National Assessment of Acid Deposition in Russia

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1. Basic Information on National Monitoring Activities in Russia

For the long time in Russia the Federal Service for Hydrometeorology and Environmental Monitoring (ROSHYDROMET, under the Ministry of Natural Resources and Ecology) is the major governmental authority who is responsible for monitoring of environmental pollution including measuring atmospheric pollutants in ambient air, precipitation chemistry and evaluating acid depositions and their effects, monitoring of transboundary transport of air pollutants, urban and regional contamination of the atmosphere and other related environmental media as well as climate changes.

The Russian Federation has been participating in EANET since the beginning with the start at the preparatory phase in 1998 with active continuation at the regular phase from 2001 and further. Roshydromet being as the National Focal Point has been conducting the relevant monitoring and coordination activities with support of national contributors, namely Russian Academy of Sciences (Siberian Branch). Institute of Global Climate and Ecology (IGCE, Moscow) was designated as Russian National EANET Activity Center, and Limnological Institute SB RAS (Irkutsk) was designated as National EANET Data Center.

The review of national monitoring activities related to precipitation chemistry and acid deposition over the Asian part of Russia is presented below. Russian EANET monitoring sites were established in the southeast Asian parts of Russia, where other meteorological stations of Roshydromet additionally operate as the sampling and measurement sites of the acidity and chemical composition of atmospheric precipitation (or wet deposition of major ions and acidity). Part of those sites were selected as WMO-GAW regional stations to provide data for global and regional assessments under the umbrella of regional GAW network as well as to trace background level of precipitation chemistry composition.

1.1 Monitoring sites

Taking into account the geographic extension of EANET defined by countries involved there were two regions in the Asian part of Russia chosen as suitable for monitoring and where monitoring needs to be established: Southeast Siberia and the Far East. During the preparatory phase, three atmospheric deposition (AD) sites were established in East Siberia (Baikal Lake / Irkutsk Region), and later, the one site more was established in the Far East (Primorsky Kray, near Vladivostok) during the regular phase of EANET.

The geographical location of the Russian EANET ecological monitoring sites is correspondent to principles to promote the collecting basic information and possibility to disclose environmental effects of atmospheric deposition by further research. According to the EANET methodology, four soil monitoring sites (sensitive and control) were established in the areas around (within the radius of 50 km) sampling AD sites connected to each of them. Preliminary surveys of vegetation (tree species and stands, overall condition of forested plots, etc.) and were also conducted at the same points with a view to establish vegetation monitoring program of EANET. Two surface water objects were also selected for monitoring inland aquatic environment (one in East Siberia and another in the Far East) with chemical composition of fresh water (Table 1.1).

Three sites in East Siberia: Irkutsk, Listvyanka, and Mondy, - have been operating since 1998. They are different in physical and geographical conditions as well as the intensity of anthropogenic emission to the

atmosphere in their surrounds. Below there are brief reviews of some geographical characteristics including their position, landscape, etc. (Table 1.1).

Table 1.1 Some geographical characteristics of Russian EANET monitoring sites

Region, site name, classification and geographical coordinates	Topography; landscape	Dry/wet deposition	Soil and vegetation	Inland Aquatic
East Siberia (Irkutsk region):				
1. Mondy (remote) (51°40' N; 101° 00' E; 2005 m)	Upper slope (N) of mountain; forest	+	+	-
2. Listvyanka (rural) (51° 51' N, 104°54' E, 700 m)	Hilly terrain, peak of the hill; forest.	+	+	+
3. Irkutsk (urban) (52° 14' N; 104°15' E; 400 m)	Slope (NE) of broad valley, city.	+	+	-
Far East (Primosky region)				
4. Primorskaya (rural) (43° 42' N; 132° 07', E; 84 m)	Lower part of slope of ridge, natural forest	+	+	+

The urban site is located in Irkutsk, a large industrial center in the south of East Siberia within Angara River valley. The population of it is over 600,000 people. The city has about 190 industrial and municipal heating plants and a large Heat Power Electric Plant. The contribution of these sources is 86% of the total sum of all atmospheric emissions of whole urban area. EANET observations were carried out in the southern part of the city while governmental air pollution monitoring stations are in other parts of city. The data obtained at this site characterize the atmospheric environment conditions of the industrial regions of Siberia.

Listvyanka is a rural site located on the southwest shore of Lake Baikal 70 km far to southeast from Irkutsk near the starting inlet of the Angara River. The site is located beyond the Listvyanka settlement at the top of the hill, 250 m above the lake water surface. The population of Listvyanka village is approximately 3,000 people. In recent years, tourism has been intensively developed in this area. Several local sources of pollution are located in the settlement such as small community boilers and stove heating. Moreover, vehicle emission and transport of contaminants from large regional cities along river valley, such as Irkutsk city, within the distance of 70 to100 km to the northwest, periodically affects the atmosphere in this area by pollution.

Mondy, a remote site, is located in the high mountain background area (near Russian-Mongolia border). The site is within area of Mount Chasovye Sopki (2005 m above sea level at the plateau between the East Sayan and Khamar-Daban ridges). This area is not affected by any local sources of air pollution, being at a distance of 250 km far from any industrial enterprises of the region. This site characterizes regional background conditions of the atmospheric composition and global transport of air pollutants.

Primorskaya is a rural site established in the Far East region (Primorsky Kray) in 2002 to monitor a long-range transport of pollutants through the Asian part of Russia and neighbor countries towards the Pacific. The Primorskaya site is situated in the boundary zone of the Ussuriysky Nature Reserve, on a branch slope of the southern part of the Sikhote-Alin mountain range, of 25 km southeast from the Ussuriysk city.

1.2. Sampling and measurements

Wet deposition

Automatic wet-only samplers are used to collect precipitation samples during rainfall. However, during the winter season, an automatic wet-only sampler has low sampling efficiency (for solid snow precipitation), and, therefore, precipitation can be collected only by manual bulk sampling. Both rain and snow were sampled for every precipitation event. Measurement parameters of rain and snow water are the same (Table 1.2).

Table 1.2 Monitoring program and parameters

Site	Monitoring environment	Frequency	Sampling method	Monitoring parameters

Irkutsk	Wet deposition Air concentration	Every day Weekly	Wet only Filter pack	pH, EC, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+} SO_4^{2-}, NO_3^-, Cl^-, HCO_3^- Gases: SO_2, HNO_3, HCl, NH_3 Aerosols: NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+} SO_4^{2-}, NO_3^-, Cl^-, HCO_3^-
Listvyanka	Wet deposition Air concentration	Every day Weekly Hourly	Wet only Filter pack Automatic	pH, EC, NH_4^+, Na^+, K^+, Ca^{2+}, $Mg^{2+}SO_4^{2-}$, NO_3^-, Cl^-, HCO_3^- Gases: SO_2, HNO_3, HCl, NH_3 Aerosols: NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+} SO_4^{2-}, NO_3^-, Cl^-, HCO_3^- Gases: SO_2, O_3
Mondy	Wet deposition Air concentration	Every day Bi-weekly	Wet only Filter pack Automatic	pH, EC, NH_4^+, Na^+, K^+, Ca^{2+}, $Mg^{2+}SO_4^{2-}$, NO_3^-, Cl^-, HCO_3^- Gases: SO_2, HNO_3, HCl, NH_3, O_3 Aerosols: NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+} SO_4^{2-}, NO_3^-, Cl^-, HCO_3^- Gases: O_3
Primorskaya	Wet deposition Air concentration	Every day Bi-weekly	Wet only Filter pack	pH, EC, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^2 $SO_4^{2-}SO_4$ Cl^-, HCO_3 Gases: SO_2, HNO_3, HCl, NH_3, Aerosols: NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+} SO_4^{2-}, NO_3^-, Cl^-, HCO_3^-
Pereemnaya River	Inland waters	Four times/year	Surface water. Plastic bottles	pH, EC, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+} SO_4^{2-}, NO_3^-, Cl^-, HCO_3^- Transparency, Water color, DOC
Komarovka River	Inland waters	Five times/year	Surface water. Plastic bottles	pH, EC, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+} SO_4^{2-}, NO_3^-, Cl^-, HCO_3^- Transparency, Water color, DOC

Dry deposition

The four-stage filter pack method is used for air sampling. At urban and rural sites in East Siberia, samples are taken weekly, and at the Primorskaya and remote site (Mondy) – bi-weekly. Measured substances are four gases and the water-soluble fractions of particulate matter (see Table 1.2). Meteorological parameters such as air temperature and humidity, wind direction and velocity, others are observed directly at sampling sites or obtained from the nearest meteorological station.

Inland aquatic environment

Monitoring objects are represented by two rivers: the Pereemnaya River (East Siberia, small river of Lake Baikal basin) and the Komarovka River (in the Far East). Measurement parameters are water temperature, pH, EC, alkalinity, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, HCO_3^-, Cl^-, transparency, water color, DOC, NO_2^-, and PO_4^{3-}. Sampling is organized in intervals of seasonal hydrological phases: four or five times per year (Table 1.2).

Soil

Soil is sampled once every three to five years. Measured parameters are pH (H_2O), pH (KCl), exchangeable Na^+, K^+, Ca^{2+}, Mg^{2+}, Al^{3+}, H^+, exchangeable acidity, and EC. This is concluded as the basic information for tracing effects of atmospheric depositions and for catchment studies. Some hydrological parameters are also obtained at the sites or in hydrometeorological offices.

Two chemical laboratories perform the analysis of collected samples:

Laboratory of Hydrochemistry and Atmosphere Chemistry at Limnological Institute SB RAS, Irkutsk (all mandatory items).

Primorsky Monitoring Center, Primorsky Department of Federal Service for Hydrometeorology and Environmental Monitoring, Vladivostok (wet deposition and surface water samples).

In Limnological Institute, the following analytical methods are used to measure ionic/elemental concentrations in precipitation, inland water, extracts from aerosols: Ion Chromatography (IC) for anions SO_4^{2-}, Cl^- and NO_3; atomic absorption and flame spectrophotometry for Ca^{2+}, Mg^{2+}, Na^+, and K^+; spectrophotometry for $NH4^+$. Primorsky Monitoring Center uses a set of methods with spectrophotometry, titration and atomic absorption.

1.3. QA/QC activities

QA/QC programs are carried out at all stages of monitoring activities. The quality of the analytical data was regularly controlled through ion balance calculations and by comparing the measured and the calculated electrical conductivities.

The laboratories are involved in the inter-laboratory comparison projects: on wet deposition, dry deposition, soil and inland aquatic environment monitoring (EANET, 1999-2024), - organized annually by Network Center for EANET (ACAP). Other inter-laboratory comparison projects (on wet and dry deposition and inland aquatic environment monitoring) were implemented within the frame of EMEP, ICP-Water of UNECE Convention, etc. The discrepancy between the obtained results and control values did not exceed 5 to 15%, which attested to the data validity.

2. State of acid deposition in the Asian part of Russia

2.1. Air concentration (aerosols)

The stationary sources, including the fuel and energy production enterprises, chemical, metallurgical, pulp and paper industries and the production of building materials, make the main contribution to the pollution of the air basin in the Baikal region (State Reports, 2008-2024). Figure 2.1 demonstrates that the area of the burnt forest had increased significantly from 2014 to 2019, in the contrast to the relatively stable emissions into the atmosphere from stationary sources between 2013 and 2024. The release of wood combustion products (gases, soot and aerosol) into the atmosphere affects not only the air quality but also the optical and microphysical characteristics of the atmosphere (Kozlov et al., 2014; Khodzher et al., 2019, 2024; Golobokova et al., 2018a, 2020).

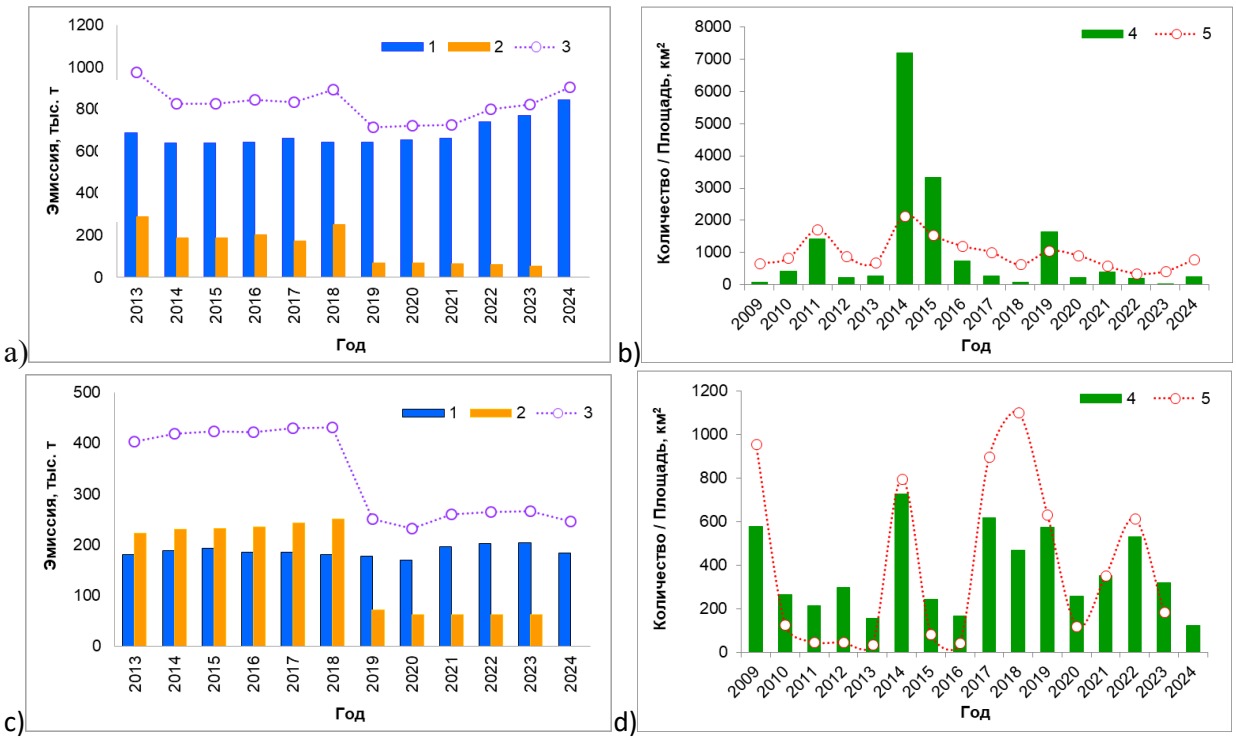


Figure 2.1 Interannual variability of the total atmospheric emissions from stationary (1) and mobile (2) sources (2013–2024), in thous. tons per year; long-term dynamics of the burned area (4, in km²) and the number of forest fires (5) (2009–2024) in the Irkutsk Region (a, b) and the Primorsky Krai (c, d) (MNRE, 2025).

According to Figure 2.1, at the Irkutsk site during the spring maximum period, the ozone in the period 2020–2024, sampling of gaseous pollutants and aerosol particles was continued at Russian EANET monitoring sites in Irkutsk, Listvyanka, and Primorskaya. The sampling at the Mondy site had been temporarily suspended since January 2023 due to intensive construction of a new building for space telescope nearby. The dynamics of the annual mean of sums of major ion concentrations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, NO_3^{-}, Cl^{-}, SO_4^{2-}) in atmospheric aerosol is presented in Figure 2.2 for the period from 2020 to 2024, while Figure 2.3 shows their long-term dynamics over the period 2000–2024.

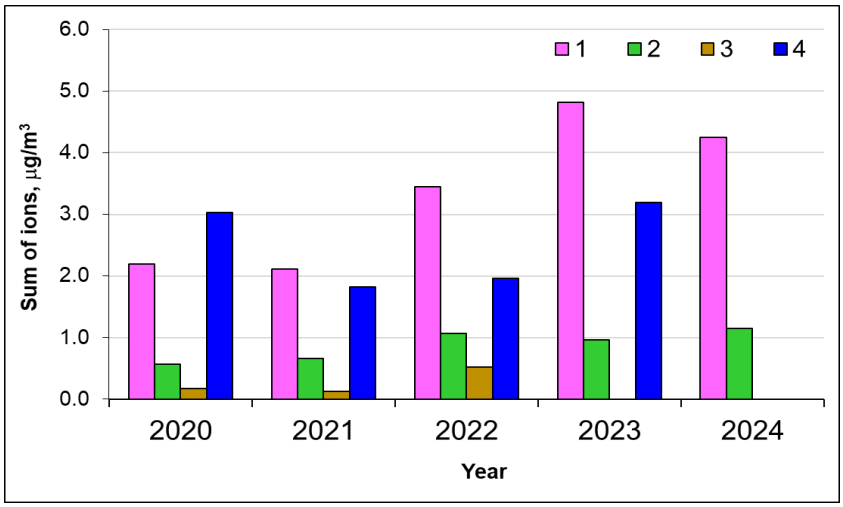


Figure 2.2 Mean annual sums of ion concentration in aerosols at the EANET monitoring sites, µg/m³ (1 – Irkutsk, 2 – Listvyanka, 3 – Mondy, 4 – Primorskaya), 2020–2024.

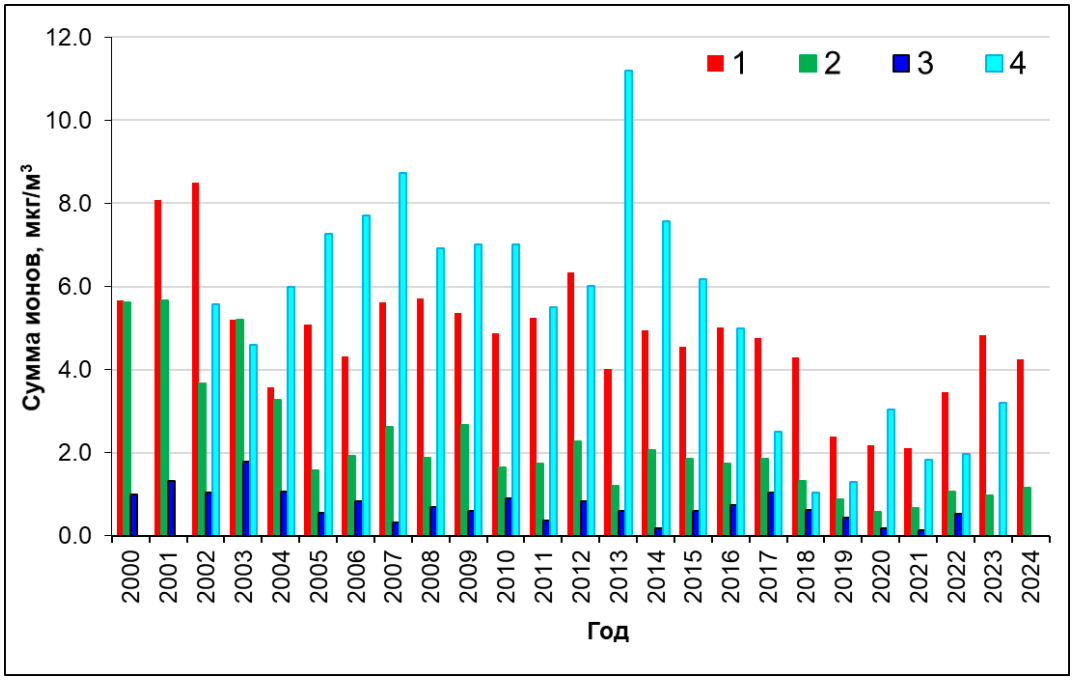


Figure 2.3 Mean annual sums of ion concentrations in aerosols at the EANET monitoring sites, µg/m³ (1 – Irkutsk, 2 – Listvyanka, 3 – Mondy, 4 – Primorskaya), 2000–2024.

The opposing trends observed in the aerosol composition at each monitoring site over the more than 20-year observation period may be associated with the synoptic and meteorological conditions of individual years. Nevertheless, the overall pattern of ion distribution in the aerosol remains consistent, with the dominating of sulfates, ammonium, and calcium among components.

Despite the evident interannual variations, the trend towards to a decrease in the total ion content in the aerosol is traced over the entire period of observations from 2000 to 2024 (Table 2.1).

Table 2.1. The 5-year averaged annual mean sum of ions in the aerosol at the EANET monitoring sites, μg/m³

Years	Irkutsk	Listvyanka	Mondy	Primorskaya
2000–2004	6.21±2.06	4.69±1.13	1.24±0.33	5.38±0.72**
2005–2009	5.22±0.55	2.13±0.48	0.60±0.19	7.53±0.75
2010–2014	5.08±0.84	1.78±0.41	0.57±0.31	7.46±2.24
2015–2019	4.20±1.05	1.53±0.42	0.68±0.23	3.19±2.29
2020–2024	3.36±1.21	0.88±0.25	0.27±0.22*	2.11±1.07

** for 2020–2022 ** for 2002–2004*

At the monitoring sites in Eastern Siberia (Irkutsk, Listvyanka, Mondy), the highest average ion concentrations in aerosol were recorded at the Irkutsk urban site. During the period 2020–2024, they exceeded the sum ion concentration in aerosol at the rural site Listvyanka by a factor of 4, and the one at the background site Mondy by more than a factor of 12. In the interannual five-year dynamics of 2020–2024, the total ion concentration in aerosol decreased by nearly 20% at the Irkutsk site, by 42% at the Listvyanka site, and by 60% at the Mondy site compared to 2015–2019. In comparison with the initial observation period (2000–2005), the mean sum ion concentration in aerosol at Irkutsk in 2020–2024 had decreased by a factor of 1.6, at Listvyanka by a factor of 4.4, and at Mondy by a factor of 3.5. This reduction at Irkutsk had occurred due to a decrease in the concentrations of all major ions (Ca^{2+}, Mg^{2+}, NH_4^+, NO_3^-, SO_4^{2-}), with the exception of Na^+ and Cl^-, whose concentrations increased slightly. It has been previously shown that the increase in the concentration of these ions in aerosol during winter is associated with local urban pollution resulting from the accumulation of de-icing agents in snow during road surface treatment to prevent icing (Golobokova et al., 2018). At the Listvyanka site, the interannual total ion concentration decreased due to a reduction in the concentrations of all ions.

At the Mondy site, an increase in the sum ion concentration was recorded over the period from 2014 to 2019 compared to the previous five-year interval (2010–2014). As demonstrated by the studies (Borjigin et al., 2024), with the intensification of southern cyclonic processes arriving from China and Mongolia into this region, the transport of substances with air masses increased due to the rising frequency of dust storms. In the aerosol composition at the Mondy site, concentrations of almost all analyzed ions (NH_4^+, Na^+, K^+, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}) were raised during the warm period. From 2020 to 2022, a certain decrease in the sum ion concentration was observed at this site, mainly as attributable to a reduction in the contribution of SO_4^{2-} ions.

The ionic composition of aerosol at the Primorskaya site has differed in recent years from that at the sites in Eastern Siberia, and its change was firstly noted in 2014–2019. In addition to NH_4^+, Ca^{2+}, and SO_4^{2-} ions, higher values were determined for K^+ ions. Na^+ ion concentrations became dominant in the aerosol composition, and an increase in the concentrations of NO_3^- and SO_4^{2-} ions was observed. In 2020–2024, however, the total ion concentration decreased by a factor of 2.6 compared to the starting measurement period (2002–2004).

In terms of seasonal variability during 2020–2024, a pronounced fluctuation in the total ion concentration in aerosol was observed at all monitoring sites, with higher values recorded during the cold period of the year (Figure 2.4.).

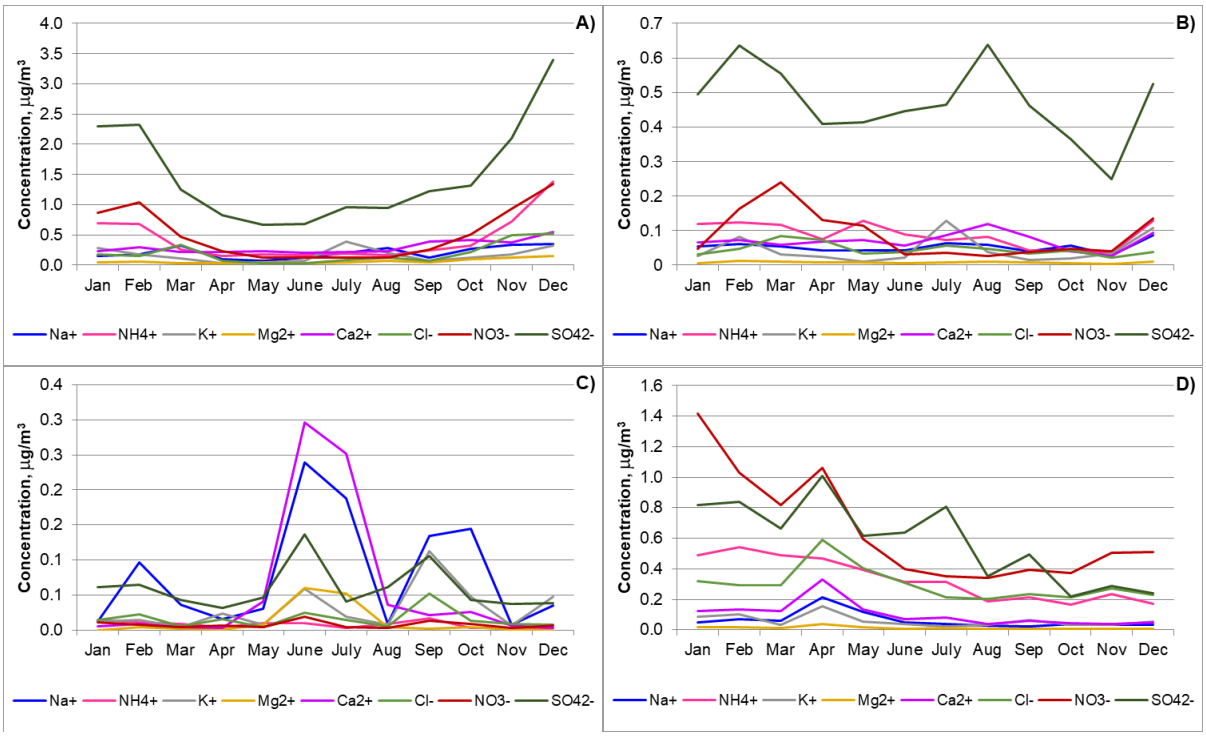


Figure 2.4 – Average monthly concentrations of major ions at EANET stations for 2020–2024, µg/m³ (A – Irkutsk, B – Listvyanka, C – Mondy, D – Primorskaya)

At Irkutsk, maximum ion concentrations in aerosol were recorded in December–February, during periods of low air temperatures and winter surface inversions under the influence of the Siberian Anticyclone. At the Listvyanka site, the peak ion concentrations in aerosol are shifted to February–March, which is explained by the site location near a large water body, Lake Baikal. As a result of intense water evaporation from the lake in December–January prior to its freezing, the atmosphere is effectively cleaned up of pollutants under conditions of high air humidity. In February, the lake becomes ice-covered, and cleansing effect weakens, leading to higher pollutant levels.

In the seasonal distribution of ions in the aerosol at the background Mondy site, three distinct maxima are consistently observed, determined by the prevailing synoptic patterns in the region (Figure 2.4 c). The first increase in the total ion sum occurs in February, been associated with the breakdown of the Asian anticyclone and the consequent intensification of wind flows. The second maximum is observed in late May–July, when the influx of solar radiation enhances turbulent heat exchange and convective processes in the atmosphere. The third maximum in the total ion sum is recorded in autumn (September–October), when cyclogenesis processes become more active, driven by the reorganization of the near-surface pressure field from summer to winter patterns. The minimum aerosol content was observed in late July–August, coinciding with frequent intrusions of deep cyclones from Mongolia. The prolonged rainfall associated with these cyclones effectively cleansed the atmosphere of pollutants, resulting in a decrease in the sum ion concentration in the aerosol.

At the Primorskaya site, the highest ion concentrations in aerosol were observed both during the cold period (December–February) and in the warmer period (April). Elevated concentrations in the aerosol composition were determined both for ions of continental, predominantly anthropogenic origin (SO_4^{2-}, NO_3^-) and for those of marine origin (Na^+, Cl^-). Furthermore, at this site, an increase in ion concentrations was also noted during the summer months (July–August), likely attributable to the high fire activity in forests of the region (Figure 2.5). The highest number of fires and burned area in Primorsky Krai were observed in 2021–2022, and in Irkutsk Oblast in 2021 and 2024.

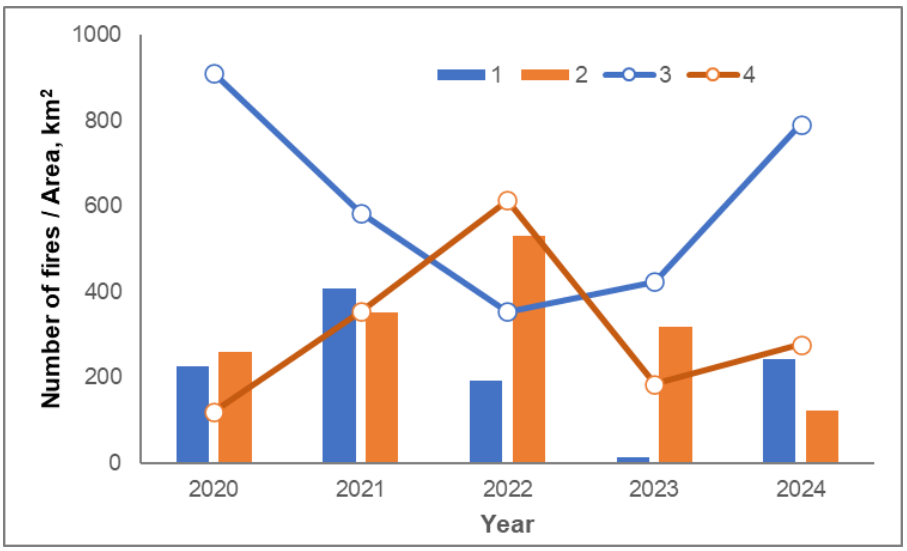


Figure 2.5 – Dynamics of burned area (*1* and *2*, km²) and the number of forest fires (*3* and *4*) from 2020 to 2024 in Irkutsk Oblast and Primorsky Krai, consequently.

2.2. Dry deposition

The intake degree of pollutants from the atmosphere is one of the criteria of the ecological condition of various natural environments. Sulfur and nitrogen coming in large amounts from the atmosphere onto the underlying surface led to acidification of surface waters and soil as well as oppression and death of forests and other natural objects. In the Baikal region, the acidification of precipitation has become the most likely unfavorable effect of the transport and deposition of sulfur and nitrogen, leading to a shift in the balance of major ions in the tributaries waters of the southern part of Lake Baikal basin (Obolkin et al., 2016). The deposition of pollutants onto the underlying surface from the atmosphere via dry deposition (gases and aerosol) was calculated, providing a means to assess loads on various environmental ecosystems. Particular attention was paid to the fluxes of sulfur and nitrogen compounds, as they are major acidifying components contributing to the degradation of various natural ecosystems.

Sulfur and nitrogen dry deposition fluxes from the atmosphere were recalculated for nitrogen from nitrates and ammonium ions, and for sulfur from sulfate. The influx of nitrogen with gases was calculated from the total amount of gaseous pollutants, HNO_3 and NH_3, and that of sulfur – from SO_2. For calculations, the following formula was used: $D = C \cdot V \cdot \Delta t$, where D is the influx of substances, C is the average concentration for the period Δt, and V is the dry deposition velocity (EANET, 2010).

Interannual variations of atmospheric nitrogen, including gaseous ammonia (NH_3), nitric acid nitrogen (HNO_3), and nitrogen in solid aerosol particles as ammonium (NH_4^+) and nitrate (NO_3^-), were analyzed over the long-term period 2000–2024. It was recognized the dominant form in the aerosol throughout the entire observation period to be a reduced nitrogen (NH_3) (Tables 2.2–2.5). In the city atmosphere of Irkutsk, a decrease in its concentration on aerosol particles ($N–NH_4^+$) and an increase in gaseous species ($N–NH_3$) were noted by 2020–2024 (Table 2.2), whereas at the Primorskaya site, conversely, a decrease in gaseous species ($N–NH_3$) and an increase in aerosol particles ($N–NH_4^+$) were observed (Table 2.5).

At the Listvyanka and Mondy sites, reduced nitrogen in the period 2020–2024 decreased both in particulate and gaseous species (Tables 2.3–2.4). The total oxidized nitrogen forms ($N–NO_3^-$, $N–HNO_3$) decreased slightly in the atmosphere at all sites in 2020–2024 compared to 2015–2019.

The contribution of reduced nitrogen to total N deposition during 2000–2024 was high at all Russian monitoring sites: in Irkutsk – 76–89%, at Listvyanka – 83–96%, at the Mondy site – 81–97%, and at the Primorskaya site – 86–97%. The obtained results are important and may play a significant role in the alteration of various ecosystems in the studied regions. As is known, prolonged input of ammonium nitrogen under conditions of retarded nitrification may lead to a decrease in pH of the underlying surface and its acidification.

Table 2.2 – Annual mean nitrogen and sulfur fluxes at the urban Irkutsk site in 2000–2024, mg/m²/year.

Period	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$	$S\text{-}SO_4^{2-}$	$N\text{-}HNO_3$	$N\text{-}NH_3$	$S\text{-}SO_2$	N	S
	Aerosols			Gaseous				
2000–2004	50	13	283	4	48	283	115	618
2005–2009	27	9	47	5	90	601	131	744
2010–2014	22	9	42	2	41	678	75	764
2015–2019	35	29	102	2	63	499	129	666
2020–2024	22	24	82	3	79	693	127	857

Table 2.3 – Annual mean nitrogen and sulfur fluxes at the rural Listvyanka site in 2000–2024, mg/m²/year

Period	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$	$S\text{-}SO_4^{2-}$	$N\text{-}HNO_3$	$N\text{-}NH_3$	$S\text{-}SO_2$	N	S
	Aerosols			Gaseous				
2000–2004	46	6	49	10	36	166	98	215
2005–2009	14	3	25	1	72	511	90	536
2010–2014	10	2	18	1	33	387	46	405
2015–2019	13	8	48	2	80	346	102	394
2020–2024	7	5	36	1	79	593	92	629

Table 2.4 – Annual mean nitrogen and sulfur fluxes at the Mondy site in 2000–2022, mg/m²/year

Period	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$	$S\text{-}SO_4^{2-}$	$N\text{-}HNO_3$	$N\text{-}NH_3$	$S\text{-}SO_2$	N	S
	Aerosols			Gaseous				
2000–2004	10.6	1.4	14.2	1.3	17.2	29.8	31	44
2005–2009	3.9	0.8	7.4	1.0	27.8	104.2	34	112
2010–2014	1.3	0.6	3.8	1.5	7.7	62.5	11	66
2015–2019	4.1	2.1	24.9	0.8	27.4	24.8	34	50
2020–2022	0.6	0.5	4.2	0.1	22.1	10.6	23	15

Table 2.5 – Annual mean nitrogen and sulfur fluxes at the Primorskaya site in 2002–2024, mg/m²/year

Period	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$	$S\text{-}SO_4^{2-}$	$N\text{-}HNO_3$	$N\text{-}NH_3$	$S\text{-}SO_2$	N	S
	Aerosols			Gaseous				
2002–2004	40	7	59	3	220	343	269	401
2005–2009	52	12	82	3	71	167	139	248
2010–2014	43	11	82	5	52	145	110	227
2015–2019	7	7	30	4	85	77	103	106
2020–2024	16	8	13	2	44	94	69	107

The largest amounts of sulfur, as well as nitrogen, were deposited onto the underlying surface with gaseous species, the fluxes of which, with the exception of the background Mondy site, increased in 2021–2024 at the other sites in Eastern Siberia (Tables 2.2–2.4). In sulfur deposition, as well as in nitrogen fluxes, no coherent overall pattern of deposition was revealed. The contribution of oxidized sulfur forms on particles to total sulfur deposition ranged from 6 to 46% at Irkutsk, 4 to 23% at Listvyanka, 2 to 67% at the Mondy site, and 7 to 50% at the Primorskaya site. Sulfur fluxes via gaseous species increased from the starting period (2000–2004) by a factor of 2.4 at the urban Irkutsk site, by a factor of 3.6 at the rural Listvyanka site, whereas at the background site Mondy they decreased by a factor of 2.8. At the rural site Primorskaya,

following a nearly 4.5-fold decrease in sulfur fluxes via gaseous species from 2002 to 2020, a slight increase by a factor of 1.2 was observed in recent years (2021–2024) (Table 2.5).

Overall, no common patterns in the distribution of nitrogen and sulfur fluxes onto the underlying surface were identified among the monitoring sites in Eastern Siberia and Primorsky Krai (Figure 2.6, Figure 2.7).

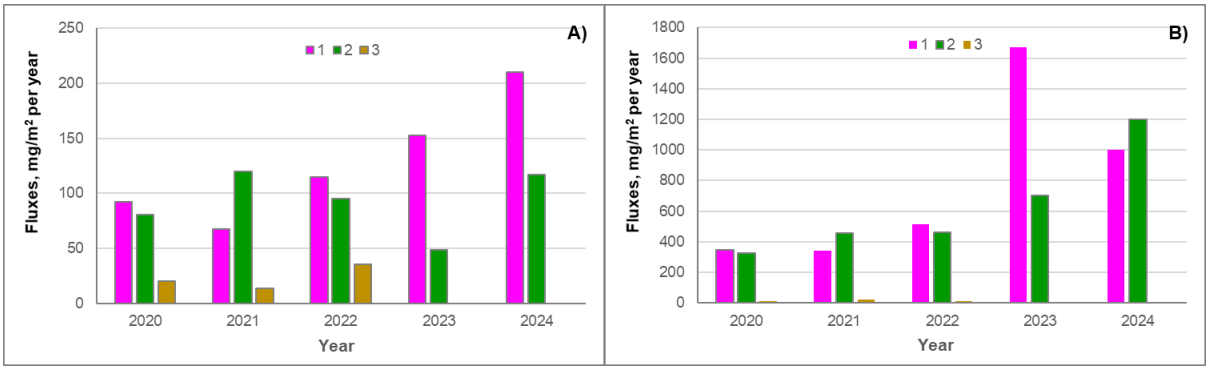


Figure 2.6 – Interannual dynamics of nitrogen (a) and sulfur (b) fluxes onto the surface at EANET sites in Eastern Siberia, mg/m² per year (1 – Irkutsk, 2 – Listvyanka, 3 – Mondy).

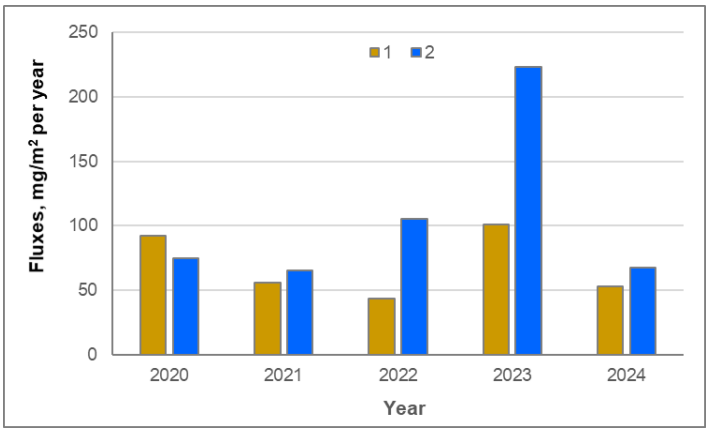


Figure 2.7 – Interannual dynamics of nitrogen (1) and sulfur (2) fluxes onto the surface at the Primorskaya site, mg/m² per year.

3. Wet deposition

3.1. Composition of precipitation

Studies of the chemical composition of atmospheric precipitation in 2020–2024 at the Russian EANET sites revealed the highest mineralization of precipitation at the urban Irkutsk site (Figure 3.1). On average over the period 2020–2024, the total ion concentration in precipitation at Irkutsk amounted to 15.5±1.9 mg/L, which is 5.6 and 2.4 times higher than at the Mondy and Listvyanka sites, respectively. From 2020 to 2024, a decreasing trend in the total ion concentration is observed in precipitation at Irkutsk, whereas at the Primorskaya site an increasing trend is recorded for this parameter. At the Listvyanka site, the total ion concentration in precipitation remained virtually unchanged over the 5-year observation period.

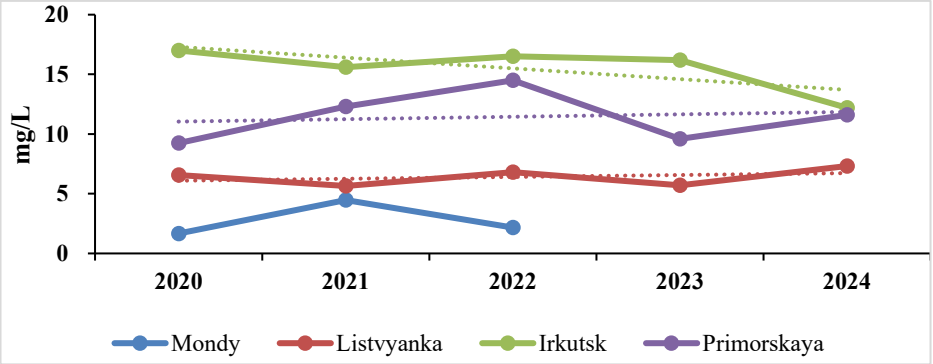


Figure 3.1 - Interannual variations of sum of ions (mg/L) in the atmospheric precipitations at the EANET monitoring sites.

The major compounds of the ionic composition of precipitation at all monitoring sites, as previously, were sulfate, calcium, and ammonium (Figure 3.2). In precipitation at Irkutsk and Listvyanka, calcium predominated among cations, whereas at the Primorskaya and Mondy sites, ammonium prevailed. Chloride, sodium, and potassium ions dominated in the relative composition in precipitation at the Primorskaya site (Figure 3.2). At Listvyanka, the highest proportion was still observed for sulfates and nitrates; at Irkutsk – for calcium and magnesium; and at the Mondy site – for bicarbonate and ammonium. The proportion of hydrogen ions was elevated at the Mondy and Listvyanka sites.

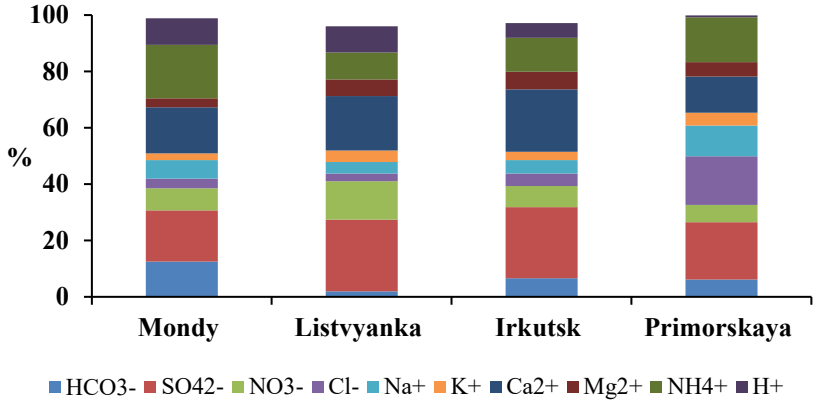


Figure 3.2 - Annual (2020-2024 average) relative ion composition of the precipitations at the EANET monitoring sites

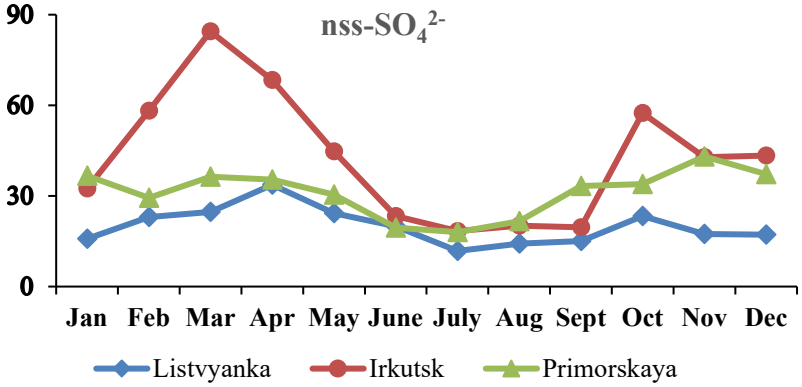
Interannual dynamics of the ionic composition of precipitation at the monitoring sites are presented in Table 3.1. At the Irkutsk site, annual mean concentrations of the majority of ions in precipitation decreased from 2020 to 2024, whereas at the Primorskaya and Listvyanka sites they increased. At the urban site, the most notable decreases were recorded for sulfates, sodium, and ammonium (by factors of 1.5–2); at Listvyanka – for sodium and chlorides (by factors of 1.5–1.6); and at the Primorskaya site – for nitrates and calcium (by a factor of 1.6). The most increases in concentration were observed for bicarbonate and potassium at Listvyanka, and for potassium and ammonium at the Primorskaya site (by factors of 2.3 and 2.9, respectively). Comparison of absolute ion concentrations at the monitoring sites revealed maximum values for cations such as NH_4^+, Na^+, K^+, as well as of Cl^- in precipitation at the Primorskaya site (Table 3.1). At the Irkutsk and Listvyanka sites, despite differing levels of anthropogenic pressure the nitrate concentrations were similar unlike to the most other ions.

Table 3.1. The ion composition of precipitations at the EANET monitoring sites, mg/L

Year	HCO_3^-	SO_4^{2-}	NO_3^-	Cl^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+
Irkutsk									
2020	3.04	5.82	1.65	1.28	0.96	0.47	2.27	0.36	0.94
2021	1.92	5.61	1.58	1.30	0.93	0.45	2.58	0.36	0.93

2022	3.59	5.27	1.61	0.73	0.50	0.59	2.90	0.39	0.76
2023	1.87	5.26	2.10	1.40	0.98	0.53	2.62	0.52	0.76
2024	2.13	3.91	1.64	0.89	0.58	0.47	1.94	0.27	0.44
Av.	**2.60**	**5.18**	**1.69**	**1.11**	**0.78**	**0.52**	**2.46**	**0.38**	**0.77**
Listvyanka									
2020	0.23	2.41	1.80	0.25	0.20	0.24	0.78	0.14	0.38
2021	0.39	2.10	1.30	0.15	0.17	0.22	0.64	0.11	0.42
2022	0.67	2.14	1.59	0.15	0.17	0.38	0.93	0.15	0.35
2023	0.07	1.98	1.74	0.19	0.19	0.27	0.75	0.14	0.21
2024	0.53	2.46	1.69	0.16	0.13	0.68	0.91	0.21	0.32
Av.	**0.38**	**2.22**	**1.62**	**0.18**	**0.17**	**0.36**	**0.80**	**0.15**	**0.34**
Mondy									
2020	0.29	0.44	0.28	0.10	0.12	0.06	0.20	0.02	0.13
2021	2.27	0.57	0.24	0.09	0.08	0.12	0.23	0.03	0.68
2022	0.61	0.54	0.30	0.06	0.06	0.06	0.29	0.03	0.19
Av.	**1.06**	**0.52**	**0.27**	**0.08**	**0.09**	**0.08**	**0.24**	**0.03**	**0.33**
Primorskaya									
2020	0.95	3.09	1.23	1.15	0.83	0.41	0.87	0.24	0.46
2021	1.28	3.02	1.66	2.56	1.04	0.44	0.93	0.20	1.15
2022	1.78	3.84	1.75	2.28	0.97	0.65	1.06	0.23	1.29
2023	1.19	2.71	0.88	2.00	0.58	0.42	0.80	0.17	0.88
2024	1.03	3.39	0.79	2.55	0.83	1.18	0.53	0.21	1.12
Av.	**1.25**	**3.21**	**1.26**	**2.11**	**0.85**	**0.62**	**0.84**	**0.21**	**0.98**

Figure 3.3 presents the interannual dynamics of volume-weighted monthly mean concentrations of the major ions – sulfates, calcium, and mineral nitrogen compounds (NO_3^-, NH_4^+) – in precipitation at the monitoring sites. In Eastern Siberia, the maximum of major ion concentrations at the Irkutsk site occurs during the spring months, March–April. Spring is a period of elevated atmospheric pollution in the study area, due to increased aerosol concentrations in the atmosphere resulting from snowmelt—which releases various pollutants accumulated on the underlying surface over the winter months—combined with low precipitation amounts during this period. At Listvyanka, maximum concentrations of individual ions in precipitation were also recorded in March–April. In Primorsky Krai, the maxima of ion concentrations in precipitation were observed in November–December (Figure 3.3). The annual dynamics of nitrate concentrations in precipitation at all sites are similar to one another; however, unlike other ions, the maximum values are shifted to the coldest months of the year (December–February). This is attributed to increased atmospheric emissions of nitrogen oxides from coal-fired thermal power facilities, combined with low precipitation amounts during this period (Figure 3.4).



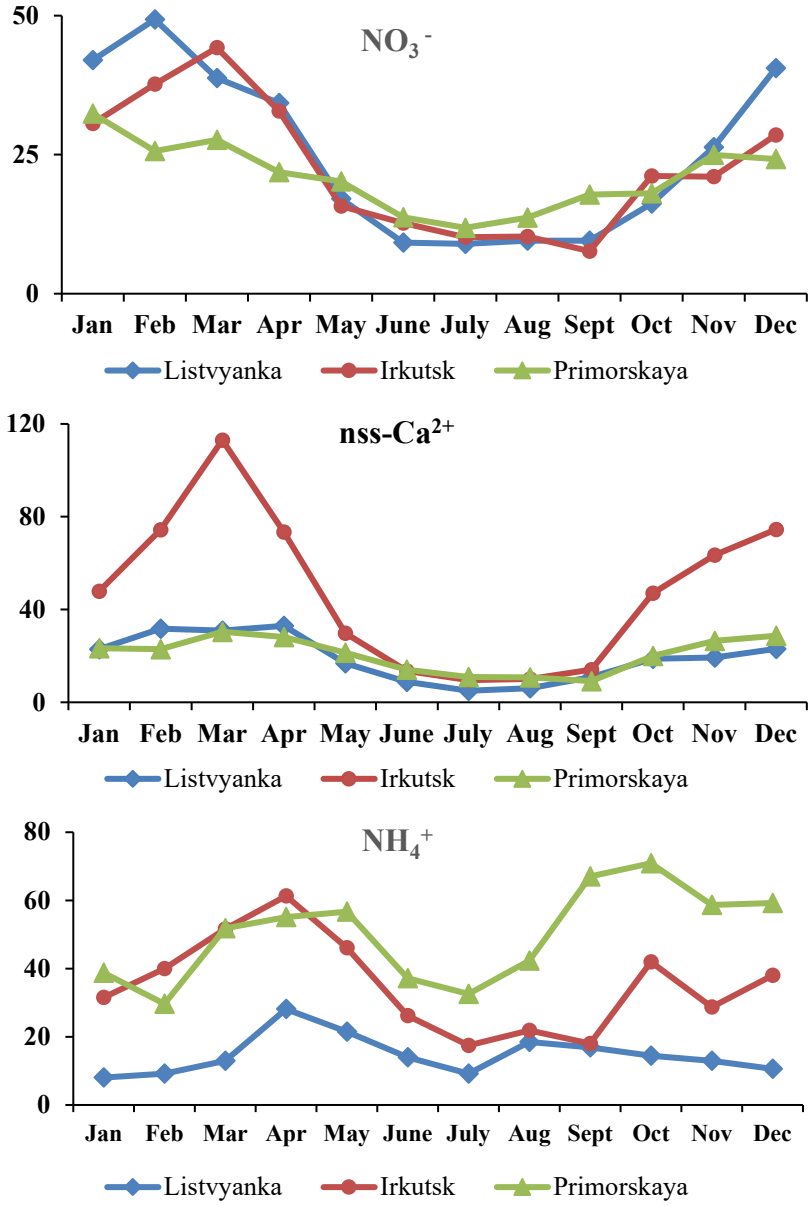


Figure 3.3 - Intra-annual variations (2020-2024) of the amount-weighted average concentrations of ions in the atmospheric precipitations at the EANET sites, µmol/L

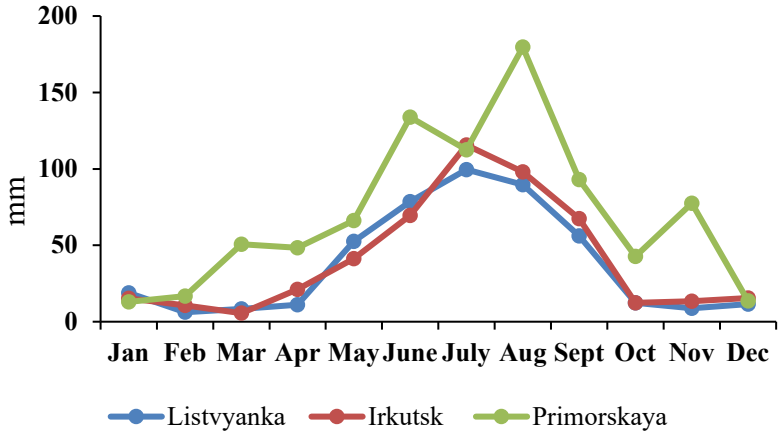


Figure3.4 - Intra-annual variations (2020-2024) of the precipitation amounts at the EANET sites, mm

During the study period, as previously, the lowest pH values in precipitation were recorded at the Listvyanka site (Figure 3.5). Interannual variations of this parameter at the Listvyanka site were not pronounced. The mean pH value over the 5-year period was 4.9±0.12. At the Irkutsk site, the pH of precipitation was higher, at 5.03±0.16. At the background Mondy site, the long-term mean pH value in precipitation was 5.47±0.14. The highest values (on average 5.72±0.18 pH units) were determined in precipitation at the Primorskaya site. In Eastern Siberia, a trend toward decreasing acidity of precipitation from 2020 to 2024 is observed, whereas in Primorsky Krai, conversely, precipitation acidity increased slightly (Figure 3.5).

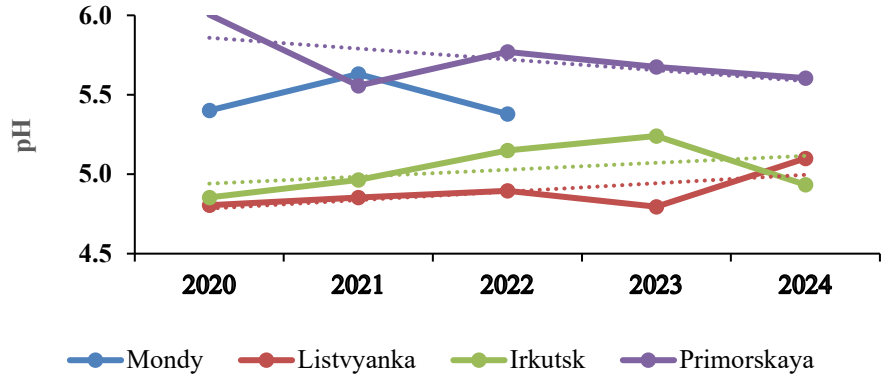


Figure3.5 - Interannual variations of the amount-weighted average pH in the atmospheric precipitations at the EANET monitoring sites.

Figure 3.6 presents the interannual dynamics of pH values in acidic precipitation at the atmospheric monitoring sites for the period 2020–2024. As can be seen from the figure, at all sites the frequency of acidic precipitation decreased from 2020 to 2024. The acidity of precipitation at the Listvyanka site decreased by 10% in 2020–2024 compared to 2015–2019, when in more than 52% of cases precipitation with pH <5.0 occurred. The maximum frequency of acidic precipitation at this site was recorded in 2023 (Figure 3.6). At the Irkutsk site, the occurrence of acidic precipitation in 2020–2024 decreased by 2% compared to the previous period and was, on average, 2 times lower (21%) than at Listvyanka. The maximum frequency of acidic precipitation at the Irkutsk site was recorded in 2020 (30.4%). At the Primorskaya site, acidic precipitation in 2020–2024 was scarce, averaging about 7%, which was 1.8% higher than in 2015–2019. The main peak of such acidic precipitation occurred in 2021. At the Mondy site, no acidic precipitation was recorded during the study period (2020–2022).

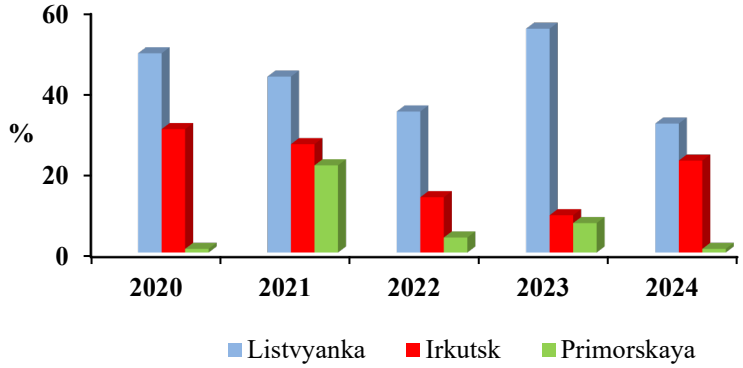


Figure3.6 - Interannual variations (2020-2024) of the percentage of precipitations with pH< 5.0.

In the intra-annual dynamics, the minimum pH values in precipitation in Eastern Siberia were recorded in summer, during June–August, while in Primorsky Krai they occurred in October. In seasonal terms, the maximum pH values in precipitation were observed during the cold season—at the urban site in December, and at the rural sites in March (Figure 3.7). In contrast to the urban site, the seasonal variation of pH at the rural sites was less pronounced.

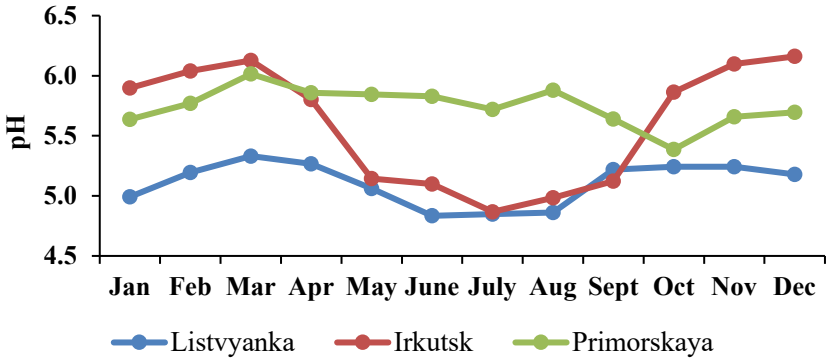


Figure 3.7 – Intra-annual dynamics of volume-weighted mean pH in precipitation in 2020–2024.

3.2. Wet deposition

Table 3.2 presents the annual values of wet deposition of ions at the monitoring sites in 2020–2024. The largest amount of salts is deposited at the Primorskaya site, owing to significantly higher precipitation amounts (on average by a factor of 1.8) than in the Eastern Siberian region (Figure 3.9). Compared to the urbanized Irkutsk site, the total ion deposition at the Primorskaya site is higher by a factor of 2.3 on average. Ion fluxes from the atmosphere at Irkutsk exceeded those at Listvyanka by a factor of 1.8, due to higher ion concentrations in precipitation. The smallest amount of atmospheric substances deposited with precipitation during the period 2020–2022 was recorded at the background Mondy site, where both ion concentrations and precipitation amounts were the lowest in the region (Table 3.2).

Table 3.2. Wet deposition of ions at the EANET monitoring sites (2020-2024), mg/m^2/y

Year	HCO_3^-	SO_4^{2-}	NO_3^-	Cl^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	H^+	$\sum_i$
Irkutsk											
2020	286	1077	338	161	115	72	289	49	209	6.8	2605
2021	236	1446	363	144	95	120	362	66	263	6.3	3106
2022	471	940	344	106	78	86	410	62	177	2.6	2681
2023	409	1141	423	186	221	160	693	103	229	3.3	3574
2024	334	1118	509	116	72	110	430	63	120	6.4	2883
Listvyanka											
2020	29	545	288	52	41	54	123	23	80	6.4	1245
2021	64	876	328	45	62	82	154	31	149	7.9	1802
2022	124	525	334	31	36	79	163	30	93	4.3	1420
2023	4	775	367	77	91	129	153	35	99	7.4	1738
2024	123	830	468	38	32	128	268	57	107	4.3	2058
Mondy											
2020	6.3	20.5	12.6	4.6	6.8	2.1	8.1	0.8	5.5	0.2	68
2021	115	34.4	12.0	5.0	3.8	8.3	10.6	1.8	35.0	0.1	227
2022	18.7	25.9	17.1	1.7	2.1	1.8	9.0	1.1	12.2	0.2	90
Primorskaya											
2020	753	1939	880	860	597	273	560	163	325	0.8	6357
2021	535	1394	812	1384	523	172	370	90	610	1.8	5895
2022	1078	2320	1085	1465	610	326	709	134	784	1.2	8515
2023	1177	2777	865	1610	461	341	848	158	837	2.3	9078
2024	571	1452	413	957	304	421	238	68	527	1.7	4955

Comparison of interannual dynamics of wet ion deposition at different monitoring sites shows that from 2020 to 2024, fluxes of the majority of ions increased in Eastern Siberia, while they decreased in Primorsky Krai. These changes in the dynamics of pollutant deposition onto the underlying surface with precipitation are mainly associated with the amount of precipitation at the sites (Table 3.2, Figure 3.10). It should also be noted that H^+ ion deposition fluxes increased sharply at Irkutsk in 2024 and at Listvyanka in 2023, whereas at the Primorskaya site a slight increase was observed throughout the entire study period (Figure 3.8).

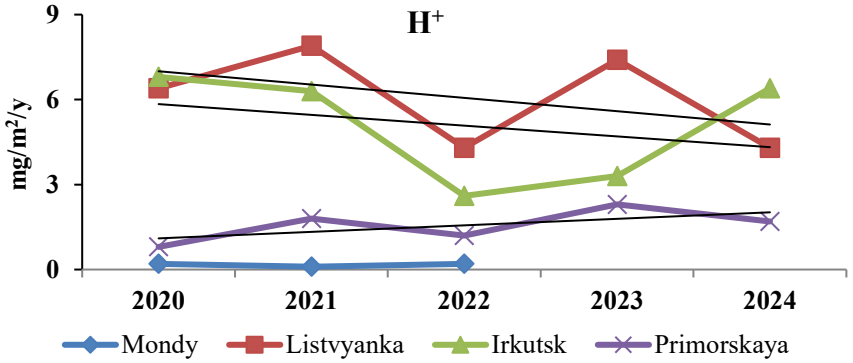


Figure 3.8 - Annual wet deposition of H+ (2020-2024) at the EANET monitoring sites, mg/m2/y.

Comparison of mean deposition values of major ions with precipitation at the monitoring sites revealed the greatest difference for NH_4^+ ion. At the Primorskaya site, fluxes of this ion are 3 and 6 times higher than the corresponding values at Irkutsk and Listvyanka, respectively. The minimum difference in ion deposition values between Primorskaya and Irkutsk was found for Ca^{2+}, with a factor of 1.2, and for NO_3^-, a factor of 2.3 between Primorskaya and Listvyanka.

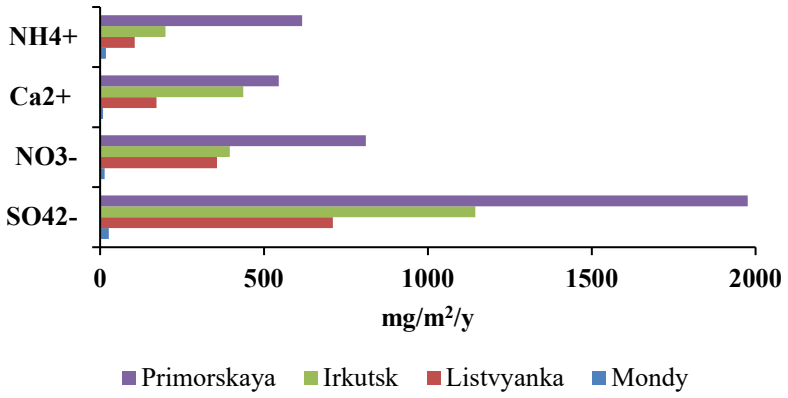


Figure 3.9 – Mean (2020–2024) wet deposition fluxes of major ions with precipitation at the EANET monitoring sites.

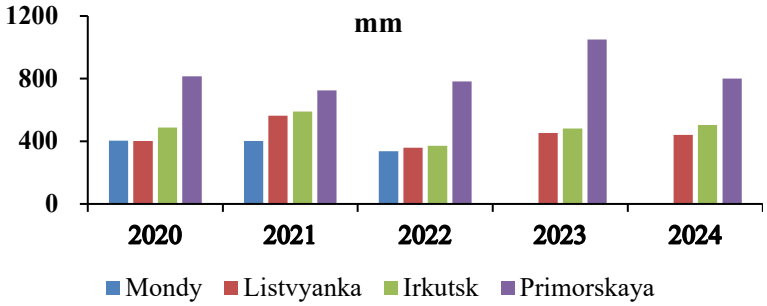


Figure 3.10 – Interannual changes in precipitation amounts at the EANET monitoring sites, mm, in 2020–2024.

Analysis of the chemical composition of atmospheric precipitation at the Russian EANET monitoring sites in 2020–2024 revealed the following:

The most mineralized atmospheric precipitation in 2020–2024, as in previous years of monitoring, occurred at the urban Irkutsk site, with a total salt content of 15.5 mg/L, while the least mineralized was recorded at the background Mondy site (2.8 mg/L). At the Irkutsk site, a decreasing trend in precipitation mineralization is observed from 2020 to 2024, whereas at the rural sites Listvyanka and Primorskaya no substantial changes in total ion concentration were noted.

The major compounds of the ionic composition of precipitation at the Irkutsk and Listvyanka sites were sulfate and calcium, while at the Primorskaya and Mondy sites they were sulfate and ammonium. At the Irkutsk site, concentrations of the majority of ions decreased from 2020 to 2024, whereas at the Listvyanka and Primorskaya sites they increased.

The lowest annual mean pH values were recorded in precipitation at Listvyanka (4.89), while the highest were at the Primorskaya site (5.72). The most acidic precipitation in the Baikal region occurred in June–July, while in Primorsky Krai it occurred in October. In 42% of precipitation events at the Listvyanka site, 21% at Irkutsk, and 7% at the Primorskaya site, precipitation with pH below 5.0 was recorded. Over the observation period from 2020 to 2024, the frequency of acidic atmospheric precipitation in the Baikal region decreased.

A direct relationship was established between the interannual variability of wet ion deposition fluxes at different monitoring sites and the amount of precipitation at the sites. The highest wet deposition of substances with precipitation was recorded at the Primorskaya site, owing to significantly higher precipitation amounts than in the Eastern Siberian region. Compared to the urban Irkutsk site, despite lower ion concentrations in precipitation at the Primorskaya site, their deposition with precipitation is, on average, twice as high. The lowest amount of atmospheric substances deposited with precipitation during the period 2020–2024 was recorded at the background Mondy site, where both ion concentrations and precipitation amounts were the lowest in the region. Comparison of mean deposition values of major ions with precipitation at the monitoring sites revealed the greatest difference for the NH_4^+ ion. At the Primorskaya site, fluxes of this ion are 3 and 6 times higher than the corresponding values at Irkutsk and Listvyanka, respectively. The minimum difference in ion deposition values between Primorskaya and Irkutsk was found for Ca^{2+} (a factor of 1.2), and between Primorskaya and Listvyanka for NO_3^- (a factor of 2.3). Wet deposition of H^+ ions was highest at Listvyanka, where the most acidic precipitation was recorded.

3.3. Calculated sulfur and nitrogen deposition fluxes in the area around Listvyanka EANET monitoring station

Total (sum of wet and dry) deposition fluxes of gaseous and aerosol forms of oxidized sulfur, oxidized nitrogen and reduced nitrogen in the area around the Listvyanka monitoring station have been calculated with the attention to the difference of the surface types. The list of considered species includes SO_2, HNO_3, NH_3 as gases in the ambient air and SO_4^{2-}, NO_3^- and NH_4^+ ions in atmospheric precipitation or as a part of aerosol composition.

Dry deposition was calculated following the EANET approach generally presented in Technical manual (2010a). Dry deposition velocity of gases and particles was calculated to low-vegetation (grassland) and high-vegetation (coniferous forests) surfaces using meteorological parameters derived from ERA5 reanalysis data. Since the EANET approach considers deposition to land-based ecosystems, additional parameterizations were applied to simulate deposition fluxes to water surface. Wet deposition flux was calculated as a product of concentration in precipitation measured at Listvyanka station and precipitation sums.

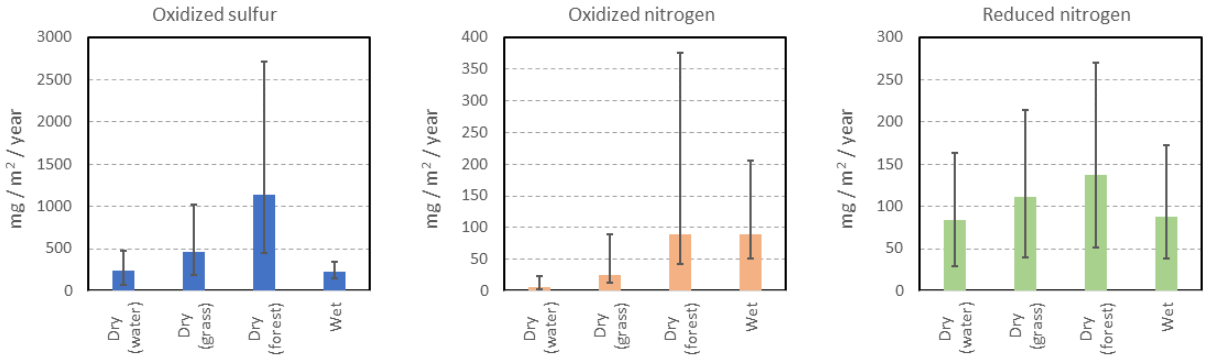
Calculated dry deposition fluxes of particulate and gaseous compounds to water surface, grasslands and coniferous forests as well as wet deposition flux at Listvyanka station are summarized in Table 3.3. “Mean” denotes annual deposition flux averaged over the 2004 – 2023 period, “min” and “max” are minimum and maximum annual deposition fluxes in the considered period. The lowest deposition fluxes are noted for water surface, and the highest – for forested areas. The large range between maximum and minimum fluxes is explained by interannual variability of measured air concentrations and meteorological conditions. Mean

total deposition of oxidized sulfur to water, grassland and forest surfaces are around 470, 690 and 1370 mg/m^2/year, respectively. Mean total deposition flux of oxidized nitrogen amounts to about 95, 115 and 180 mg/m^2/year to water, grassland and forest surfaces, respectively. The corresponding total deposition fluxes of reduced nitrogen are about 170, 200 and 225 mg/m^2/year.

Table 3.3. Calculated mean, maximum and minimum annual deposition fluxes (mg/m^2/year) to water, grassland and coniferous forest surfaces at Listvyanka station

Component	Parameter	Dry (water, part.)	Dry (grass, part.)	Dry (forest, part.)	Dry (water, gas)	Dry (grass, gas)	Dry (forest, gas)	Wet
Oxidized S	Mean	5.1	30.1	55.4	236.3	432.9	1088.0	226.2
	Min	1.7	10.9	19.1	60.1	135.4	333.8	152.1
	Max	10.4	55.4	113.9	476.6	1010.6	2685.4	339.6
Oxidized N	Mean	0.6	3.2	7.9	4.7	21.5	81.2	88.4
	Min	0.05	0.3	0.7	2.3	10.8	38.3	51.6
	Max	1.0	5.7	14.0	22.6	85.8	361.0	205.1
Reduced N	Mean	2.9	17.0	28.0	81.4	93.6	108.9	87.9
	Min	0.3	2.2	2.7	25.6	21.7	20.4	38.3
	Max	8.4	46.4	84.3	160.6	193.7	236.3	172.4

Contribution of wet and dry deposition components to total deposition varies with particular land-cover type and substance. Mean contribution of sulfur wet deposition flux makes up about 50%, 33% and 17% for water surfaces, grasslands and coniferous forest (Figure 3.11a). In case of oxidized nitrogen wet deposition is predominant over water surface and grassland, contributing on average around 95% and 80% to total deposition, respectively (Figure 3.11b). Contribution wet deposition to total deposition over forest is comparable with that of dry deposition and is around 45%. Mean contributions of wet to total deposition of reduced nitrogen are comparable and amount to around 50%, 45% and 40% for water, grasslands and coniferous forests, respectively (Figure 3.11c).



a b c

Figure 3.11 - Dry and wet annual deposition fluxes of oxidized sulfur (a), oxidized nitrogen (b) and reduced nitrogen (c) to different land-cover types, averaged over the 2004 - 2023 period. "Whiskers" denote the range between minimum and maximum annual deposition flux in the considered period.

4. Inland aquatic environment

4.1. Pereemnaya River

The Pereemnaya River, a tributary in the southern basin of Lake Baikal, was chosen as a research object for studying the influence of acidified precipitation on the chemistry of surface waters. The river starts near Sokhor Mounts of the northern macro slope of the Khamar-Daban Ridge at an altitude of 2,316 m. Its length is 42 km, and it drainages the watershed basin of about 462 km2 with average height of 1,260 m a.s.l. The

Archean rocks represented mainly by gneisses, schists and pegmatites are developed in the basin. The most part of the basin is in the taiga soil zone, with the soils characterized mainly by acidic pH. The river is fed by precipitation. In the area of the Khamar-Daban Ridge and the Pereemnaya River basin, the annual amount of precipitation is the highest in the Baikal region: up to 1,060-1,720 mm. The thickness of snow may reach 2 m.

The observations of the Pereemnaya River mainly aim to estimate the impact of acidic components coming from the atmosphere on the chemical composition of the river waters near the southeast coast of Lake Baikal located 38 km from the atmospheric monitoring station, Listvyanka. According to the previous studies, the Pereemnaya River is the most representative for reflecting the changes in the chemical composition of river waters caused by the influx of pollutants through the atmospheric channel (Netsvetaeva et al., 2010).

In the vicinity, the Baikalsk Pulp and Paper Mill (BPPM) in 70 km far from the river was a substantial source of technogenic emissions from 1966 to 2013. After the terminating operation of BPPM in 2013, the main sources of polluting components are the thermal power plant of the Baikalsk town, the Trans-Siberian Railway and the highway running along the lakeshore, local sources of the Tankhoy settlement as well as industrial emissions in the southern part of the Baikal region penetrating this area with air masses along the valley of the Angara River (Tomberg et al., 2016). Figure 4.1 shows sites for monitoring the atmosphere and river waters. Numbers in Figure 4.1 show annual SO2 emissions (thou tons per year) in the largest cities and towns of the region.

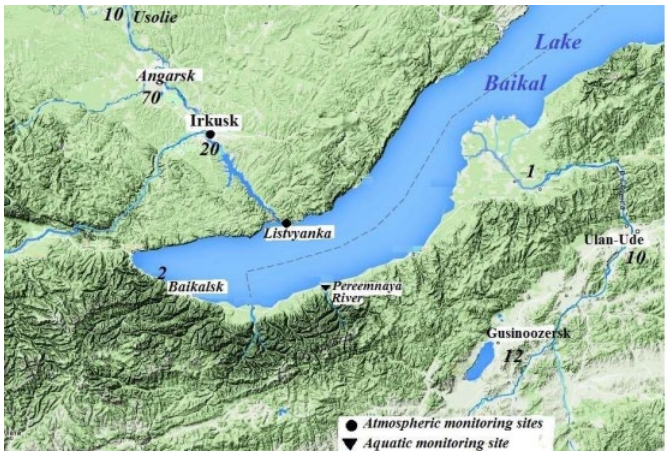


Figure 4.1 - The layout of atmospheric monitoring stations Irkutsk (urban site) and Listvyanka (rural site) as well as Pereemnaya River (aquatic monitoring site).

Hydrochemical studies of the Pereyemnaya River, conducted over the period from 2020 to 2024, represent a continuation of long-term observations carried out by the Limnological Institute of the Siberian Branch of the Russian Academy of Sciences since 2004 within the framework of the EANET program. The main objective of the research is to assess the impact of atmospheric deposition contaminated with acidic components on the formation of the chemical composition of river waters in the area of the southeastern coast of Lake Baikal (Eastern Siberia).

In 2020–2024, water samples were collected approximately 0.5 km upstream from the river mouth from the surface layer four times per year under different hydrological conditions (winter low-water period, flood period, summer and autumn low-water periods). At the sampling site, pH, electrical conductivity, and dissolved oxygen were measured in situ. In the chemical laboratory of the Institute, water samples were filtered through membrane filters with a pore diameter of 0.45 μm. Chemical analyses were performed using standard methods commonly employed in freshwater hydrochemistry (Boeva, 2009), as well as methods developed at the Limnological Institute SB RAS (Khodzher et al., 2016). Cations were determined by atomic absorption spectrometry, anions by high-performance liquid chromatography (HPLC) with an error of 5–10%, biogenic elements by photocolorimetry (error 3–5%), and pH by potentiometry. The reliability of the obtained results was verified by calculating the balance of major anions and cations (error not exceeding 3%) and by comparing calculated and measured specific electrical conductivity (EANET,

2010b). The accuracy of biogenic element determinations was verified through regular quality assurance/quality control (QA/QC) procedures within the framework of the international program (EANET) by testing standard "surface water" samples (Inter-Laboratory Comparison Project Report, 2021–2024).

The pH of the Pereyemnaya River water during the observation period (2020–2024) ranged from 6.43 to 7.01, falling within the long-term range of variability (Figure 4.2). Higher pH values were recorded mainly in the summer period, while the lowest values occurred in spring, during snowmelt and the influx of large volumes of melted snow water into the river. The decrease in pH during the summer–autumn period is generally attributed to flood events and the influx of acidic atmospheric precipitation into the river basin, transported from industrial areas of Siberia.

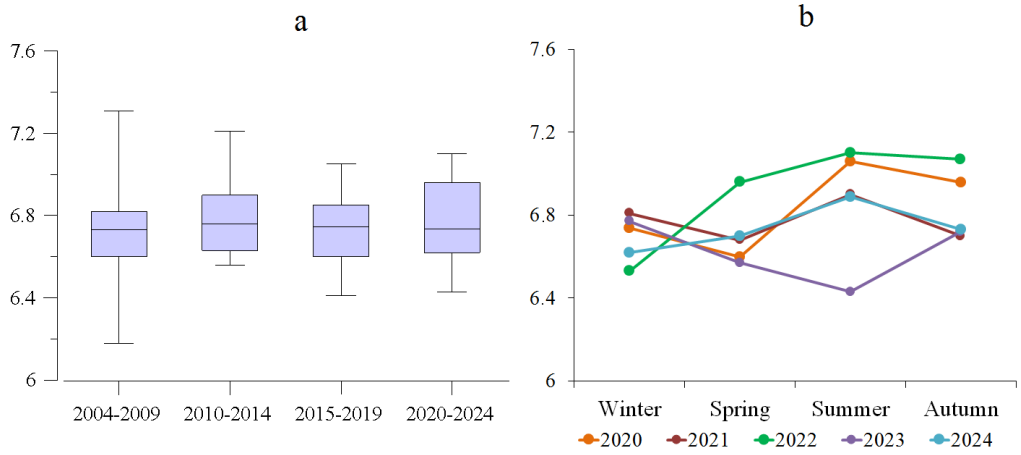


Figure4.2 - Annual (a) and seasonal (b) fluctuations of the pH in Pereemnaya River water

The waters of the Pereyemnaya River are well aerated; dissolved oxygen concentrations during the study period ranged from 9.66 to 13.45 mg/L. Minimum concentrations were recorded in summer, while maximum values were observed during the cold period, which is attributed to the increased solubility of oxygen in water at lower temperatures.

The total content of major ions (HCO_3^- + SO_4^{2-} + Cl^- + Na^+ + K^+ + Ca^{2+} + Mg^{2+}) in the water of the Pereyemnaya River during the study period (2020–2024) ranged from 20.4 to 34.7 mg/L (Figure 4.3). Low ion concentrations in the river water were observed during the spring flood period, when low-mineralized snowmelt water entered the channel. Following the spring minimum, the concentrations of major ions, as well as their total content in the river, gradually increased, reaching a maximum during the winter period. High summer and autumn floods could also cause short-term decreases in river water mineralization. For instance, in 2021, the minimum salt concentrations in the river were recorded in July, when sampling coincided with a flood event caused by prolonged rainfall in the mountains (Figure 4.3b).

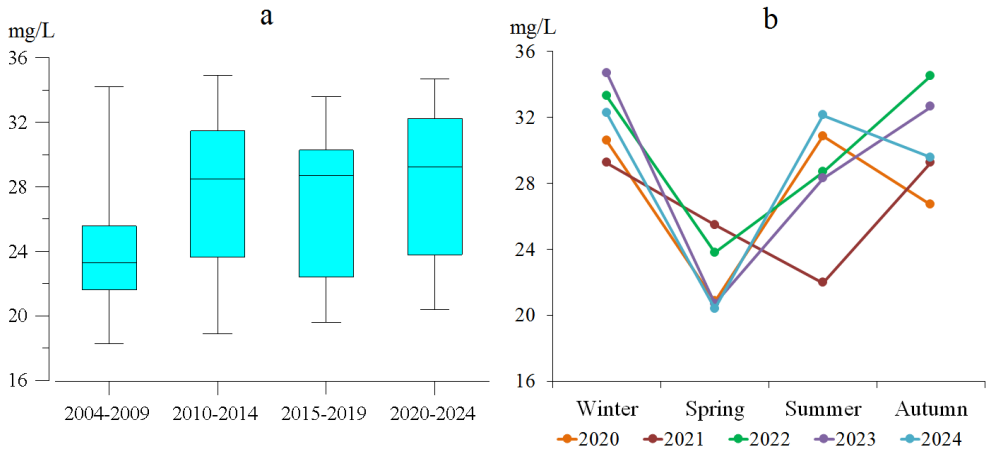


Figure 4.3 - Annual (a) and seasonal (b) fluctuations of the sum of ions in Pereemnaya River water

In the long-term perspective of observations, the total mineralization of water in the Pereemnaya River is gradually increasing. The mean total ion content during the period 2004–2009 was 24 mg/L; in 2010–2019 it was recorded at 27.5 mg/L; and in 2020–2024 it reached 28.3 mg/L. The increase in ion concentrations may be attributed to reduced water discharge of the river during this period, as well as to the intensification of rock weathering processes in its catchment area under the influence of precipitation with high acidity (the mean pH of snowmelt water in this area is 4.4–4.6). Compared to data from 1996, current values of the total ion concentration in the river water, depending on hydrological conditions, have increased by 20–32%. It should also be noted that in 2021–2023, construction of a road bridge was underway in the lower reaches of the Pereemnaya River, which could have affected the composition of river waters, although sampling for chemical analysis was conducted upstream.

The intra-annual dynamics of major ion concentrations remain unchanged and are determined primarily by variations in water discharge. Sulfate concentrations in 2020–2024 ranged from 7.1 to 15.4 mg/L and were higher than those in 2015–2019 (6.9–13.6 mg/L) (Figure 4.4a). In the interannual aspect, sulfate concentrations varied mainly within a narrow range (Figure 4.4b).

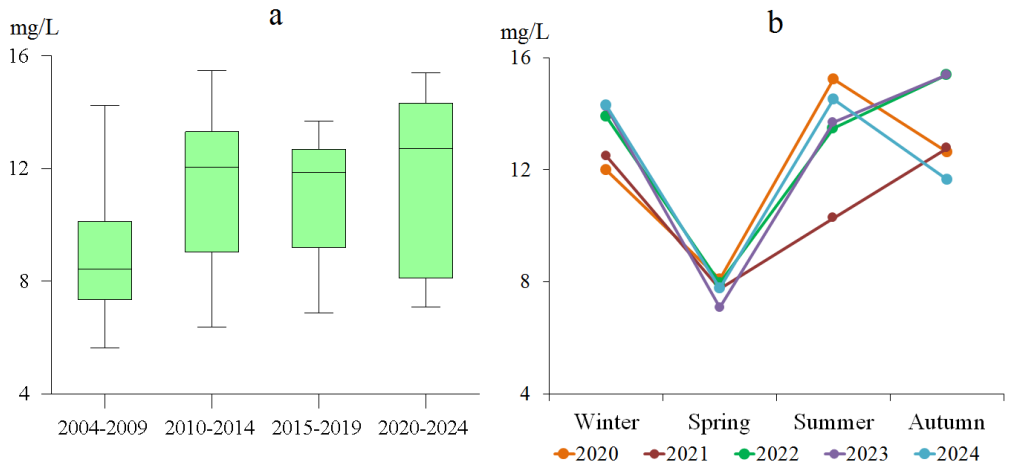


Figure 4.4 - Annual (a) and seasonal (b) fluctuations of the sulfates in Pereemnaya River water

In the pre-industrial period of the Southern Baikal region area (1950–1960), the major components in the relative composition of the Pereemnaya River waters were HCO_3^- and Ca^{2+} ions (Votintsev et al., 1965). At the end of the last century, during the operation of the Baikal Pulp and Paper Mill (BPPM), with intensive input of acidic components from the atmosphere onto the river catchment area via precipitation and dry deposition, a significant change in the relative composition of major ions in the river waters was observed, accompanied by an increase in sulfate and nitrate concentrations in the water (Sorokovikova et al., 2020). In the long-term perspective (1955–2024), a trend toward decreasing bicarbonate concentrations and increasing calcium and sulfate concentrations in the water of the Pereemnaya River is currently observed. At present, the relative composition of major ions in the water of the Pereemnaya River corresponds to the sulfate class, calcium group (Figure 4.5).

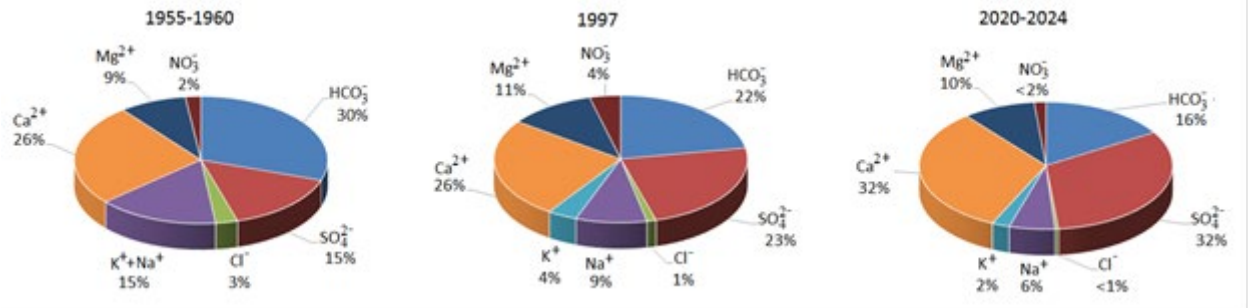


Figure 4.5 - Changes in the relative content of major ions in the waters of the Pereemnaya River

In the last decade, a decrease in nitrate nitrogen content in atmospheric precipitation has been observed in this territory (Sorokovikova et al., 2021), which has led to a certain reduction in the concentrations of this

component in river water as well, although in the modern period, nitrate nitrogen concentrations in the river water remain 40–60% higher compared to data from the 1950s.

A distinctive feature of the seasonal dynamics of nitrate nitrogen concentrations is an increase in its values during spring snowmelt, while in the summer–autumn period it remains stable (Figure 4.6). In summer, during the period of intensive plankton development, NO_3^- content becomes minimal; in autumn, its concentrations in river waters gradually increased (Figure 4.6).

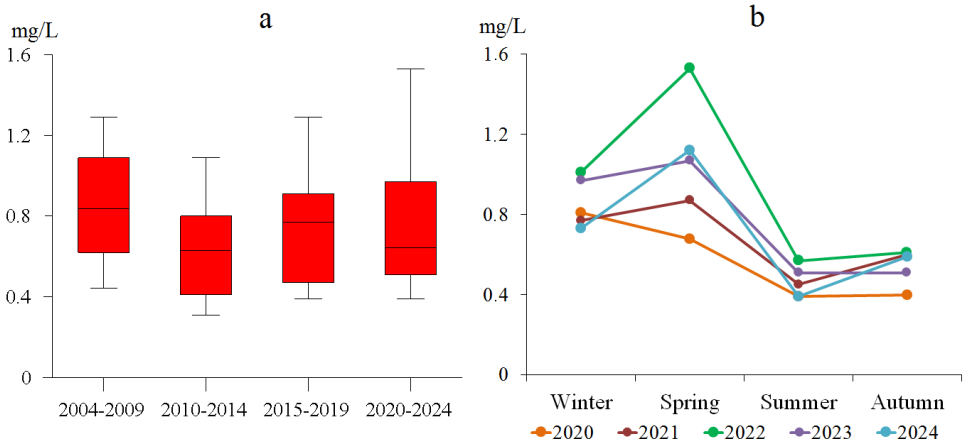


Figure 4.6 - Annual (a) and seasonal (b) fluctuations of the nitrate nitrogen in Pereemnaya River water

Changes in ammonium nitrogen concentrations in river waters are mainly associated with the dynamics of water runoff and the input of NH_4^+ from the catchment area during the flood period and summer high-water events. Ammonium nitrogen concentrations during the winter low-water period ranged from 0.002 to 0.024 mg NH_4^+/L; during summer and autumn low-water periods they were generally within the range of 0.001–0.008 mg NH_4^+/L, increasing to 0.014 mg NH_4^+/L during flood events. Elevated ammonium nitrogen concentrations in winter were likely associated with the impact of road bridge construction activities in the lower reaches of the river, which induced freezing, ice formation, and backwater effects over a large area upstream. Nitrite nitrogen concentrations in the water of the Pereemnaya River throughout the entire observation period remained at low levels, ranging from 0.001 to 0.003 mg NO_2^-/L. No discernible pattern in the variation of nitrite nitrogen concentrations was established.

The total phosphorus (TP) content in the water of the Pereemnaya River during the study period remained low across all seasons, at less than 12 µg P/L. The share of mineral phosphorus (MP, phosphate) was insignificant, averaging approximately 26% of the total phosphorus content in river water (Figure 4.7), with MP concentrations not exceeding 2 µg P/L. No discernible pattern in either seasonal or interannual dynamics was established for either mineral or total phosphorus. Maximum concentrations of mineral and total phosphorus were recorded in winter and summer of 2022.

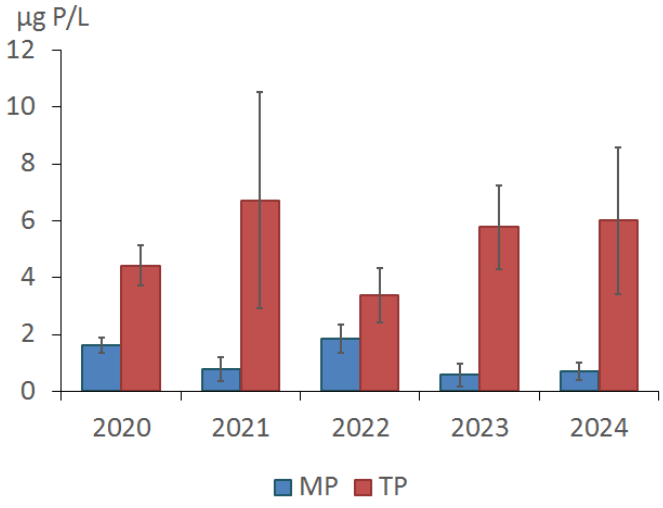


Figure 4.7 - Average content of mineral (phosphate) and total phosphorus (with standard deviation) in the water of the Pereemnaya River

To characterize organic matter (OM) in the river waters of the Pereemnaya River, permanganate oxidizability (PO) was determined. The PO values in 2020–2024 ranged from 0.3 to 3.9 mg O/L and were higher than those in 2010–2014 (0.31–1.9 mg O/L), which may also be associated with bridge construction on the river. The lowest concentrations were recorded in winter, while the maximum values occurred during summer–autumn flood events, resulting from the input of organic compounds from forest litter via the catchment area (Figure 4.8).

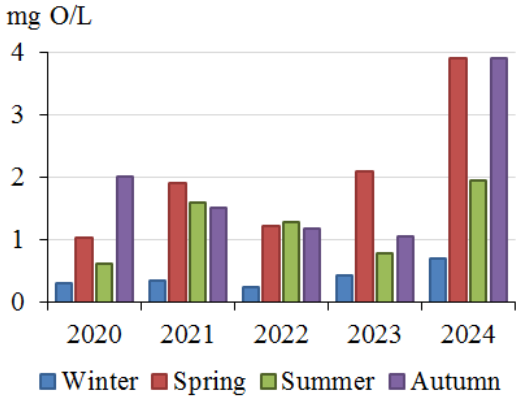


Figure 4.8 - Seasonal fluctuations of PO in water of the Pereemnaya River in 2015-2019

Thus, the research conducted over the last five years on the Pereemnaya River, together with their comparison against long-term observational data, allows the following conclusions to be drawn: The river waters, as previously, are characterized by low salt content. In terms of the relative composition of major ions, the river water in the modern period corresponds to the sulfate class, calcium group, which in earlier studies was recorded only episodically. At present, the waters of the Pereemnaya River are characterized by elevated sulfate and nitrate nitrogen concentrations and rather low pH values (6.43–7.01). Owing to the predominantly atmospheric precipitation feeding of the river, a low buffering capacity of the river waters is noted, which renders them susceptible to acidification.

4.2. Komarovka River

The Komarovka River, a mountain river, was chosen as a model object for studying the influence of atmospheric precipitation on the chemistry of surface waters in the Primorsky region. The river originates in spurs of the Sikhote-Alin Ridge at an altitude of 380 m above sea level. Being the left tributary of the Razdolnaya River, the Komarovka River belongs to the Japanese Sea basin. Its length is about 66 km. Mean annual water discharge varies from 0.66 m^3/s to 3.79 m^3/s, averaging 1.67 m^3/s.

The observation site is located at the hydrological post “Tsentralny” within the area of station Primorskaya, 34 km far from the Ussuriysk city and 44 km from the river mouth. There are no stationary pollution sources of the river stream at the observation site and upward. The river is likely affected by rain flow from the watershed and by snow waters. Hydrochemical observations have been carried out on the river since 2005. From 2020 to 2024, like in previous years, the studies were carried out 5 times per year: in February, April, June, September, and November, thus, recording changes in the chemical composition of the river waters during different hydrological periods and different years.

The water temperature in the river varied from 0.1°C to 19.8°C with its maximum recorded in September. The warmest month was September 2021. Water in the Komarovka River is low-mineralized and soft. From 2020 to 2024, mineralization of water varied throughout the year within a range from 20.4 to 81.3 mg/L (Figure 4.9).

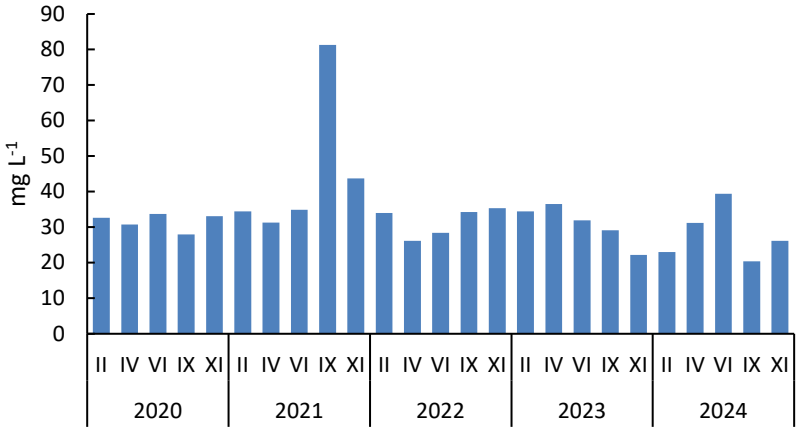


Figure 4.9 - Seasonal fluctuations of the total amount of ions in the water of the Komarovka River from 2020 to 2024.

Figure 4.10 presents the interannual and seasonal dynamics of the SO_4^{2-} concentrations in the river water. There was no definite pattern in the seasonal dynamics of the concentrations. In 2021, elevated concentrations of $SO4^{2-}$ were observed in autumn. While at the same period in 2020, the lowest SO_4^{2-} concentration was observed.

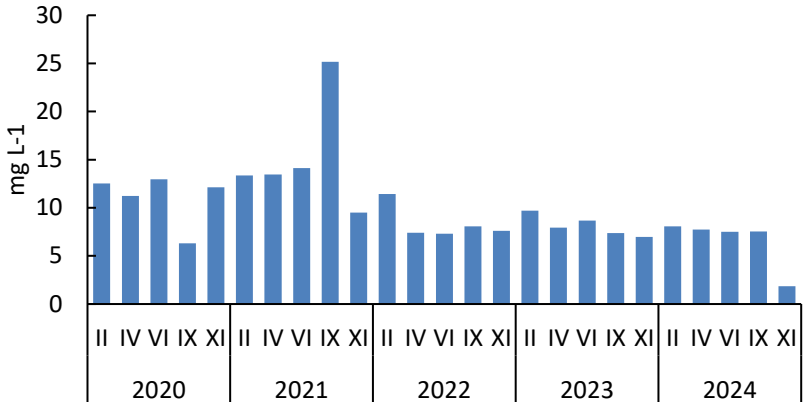


Figure 4.10 - Annual fluctuations of SO_4^{2-} (mg/L) in surface water of the Komarovka River in 2020-2024.

From 2020 to 2024, the concentrations of Cl^- in the Komarovka river water varied from 1.5 to 12.4 mg/L, with average of 3.8 mg/L. The concentrations of Na^+ fluctuated from 3.6 to 13.0 mg/L, K^+– from 0.5 to 3.6 mg/L, Ca^{2+}– from 4.7 to 25.7 mg/L, and Mg^{2+}– from 0.4 to 7.1 mg/L (Figure 4.11). The analysis of the obtained results revealed that there were no definite seasonal and interannual patterns in the dynamics of their concentrations.

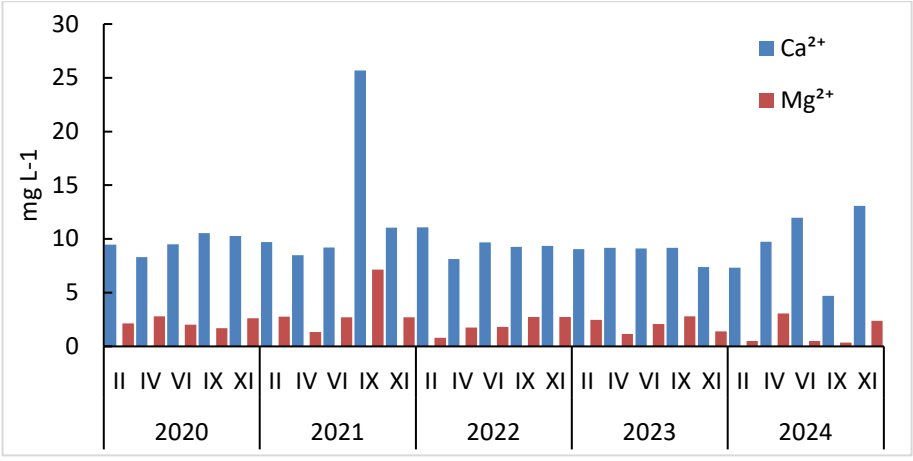


Figure 4.11 - Annual fluctuations of Ca^{2+} and Mg^{2+} (mg/L) in surface water of the Komarovka River in 2020-2024.

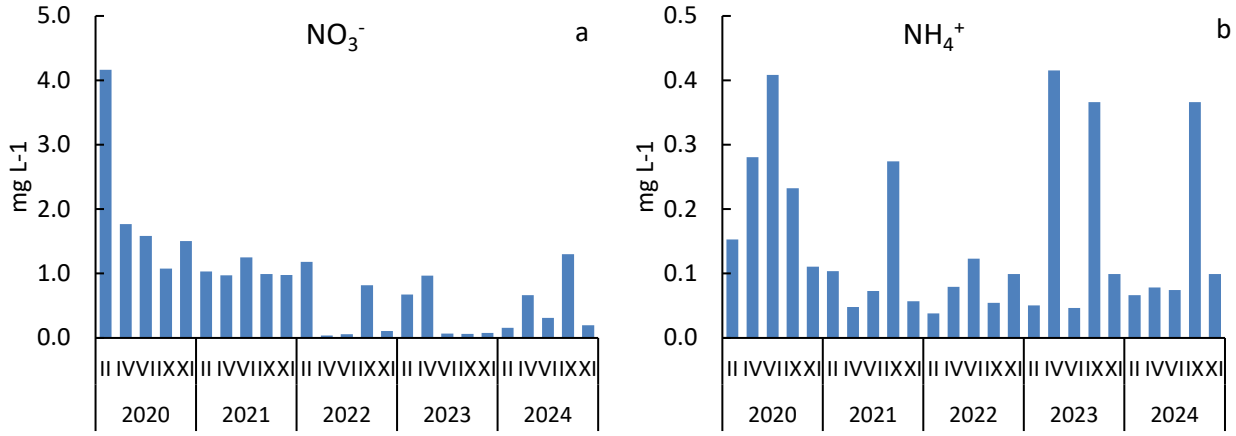


Figure 4.12 - Fluctuations of the NO_3^- and NH_4^+ concentrations in the water of the Komarovka River from 2020 to 2024.

Figure 4.12 shows the data on the dynamics of NO_3^-(a) and NH_4^+(b) in the water of the Komarovka River from 2020 to 2024. The concentration of NO_3^- in the water of the Komarovka River varied from 0.04 to 4.2 mg/L; a decrease was observed in 2022 year and from autumn in 2023 to spring in 2024. The highest concentration was observed in February 2020 – 4.2 mg/L. The NH_4^+ concentrations varied from 0.04 to 0.42 mg/L without visible relation to seasons. The concentration of NO_2^- in the water of the Komarovka River varied from 0.003 to 0.08 mg/L. There was no definite pattern in the seasonal and interannual dynamics of the NO_2^- concentration too.

The pH value of the water in the Komarovka River varied from 6.4 to 8.4 (Figure 4.13), with the minimum values in spring and summer. Period from spring 2021 to summer of 2023 characterized by the pH value above 7.0. The river water is rich in dissolved oxygen ranging from 7.1 to 14.4 mg/L. Its lowest vales were observed at late autumn in 2022 and 2024.

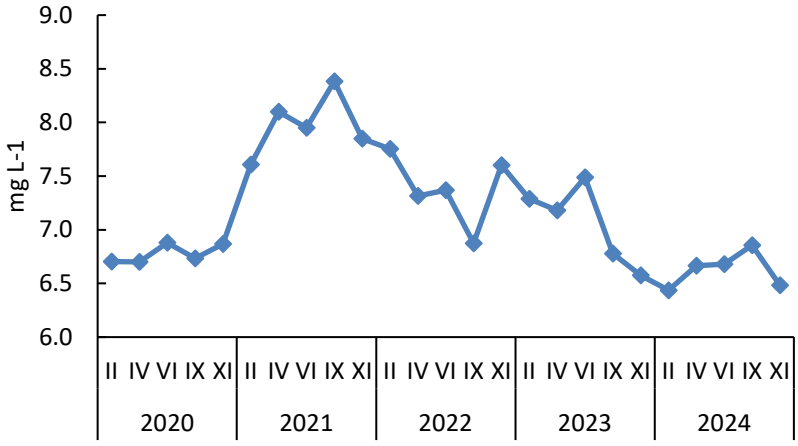


Figure 4.13 - Fluctuations of the pH value in the water of the Komarovka River from 2020 to 2024.

Long-term monitoring observations that were carried out on the rivers of the Asian part of Russia

under the EANET program have revealed that the Komarovka River has low concentrations of major ions and low mineralization of water. In terms of the relative concentrations of major ions, the water in the river in the modern period (from 2020 to 2024) corresponds to the sulfate class and the calcium group. There are elevated concentrations of sulfates and nitrate nitrogen as well as low pH values. With the main feeding of

the river by precipitation, there is a low buffer capacity of the river water, which predetermines its non-resistance to acidification.

For the period 2020-2024 concentrations of major ions in Komarovka River did not show specific seasonal trends. One case of elevated concentrations in September 2021 was monitored for most of monitored ions. At the same time the highest pH level was observed.

References

Boeva L. (Ed.), 2009. Manual for chemical analysis of surface water. Rostov-on-Don: RosHydromet, 1032 p. (in Russian)

Borjigin A., Bueh C., Yong M., Purevjav G., Xie Z., 2024. Cross-Border Sand and Dust Storms between Mongolia and Northern China in Spring and Their Driving Weather Systems. Remote Sensing, Vol. 16, 12, p. 2164. https://doi.org/10.3390/rs16122164.

Golobokova L., Khodzher T., Khuriganova O., Marinayte I., Onishchuk N., Rusanova P., Potemkin V., 2020. Variability of Chemical Properties of the AtmosphericAerosol above Lake Baikal during Large Wildfires in Siberia. Atmosphere. doi: 10.3390/atmos11111230.

Golobokova L. P., Khodzher T.V., Obolkin V.A., Potyomkin V.L., Khuriganowa O. I., 2018a. Long-term investigations of atmospheric aerosol and gaseous impurities in Southern Pribaikalye, East Siberia (Russia). Int. J Environ Sci Nat Res., Vol.10, 3, p. 555786. DOI: 10.19080/IJESNR.2018.10.555786

Golobokova L.P., Khodzher T.V., Obolkin V.A., Potemkin V.L., Khuriganova O.I., Onischuk N.A., 2018b. Aerosol in the atmosphere of the Baikal region: history and contemporary researches. Limnology and Freshwater Biology, N 1, p. 49-57, doi: 10.31951/2658-3518-2018-A-1-49.

EANET, 1999-2024. Inter-Laboratory Comparison Project Reports. https://monitoring.eanet.asia/document/public/index

EANET, 2010b. Technical Manual for Wet Deposition Monitoring in East Asia - 2010 . Network Center for EANET. https://www.eanet.asia/resources/publications/.

EANET, 2010a. Technical manual on dry deposition flux estimation in East Asia. Network Center for EANET. https://www.eanet.asia/wp-content/uploads/2019/04/techdry.pdf [accessed 1 March 2026].

Khodzher T. V., Zhamsueva G. S., Zayakhanov A. S., Dement'eva A. L., Tsydypov V. V., Balin Yu. S., Penner I. E., Kokhanenko G. P., Nasonov S. V., Klemasheva M. G., Golobokova L. P., Potemkin V. L., 2019. The results of shipborne studies of the aerosol-gas impurities of the atmosphere over Lake Baikal. Atmos. Ocean Optics, Vol. 32, N 4, p. 289–295. DOI: 10.15372/AOO20190406 (in Russian).

Khodzher, T.V., Domysheva, V.M., Sorokovikova, L.M., Golobokova, L.P., 2016. Methods for monitoring the chemical composition of Lake Baikal water. In: Novel Methods for Monitoring and Managing Land and Water Resources in Siberia, Cham: Springer, pp. 113–132.

Martynov V.P. 1965. Soils of the mountainous Baikal region – Ulan-Ude, 165 p. (in Russian).

Martusova E.G. 1988. Vegetation of the Pereemnaya – Abiduy River Basins. Vegetation of the Khamar-Daban Ridge – Novosibirsk: Nauka, pp. 56-68 (in Russian).

MNRE, 2025. State of the Environment and Environmental Protection in the Russian Federation in 2024. State Report. / Moscow: Ministry of Natural Resources and Environment of the Russian Federation; FSBI "VNII Ecology", 721 p. (in Russian)

Netsvetaeva O.G., Khodzher T.V., Golobokova L.P., Kobeleva N.A., Pogodaeva T.V., 2004. Chemical composition of snow cover in Prebaikalian reserves. Geography and natural resources, Vol.1, p. 66-72.

Obolkin V., Khodzher T., Sorokovikova L., Tomberg I., Netsvetaeva O., Golobokova L., 2016. Effect of long-range transport of sulphur and nitrogen oxides from large coal power plants on acidification of river waters in the Baikal region, East Siberia. International Journal of Environmental Studies, Vol. 73, p. 452-461.

Sorokovikova, L.M., Sinyukovich, V.N., Korovyakova, I.V., Bashenkhaeva, N.V., Golobokova, L.P., Chubarov, M.P., 2001. Peculiarities of water regime of rivers of the basin of South Baikal at the increased humidity conditions. Geography and Natural Resources, Vol. 4, pp. 54-59.

Sorokovikova L.M., Netsvetaeva O.G., Tomberg I.V., Molozhnikova Y.V., 2020. Monitoring of the snow cover chemical composition and its role in the acidification of the southern Baikal tributaries. Proceedings of SPIE. № Art. 1156038, pp. 1-10.

Sorokovikova L.M., Netsvetaeva O.G., Tomberg I.V., Molozhnikova Y.V. 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. Vol. 11916, pp. 1-8.

Surface water resources of the USSR, 1973. L.: Gidrometeoizdat, V 16, Is. 3, 595 p. (in Russian)

Tomberg I.V., Sorokovikova L.M., Netsvetaeva O.G., Sezko N.P., Zhuchenko N.A., 2016. Chemical composition and tendency of acidification of snow waters and waters of the tributaries in the southern basin of Lake Baikal. Atmospheric and Oceanic Optics, Vol. 29, N 6, pp. 516-520 (in Russian).

Votintsev, K.K., Glazunov, I.V. and Tolmacheva, A.P., 1965. Hydrochemistry of rivers in Lake Baikal basin. Moscow: Nauka, 495 p. (in Russian).