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Mountain Lakes as Indicators of Air Pollution

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Abstract—The tendency to acidification of waters and accumulation of heavy metals in bed-load deposits in mountain lakes of the Kola North due to atmospheric pollution is shown. From the analysis of diatomic flora, paleoecologic evidence for the transformation of ecosystems of mountain arctic lakes is obtained. It is shown that this transformation is associated with both the industrial development of the region considered and the trans-boundary flows of polluted air masses from Europe.

INTRODUCTION

Numerous European mountain lakes far away from industrial centers (in Scotland, Southern Norway, as well as in the Alps, Pyrenees, and Tatra Mountains) are acidified and polluted by heavy metals (HM), pesticides, and other pollutants due to the trans-boundary transfer of polluted air masses from highly developed industrial centers [6, 21].

The arctic and high-altitude lakes are the best indicators of global and local changes in air quality due to the following reasons:

The formation of water quality is principally determined by atmospheric fallouts, with which the pollutants (SO_4^{2-}, NO_3^-, HM, organic xenobiotics, and others) arrive into water;

Atmospheric fallouts experience virtually no transformation on watersheds because of poor development or absence of soil and vegetation cover;

Low temperature and the ultrafresh and oligotrophic character of water are responsible for its poor self-purification capacity.

There are no direct sources of agricultural or industrial pollution in their drainage areas.

The parameters of the state of ecosystems in mountain lakes can obviously serve as markers for air quality and be used to truly assess the present anthropogenic impact associated with air pollution. In addition, the results of paleoecologic studies make it possible to reconstruct the development of ecosystems over the historical period.

The central part of the Kola North is represented by mountains (the Khibinskie and Lovozerskie mountains) and high-altitude tundra (Chuna, Volch'ya, and Sal'naya). The Khibines (1190 m above sea level) are widely known for their phosphorus-containing rocks (apatite–nepheline syenites). They are remarkable for potassium, sodium, and aluminum geochemical associations. These associations provide a high buffer capacity of mountain lake watersheds with respect to acid fallouts. The geologic structure of the Chuna-Tundra (1114 m above sea level) is composed of gabbro. Because of the low content of difficultly soluble alkaline elements (Ca and Mg), these rocks have a poor capacity for neutralization of acid fallouts.

The Kola North with its mountains is situated in the path of the trans-boundary transfer of air masses from Europe to the Arctic [1]. A large metallurgic concern, Severonikel, located between two mountain masses, is a source of acidic substances and heavy metals that may pollute the adjacent mountain lakes.

In 1993 and 1994, comprehensive studies of two mountain lakes in the Kola North of Russia were carried out according to a methodology unified with European countries in the framework of the International project "Acidification of Mountain Lakes: Paleolimnology and Ecology (AL : PE–2)." Two lakes met the criteria of the Project: Lake Serdtsevidnoe in the Khibines (maximal depth is 5.6 m) and a lake in the Chuna-Tundra (maximal depth is 18 m). These small lakes differ dramatically in the conditions of the formation of their water chemical composition: the first one is tolerant of acid loads, whereas the second one is vulnerable to them. The general characteristics of the lakes are presented in Table 1.

The results of the analysis of snow cover samples from the lake watersheds show that the air masses highly polluted by emissions of regional origin do not ascend to high-altitude areas. The fallout of S is low here (0.4–0.6 g S/m^2) and corresponds to the current regional level for Northern Fennoscandia. In drainage areas near the foothills of mountains (about 200 m above sea level), the fallout of S makes up 1.0–1.5 g S/m^2 [4, 14].

Water samples from the lake in the Chuna-Tundra (hereafter referred to as "the Chuna-Tundra lake") were taken from under the ice (March–April), during the period of maximal vegetation (July–August), and in fall (September–October); and Lake Serdtsevidnoe was

Table 1. General characteristics of the studied mountain lakes

Parameter, dimensions	Chuna-Tundra Lake	Lake Serdtsevidnoe
Latitude	67°57′	67°41′
Longitude	32°29′	33°37′
Altitude above sea level, m	475.3	434.4
Area of lake, ha	12.5	3.5
Maximal depth, m	18	5.6
Mean depth, m	10	3.2
Volume of water, 10^6 m^3	1.25	0.11
Period of water exchange, yrs	1	0.03
Period of open water, months	6	6
Drainage area, km^2	2.05	5.25
Mean annual precipitation, mm	900	850
Fallout of S onto the drainage area, g S/m^2	0.4	0.6

sampled in summer and in fall. The analytic program included the determination of the following indices of water samples (according to the standard procedures [19]): pH; electrical conductivity κ; concentrations of Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NO_3^{2-}, P_{tot}, and HCO_3^-; and the permanganate oxidizability (COD_{Mn}). In addition, the method of atomic absorption with flameless atomization (Perkin-Elmer-5000) was used to determine the total metal content (Ni, Sr, Cu, Co, Zn, Cr, Mn, Fe, Al, Pb, Cd, and Hg) and their ionic labile forms. The correctness of results was ascertained by the international intercalibration in the European laboratories in the framework of the Project “AL : PE–2” [5].

Bed-load deposits (BD) in the lakes were sampled at a maximal depth (in the accumulation zone). The sampling was performed by a tube of the gravity type with an automatically closing diaphragm [18]. The cores of BD from the Chuna-Tundra lake and Lake Serdtsevidnoe (18 and 14 cm long, respectively) were divided at vertical intervals of 1 cm. These portions of samples were analyzed for moisture content; losses on ignition (indirect indicator for organic matter (OM) content); as well as the concentrations of Ni, Sr, Cu, Co, K, Ca, Mg, Na, Zn, Mn, Fe, Al, Pb, and Cd. (The concentrations were determined by the method of atomic absorption [8]). The concentrations of elements in the deepest horizons of BD mass (more than 10 cm from its surface) were taken as background values.

Each 1-cm-long segment of the core was analyzed for the composition of diatomic flora with the aim to reconstruct pH of water over the historical period. The samples were boiled in a 30% solution of H_2O_2 in order to remove OM and were treated with $Na_4P_2O_7$ to disintegrate the rock and to clean the valves of diatomic algae from pollution. From 400 to 600 valves were calculated in each specimen to determine the distribution of their indices and to classify them into pH groups [12]. The concentration of valves per 1 g of dry deposit was calculated, and the species diversity of organisms was determined [13].

CHEMICAL COMPOSITION OF WATERS

The hydrochemical regimes of mountain lakes in the Kola North have both common and specific features. Both investigated lakes are ultrafresh and oligotrophic water bodies. The concentrations of biogenous elements (N and P) and organic matter in their waters are typical of arctic and high-altitude lakes. The water in the Chuna-Tundra lake has a weakly acid reaction (pH is equal to 6.24–6.72), and Ca^{2+} prevails among cations. The water from Lake Serdtsevidnoe features a weakly alkaline reaction (pH ranges from 7.15 to 7.46) and the prevalence of Na^+ among cations. A rather high alkalinity of water provides its acid-neutralizing capability (Table 2).

The concentration of SO_4^{2-} (less than 80 μequiv/l) in the studied lakes corresponds to its average concentration in the surface waters of the Kola North [4, 15]. Yet, this is higher than its natural background value (15–20 μ equiv/l) for Fennoscandia [11]. Air masses highly polluted by the emissions from the Severonikel concern affect the composition of lake waters in the nearest mountains to a far smaller extent than at their foothills, where the SO_4^{2-} concentration in lake water is as high as 150–250 μequiv/l. In mountain lakes, such SO_4^{2-} concentrations are observed at a distance of more than 100 km from industrial centers [4].

Concentrations of Ni and Cu (markers of local pollutants) in mountain lakes are similar to the average regional values for distant lakes (0.5–1.4 μg/l). It is also found that 70% of Ni occurs in the ionic form (Table 3). In Lake Serdtsevidnoe, unusually high concentrations of ionic (most toxic) forms of Al and Sr are found. They

Table 2. Hydrochemical characteristics of the Kola North mountain lakes (1993, 1994)

Parameter, dimensions	Lake Serdtsevidnoe			Chuna-Tundra Lake		
	average value	min	max	average value	min	max
pH	7.3	7.15	7.46	6.47	6.24	6.72
æ, μS/cm, at $T = 20$°C	33	32	35	16	10	25
Col., °Pt	2	0	3	5	0	9
COD_{Mn}, mg O/l	0.45	0.15	0.98	4.8	0.05	2.5
HCO_3^-, μequiv/l	234	226	251	40	23	62
N_{tot}, μg/l	154	140	167	550	287	1091
$(NO_2^- + NO_3^-)$, μg/l	140	79	215	83	17	162
NH_4^-, μg/l	7	0	14	22	2	45
P_{tot}, μg/l	6	3	8	10	3	16
PO_4^{3-}, μg/l	2.5	0	5	2	0	3
Si^{4+}, mg/l	2.5	1.95	3.13	1.5	0.88	2.36
Ca^{2+}, mg/l	0.47	0.33	0.68	1.3	0.85	2.0
Mg^{2+}, mg/l	0.06	0.06	0.07	0.22	0.14	0.34
Na^+, mg/l	5.8	5.6	6.0	0.78	0.49	1.2
K^+, mg/l	1.4	1.2	1.5	0.16	0.04	0.30
SO_4^{2-}, mg/l	2.9	2.7	3.2	2.3	1.7	3.2
Cl^-, mg/l	0.85	0.80	0.90	1.3	0.6	1.5

are the constituents of apatite–nepheline syenites that compose the Khibinskie Mountains. Under the effect of acid rains, these elements easily leave the rocks and enter the water. It is well-known that consequences of lake acidification unfavorable for biota are associated with the high toxicity of Al labile forms, whose concentration abruptly increases in an acid environment [2].

Acidification of water in the Chuna-Tundra Lake, formed with rocks containing weakly labile cations, is more critical than in Lake Serdtsevidnoe. However, the secondary effects of acid fallouts, associated with chemical weathering of toxic forms of Al and Sr out of rocks, also may be unfavorable for biota. During the period of snow melt, in both the Khibines and the Chuna-Tundra, short-term but drastic drops of pH (to 4.7 and 4.2 with $HCO_3^- = 0$) were recorded in streams. They could give rise to “pH-shock” in living organisms [4].

Thus, the Kola mountain lakes are regional indicators of total pollution associated with both its transboundary transfer from Europe (in the upper layers of the atmosphere) and the emissions from local metallurgic concerns.

CHEMICAL COMPOSITION OF BED-LOAD DEPOSITS

The investigation of bed-load deposits in the Kola mountain lakes allowed us to reveal the general tendencies in alteration of their chemical composition. The concentrations of alkaline elements decrease toward the water surface. The release of Ca, Mg, and Na from the top BD layers under acid load is particularly distinct in Lake Serdtsevidnoe. The behavior of Sr and Al, which results in an increase in their content in lake water (Table 4) is similar. Thus, acid fallouts contribute to decreasing the concentrations of alkaline and labile elements in deposits of lakes, whose watersheds are composed of rocks pliant to weathering. In the Chuna-Tundra Lake, whose watershed is composed of rocks resistant to weathering, the concentrations of major cations in the bed-load deposits do not change so distinctly (Table 4).

In both lakes studied, the acidification leads to an increase in the Fe content of the upper layers of deposits [6–8, 15]. In addition, the upper 4–5 centimeters of deposits are found to accumulate heavy metals, particularly Ni, Cu, Co, Pb, and Cd (Fig. 1). The increase in the Ni, Cu, and Co content is associated with the emissions of pollutants from the Severonikel concern.

Despite rather low concentrations of these elements in water, their falling onto watersheds over a long

Table 3. Concentrations of metals in lake water in the Kola North (above the line is the total content, below the line is the ionic form; a dash means the lack of data)

Element, μg/l	Lake Serdtsevidnoe			Chuna-Tundra Lake		
	average value;	min	max	average value	min	max
Sr	$\frac{60}{56}$	$\frac{55}{53}$	$\frac{62}{58}$	$\frac{6.8}{5.8}$	$\frac{5.2}{4.5}$	$\frac{8.5}{7.0}$
Al	$\frac{60}{31}$	$\frac{47}{25}$	$\frac{77}{40}$	$\frac{15.3}{2.0}$	$\frac{7.0}{1.0}$	$\frac{41}{2.5}$
Ni	$\frac{0.80}{0.65}$	$\frac{0.5}{0.6}$	$\frac{1.1}{0.7}$	$\frac{1.1}{0.8}$	$\frac{0.8}{0.5}$	$\frac{1.4}{1.1}$
Cu	$\frac{0.23}{\text{–}}$	$\frac{0.2}{\text{–}}$	$\frac{0.3}{\text{–}}$	$\frac{1.3}{0.4}$	$\frac{0.6}{0.1}$	$\frac{2.6}{0.8}$
Fe	$\frac{3.40}{0.13}$	$\frac{1.1}{0.1}$	$\frac{6.0}{0.2}$	$\frac{6.1}{0.3}$	$\frac{4.2}{0.1}$	$\frac{7.0}{0.5}$
Zn	$\frac{1.1}{\text{–}}$	$\frac{0.6}{\text{–}}$	$\frac{1.7}{\text{–}}$	$\frac{9.4}{\text{–}}$	$\frac{1.0}{\text{–}}$	$\frac{25}{\text{–}}$
Cd	$\frac{<0.1}{\text{–}}$	$\frac{\text{–}}{\text{–}}$	$\frac{\text{–}}{\text{–}}$	$\frac{0.13}{\text{–}}$	$\frac{\text{–}}{\text{–}}$	$\frac{\text{–}}{\text{–}}$
Pb	$\frac{<0.5}{\text{–}}$	$\frac{\text{–}}{\text{–}}$	$\frac{\text{–}}{\text{–}}$	$\frac{0.5}{\text{–}}$	$\frac{\text{–}}{\text{–}}$	$\frac{\text{–}}{\text{–}}$
Hg*	$\frac{<2}{\text{–}}$	$\frac{\text{–}}{\text{–}}$	$\frac{\text{–}}{\text{–}}$	$\frac{4.5}{\text{–}}$	$\frac{\text{–}}{\text{–}}$	$\frac{\text{–}}{\text{–}}$

* In ng/l

period (since the 1940s) has resulted in accumulation of metals in bed-load deposits of mountain lakes. For example, Ni and Cu concentrations in deposits of the Chuna-Tundra Lake exceed the background values by factors of 7.5 and 2.5, and in Lake Serdtsevidnoe by a factors of 4 and 2, respectively.

The rate of sedimentation for similar lakes in the Kola North is about 1 mm/yr [8]. Consequently, the intensified accumulation of metals in lakes had to begin about 50 years ago. The increase in Pb content (by factors of 4.6 and 3.4 in the Chuna-Tundra and Serdtsevidnoe lakes, respectively) may be associated with both the beginning of the Kola North industrial management and the general increase in Pb global pollution of the atmosphere over northern regions. This concerns the pollution by Cd as well [15].

The consequences of any local and global air pollution (by SO_2, NO_2, and HM) markedly affect the chemical composition of bed-load deposits. The acid fallouts lead to the disbalance of cation natural flow from watersheds, intensify the inflow of labile forms of elements into water bodies, and reduce the concentrations of alkaline and labile elements in surface layers. Heavy metals falling out with precipitation onto watersheds are accumulated in bed-load deposits.

The intensity of lake pollution is assessed with the use of the coefficient C_f and the degree C_d of BD pollution by heavy metals, calculated by the method proposed by L. Hokanson [10]. These indicators are determined as ratios of HM concentrations in surface layers to those in deeper horizons formed in the preindustrial

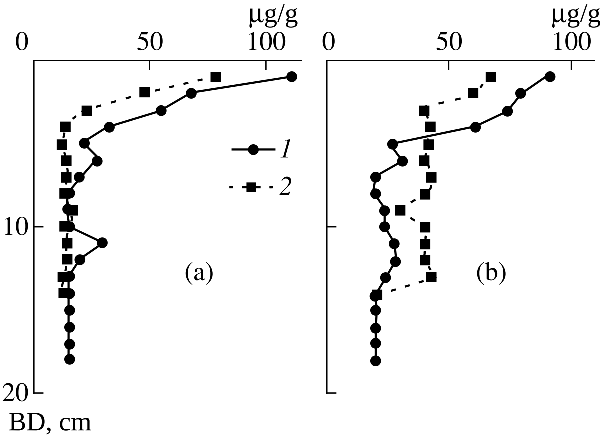

Fig. 1. Concentrations of Ni (a) and Pb (b) in bed-load deposits in the Chuna-Tundra Lake (*1*) and Lake Serdtsevidnoe (*2*).

Table 4. Values of humidity (H_2O), %, losses on ignition (LOI), %, and concentrations of metals in cores of lake BD in μg/g of dry weight

Layer, cm	H_2O	LOI	Cu	Ni	Zn	Co	Cd	Pb	Mn	Fe	K	Na	Sr	Ca	Mg	Al	Cr
Lake Serdtsevidnoe																	
0–1	83.6	22.9	58	79	122	7	1.19	27	95	8304	1980	2022	5	29	761	64815	–
2–3	84.2	21.3	56	48	118	7	1.06	24	71	5826	1808	2087	7	29	774	61612	–
2–3	81.0	19.1	30	23	116	7	1.25	16	67	5709	1694	2243	7	32	793	59986	–
3–4	74.8	17.1	27	14	117	7	1.28	17	75	5855	1905	3638	7	39	1002	59470	–
4–5	72.3	17.5	27	12	116	5	1.32	17	72	6005	1784	4125	7	43	961	66142	–
5–6	75.1	18.0	23	14	121	6	0.98	16	74	6148	1828	2464	9	75	1571	52998	–
6–7	74.2	16.8	28	14	117	4	1.33	17	77	6238	1910	4267	7	45	1386	66679	–
7–8	73.5	17.9	28	14	137	6	1.31	16	82	6342	1887	3678	15	129	1780	44610	–
8–9	74.4	18.3	28	16	127	4	1.31	12	82	6681	1600	2300	16	124	1701	45053	–
9–10	74.2	18.3	29	14	117	6	1.63	16	82	5754	1691	1964	7	33	1478	66180	–
10–11	76.7	18.6	46	14	120	4	1.16	16	84	5735	1744	1906	11	30	1381	65260	–
11–12	75.0	17.9	27	14	118	6	1.17	16	82	5975	1121	2158	7	32	1393	66569	–
12–13	72.1	17.2	25	12	121	6	1.18	17	80	6207	2069	4618	19	174	1699	47914	–
13–14	67.6	16.7	25	12	121	5	1.19	8	81	6437	1851	4315	19	134	2083	45309	–
Chuna-Tundra Lake																	
0–1	88.7	27.8	50	111	53	9	0.90	36	32	5128	744	434	13	449	2216	17321	23
2–3	89.6	27.7	47	68	65	9	1.08	32	29	5034	692	430	7	366	2062	16912	26
2–3	94.0	26.5	37	55	40	5	0.73	29	31	4723	708	455	9	372	2053	17190	16
3–4	91.7	24.4	28	32	84	5	0.94	24	30	4455	699	515	8	378	2223	18898	19
4–5	88.7	23.4	29	22	57	5	0.19	11	29	4003	631	493	6	360	2051	18177	22
5–6	87.6	23.6	23	27	33	5	0.19	12	27	4197	629	387	8	373	2001	18863	19
6–7	89.2	22.7	19	19	28	6	0.39	8	25	3935	628	385	8	339	1865	17268	19
7–8	89.6	22.4	17	15	29	5	0.19	8	25	3638	611	376	6	350	1940	17008	19
8–9	90.6	22.5	17	15	29	3	0.19	9	25	3632	551	403	8	364	1649	16133	19
9–10	91.0	22.6	22	15	32	1	0.39	9	25	3524	550	383	6	377	1616	17196	41
10–11	89.1	22.2	22	15	33	3	0.45	11	25	3578	555	385	6	381	1715	17284	27
11–12	90.7	21.7	22	20	49	5	0.59	11	25	3671	626	389	6	387	1958	17400	25
12–13	88.9	21.9	24	15	35	3	0.59	9	21	3452	625	383	6	356	1614	16703	24
13–14	88.7	20.9	20	15	31	5	0.79	8	20	2967	491	312	6	346	1857	14088	27
14–15	89.9	20.9	22	15	33	5	0.79	8	26	3603	619	345	6	381	1897	15172	25
15–16	89.4	20.8	20	15	34	5	0.59	8	22	2970	546	310	6	351	1657	14104	27
16–17	90.5	21.2	22	15	33	3	0.20	8	24	3061	533	309	6	349	1628	13385	25
17–18	88.8	21.3	20	15	30	3	0.20	8	24	2736	529	305	6	334	1544	13138	25

period. The ratio for the individual metal is C_f, and their sum is C_d.

To characterize the pollution by six metals (Ni, Cu, Zn, Co, Cd, and Pb), we used the following classification for HM pollution [10]: $C_d < 6$, low, $6 \le C_d < 12$, moderate, $12 \le C_d < 24$, significant, and $C_d \ge 24$, high degree of pollution, testifying to the existence of strong human impact. The concentrations of HM accumulated in the upper layers of bed-load deposits in the Chuna-Tundra and Serdtsevidnoe lakes are indicative of the high and significant degree of their pollution (C_d is equal to 24.0 and 15.7, respectively).

DIATOMIC COMPOSITION OF BED-LOAD DEPOSITS

Recently, particular emphasis has been placed on the paleoecologic investigations of lakes based on the analysis of the diatom species and concentrations of diatomic valves in the mass of bed-load deposits. Diatoms are highly vulnerable to acidification of water and any other changes in the aquatic environment. The data on diatom species composition can be used to reconstruct the external impacts on water bodies and their ecologic conditions over the historic period. Specifically, it is possible to reconstruct the changes in water pH [9, 16, 17].

Diatoms in the amount of 90 species were found in the 18-cm BD layer in the Chuna-Tundra Lake, and 108 species, in the 10-cm layer in Lake Serdtsevidnoe. The species were grouped according to their pH-optimum (by the system [12]). Four groups were singled out: acb.—acidobionts, prefering the aquatic environment with pH < 5.5; acf., acidophiles (pH < 7); circ., circumneutrales (pH 7); alkf., alkaliphyles (pH > 7). The percent proportion of these groups for each layer of bed-load deposits is displayed in Fig. 2. The species composition of flora in the studied lakes is represented in Figs. 3 and 4.

The theoretical pH value for each layer of bed-load deposits was calculated with the use of the equation of linear regression by the index B developed for the lakes of Sweden [17].

$$B = \frac{\%\text{circ.} + 5\%\text{acf.} + 40\%\text{acb.}}{\%\text{circ.} + 3.5\%\text{alkf.}}.$$

For the determination of coefficients in the equation relating pH to the diatom composition, we studied the present diatomic flora in upper layers of bed-load deposits in the lakes where pH values were known, and the conditions of water formation were similar to those of the lakes studied. The following equations were obtained from the above analysis:

$$\text{pH} = 7.5 - 0.85\log B, \qquad r = 0.95,$$

for the Serdtsevidnoe Lake;

$$\text{pH} = 7.13 - 0.6\log B, \qquad r = 0.87.$$

for the Chuna-Tundra Lake.

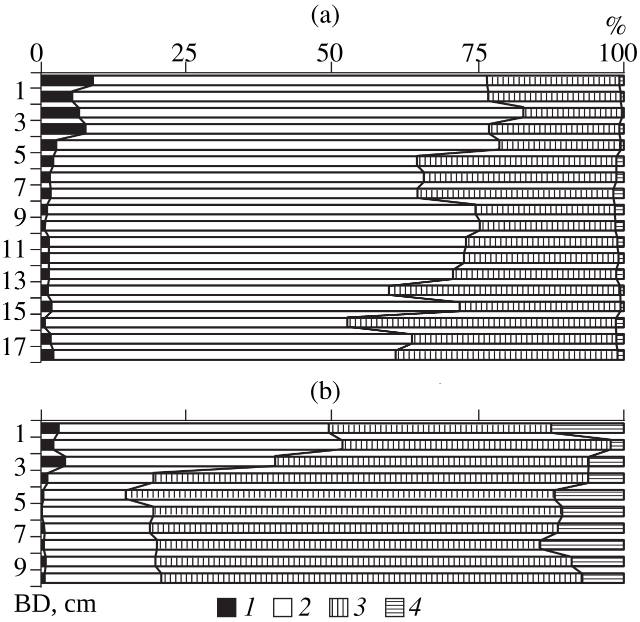

Fig. 2. Percent proportion of species of diatomic flora according to their pH ecological optimum, in bed-load deposits of the Chuna-Tundra Lake (a) and Lake Serdtsevidnoe (b): (*1*) acidobionts, (*2*) acidophyles, (*3*) circumneutrales, (*4*) alkaliphyles.

It was found that, in the mass of bed-load deposits in Lake Serdtsevidnoe, circumneutral species predominate in the deposit layer from 3 to 10 cm (74%). Cyclottella kuetzingiana v. kuetzingiana and C. kuetzingiana v. radiosa are the prevalent species of the planktonic forms. From the layer of 3 cm upward, the share of acidophiles increases, with C. kuetzingiana v. planetophora being predominant. This species prefers waters with pH equal to 6.7–7.0 [3]. The share of acidobionts (Eunotia exigua and E. monodon), which prefer water with pH 5.5, also increases (up to 4%). Their share may be as large as 30% in the acidified (pH 4.5) lakes of Sweden [17] and 45% (according to our data) in those of the Kola North.

The relative number of the alkaliphile population in bed-load deposits in Lake Serdtsevidnoe is maximal in the 7–8 cm layer (14.4%) and decreases upward (to 2.8% near the surface). The structure of diatomic communities starts to change in the layers of 4–1 cm. Here, their biological diversity diminishes by a factor of 1.5 relative to that in deeper horizons (10–4 cm). The pH values reconstructed by the index B for the 1–3 and 3–0-cm layers are 7.3 and 6.9, respectively (Fig. 5). Thus, the analysis of diatomic flora shows that the slightly alkaline lake transforms into a slightly acid one. The calculated pH value seems to be inconsistent with the measured ones. However, the analysis of diatoms yielded an integral estimate of the effect exerted on them by pH values throughout a year including short spring and rain flood periods, when decreases in pH

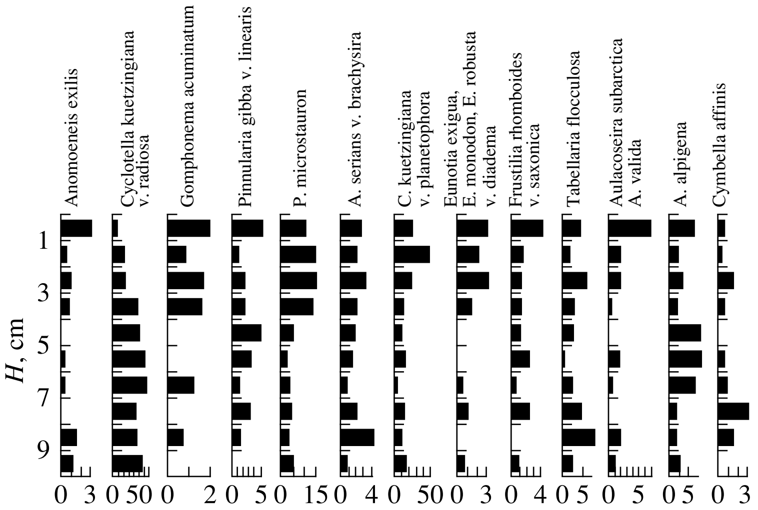

Fig. 3. Species composition, (%), of diatomic flora in bed-load deposits of Lake Serdtsevidnoe.

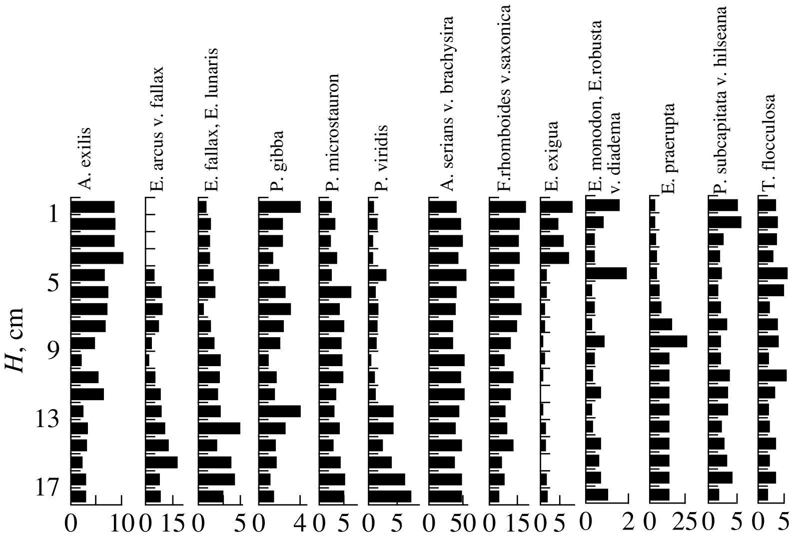

Fig. 4. Species composition, (%), of diatomic flora in bed-load deposits of the Chuna-Tundra Lake.

were recorded in streams in Khibines. The data on diatoms in mountain lakes have confirmed that diatoms are the most sensitive indicator of environmental acidification.

The situation with diatoms in the Chuna-Tundra Lake is different; acidophilic species of benthos and periphyton (up to 70%, Fig. 5) dominate here througout the BD thickness (18 cm). The most abundant among them are An. s serians v. brachysira (up to 50% in the 4–5-cm layer) and Fr. rhomboides (up to 18% in the 0–1-layer). The great diversity of the species Eunotia (26) and Pinnularia (14) suggests that the lake initially had a subacid natural environment [16].

The value of pH calculated by the index *B* for the period of deposition of BD now at a depth of 5–18 cm is 6.5 (the value typical of such lakes, Fig. 5). Starting from the 5-cm-layer of BD, the composition of diatomic flora changes: the populations of circumneutral species and alkaliphiles decrease by factors of 1.5 and 3, respectively, whereas the population of acidobionts increases by a factor of 5 (up to 10% near the BD surface). Among them, E. exigua, E. monodon, E. robusta v. diadema, P. biceps, and St. intermedia are most numerous. The total population of diatoms and their biological diversity decrease by factors of 2.5 and 1.5, respectively. The theoretical values for pH determined by the index B for the surface layer (i.e., the latest) of bed-load deposits is 6.2–6.3 (Fig. 5). Such pH values were recorded at intervals in the Chuna-Tundra Lake (Table 2). Starting from the layer of 5 cm of BD, abnormal forms of Eunotia occur, and cases of destruction of the central part of P. viridis v. intermedia are

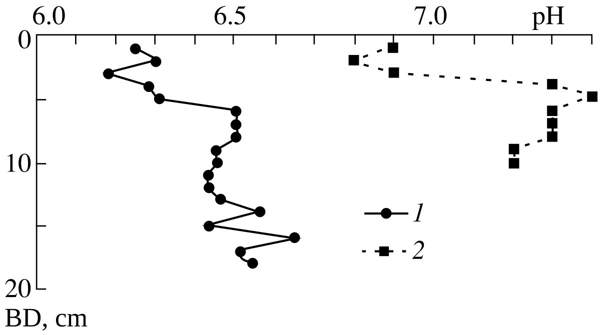

Fig. 5. Theoretical values of water pH calculated on the basis of diatomic spectra for bed-load deposits of the Chuna-Tundra Lake (*1*) and Lake Serdtsevidnoe (*2*).

observed. On the whole, the essential alterations of diatomic communities are concurrent with changes in the chemical composition of bed-load deposits and began with the industrial development of the Kola North (the 1940s–1950s).

Initial changes in diatomic flora are also observed for the earlier stages of development of the Chuna-Tundra lake (starting from a depth of 10–12 cm). This may testify to the earlier impact of acid-forming substances on mountain lakes. This is likely to be associated with the trans-boundary transfer of air masses from Europe. The beginning of appreciable alterations of diatomic flora in a number of mountain lakes in Europe dates from the beginning of the 20th century [6, 16, 20]. The analysis of published data allows us to suggest that the general change in air quality over Europe has had an adverse effect on the European North, including the Kola Peninsula.

CONCLUSION

Investigation of mountain lakes is topical for revealing the global and local pollution of the atmosphere and assessing the anthropogenic impact on ecosystems. The air quality over the Kola region is formed under the influence of the trans-boundary transfer of air masses from Europe and emission of pollutants from regional and local works of nonferrous metallurgy. The Chuna-Tundra Lake is now in the initial stage of acidification, which is indicative of pollution of the upper layers of the atmosphere with acid-forming substances. For Lake Serdtsevidnoe, whose watershed is composed of readily soluble apatite–nepheline syenites of the Khibines, secondary effects of acid deposits were revealed to be associated with washing out of the labile toxic forms of metals (Al and Sr) from rocks. A decrease in concentrations of the main cations (Ca, Mg, and Na) is detected in the surface layers of bed-load deposits. This also confirms the adverse effect of atmospheric acid fallouts. The accumulation of heavy metals in bed-load deposits of lakes is observed starting from the 4–5 cm layer. There, Ni, Cu, and Co are markers of the emission from local works, whereas Pb and Cd are markers of global atmospheric pollution over northern regions.

The changes in diatomic flora in the above layers of bed-load deposits also provide evidence for the development of water acidification. In this case, the share of acidobiont and acidophile species increases upward, whereas the biodiversity of diatoms decreases. The existence of abnormal forms of diatoms testifies to the unfavorable state of the environment due to atmospheric pollution. The theoretical value of water pH, reconstructed by the composition of diatomic flora (index *B*) in both lakes, supports the revealed tendency for the development of lake acidification.

The above tendency is observed (according to diatomic flora) starting from the 9–10-cm layer, which had been deposited at the beginning of the 20th century, i.e., prior to the industrial development in Europe and the relevant atmospheric pollution. The intense alterations in the diatomic composition and the accumulation of heavy metals in bed-load deposits began in the 1940s–1950s (judging from the rate of sedimentation) and are associated with the beginning of industrial management in the Kola region.

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REFERENCES

1. Bryukhanov, A.P., Kryukov, E.V., Nazarov, I.M., and Ryaboshapko, A.G., *Tr. Inst. Prikl. Geofiz.*, 1982, no. 41, p. 14.
2. Izrael’, Yu.A., Nazarov, I.M., Pressman, A.Ya., *et al.*, *Kislotnye dozhdi* (Acid Rains), Leningrad: Gidrometeoizdat, 1989.
3. Komarenko, L.E. and Vasil’eva, I.I, *Presnovodnye diatomovye i sinezelenye vodorosli vodoemov Yakutii* (Freshwater Diatoms and Cyanophyceae in Water Bodies of Yakutia), Moscow: Nauka, 1975.
4. Moiseenko, T.I., *Zakislenie i zagryaznenie tyazhelymi metallami poverkhnostnykh vod Kol’skogo Severa* (Acidification and Heavy Metal Pollution of Surface Waters of the Kola North), Apatity: Kol’sk. Nauch. Tsentr, 1991.
5. Acid Rain Analysis, Documenta dell’Instituto di Idrobiologia, Italia, 1994, no 47.
6. Acidification of Mountain Lakes: Palaeolimnology and Ecology (AL : PE), Wathne, B.M., *et al.*, Eds., European Commission Report EUR 16129 EN, Brussels, 1995.
7. Carignan, R. and Tessier, A., *Science,* 1985, vol. 228, p. 1524.
8. Dauvalter, V., *Sci. Total Environ.*, 1994, vol. 158, p. 51.
9. *Diatoms and Lake Acidity,* Smol, J.P., *et al.*, Eds., The Hague, Netherlands: W. Junk and Sons, 1986.
10. Hokanson, L., *Water Res.*, 1980, vol. 14, p. 975.
11. Henriksen, A., Kamari, J., Posch, M., and Wilander, A., *Ambio,* 1992, vol. 21, p. 356.

12. Hustedt, F., *Arch. Hydrobiol.*, 1939, Suppl. 15, p. 274.
13. Menhinick, E.F., *Ecology,* 1964, vol. 45, p. 859.
14. Moiseenko, T., *Ambio*, 1994, vol. 23, no. 7, p. 418.
15. Norton, S.A., Dillon, P.J., Evans, R.D., *et al*., *Sources, Deposition, and Canopy Interactions. Acidic Precipitation,* New York: Springer-Verlag, 1990, vol. 3, p. 73.
16. Renberg, I., Krosman, T., and Anderson, J., *Ambio*, 1993, vol. 22, no. 5, p. 264.
17. Renberg, J. and Hellberg, T., *Ambio*, 1982, vol. 11, no. 1, p. 300.
18. Skogheim, O.K., *Rapport fra Arungenprosjektet*, Oslo: As–NLH, 1979, no. 2, p. 7.
19. *Standard Method for Examination of Water and Wastewater,* Washington D. C.: Am. Publ. Health Assoc., 1975.
20. Wathne, B.M., *Strategies for Lake Ecosystems Beyond 2000,* Stressa, Italy, 1993.
21. White, J.R. and Gubala, C.P., *J. Paleolim*., 1990, vol. 3, p. 243.