moderate level of pollution. A low level of contamination for this indicator was not recorded in any layer of any of the studied sediment cores.

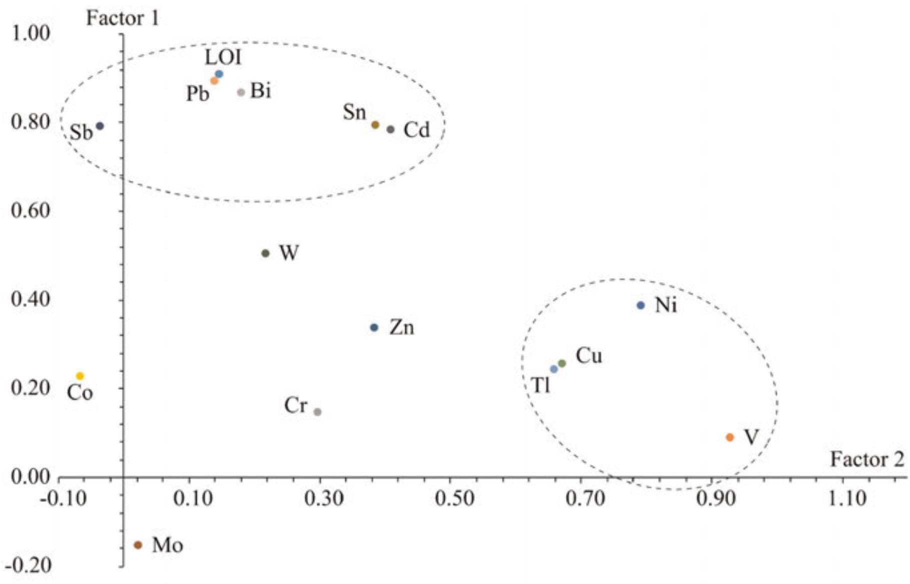

Fig. 8. The result of the factor analysis of data on the concentrations of trace elements and organic matter in the sediments of the Vygozero Reservoir.

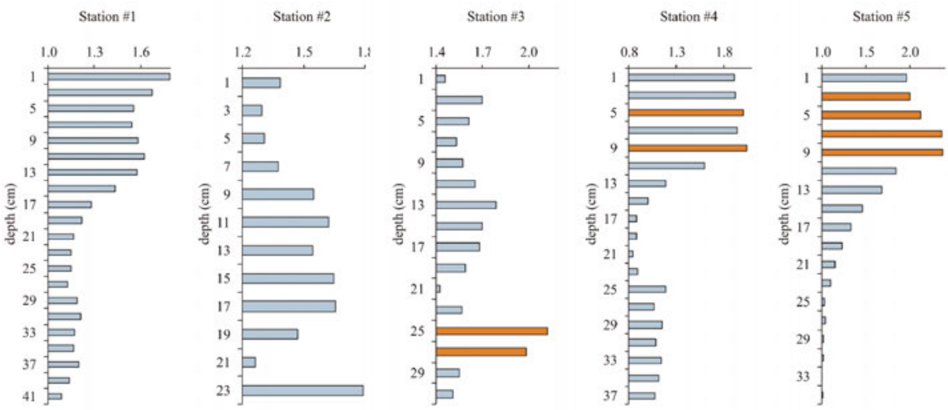

Fig. 9. Values of the pollution load index (PLI) over the depth of the studied sediment cores of the Vygozero Reservoir.

Conclusions

The conducted studies of recent sediments of the Vygozero Reservoir, formed after the transformation of the lake into a reservoir, showed that the sediments bear the imprint of anthropogenic impact. The main indicators of this process are the increased concentrations of trace elements relative to their average content in the continental crust, small lakes in the south of Karelia, and the background content of metals in the sediments of the Vygozero Reservoir. The largest excess was found for Sb, Pb, Cd, Bi, Zn, Cu, and W. The main technogenic factor of the enrichment of the upper layers of the Vygozero reservoir with trace elements should be considered the long-range atmospheric transport of pollutants from industrial enterprises located in the North of Russia and Europe. At the same time, in the northern part of the Vygozero Reservoir, local anomalies of V and Ni were established, which arose from operation of the fuel-oil thermal power plant in the city of Segezha. However, Sb and Pb should be considered the main pollutants for the entire reservoir. It is for these two metals that the highest geo-accumulation indices I_{geo} were obtained, indicating a moderate and high level of lake pollution. The calculation of the integral pollution load index (PLI) showed that most polluted regions of the Vygozero Reservoir are its northern and central parts. In these areas, the studied sediment cores revealed a high level of pollution. However, in general, all studied stations on the Vygozero Reservoir are characterized by a moderate level of pollution. In addition, some metals (Pb, Sb, Cd, Sn, Bi) have a close relationship with the organic matter of sediments because detritus and humic substances are good sorbents of pollutants in the aquatic environment.

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