

# Current assessment of nitrogen and phosphorus content in the river water and snow cover of the Southern Baikal basin

LIMNOLOGY  
FRESHWATER  
BIOLOGY

Onishchuk N.A.<sup></sup>, Tomberg I.V.<sup></sup>, Netsvetaeva O.G.<sup></sup>

Limnological Institute Siberian Branch of the Russian Academy of Sciences, Ulan-Batorskaya Str., 3, Irkutsk, 664033, Russia

**ABSTRACT.** The paper presents the results of long-term studies of chemical composition of water of tributaries and snow cover of the south-eastern and south-western coasts of Lake Baikal. The content of different forms of nitrogen and phosphorus in river water and snow cover was analyzed. A quantitative assessment of total nitrogen and phosphorus input from the atmosphere to the Southern Baikal catchment area for 2019-2023 is given. The south-western coast of the lake experiences a great load in terms of the content of various forms of nitrogen and phosphorus in the snow cover and water of tributaries. Nitrogen in the snow cover and tributaries of Southern Baikal is represented mainly by its mineral form. The rivers of the south-eastern coast, which are exclusively atmosphere-fed, are generally not subjected to anthropogenic impact. In contrast, the minor watercourses of the south-western coast of the lake (Listvyanka settlement) are significantly influenced by economic activities. The organic form of phosphorus predominates in the snow cover of Southern Baikal and in river waters of the south-eastern coast. In the water of tributaries of the south-west coast phosphorus is found in its mineral form. A comparison of current data with the results of previous years was carried out.

**Keywords:** tributaries of Southern Baikal, snow cover, phosphorus, nitrogen, Listvyanka settlement

**For citation:** Onishchuk N.A., Tomberg I.V., Netsvetaeva O.G. Current assessment of nitrogen and phosphorus content in the river water and snow cover of the Southern Baikal basin // Limnology and Freshwater Biology. 2024. - № 5. - P. 1337-1356. DOI: 10.31951/2658-3518-2024-A-5-1337

## 1. Introduction

The most detailed hydrochemical studies of the Southern Baikal tributaries were carried out in the 1950s, in the pre-industrial period. Votintsev et al. (1965) characterized the ionic and gas composition and concentrations of biogenic elements. The results of these studies reflect the natural background in the region and can be used for comparison with current data. Recent studies indicated an increase in the input of phosphorus and nitrogen compounds into the littoral water of Lake Baikal, which can be attributed to an increased anthropogenic load on the nearshore areas of the lake. The work showed that high concentrations of nitrate, ammonium, and phosphate were recorded in urbanized areas of the lake and in the water of rivers flowing through settlements and cities (Malnik et al., 2022; Onishchuk et al., 2022). The input of biogenic elements resulted in a significant increase in the productivity of the biocenoses of the Baikal littoral waters. This led to the proliferation of macroalgae species that are not typically found in the lake, a shift in the dom-

inant species at the lake bottom, and a disruption in the natural distribution of species within the ecosystem (Kravtsova et al., 2014; Timoshkin et al., 2016).

The settlement of Listvyanka, a well-known tourist destination with a well-developed infrastructure that includes numerous hotels, cafes, and a large number of motor and river transports, is one of the most important sources of nitrogen and phosphorus inputs on the south-western coast of Lake Baikal. The study of watercourses (Krestovka River, Bol. and M. Cheremshanka and Kamenushka streams) flowing through the settlement is being conducted in response to the increasing anthropogenic load and the threat of eutrophication of Listvennichny Bay. According to Zagorulko et al. (2014), Vorobyeva et al. (2017), and Kostyukova (2022), the water composition of the Krestovka River has changed significantly over the last 50 years towards a decrease in water quality. Comprehensive research has demonstrated that human activity affects not only groundwater and surface water but also soils, vegetation, and atmospheric precipitation (Monitoring..., 2010; Vorobyova et al., 2016; Suturin et al., 2016; Chebunina

\*Corresponding author.

E-mail address: [onishchuk@lin.irk.ru](mailto:onishchuk@lin.irk.ru) (N.A. Onishchuk)

**Received:** September 27, 2024; **Accepted:** October 28, 2024;

**Available online:** October 31, 2024

© Author(s) 2024. This work is distributed under the Creative Commons Attribution-NonCommercial 4.0 International License.



et al., 2018; Yanchuk et al., 2021). In Listvyanka settlement, sustainable pollution of groundwater by nitrate ions, less frequently by ammonium ions, has been noted (Naprasnikova et al., 2007; Alekseev et al., 2016; Alekseev et al., 2018; Alekseeva et al., 2023; Alekseeva and Alekseev, 2023).

River waters on the south-eastern coast of Lake Baikal are subjected to nitrogen acidification under the influence of atmospheric precipitation. The main sources of atmospheric pollution in this area are the railway and motorway, as well as the transfer of pollutants from the Irkutsk-Angarsk industrial complex (Sorokovikova et al., 2015; Sorokovikova et al., 2020; Sorokovikova et al., 2021). Currently, most of the nitrogen compounds entering terrestrial systems with precipitation are of anthropogenic origin and are associated with nitrogen emissions from industrial enterprises and motor transport. Throughout Russia, emissions of these gases from stationary sources increased by 11% for the period 2018-2022 and in Irkutsk region by 3% (State Review..., 2023; State Report..., 2023).

As it is known, snow cover is a convenient indicator of atmospheric air pollution. The sensitivity of snow cover to changes in the level of anthropogenic load in the region enables us to assess the impact of atmospheric fallout, including nitrogen and phosphorus, on the chemical composition of surface waters.

The aim of this work is to assess the current input of nitrogen and phosphorus compounds from the atmosphere, to study the seasonal and interannual dynamics of these components in the water of the Southern Baikal tributaries.

## 2. Materials and methods

The content of nitrogen and phosphorus compounds in the water of 2 groups of the Southern Baikal tributaries was studied. The first group includes rivers originating on the northern slope of the Khamar-Daban ridge, which are the most representative of the changes in chemical composition of river water caused by pollutants from the atmosphere (Sorokovikova et al., 2020). These tributaries are fed only by precipitation. The river basins are highly humidified due to their favorable position in relation to the direction of the prevailing moisture transport. The largest amount of precipitation for the Southern Baikal region falls here, up to 1060-1720 mm, and snow cover thickness can reach 2 m (Obolkin, 1989).

The second group of rivers flows through the settlement of Listvyanka, which is situated on the western coast of Southern Baikal on the right bank of the Angara River source. The streets of the settlement stretch along the creek valley, where small watercourses flow, the most abundant of which is the Krestovka River.

Samples were collected from the tributaries of Southern Baikal, which flow from the north-western slope of the Khamar-Daban Range, at the river mouths in different hydrological seasons (March, May, July, and September) 2019-2023. Taking into account high pollution of littoral territories of the western coast of Southern Baikal, observations were carried out monthly

at watercourses in Listvyanka settlement in two stations: above the settlement (background station) and in the estuary part. Snow cover samples were taken in February (maximum moisture content in the snow cover) to quantify nitrogen and phosphorus inputs from the atmosphere. The content of nitrogen and phosphorus in snow water was determined and their accumulation in the basins of the studied rivers was calculated. The scheme of sampling of snow cover and tributaries of Southern Baikal is presented in Figure 1.

The mineral forms of nitrogen -  $N_{min}$  (nitrates, nitrites, ammonium ions) and phosphorus (phosphates)  $P_{min}$  and their total content ( $N_{tot}$ ,  $P_{tot}$ ) were determined in river water. From the difference of total and mineral forms, the organic part ( $N_{org}$ ,  $P_{org}$ ) was calculated. The concentrations of mineral forms in river water were determined using a spectrophotometer (PE-5400VI, Russia). The analysis of nitrite was conducted with Griess reagent, nitrate with sodium salicylic acid, ammonium nitrogen by the indophenol method, and phosphate by the Deniger-Atkins method with tin chloride as a reducing agent. In snow melts, nitrite and phosphate were determined in the same way as in river water, ammonium nitrogen was measured spectrophotometrically with Nessler's reagent, and nitrate was measured by ion chromatography. The total phosphorus and nitrogen contents of the samples were determined on a spectrophotometer following persulfate oxidation to phosphate and nitrate, respectively (Wetzel and Likens, 2000; Khodzher et al., 2016; Analytical..., 2017).

## 3. Results and discussion

### 3.1. Content of nitrogen and phosphorus compounds in snow cover of the studied areas

As illustrated, the mean annual concentration of  $N_{tot}$  in the snow cover of the south-eastern coast of the lake was 0.66 mg/L, with variations from 0.45 to 1.13 mg/L. The highest mean value was observed in the

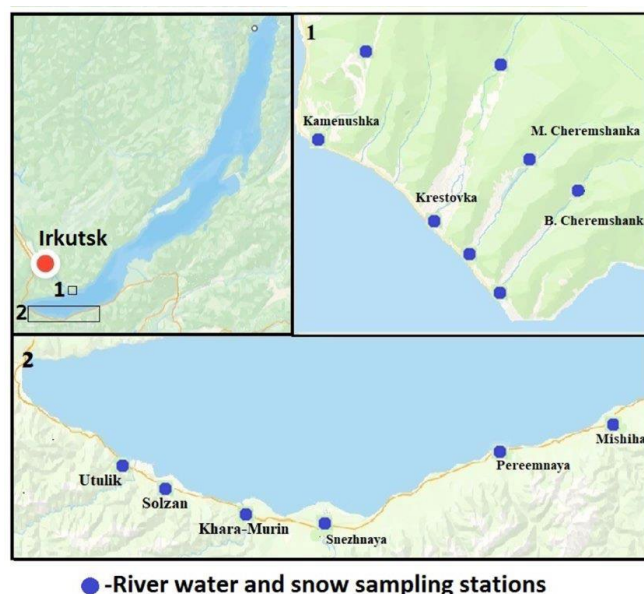


Fig.1. Sampling scheme.

Pereemnaya River basin ( $0.78 \pm 0.21$  mg/L), which is subjected to additional anthropogenic impact due to the transfer of gas components and impurities (nitrogen oxides) from industrial sources located in the Irkutsk agglomeration (Irkutsk, Angarsk, Shelekhov). Snow cover in the Khara-Murin River basin is characterized by the lowest content of  $N_{tot}$  (average  $0.56 \pm 0.09$  mg/L). The most “clean” snow cover in terms of the content of  $N_{tot}$  was recorded in this area in 2020 (0.55 mg/L), while the most “polluted” was recorded in 2019 (0.74 mg/L). Table 1 shows that the majority of the nitrogen in the snow cover is in its mineral form (on average, 73%). The highest concentration of this form of nitrogen in the snow cover was found at the mouth of the Mishiha River.

The mean long-term  $P_{tot}$  content in the snow cover of this area was found to vary significantly, from 9 to 109  $\mu\text{g/L}$  (Table 1), with a mean value of  $27 \pm 12$   $\mu\text{g/L}$ . The Pereemnaya River basin had the highest average content at 44  $\mu\text{g/L}$ , while the Khara-Murin River area had the lowest at 2.6 times less. The highest concentrations of  $P_{tot}$ , as well as  $N_{tot}$ , on the south-eastern coast were recorded in 2019. Table 1 indicates that the organic form of phosphorus predominates in the snow cover of this territory. Its content is on average 76%. The maximum content of  $P_{tot}$  was recorded in the Snezhnaya River basin. The share of mineral P in the snow cover of the area did not exceed 30%, its maximum content was recorded in the Utulik River basin.

The mean long-term concentration of  $N_{tot}$  in the snow cover of the south-western coast of Lake Baikal was 1.1 mg/L, with fluctuations from 0.6 to 2.0 mg/L. The highest average value was observed at the mouth of the Bol. Cheremshanka River, with concentration of  $1.53 \pm 0.46$  mg/L. The atmospheric air in the area of Listvyanka settlement is subjected to a considerable anthropogenic load during the cold period. This is due to the functioning of the local boiler facility burning fuel oil residue, stove heating and a high volume of traffic on the automobile road along the settlement and on the lake ice in this tourist area. Besides, it has been established that under certain meteorological conditions, polluted air masses with north-westward air transfer enter this region from the nearest industrial towns of the Baikal region (Obolkin et al., 2021; Shikhovtsev et al., 2022). The lowest  $N_{tot}$  content was recorded in the snow cover in the upper reaches of the

Bol. Cheremshanka River, 2 times lower than at the mouth. The same trend can be observed for the snow cover sampled in the upper and lower reaches of the other rivers studied in the settlement. The lowest concentrations of  $N_{tot}$  in Listvyanka were observed in 2021. Compared to the south-eastern coast, the  $N_{tot}$  content on the south-western coast of Lake Baikal is 1.6 times higher, which is related to the greater anthropogenic load on the air environment in the settlement.

Table 2 demonstrates that nitrogen in the snow cover of Listvyanka settlement, as well as on the south-eastern coast, is represented predominantly by its mineral form. The highest content of this form of nitrogen was recorded at the mouth of M. Cheremshanka stream. The maximum content of  $N_{org}$  was determined in the snow cover at the mouth of the Krestovka River. On both coasts, nitrate nitrogen is the predominant form of nitrogen in the mineral form. Its content varies between 71-98%. The share of  $N_{min}$  in the total nitrogen content in the snow cover of the western coast is analogous to that of the eastern coast (74%).

The mean long-term concentration of  $P_{tot}$  in the snow cover of the south-western coast is  $61 \pm 32$   $\mu\text{g/L}$ , which is 2.3 times more than on the south-eastern coast. This value fluctuates considerably, ranging from 10 to 610  $\mu\text{g/L}$ . The maximum content was registered in the lower reaches of the Kamenushka River. The highest average value was noted in 2022, 2 times higher than the mean long-term value. The lowest content of  $P_{tot}$  (26  $\mu\text{g/L}$ ) was found in the snow cover of the upper reaches of the M. and Bol. Cheremshanka streams above the settlement in the forest zone. We should note that in the upper reaches of the studied watercourses, above the settlement, the content of  $P_{tot}$  in the snow cover is two to four times lower than in the lower reaches of the rivers, on the territory of the settlement itself.

The calculation of the ratios of different forms of phosphorus in the snow cover in the upper reaches of the rivers on the south-western coast of Lake Baikal revealed that  $P_{org}$  was the dominant form (Table 2), as well as on the south-eastern coast. The average  $P_{org}$  content represented 78% of the total phosphorus content, which was in line with the figure observed on the south-eastern coast (76%). The highest recorded value was observed at the mouth of the Bol. Cheremshanka stream. The highest contribution of  $P_{min}$  was recorded in the snow cover at the mouth of the Krestovka River.

**Table 1.** Content of different forms of phosphorus and nitrogen in snow cover in the basin of tributaries of the south-eastern coast of Lake Baikal, 2019-2023.

Rivers	Range of concentrations	% from $P_{tot}$		Range of concentrations	% from $N_{tot}$	
	$P_{tot}$ , $\mu\text{g/L}$	$P_{min}$	$P_{org}$	$N_{tot}$ , mg/L	$N_{min}$	$N_{org}$
Utulik	9-88	29	71	0.58-0.83	72	28
Solzan	12-88	18	82	0.54-0.78	74	26
Khara-Murin	9-31	23	77	0.45-0.64	72	28
Snezhnaya	10-46	14	86	0.49-0.70	69	31
Pereemnaya	14-109	20	80	0.58-1.13	73	27
Mishiha	10-60	26	74	0.61-0.78	78	22

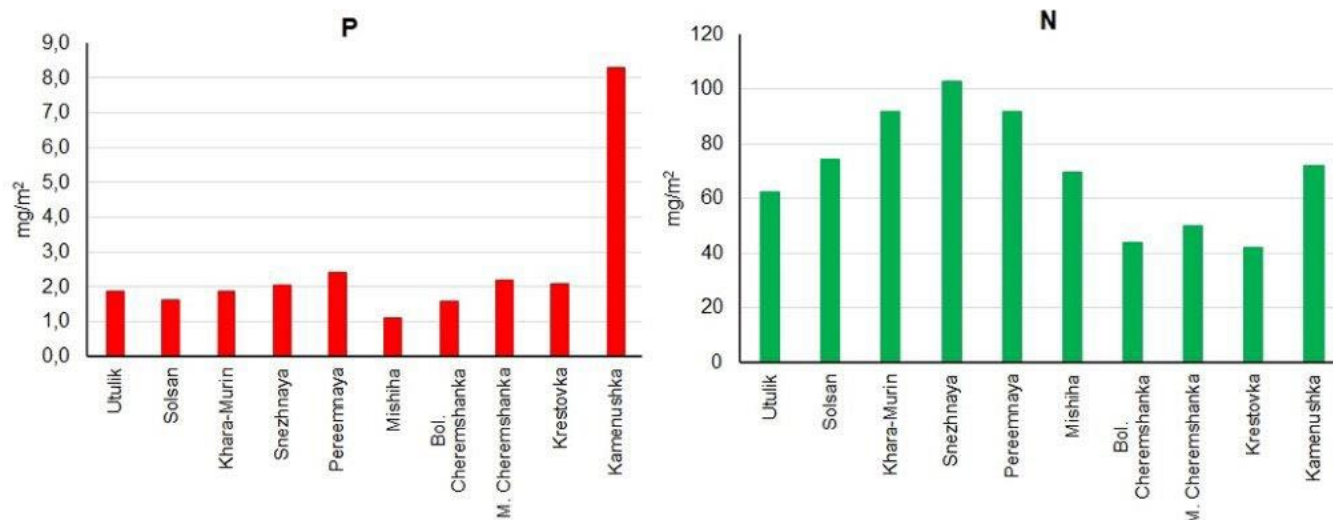
**Table 2.** Content of different forms of phosphorus and nitrogen in snow cover in the basin of tributaries of the south-western coast of Lake Baikal, 2019-2023.

Watercourses	Range of concentrations	% from $P_{tot}$		Range of concentrations	% from $N_{tot}$	
	$P_{tot}$ , $\mu\text{g/L}$	$P_{min}$	$P_{org}$	$N_{tot}$ , $\text{mg/L}$	$N_{min}$	$N_{org}$
Bol. Cheremshanka, estuary	40-127	6	94	0.78-2.00	80	20
Bol. Cheremshanka, beyond the settlement	22-29	25	75	0.60-0.86	72	28
M. Cheremshanka, estuary	10-75	13	87	0.76-1.87	88	18
M. Cheremshanka, beyond the settlement	22-30	20	80	0.67-0.81	69	31
Krestovka, estuary	23-127	37	63	0.73-1.51	65	35
Krestovka, beyond the settlement	17-59	23	77	0.69-0.79	76	24
Kamenushka, estuary	60-610	32	68	0.89-1.65	67	33
Kamenushka, beyond the settlement	34-70	23	77	0.76-1.91	77	23

Based on long-term data, the accumulation of  $P_{tot}$  and  $N_{tot}$  in the snow cover of the studied areas was calculated. Figure 2 illustrates that the accumulation of total nitrogen varies in the range of 28-103  $\text{mg/m}^2$ . The accumulation of this compound is, on average, 1.5 times higher on the south-eastern coast due to a greater moisture content (2-3 times), with a maximum at the estuary of the Snezhnaya River. In Listvyanka, the basin of the Kamenushka River exhibits the highest accumulation of  $N_{tot}$ . The accumulation of  $P_{tot}$  in snow cover was found to vary from 1.1 to 8.3  $\text{mg/m}^2$ . The lowest accumulation was recorded at the estuary of the Mishiha River, while the highest was found in the lower reaches of the Kamenushka River. A comparison of the average values of phosphorus accumulation in two areas of Southern Baikal revealed a higher accumulation (1.9 times) on the south-western coast, which can be attributed to higher concentrations in the lower reaches of the Kamenushka River. With the exception of this area, the accumulation of this compound in the snow cover on the two coasts is at the same level and does not exceed 3  $\text{mg/m}^2$ .

According to the data of snow measurement surveys and monitoring of atmospheric precipitation at Listvyanka station in 2019-2023 and at Tankhoy station (south-eastern coast of the lake) in 2023, the annual fallout of total nitrogen and phosphorus from the atmosphere to the underlying surface was calculated and their input to the water area of Southern Baikal was estimated (Table 3). The values of fallout of  $P_{tot}$  do not differ much on the studied coasts of Southern Baikal, as can be seen. Precipitation of  $N_{tot}$  on the eastern coast is 34 % higher due to a greater (2 times) amount of precipitation.

We made certain assumptions to enable comparison of our data with those obtained previously (in 1986-1987) for the entire lake. The analysis of data from long-term monitoring of atmospheric precipitation at Listvyanka station showed that the concentrations of  $N_{tot}$  in snow and rainfall fallout do not differ much. The content of  $P_{tot}$  in warm periods is, as a rule, two times higher. Therefore, due to the lack of data on the content of the studied compounds in the rainfall in Middle and Northern Baikal, their average concentra-

**Fig.2.** Accumulation of total phosphorus and total nitrogen in the snow cover of the south-eastern and south-western coasts of Lake Baikal,  $\text{mg/m}^2$  (2019-2023).



**Table 3.** Atmospheric inputs of total phosphorus and nitrogen to the Lake Baikal water area (in the numerator, range of fluctuations, in the denominator, average values), 2019-2023.

Study area	Annual fallout, t/km <sup>2</sup> per year		Southern basin (7,432 km <sup>2</sup> ), ths. t/year		Water area of Lake Baikal (31,722 km <sup>2</sup> ), ths. t/year	
	P <sub>tot</sub>	N <sub>tot</sub>	P <sub>tot</sub>	N <sub>tot</sub>	P <sub>tot</sub>	N <sub>tot</sub>
South- western coast	0.027	0.50	0.20	3.7	-	-
South- eastern coast	0.030	0.67	0.22	5.0	-	-
Whole lake (2019-2023)	<u>0.008-0.057</u> 0.017	<u>0.16-1.1</u> 0.33	-	-	<u>0.3-1.8</u> 0.6	<u>5.0-34.9</u> 10.6
Whole lake (1986-1987) *	-	-	-	-	<u>0.6-0.8</u> 0.7	<u>5.9-8.3</u> 7.1

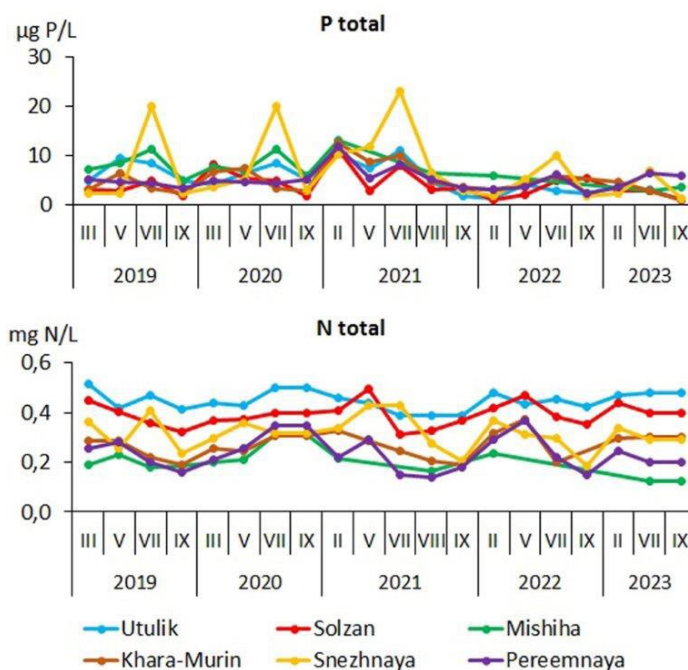
Note: \* - Atlas of Lake Baikal, 1993.

tions in the snow cover sampled in different locations of the lake's coast and water area were taken to calculate annual nitrogen fallout. The mean annual content of P<sub>tot</sub> in moist fallout was found taking into account its large values in warm periods. The concentrations determined in this way were multiplied by the annual amount of precipitation in different regions of the lake, 1320 mm for Khamar-Daban station (Southern Baikal) and 190 mm for Uzur station (Olkhon Island, Middle Baikal). The precipitation amount was taken from the work by Obolkin and Khodzher (1990). Table 3 presents the minimum and maximum values of inputs to the lake water area. Due to a significant difference in precipitation amount at the selected stations (7 times), the range of fluctuations is rather wide. The mean values, which seem to be more reliable, are calculated from the average for Lake Baikal precipitation (400 mm) (Obolkin, 1989).

Our findings show that over the past 35 years, the input of N<sub>tot</sub> from the atmosphere to the Baikal water area has increased by an average of 1.5 times, while the P<sub>tot</sub> input has not changed (Table 3). It is important to note that these are the first estimates of the input of selected compounds to the water area of the whole lake. Therefore, they are preliminary and require further, more detailed studies of the content of organic forms of phosphorus and nitrogen in atmospheric fallout in Middle and Northern Baikal area. The observed increase in fallout of N<sub>tot</sub> from the atmosphere compared to the 1980s is probably caused by an increase in nitrogen oxide emissions from stationary sources and in the number of motor vehicles, as they now occupy the leading place in environmental pollution.

### 3.2. Content of nitrogen and phosphorus compounds in the water of tributaries of the south-eastern coast of Lake Baikal

Analysis of long-term data showed that the content of P<sub>tot</sub> in the water of tributaries of the south-eastern coast of Lake Baikal is mainly low, at 1-12 µg/L. Higher concentrations were registered only in the water of the Snezhnaya River in summer (up to 23 µg/L) (Fig. 3). This river is the largest and most abundant watercourse in the area, with a length of more than 170 km. An increase in the concentrations of P<sub>tot</sub> in summer in the water of this river and in other rivers (Utulik, Mishiha) is probably linked to the increase in the content of



**Fig.3.** Seasonal and interannual dynamics of the content of total phosphorus and total nitrogen in the water of tributaries of the south-eastern coast of Lake Baikal, 2019–2023.

organic matter as a result of summer phytoplankton vegetation. No seasonal dynamics could be detected in other tributaries of this area. A decrease in the concentration of P<sub>tot</sub> in 2022-2023 is probably related to the high water content of rivers in these years.

As is the case with snow cover, the organic form of phosphorus dominates in tributary water, accounting for 58-97% of the total phosphorus content (average 73%); therefore, the mean annual values of P<sub>org</sub> and the dynamics of concentrations basically coincide with those of P<sub>tot</sub>. The mineral form of P in rivers has a very low content, with an average annual value of 1 µg/L. Maximum concentrations of P<sub>min</sub> were recorded in winter and spring reaching up to 5 µg/L, while in summer, due to bioaccumulation by algae, they decreased to trace values (Table 4).

The content of N<sub>tot</sub> in the water of tributaries varied from 0.12 to 0.51 mg/L. The highest concentrations were recorded in the Utulik and Solzan rivers, with mean annual values of 0.45 and 0.39 mg/L, respectively. The lowest recorded concentration, with mean annual values of 0.21 and 0.24 mg/L, was observed in the Pereemnaya and rivers (Fig. 3).

**Table 4.** Seasonal dynamics of the content of different forms of phosphorus in the water of tributaries of the south-eastern coast of Lake Baikal, 2019-2023.

Rivers	Winter			Spring			Summer			Autumn		
	P <sub>tot</sub>	P <sub>min</sub>	P <sub>org</sub>	P <sub>tot</sub>	P <sub>min</sub>	P <sub>org</sub>	P <sub>tot</sub>	P <sub>min</sub>	P <sub>org</sub>	P <sub>tot</sub>	P <sub>min</sub>	P <sub>org</sub>
	µg /L	% from P <sub>tot</sub>		µg /L	% from P <sub>tot</sub>		µg /L	% from P <sub>tot</sub>		µg /L	% from P <sub>tot</sub>	
Utulik	1-10	18	82	4-9	3	97	3-11	22	78	1-5	31	69
Solzan	1-11	11	89	2-6	42	58	3-8	37	63	1-5	23	77
Khara-Murin	3-13	25	75	4-9	16	84	3-10	19	81	1-4	20	80
Snezhnaya	2-10	30	70	2-12	9	91	6-23	9	91	1-3	26	74
Pereemnaya	3-12	21	79	3-5	25	75	3-9	30	70	2-6	28	72
Mishiha	6-13	42	58	3-9	20	80	3-11	35	65	4-6	13	87
Selenga*	36-52 41			26-198 84			52-112 79			21-43 31		

**Note:** \*Sorokovikova et al. (2018), in the numerator is the range of concentrations, in the denominator is the mean concentration.

In contrast to phosphorus, which was predominantly in its organic form for the majority of the year, the mineral component (on average, 70% of N<sub>tot</sub>) was the dominant in the composition of nitrogen. Concentrations of N<sub>min</sub> during the study period varied from 0.07 to 0.47 mg/L. In winter, the share of N<sub>min</sub> reached 79-92 % of the total content. In summer, plankton development and input of organic matter from the basin caused some decrease in concentrations of N<sub>min</sub> and increase in N<sub>org</sub>/L to 0.29 mg/L; however, mineral nitrogen prevailed in the water of most rivers even in this period (Table 5).

The contribution of nitrates (90–100% of the content of N<sub>min</sub>) is the primary cause of the high relative content of N<sub>min</sub> in the water of rivers that flow from the Khamar-Daban ridge. Nitrate nitrogen concentrations in the water of rivers during the study period varied from 0.08 to 0.47 mg/L. The highest values of this component were observed in winter and during the flood period, while the lowest values were recorded in summer. Content of ammonia nitrogen in tributary water was usually below 0.01 mg/L, and only during high water or high summer floods concentrations increased up to 0.04 mg/L (about 10% of N<sub>min</sub>). Nitrite nitrogen in the river water was either absent or recorded in trace amounts (below 1 µg/L).

Compared to the data of the 1950s (Votintsev et al., 1965), nitrate nitrogen concentrations in the waters

of tributaries of the south-eastern coast have increased by 40-60 % in the present period. The content of phosphate phosphorus remained almost unchanged.

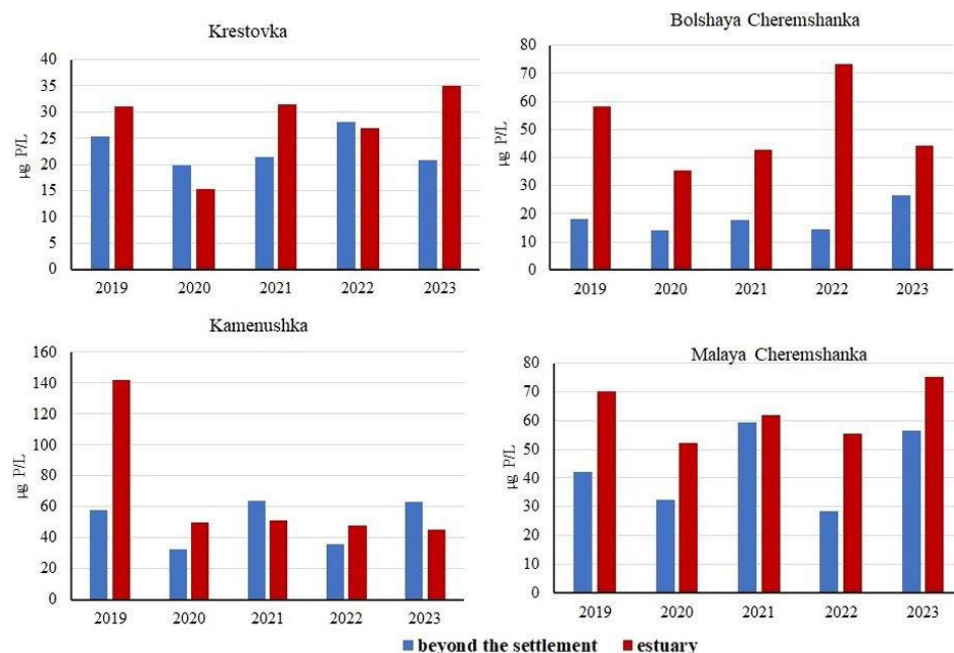
### 3.3. Content of nitrogen and phosphorus compounds in the water of tributaries of the south-western coast of Lake Baikal

In Bol. and Mal. Cheremshanka, streams show higher concentrations of P<sub>tot</sub> in the estuaries than in the upper reaches between 2019 and 2023 (Fig. 4). The Krestovka River and Kamenushka Stream statistics, however, show a different trend. Certain years (2020 and 2023 for the Krestovka River, 2021 and 2023 for Kamenushka Stream) have a higher content of P<sub>tot</sub> in the upper reaches.

The results of our study indicate that the concentration of P<sub>tot</sub> in the estuary of the Krestovka River ranged from 3 to 190 µg/L, with an average value of 19 µg/L; above the settlement, the concentration ranged from 3 to 74 µg/L, with an average value of 18 µg/L (Table 6). Based on the available literature, the concentration of this component in the Krestovka water between 2008 and 2011 was within the range of 10 to 360 µg/L. From January to August 2012, the average total phosphorus content was 37 µg/L, with a maximum of 90 µg/L (Zagorulko et al., 2014).

**Table 5.** Seasonal dynamics of the content of different forms of nitrogen in the water of tributaries of the south-eastern coast of Lake Baikal, 2019-2023.

Rivers	Winter			Spring			Summer			Autumn		
	N <sub>tot</sub> mg/L	N <sub>min</sub>	N <sub>org</sub>	N <sub>tot</sub> mg/L	N <sub>min</sub>	N <sub>org</sub>	N <sub>tot</sub> mg/L	N <sub>min</sub>	N <sub>org</sub>	N <sub>tot</sub> mg/L	N <sub>min</sub>	N <sub>org</sub>
	% from N <sub>tot</sub>		% from N <sub>tot</sub>		% from N <sub>tot</sub>		% from N <sub>tot</sub>		% from N <sub>tot</sub>		% from N <sub>tot</sub>	
Utulik	0.44-0.51	91	9	0.42-0.44	53	47	0.39-0.50	71	29	0.39-0.50	82	18
Solzan	0.37-0.45	92	8	0.37-0.50	80	20	0.31-0.40	60	40	0.31-0.37	67	33
Khara-Murin	0.26-0.53	79	21	0.25-0.37	56	44	0.20-0.31	57	43	0.19-0.24	78	22
Snezhnaya	0.29-0.37	88	12	0.26-0.43	57	43	0.27-0.43	48	52	0.19-0.23	81	19
Pereemnaya	0.20-0.31	87	13	0.24-0.37	73	27	0.14-0.47	52	48	0.15-0.39	56	44
Mishiha	0.19-0.22	84	16	0.23-0.25	52	48	0.12-0.31	40	60	0.18-0.34	47	53



**Fig.4.** Interannual dynamics of total phosphorus content in the water of tributaries of the south-western coast of Lake Baikal, 2019-2023.

Our data indicate a direct correlation between the interannual dynamics of phosphorus ( $P_{\text{tot}}$ ) content in tributaries of the south-western coast of Lake Baikal and tourist traffic. In 2020, there was a significant decrease in total phosphorus in the water of all water-courses of Listvyanka settlement, which was most likely related to restrictive measures on visiting tourist locations because of the COVID-19 incidence. The decrease in the concentration of  $P_{\text{tot}}$  in all watercourses in this period compared to 2019 was 2-fold (Fig. 4). According to the data (State Report..., 2023), the number of tourists visiting Irkutsk region decreased from 1728 thousand in 2019 to just 938 thousand in 2020. In 2021, after the removal of restrictive measures, the annual

average concentration of total phosphorus in water-courses increased coupled with the growth of tourist flow (1241 thousand) in Listvyanka settlement.

The concentration of  $P_{\text{tot}}$  in the water of the tributaries on the south-western coast is 3-17 times higher than on the south-eastern coast of the lake. The content of this component in the water of the Selenga River (the main tributary of the lake) in the period 2010-2016 was as follows: 31  $\mu\text{g/L}$  in autumn, 84  $\mu\text{g/L}$  in spring, with a mean annual value of 59  $\mu\text{g/L}$  (Table 4). These concentrations are comparable to those in the streams of Listvyanka settlement (Table 6). The average annual concentration in the Krestovka River was three times higher.

**Table 6.** Content of different forms of phosphorus and nitrogen in the water of tributaries of the south-western coast of Lake Baikal, 2019-2023. In the numerator is the range of concentrations, in the denominator is the average content for the observation period.

Watercourses	Range of concentrations	% from $P_{\text{tot}}$		Range of concentrations	% from $N_{\text{tot}}$	
	$P_{\text{tot}}$ , $\mu\text{g/L}$	$P_{\text{min}}$	$P_{\text{org}}$	$N_{\text{tot}}$ , $\text{mg/L}$	$N_{\text{min}}$	$N_{\text{org}}$
Bol. Cheremshanka, beyond the settlement	$\frac{1-62}{15}$	37	63	$\frac{0.12-2.57}{0.74}$	59	41
Bol. Cheremshanka, estuary	$\frac{5-221}{52}$	71	29	$\frac{0.5-28}{3.15}$	78	22
M. Cheremshanka, beyond the settlement	$\frac{3-140}{31}$	41	59	$\frac{0.12-2.56}{0.66}$	28	72
M. Cheremshanka, estuary	$\frac{5-400}{71}$	66	44	$\frac{0.23-14}{2.87}$	70	30
Krestovka, beyond the settlement	$\frac{3-74}{18}$	40	60	$\frac{0.05-3}{0.40}$	31	69
Krestovka, estuary	$\frac{3-190}{19}$	39	61	$\frac{0.15-4}{0.60}$	45	55
Kamenushka, beyond the settlement	$\frac{11-190}{38}$	60	40	$\frac{0.19-5.57}{0.72}$	55	45
Kamenushka, estuary	$\frac{16-235}{70}$	71	29	$\frac{0.18-4.68}{1.20}$	65	35

Figure 5 presents the dynamics of the total nitrogen content in the water of the tributaries of Listvyanka settlement. Concentrations in the water of watercourses have decreased compared to 2019, which is probably linked to a reduction in tourist activity. The content of  $N_{\text{tot}}$  was definitively decreasing in Bol. and M. Cheremshanka streams in 2021. In terms of total phosphorus, there is a clear increase in the concentration of  $N_{\text{tot}}$  downstream of the river. The content of  $N_{\text{tot}}$  in Bol. and M. Cheremshanka streams increases by 5-10 times from upstream to the estuary. In the Krestovka river, its concentration changes insignificantly along the river flow, increasing 1.5 times to the estuary and 2 times in the Kamenushka stream. The results of the groundwater study in Listvyanka settlement also revealed a decrease in nitrate nitrogen concentrations in water over the period 2018-2021. The authors attribute this to two factors: an increase in precipitation in the region, which resulted in increased groundwater aquifer recharge and groundwater surface water elevation, and the elimination of anthropogenic sources of groundwater contamination (Alekseeva et al., 2023).

The concentration of total phosphorus and nitrogen increases along the course of streams, as does the change in their form of location (Table 6). The share of mineral forms of phosphorus and nitrogen increases in all streams upstream of the estuary. In the watercourses of M. and Bol. Cheremshanka,  $N_{\text{min}}$  is represented by 91% and 98% nitrate nitrogen, respectively. For the waters of the Krestovka River, the share of nitrate nitrogen is 79% and ammonium nitrogen is 20% of the total content of  $N_{\text{min}}$  in the waters of the Krestovka River, and for the waters of the Kamenushka River, 75 and 24%, respectively.

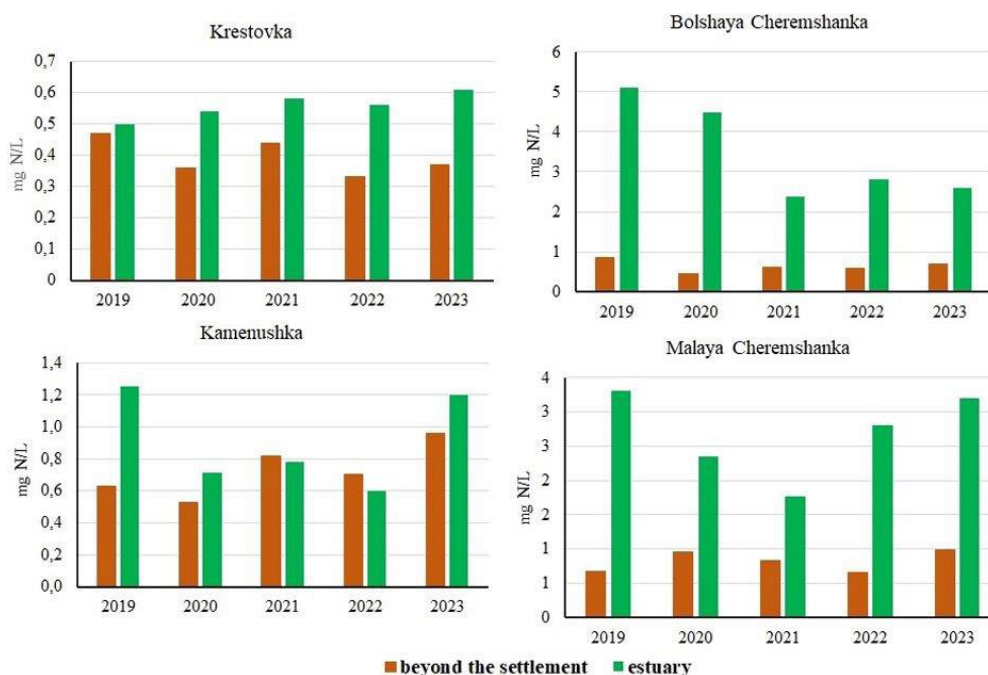
The concentration of  $N_{\text{tot}}$  in the waters of the tributaries on the south-western coast is 2-10 times higher than that observed in the south-eastern coast of the lake.

Determination of total nitrogen in the water of tributaries of the south-western coast of Lake Baikal was not carried out before, therefore the nitrate content as a component of mineral nitrogen is compared. The nitrate nitrogen content of the Krestovka River in 1950-1955 was found to vary from 0 to 0.14 mg/L with an average value of 0.05 mg/L (Votintsev et al., 1965). The concentrations of this component were higher in 2007-2012, at 0.02 - 0.23 mg/L, averaging 0.08 mg/L (Zagorulko et al., 2014). The range of variation for the period 2019-2023 was 0.02-1.01 mg/L. The average nitrate concentration was found to be five times higher than that observed 70 years ago, and three times higher than that observed 10 years ago. For Bol. Cheremshanka stream, nitrate content was recorded at a range of 0.02-0.81 mg/L between 1950-1955, with an average value of 0.33 mg/L. In 2019-2023, the concentration of this component ranged from 0.18 to 5.4 mg/L. The average value was six times higher than that recorded in the 1950s.

#### 4. Conclusion

Thus, a comprehensive assessment of the air and water environment in the Southern Baikal basin, based on a long-term study of river and snow waters, allowed us to conclude on the factors of formation of the chemical composition of the waters of Lake Baikal tributaries on the south-western and south-eastern coasts, identify the causes affecting the spatial and temporal dynamics of concentrations of total phosphorus and nitrogen in snow and river waters, and quantify the levels of N and P accumulation in the snow cover of the studied areas.

The content of  $N_{\text{tot}}$  on the south-western coast of Lake Baikal is 1.6 times higher than on the south-eastern coast, this fact is correlated to the greater anthropogenic load on the air environment in Listvyanka settlement. The mean annual concentration of  $P_{\text{tot}}$  in the snow



**Fig.5.** Interannual dynamics of total nitrogen content in the water of tributaries of the south-western coast of Lake Baikal, 2019-2023.



cover of the south-western coast is 2.3 times higher than on the south-eastern coast. Since the 1980s, the atmospheric input of  $N_{\text{tot}}$  from the atmosphere to the Baikal water area has increased on average by 1.5 times, while the input of  $P_{\text{tot}}$  has not changed significantly.

Low concentrations of total phosphorus and nitrogen were detected in the waters of tributaries on the south-eastern coast of the lake because of their higher water flow and less anthropogenic load on their catchment area. Changes in the content in different years are mainly determined by climatic changes of regional origin. Seasonal dynamics of nitrogen and phosphorus concentrations for these rivers is primarily related to natural processes occurring in water bodies.

On the south-western coast, the anthropogenic factor has a great influence on the formation of the chemical composition of water of the lake tributaries and snow cover. The content of total phosphorus and nitrogen in the water downstream of the rivers in the territory of Listvyanka settlement increases, and in the snow cover at the estuary areas the concentrations increase 2-4 times.

The Krestovka River, with the largest water flow of all the watercourses in the Listvyanka settlement, is the least affected by anthropogenic impact. This leads to a reduction in pollutant concentrations in the water due to dilution.

The inter-annual dynamics of phosphorus and nitrogen content in the watercourses of Listvyanka settlement revealed a direct correlation of tourist load on the chemical composition of water in this area. With restrictions on tourist visits to Listvyanka settlement during the pandemic in 2020-2021, the content of total phosphorus and nitrogen in rivers and snow cover decreased.

When comparing the relative composition of river waters of the two coasts of Southern Baikal, the predominance of mineral forms of nitrogen and phosphorus in the estuaries of the rivers of the south-western coast was noted, which can be considered an indicator of the influence of human activity on the processes of water formation. The predominance of organic forms of phosphorus in the river waters of the south-eastern coast is an indicator of natural processes in the river catchment.

The study revealed an increase in nitrate nitrogen concentrations in the waters of the tributaries in the present period. The total amount of nitrogen entering Lake Baikal from the atmosphere has increased.

## Acknowledgements

The study was carried out within the Stare Assignment of LIN SB RAS No. 0279-2021-0014 (121032300199-9).

## Conflict of interests

The authors declare that there is no conflict of interests.

## References

- Alekseev S.V., Alekseeva L.P., Alekseev V.R. et al. 2016. Hydrogeologic conditions of Listvyanka settlement. *Geografiya i Prirodnye resursy* [Geography and natural resources] 6: 32-36. DOI: [10.21782/GIPR0206-1619-2016-6\(32-36\)](https://doi.org/10.21782/GIPR0206-1619-2016-6(32-36)) (in Russian)
- Alekseev S.V., Alekseeva L.P., Sholokhov P.A. et al. 2018. Groundwater and surface water quality in the area of Listvyanka settlement (south-western coast of Lake Baikal). *Geografiya i Prirodnye resursy* [Geography and Natural Resources] 4: 105-114. DOI: [10.21782/GIPR0206-1619-2018-4\(105-114\)](https://doi.org/10.21782/GIPR0206-1619-2018-4(105-114)) (in Russian)
- Alekseeva L.P., Alekseev S.V., Sholokhov P.A. et al. 2023. Groundwater quality monitoring in Listvyanka settlement (south-western coast of Lake Baikal). *Geodinamika i tektonofizika* [Geodynamics & Tectonophysics] 14(2): 1-11. DOI: [10.5800/GT-2023-14-2-0697](https://doi.org/10.5800/GT-2023-14-2-0697) (in Russian)
- Alekseeva L.P., Alekseev S.V. 2023. Nitrate and ammonium pollution of groundwater in Listvyanka settlement on Lake Baikal. *Izvestiya Irkutskogo gosudarstvennogo universiteta. Seriya: Nauki o Zemle* [Proceedings of Irkutsk State University. Series of Earth Sciences] 46: 3-15. DOI: [10.26516/2073-3402.2023.46.3](https://doi.org/10.26516/2073-3402.2023.46.3) (in Russian)
- Analytical, kinetic and calculation methods in hydrochemical practice. 2017. In: Lazovik P.A., Efremenko N.A. (Eds.) Saint Petersburg: Nestor-Istoriya. (in Russian)
- Atlas of Lake Baikal. 1993. In: Galazii G.I. (Ed.). Moscow: Roskartografia.
- Chebunina N.S., Onishchuk N.A., Netsvetaeva O.G. et al. 2018. Dynamics of the content of mineral forms of nitrogen in watercourses and atmospheric precipitation of Listvyanka settlement (Southern Baikal). *Izvestiya Irkutskogo gosudarstvennogo universiteta. Seriya: Nauki o Zemle* [Proceedings of Irkutsk State University. Series of Earth Sciences] 24: 124-139. DOI: [10.26516/2073-3402.2018.24.3](https://doi.org/10.26516/2073-3402.2018.24.3) (in Russian)
- Khodzher T.V., Domyseva V.M., Sorokovikova L.M. et al. 2016. Part II. Method and case studies for understanding and monitoring the landscapes of Siberia. Chapter 3. Methods for monitoring the chemical composition of Baikal water. In: Mueller L. et al. (Eds.), *Novel Methods for Monitoring and Managing Land and Water Resources in Siberia*. Cham, pp. 113-132. DOI: [10.1007/978-3-319-24409-9\\_3](https://doi.org/10.1007/978-3-319-24409-9_3)
- Kostyukova M.S. 2022. Current ecologico-geochemical state of small tributaries of Lake Baikal (on the example of Listvyanka settlement). *Vestnik VGU. Seriya: Geografiya. Geoekologiya* [Bulletin of the VSU. Series: Geography. Geoecology] 4: 118-125. DOI: [10.17308/geo/1609-0683/2022/4/118-125](https://doi.org/10.17308/geo/1609-0683/2022/4/118-125) (in Russian)
- Kravtsova L.S., Izboldina L.A., Khanaev I.V. et al. 2014. Nearshore benthic blooms of filamentous green algae in Lake Baikal. *Great Lakes Research* 40: 441-448.
- Malnik V., Masumi Y., Tomberg I. et al. 2022. Lacustrine, wastewater, interstitial and fluvial water quality in the Southern Lake Baikal region. *Journal of Water and Health* 20(1): 23-40. DOI: [10.2166/wh.2021.064](https://doi.org/10.2166/wh.2021.064)
- Monitoring and forecasting of material-dynamic state of geosystems of Siberian regions. 2010. In: Nechaeva E.G., Belozertseva I.A., Naprasnikova E.V. et al. (Eds.). Novosibirsk: Nauka. (in Russian)
- Naprasnikova E.V., Vorobyeva I.B., Vlasova N.V. et al. 2007. Sanitary-ecological assessment of water of wells on the Baikal coast (Listvyanka settlement). *Siberian Medical Journal* 8: 6-8.
- Obolkin V.A., Khodzher T.V. 1990. Annual atmospheric input of sulfate and mineral nitrogen in the Lake Baikal region. *Meteorologiya i gidrologiya* [Meteorology and Hydrology] 7: 71-76. (in Russian)

Obolkin V.A., Molozhnikova E.V., Shikhovtsev M.U. et al. 2021. Sulfur and nitrogen oxides in the atmosphere of Lake Baikal: sources, automatic monitoring, and environmental risks. *Atmosphere* 12(1348): 1-10. DOI: [10.3390/atmos12101348](https://doi.org/10.3390/atmos12101348)

Obolkin V.A. 1989. Regime and distribution of atmospheric precipitation on the Khamar-Daban Ridge. Climate and vegetation of the Southern Baikal Region. Novosibirsk: Nauka. (in Russian)

Onishchuk N.A., Tomberg I.V., Khodzher T.V. 2022. Features of Interannual Dynamics of the Hydrochemical Parameters of Baikal Tributaries near the Village of Listvyanka. *Geography and Natural Resources* 43: 50-55. DOI: [10.1134/S1875372822050158](https://doi.org/10.1134/S1875372822050158)

Review of the state and pollution of the environment in the Russian Federation for 2022. 2023. Moscow. (in Russian)

Shikhovtsev M.Y., Obolkin V.A., Molozhnikova Y.V. 2022. Dependence of the concentration of small gas impurities in the air basin of the Southern Baikal region on synoptic and meteorological conditions according to the Listvyanka station. *Proceedings of SPIE* 12341: 1-7. DOI: [10.1117/12.2643498](https://doi.org/10.1117/12.2643498)

Sorokovikova L.M., Netsvetaeva O.G., Tomberg I.V. et al. 2020. Monitoring of the snow cover chemical composition and its role in the acidification of the southern Baikal tributaries. *Proceedings of SPIE* 11560: 1-10. DOI: [10.1117/12.2574786](https://doi.org/10.1117/12.2574786)

Sorokovikova L.M., Netsvetaeva O.G., Tomberg I.V. et al. 2021. Snow cover as a factor of impact on the chemical composition of the Pereemnaya River water (South-Eastern coast of Baikal). *Proceedings of SPIE* 11916: 1-8. DOI: [10.1117/12.2602049](https://doi.org/10.1117/12.2602049)

Sorokovikova L.M., Sinyukovich V.N., Netsvetaeva O.G. et al. 2015. Chemical composition of snow and river waters of the south-eastern coast of Lake Baikal. *Meteorologiya i gidrologiya* [Meteorology and Hydrology] 5: 17-83. (in Russian)

Sorokovikova L.M., Tomberg I.V., Sinyukovich V.N. et al. 2018. Phosphorus in the Selenga River water and its transfer to Lake Baikal under low water content conditions. *Geografiya i Prirodnye resursy* [Geography and Natural Resources] 39(4): 88-94. DOI: [10.21782/GiPR0206-1619-2018-4\(88-94\)](https://doi.org/10.21782/GiPR0206-1619-2018-4(88-94)) (in Russian)

State report “On the state of Lake Baikal and measures for its protection in 2022”. 2023. Irkutsk: FSBIS Institute of Geography named after V.B. Sochava SB RAS. V.B. Sochava SB RAS.

Suturin A.N., Chebykin E.P., Malnik V.V. et al. 2016. The role of anthropogenic factors in the development of environmental stress in the littoral zone of Lake Baikal (water area of Listvyanka settlement). *Geografiya i Prirodnye resursy* [Geography and Natural Resources] 6: 43-54. DOI: [10.21782/GiPR0206-1619-2016-6\(43-54\)](https://doi.org/10.21782/GiPR0206-1619-2016-6(43-54)) (in Russian)

Timoshkin O.A., Samsonov D.P., Yamamuro M. et al. 2016. Rapid ecological change in the coastal zone of Lake Baikal (East Siberia): Is the site of the world's greatest freshwater biodiversity in danger? *Journal of Great Lakes Research* 42: 487-497. DOI: [10.1016/j.jglr.2016.02.011](https://doi.org/10.1016/j.jglr.2016.02.011)

Vorobyeva I.B., Vlasova N.V., Naprasnikova E.V. 2017. Assessment of the ecological state of water bodies of the Baikal natural territory (south-western coast of Lake Baikal, Listvyanka settlement). *Voda: himiya i ekologiya* [Water: Chemistry and Ecology] 6: 86-93. (in Russian)

Vorobyova I.B., Vlasova N.V., Gagarinova O.V. et al. 2016. Current state of the territory of Listvyanka settlement according to the analysis of vegetation, surface water and snow cover. *Geografiya i Prirodnye resursy* [Geography and Natural Resources] 6: 93-98. DOI: [10.21782/GiPR0206-1619-2016-6\(93-98\)](https://doi.org/10.21782/GiPR0206-1619-2016-6(93-98)) (in Russian)

Votintsev K.K., Glazunov I.V., Tolmacheva A.P. 1965. *Hydrochemistry of the rivers of the Lake Baikal basin*. Moscow: Nauka. (in Russian)

Wetzel R.G., Likens G.E. 2000. *Limnological analyses*. New York: Springer.

Yanchuk M.S., Vorobyova I.B., Vlasova N.V. 2021. Geoecological assessment of snow and ice conditions on the southern coast of Lake Baikal. *Vestnik VGU. Seriya: Geografiya. Geoekologiya* [Bulletin of the VSU. Series: Geography. Geoecology] 3: 59-68. (in Russian)

Zagorulko N.A., Grebenshchikova V.I., Sklyarova O.A. 2014. Multiyear dynamics of chemical composition of waters of the Krestovka River (a tributary of Lake Baikal) *Geografiya i Prirodnye resursy* [Geography and Natural Resources] 3: 76-82. (in Russian)