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Articles

Taxonomic diversity and structure of phytoplankton in heterotypic lakes of Kulunda basin (Altai Krai)

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In 2001–2021, the taxonomic composition and structure of phytoplankton in the heterotypic lakes of the Kulunda basin were studied. By the average and maximum depths and the way of salt accumulation, these lakes belong to deep-water brine, medium-deep brine, shallow-water brine, shallow-water self-sediment and drying up in summer period types of reservoirs. 241 species, 5 varieties and 3 forms of algae from 7 divisions, 17 classes, 7 subclasses, 44 orders, 78 families, and 130 genera were identified. The greatest taxonomic diversity was noted in the divisions Cyanobacteria, Chlorophyta, and Ochrophyta; the most classes (5) were in the division Ochrophyta; the most taxa with a rank above the family were in the subdivision Diatomeae (3 classes, 4 subclasses, 14 orders) and the division Chlorophyta (3 classes, 11 orders). In the spectrum of families, 12 ones (of 78) are leading with 34.6% of the total number of genera and 48.5% of the total number of species. The taxa spectrum is characterized by one-, two- and three-species families. The largest number of species in phytoplankton was found mostly in deep- and medium-deep lakes with a wide variety of biotopes both horizontally and vertically. The dependence of the number of species in the phytoplankton of the lakes on various environmental factors and features of the reservoirs (morphometric characteristics, water and air temperature, precipitation, salinity, pH, the Wolf number, some anions and cations) was analyzed. It was revealed that the correlation was higher for the smaller on area and volume water bodies, and less – for the larger and deeper ones.

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Keywords

Altai Krai, environmental factors, Kulunda basin, salt lakes, phytoplankton, structure, taxonomic composition.

Introduction

One of the hydrographic features of the steppe and forest-steppe zones of Western Siberia is the abundance of water bodies, diverse in size, depth, presence of salts dissolved in water, and their chemistry. Four basins of hyperhaline lakes have been identified in the West Siberian Plain: Tobolo-Ubagansky, Ishimsky, Priirtyshsky, and Kulundinsky (Water reservoirs..., 1999). The Kulunda basin is characterized by low, narrow, linearly elongated elevations with flood meadow, with lakes in the depressions that are salt-gathering basins, within which salts migrate to the center of the basin with surface and ground runoff. The river network is poorly developed (Water reservoirs..., 1999; Solovov et al., 2001). The southern regions of the West Siberian Plain, within which the Kulunda basin is located, are surrounded by mountain ranges of the Urals and Kazakhstansky Melkosopochnik, Altai and Sayan, Salair and Kuznetsky Alatau. Drainless basins of the hyperhaline lakes are located in sedimentary rocks of the Late Holocene. The upper layers of rocks are represented by sands, sandy loams and loams, the lower (tertiary) – by clays containing gypsum and other mobile salts. The zones of location of the hyperhaline lakes usually coincide with internal artesian basins, the mineral underground waters of which play an important role in the regime of reservoirs (Dzens-Litovsky, 1968). Regardless of the way of origin of the lake basins, there is no doubt that the formation of a large number of lakes here is associated with the features of the relief (almost perfect plain), the water and heat balance of this territory (large evaporation losses, low surface runoff) (Sokolov, 1952; Maksimov, 1982; Anderson, 1985).

Hydrobiological studies in the plain water bodies of Altai Krai began to be carried out systematically from the end of the 1920s in order to study the food supply to determine the possibility of growing valuable fish species (Water reservoirs.., 1999), but an information about phytoplankton of the lakes of the region was fragmentary (Voronikhin, 1929; Voronikhin and Khakhina, 1929; Isachenko, 1951). Later, in the 1970–1980s, the phytoplankton of many saline lakes in the flat part of the Altai Territory was studied more fully (Filippova, 1979; Golubykh and Popkova, 1983; Vereshchagina, 1988; Vesnina, 2000; Vesnina et al., 2008; Mitrofanova, 2010), but there is still no sufficient understanding of the phytoplankton composition and structure in most water bodies of the studied region, its abundance, and changes in seasonal and long-term aspects (Samylina et al., 2010; Vesnina, 2016). At present, there is a need to revise the algological population of the water bodies due to the intensive use of the lakes in economic and recreational purposes. The aim of this investigation is to study the taxonomic composition and structure of the phytoplankton in the lakes of different salinity in the Kulunda basin.

Materials and methods

The material for the study was the data on the phytoplankton obtained by the monitoring of 14 hyperhaline lakes in Western Altai during the growing seasons of 2001–2021 (Fig. 1).

The studied lakes are located in the Kulunda basin in the west of Altai Krai stretching in a discontinuous chain from the north to the south. For most of them, the water surface area is in the range of 1.4–12.4 km^2 except lakes Kulundinskoye, Bolshoye Yarovoe (B. Yarovoe), and Kuchukskoe which water surface areas are significantly larger (Table 1). Lake Kulundinskoye is the largest ultrahaline reservoir in the Russian Federation (the surface area varies within 8 km^2 in different years), occupying the central part of the Kulunda Depression. The rivers Kulunda and Suetka flow into the lake; the basin is well defined. The northern and western shores of the lake are steep, 5.0–6.0 m high, the eastern one is gentle, indented with bays with many islands, the bottom is silted. The lake is bitter-salty, drainless, connected by a channel with Lake Kuchukskoye, the basin of which has an ellipsoidal shape with a long axis of the submeridian direction. The water surface area of Lake Kuchukskoye can vary within 10 km^2. The greatest depth of the lake at the minimum water level was 2.4 m, while the average depth – 1.6 m. The water volume is 270–340 million m^3, depending on the phase of water content. The third largest lake, B. Yarovoye, has an elliptical shape, elongated from the northwest to the southeast. The range of changes in the surface area of the lake is within 4 km^2. The banks are open, steep, accessible along the entire perimeter, 10.0–15.0 m high, eroded. Lake Maloye Yarovoye (M. Yarovoye) is located on the southern outskirts of the West Siberian Plain, namely, in the Kulunda Depression, the lowest part of the flat concave plain. The water edge of Lake M. Yarovoye is at an altitude of 98 m above sea level. The lower part of the plain is the bed of a large lake basin that once existed here. The lake basin being a relic on the lacustrine-alluvial plain has a saucer-like shape. The soils of Lake M. Yarovoye are represented by different types: sandy, silty sand, and silty. Nature of water supply is groundwater and atmospheric precipitation. Lake Lomovoye is the smallest in water surface area in the studied region. It belongs to the lake system of Salt-Lake Steppe and is located close to Lake Malinovoye on the border with Mikhailovsky pine forest. The water volume of the Lake Lomovoye is 650 thousand m^3. Like in the Lake Kuchukskoye, the maximum depth in Lake Malinovoye is more than two meters. In the rest lakes, the maximum and average depths do not exceed 1.3 m. Lake Petukhovo is distinguished by the value of the maximum and average salinity. It is known that water bodies of Western Altai are classified as deep-water brine, medium-deep brine, shallow-water brine, shallow-water self-sediment and drying up in summer period by the average and maximum depths and salt accumulation method (Water reservoirs..., 1999). The distribution of the studied lakes among these groups is shown in Table 1.

The phytoplankton sampling was carried out using a small motor vessel at permanent observation stations, as well as by driving a car around the perimeter of water bodies. Samples with a volume of 1.0–1.5 liters were taken by scooping from a depth of at least 0.2 m in the central and littoral parts of the lakes during the growing season from April to October, taking into account the morphological features of the lakes and diversity of biotopes (Methodological recommendations.., 1982). The sampling in lakes drying up in summer period was carried out once in spring. In parallel, the depth of the reservoir, temperature, transparency, and salinity of the water were measured. The samples were fixed with a 4% formalin solution and then treated according to generally accepted hydrobiological methods (Kiselev, 1969; Methodological recommendations.., 1984). In the laboratory, samples were thickened by decantation of the upper layer to a volume of 10–12 ml after settling for 10 days and examined under the Laboval 4 light microscope (Karl Zeiss, Germany). For identification of the algae, various guides, atlases, and modern summaries of species were used (Diatom analysis, 1950; Gollerbakh and Polyanskii, 1951; Gollerbakh et al., 1953; Matvienko, 1954; Moshkova and Gollerbakh, 1986; Tsarenko, 1990). The taxonomic structure and nomenclatural names of the taxa are given according to AlgaeBase (Guiry and Guiry, 2022). Pearson correlation coefficients were used in analyzing the relationship between phytoplankton species diversity and environmental factors. Data analysis was performed with Microsoft Office Excel (statistical significance level p˂0,05).

Group	Lake	Area, km2	Depth, m		Salinity, g/l	
			min	max	min	max
I. Deep-water brine	Bolshoye Yarovoye	65.0	4.9	10.2	120.0	164.0
II. Medium-deep brine	Kulundinskoye	720.0–728.0	2.3	3.3	52.67	166.48
	Maloe Yarovoye	35.2	2.8	3.6	171.0	253.7
	Kuchukskoye	181.0	2.3	3.3	78.0	380.0
	Malinovoye	11.4	1.1	2.1	99.0	265.0
III. Shallow-water brine	Shukurtuz	5.2	0.4	0.8	152.0	284.0
	Iodnoye	2.65	0.8	1.2	40.0.	320.0
	Bolshoye Shklo	3.3	0.8	1.3	98.0	179.0
	Lomovoye	1.4	0.5	2.0	94.0	273.0
IV. Shallow-water self-sediment	Gornostalevo	4.8	0.2	0.4	73.0	334.0
	Kurichye	15.0	0.5	0.9	98.0	179.0
	Petukhovo	12.4	0.5	0.6	226.0	400.0
	Maloye Shklo	1.9	0.2	0.6	95.0	180.0
V. Drying up in summer period	Krivaya Puchina	6.1	0.4	0.7	144.0	378.0

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Table 1. *Morphometric and hydrochemical characteristics of the studied lakes in the Kulunda basin*

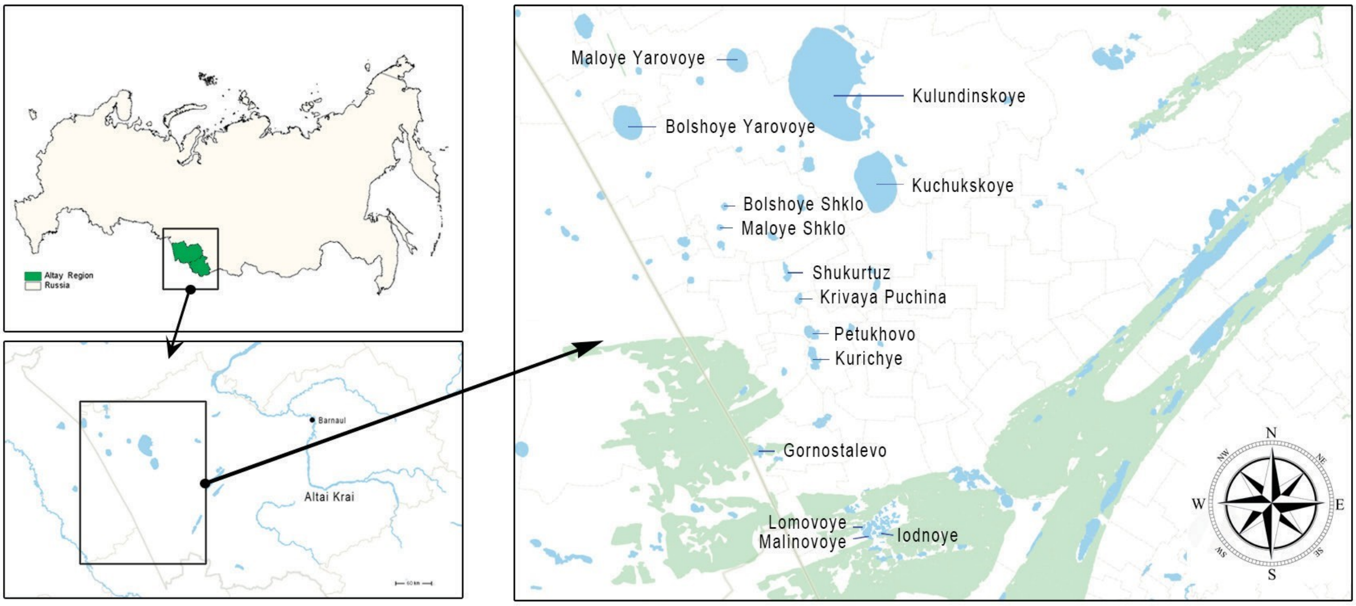

Figure 1. *The map-scheme of location of the studied lakes in the Kulunda basin.*

Result

During the study period, 241 species, 5 varieties, and 3 forms of algae from 7 divisions, 17 classes, 7 subclasses, 44 orders, 78 families, and 130 genera were identified in the phytoplankton of 14 hyperhaline lakes (Table 2). The greatest taxonomic diversity was noted in the divisions Cyanobacteria, Chlorophyta, and Ochrophyta; the most classes (5) were in the division Ochrophyta; the most taxa with a rank above the family were in the subdivision Diatomeae (3 classes, 4 subclasses, 14 orders) and the division Chlorophyta (3 classes, 11 orders). The diversity of algae taxa in other divisions was much less. Two divisions of algae were especially small and had only two (Charophyta) and three (Dinophyta) species, also Cryptophyta (8 species) was not numerous. The appearance of representatives of Charophyta, Dinophyta, Cryptophyta, Chrysophyta, and Euglenophyta in the plankton of the hyperhaline water bodies was most likely an exception to the rule, because hyperhaline lakes are not a typical habitat for them. Probably, these algae entered saline water bodies in spring during the flood period from the drainage basin or developed in the estuarine part of their freshwater tributaries.

Division	Class	Subclass	Order	Family	Genera	Species	Varieties	Form
Cyanobacteria	1	3	6	15	34	77	1	3
Ochrophyta	8	4	20	28	40	67	0	0
Cryptophyta	1	0	1	1	4	8	0	0
Dinophyta	1	0	3	3	3	3	0	0
Euglenophyta	2	0	2	4	5	13	2	0
Chlorophyta	3	0	11	26	43	71	2	0
Charophyta	1	0	1	1	1	2	0	0
Total :	17	7	44	78	130	241	5	3

Table 2. *Taxonomic spectrum of phytoplankton in the lakes of the Kulunda basin*

There are 12 leading families out of 78, which account for 34.6% of the total number of genera and 48.5% of the total number of species: cyanobacteria (Oscillatoriaceae – 23 species, Synechococcaceae – 10, Merismopediaceae – 9, Chroococcaceae – 7) and green algae (Scenedesmaceae – 10, Chlamydomonodaceae – 10, Selenastraceae – 8, Oocystaceae – 6), four in each, two from diatom algae (Bacillariaceae – 11 and Fragilariaceae – 8), the divisions Cryptophyta (Cryptomonadaceae – 8) and Euglenophyta (Euglenidae – 7), one in each.

In the spectrum of genera, ten genera are leading, four of them are cyanobacteria: *Phormidium* – 9 species, *Lyngbya* – 9, *Jaaginema* – 6, and *Oscillatoria* – 5. Species of the genus *Jaaginema* (according to the systematics adopted in AlgaeBase) previously were included in the genus *Oscillatoria*. In such case, this genus could contain 11 species. Four genera also belong to green algae: *Chlamydomonas* – 7 and *Scenedesmus* – 7, *Ulothrix* – 5, and *Oocystis* – 4 species. Diatom algae from genera *Nitzschia* and *Fragilaria* (6 species each) play an important role in the phytoplankton composition. The leading genera account for 26.4% of the total number of species. In general, the taxonomic spectrum of the phytoplankton in the studied lakes of the Kulunda basin is characterized by one- and two-three-species families and genera.

Among the richest on the plankton composition, lakes with a large water surface area stand out because of the presence of more diverse biotopes, both in the littoral and pelagic zones. There are, above all, lakes Kulundinskoye with its 157 species from seven divisions and B. Yarovoye with 86 species from six divisions. The smallest number of species was in the lakes Lomovoye – 5 and Iodnoye – 6 species from two and three divisions, respectively (Fig. 2). Species from six divisions are noted in Lake Krivaya Puchina, five each – in the lakes M. Yarovoye and Kuchukskoye, four – in lakes Gornostalevo, Kurichye, and M. Shklo, representatives of three divisions mainly green algae and cyanobacteria were identified in the other lakes.

One of the taxonomic composition peculiarities noted was the predominance of cyanobacteria by the absolute number of species, as well as diatoms of the division Ochrophyta and green algae in the lakes Kulundinskoye and B. Yarovoye (Fig. 2A). The largest proportion of cyanobacteria species was observed in the lakes Petukhovo (66.7% of the total composition of species), Malinovoye (46.2%), and Lomovoye (40.0%), diatoms – in Shukurtuz (62.5%), Gornostalevo (56.3%), and B. Yarovoye (38.4%), green algae – in Lomovoye (60.0%), B. Shklo (53.8%), and Malinovoye (38.5%) (Fig. 2B). Euglenophyta representatives were found only in two lakes: Krivaya Puchina and Kuchukskoe.

Speaking about individual species, it can be noted that *Jaaginema geminatum* (Meneghini ex Gomont) Anagnostidis & Komárek (= *Oscillatoria geminata* (Meneghini) Gomont) and *Phormidium tenue* (Meneghini) Gomont from cyanobacteria (Oscillatoriaceae) developed almost in all lakes, as well as *Dunaliella salina* (Dunal) Teod. from green algae which occurred both in the vegetative state, cysts and zoospores. In Lake Kulundinskoye, huge accumulations of algae (“mats”) washed ashore by the wind are formed by both green algae *Cladophora glomerata* (L.) Kütz. and cyanobacteria *Lyngbya aestuarii* Liebman ex Gomont. Many small-celled taxa developed in the lake plankton can linger in the threads interweaving of these two species. Some more representatives of green algae, namely *Botryococcus braunii* Kütz., *Ankyra judayi* (G.M. Smith) Fott., *Schroederia setigera* (Schröd.) Lemm. are met in Lake Kulundinskoye phytoplankton, and the latter species can massively multiply in the lake in some years. In general, the diversity of green algae is higher in the estuary zone of two freshwater tributaries in Lake Kulundinskoye.

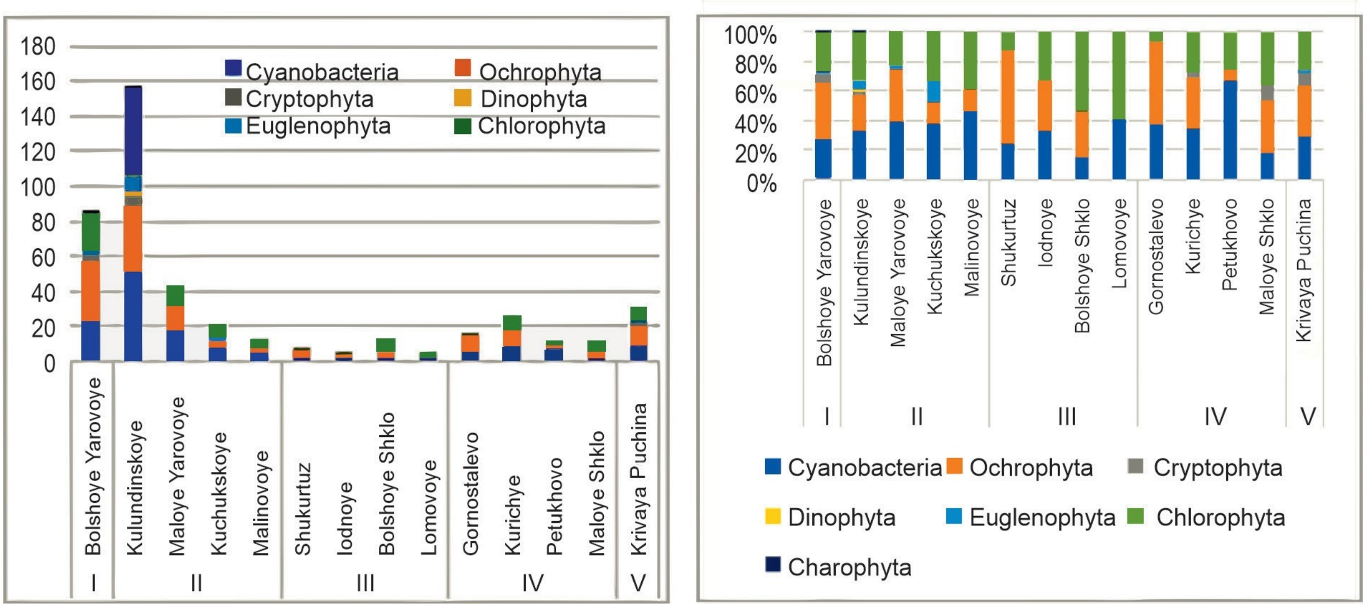

Figure 2. *Absolute (**A**) and relative (**B**) number of species and the ratio of the main divisions of algae in the phytoplankton of the studied lakes in the Kulunda basin.*

The phytoplankton in Lake Kulundinskoye is quite diverse in different periods of the year, while it was the almost monodominant in some water bodies from time to time. For example, in Lake M. Yarovoye in August 2005, the only cyanobacteria *Aphanocapsa salina* Woronichin (=*Microcystis salina* (Woronichin) Elenkin) was found in phytoplankton samples, while in other months the phytoplankton was represented exclusively by green algae *Dunaliella salina* or *Scenedesmus quadricauda* (Turp.) Breb. Once in 2010, cyanobacteria *Dzensia salina* Woronichin was recorded in the lake. The representatives of chrysophycean algae *Chrysococcus rufescens* Klebs and euglenophyte *Trachelomonas* sp. can be met in autumn in Lake Kuchukskoye. The first of them was noted for Lake Krivaya Puchina as well. *Chlamydopodium sieboldii* var. *simplex* (Korsch.) Tsarenko (=*Characium sieboldii* var. *simplex* (Korsch.) Tsarenko) was developed in Lake Malinovoye, *Chlamydomonas anuraeae* Korsch. – in Lake Lomovoye. Lake Iodnoye is characterized by the massive “bloom” of, for example, green algae *Chlorella vulgaris* Beijer or small-celled cyanobacteria *Microcystis pulverea* (Wood) Forti. In Lake Krivaya Puchina, a greater variety of diatoms was observed more than once – *Halamphora coffeiformis* (Ag.) Mereschkowsky (=*Amphora coffeiformis* (Ag.) Kütz.), *Epithemia argus* (Ehr.) Kütz., *Encyonema ventricosum* (Ag.) Grun. (=*Cymbella ventricosa* (Ag.) Ag., *Achnanthes adnata* Bory (=*Achnanthes brevipes* Ag.). Euglenophyte *Lepocinclis ovum* (Ehr.) Lemm. was encountered in some years. The ulotrix alga *Leptosira mediciana* Borzì was found in Lake M. Shklo. Thus, the composition of the phytoplankton in the studied lakes differed significantly, but most of the species were found almost once in any one water body.

Discussion

The development of phytoplankton in water bodies depends on various factors. The algae diversity is largely determined by the geographic location of the water body and the climatic features of the region, the morphometric features of lakes, their hydrophysical and hydrochemical regimes, and the amount of incoming biogenic elements (Sudnitsyna, 2005). The development of algae is influenced by the ionic composition of water, pH, hydrological features, human intervention, various forms of biotic interaction, as well as air and water temperature (Comin and Alonso, 1988; Williams, 1998; Alimov, 2008). It was noted for many water bodies including lakes in the Omsk Region, Onon-Torey plain (North-Eastern Mongolia), and Uldza-Torey basin (South-Eastern Transbaikalia) (Afonina and Tashlykova, 2018, 2019). In nature, all factors are in interaction with each other, so it is very difficult to isolate the influence of any factor.

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The size of the lakes, as well as the diversity of biotopes and the degree of overgrowth for small ones are of particular importance for the diversity of algae in water bodies and streams. We analyzed the correlation dependence between the number of species in the phytoplankton of the studied mineralized lakes in the Kulunda basin and some environmental factors. A positive correlation was found between the number of species and the water surface area of the lakes (correlation coefficient – 0.88). The largest number of species was typical mainly for the lakes of groups I and II – deep-water brine and medium-deep brine (Table 1). Although there are exceptions in each group, for example, Lake B. Shklo is distinguished in group III, as well as lakes Gornostalevo and Kurichye in IV (Fig. 2A). It was noted that the number of species was greater in the phytoplankton of Lake Krivaya Puchina from the group V, water bodies of which dry up in summer period, than in the lakes of group IV. It was probably because of the sampling there was carried out in the spring, when a slight desalination due to melt water was in saltwater bodies and, in addition, algae can inflow from the adjacent territories. Therefore, the diversity in the plankton was slightly increased.

In mineralized water bodies, the most important factors affecting the composition, abundance, and distribution of algae, the so-called limiting factors, include the total salinity and mineral composition of water (Comin, Alonso, 1988; Williams, 1998; Akhmadullova, 2011; Afonina, Tashlykova, 2014, 2016, 2019). The difference between the maximum and minimum salinity in a reservoir may indicate how cardinally salinity can change in different periods of the year and in different years. The range of 200–300 g/l was noted in five lakes out of 14 – Kuchukskoye (302), Iodnoye (280), Gornostalevo (261), Krivaya Puchina (234), and Petukhovo (226), where the functioning of plankton algae, perhaps, is especially extreme. The number of the species in these water bodies varied within 6–31, while in the rest ones it reached 43 and up to 86 and 157 in lakes B. Yarovoye and Kulundinskoye. Thus, such a significant range of salinity change is generally unfavorable for the development of plankton algae in the studied lakes.

The temperature influences significantly on the algae development, especially in small shallow lakes in the steppe zone of the south of Western Siberia. This factor affects the level of algae metabolism, the rate of their development, vertical distribution, etc. Salt lakes have their own features of the hydrothermal regime. First of all, mineralized lakes have noticeably lower evaporation, the values of which decrease with increasing mineralization. Tentatively, it can be assumed that evaporation from brine lakes is only 69% of its value in freshwater reservoirs. The temperature regime of the surface layers of brine is higher than that of the water mass of freshwater lakes, since the specific heat capacity of ultrahaline lakes is 25% less than fresh water (Permyakova, 2012). In shallow hyperhaline water bodies of the Altai Territory, temperature stratification is not observed during one season, while in the deep-water Lake B. Yarovoye at a depth of 8.0–9.0 m, negative temperatures are noted even in June (Permyakova, 2012). High summer air and water temperatures and lack of precipitation lead to increased evaporation and a significant reduction of the water surface area and volume of lakes, which negatively affects the condition of the algoflora in the reservoir. We analyzed the dependence of the number of species in the phytoplankton of the studied lakes in the Kulunda basin on the level of salinity, air and water temperature, precipitation, the Wolf number, HCO_3^-, Cl^-, SO_4^{2-} anions, and Na^+ cation (Table 3).

	Gornostalevo	Lomovoye	Malinovoye	Iodnoye	Kurichye	Krivaya Puchina	Kuchukskoye	Petukhovo	Shukurtuz	Maloye Shklo	Kulundinskoye	Bolshoye Yarovoye	Maloye Yarovoe
Amount of precipitation	-0.6	-0.4	0.4	0.9	0.6	0.6	-0.2	0.4	-0.8	0.9	0.6	0.2	0.6
Air temperature	0.5	0.2	0.4	0.01	-0.1	-0.3	0.4	0.6	-0.6	0.5	-0.03	0.1	-0.01
Water temperature	-	-	-	-	-	-	0.03	-	-	-	0.2	0.4	0.34
Wolf	-0.1	0.4	0.8	0.8	0.2	0.3	-0.3	-0.2	-0.9	-0.7	0.41	0.2	0.3

number W													
Salinity	-	-	0.8	-0.6	-0.1	-0.5	-0.9	-0.03	0.9	0.9	-0.5	-0.04	-0.3
pH	-	-	-0.6	0.9	0.4	0.6	0.8	0.7	-0.9	0.3	0.3	-0.2	-0.09
Cl–	-	-	0.7	-0.7	-0.1	-0.4	-0.9	-0.01	-	-0.5	-0.5	0.1	-0.1
Na+	-	-	0.7	-0.7	-0.1	-0.5	-0.9	-0.01	-	0.8	-0.4	0.1	0.07
HCO3–	-	-	0.3	-0.7	0.6	-0.2	-0.8	-	-	-0.01	0.2	0.5	0.1
SO42–	-	-	0.8	-0.7	-0.1	-0.5	-0.7	1.0	-	-0.9	-0.4	-0.03	0.1

Table 3. *Correlation coefficients of phytoplankton biodiversity (species number) with abiotic parameters in the lakes of the Kulunda basin in 2001-2021.*

Note: interpretation of the correlation coefficient: up to 0.2 – very weak (˂0.2), up to 0.5 – weak (˂0.5), up to 0.7 – medium (˂0.7), up to 0.9 – high (˂0.9), over 0.9 – very high (0.9-1.0) (Kozhevnikov, 2022)

With the amount of precipitation, a very high positive correlation was found in the lakes Iodnoye and M. Shklo, medium positive correlation – in Kulundinskoye, Kurichye, Krivaya Puchina, and M. Yarovoye, and high negative correlation – in Shukurtuz, medium negative – Gornostalevo (Table 3). In other lakes, correlations with precipitation were weak or very weak, both negative and positive, or absent, i.e. the larger the area and volume of the reservoir, the dependence of the species number on the amount of precipitation decreases in most cases. Air temperature had an indirect effect on the algae diversity in the phytoplankton of the lakes. A medium positive and negative correlation was revealed in the lakes Gornostalevo, M. Shklo, Petukhovo, and Shukurtuz. In other lakes, the dependence of the number of species in phytoplankton with air temperature was not revealed, as well as on water temperature. With the total salinity, a high and very high positive dependence was found for lakes Malinovoye, Shukurtuz, and M. Shklo, a very high negative dependence – Lake Kuchukskoye, weak and medium negative – for the lakes Iodnoye, Krivaya Puchina and Kulundinskoye. The following correlations were revealed with the pH value in the studied lakes: a very high positive and negative for lakes Iodnoye and Shukurtuz, high negative – for lakes Kuchukskoye and Petukhovo, the medium positive correlation was observed for Lake Krivaya Puchina, the medium negative – for Lake Malinovoye.

The hydrochemical composition of water is essential for algae development. All natural waters contain macrocomponents: K^+, Na^+, Mg^{2+}, Ca^{2+} cations and Cl^-, SO_4^{2-}, HCO_3^- anions; their content and ratios in surface waters and precipitation vary within a fairly wide range depending on the physical and geographical features of the area (Shilova, 2014). The main source of hydrocarbonate and carbonate ions in surface waters are the processes of chemical weathering and dissolution of sulfur-containing minerals, mainly gypsum, as well as the oxidation of sulfides and sulfur. Sulfate ions, like chloride ions, are the main component of sea and some mineral waters. The content of the Cl^- ion in saline waters prevails over the content of the SO_4^{2-} one. In amounts up to 1 g/l, sulfates do not adversely affect aquatic organisms (Volkova et al., 2019). Plants and other autotrophic organisms extract sulfates dissolved in water to build proteins. Sulphate concentrations in surface waters are subject to marked seasonal fluctuations and usually correlate with changes in the overall salinity of the water. Chlorides are the predominant anion in highly mineralized waters. The concentration of chlorides in surface waters is also subject to noticeable seasonal fluctuations, which correlate with changes in the total salinity of the water. The primary sources of chlorides are igneous rocks, which include chlorine-containing minerals and salt-bearing deposits. Sodium is a macroelectrolyte that plays an important role in water-salt metabolism, and one of the main components of the chemical composition of natural waters, which determine their type. An analysis of the correlation dependences of the species number in the phytoplankton of the studied lakes with Cl^- ions revealed high positive and negative correlation in lakes Malinovoye, Kuchukskoye and Iodnoye, medium negative for lakes M. Shklo and Kulundinskoye. In the rest lakes, no correlations were found. Similar dependences were noted for Na^+ cations. A very high and high positive correlation between the number of species in phytoplankton and sulfate ions SO_4^{2-} was shown for the lakes Petukhovo, M. Shklo, and Malinovoye, and medium negative correlation – Iodnoye and Kuchukskoye. Medium negative correlation was noted for the lakes Kuchukskoye and Iodnoye, a weak positive one was observed in Lake Krivaya Puchina. With carbonate ions HCO_3^-, a medium positive dependence was revealed for the lakes B. Yarovoye and Kurichye, high negative – for Iodnoye and Kuchukskoye; with sulfat ions SO_4^{2-} – high positive and negative correlations for lakes Malinovoye, Iodnoye, Kuchukskoye and M. Shklo, medium negative for Lake Krivaya Puchina.

Sunlight is of great importance for the algae development because of these organisms are autotrophs and need light energy to produce organic matter. Strong insolation has a detrimental effect on algae, while moderate insolation increases their diversity and abundance. The measure of solar activity is the Wolf number. We analyzed data for this indicator from publicly available data (SILSO, 2022). For the study period 2001–2021, the Wolf number tends to decrease slightly, as evidenced by its trend line (Fig. 3). A very high negative correlation between the taxa number in phytoplankton and the Wolf number was found for lakes Gornostalevo and Shukurtuz, i.e. the number of species decreases significantly with increasing of solar activity. The high positive correlation with the Wolf number was noted for the lakes Malinovoye and Iodnoye, while, on the contrary, the high negative –M. Shklo. In the lakes with a large water surface area and a significant volume of water mass (Kulundinskoye, B. Yarovoye, Kuchukskoye), no significant dependences on this factor were found, although the trends of a decrease of the Wolf number, of the amount of precipitation, and of the number of species in phytoplankton with an increase of the water salinity were noted for these reservoirs (Fig. 3, 4).

In salt lakes, almost all ecologically significant environmental parameters can reach extreme values, so this requires special biochemical and physiological adaptations in living organisms (Padisak and Luigi, 2021). It is often difficult to explain the response of phytoplankton to extremes of various factors, as multiple stresses are common. Some lakes have a high salt content and a high pH value, while others have an unstable level regime, when some of them can dry up completely. Such conditions are suitable for a limited species number with appropriate morphological and biochemical adaptations. This determines an important feature of the phytoplankton in salt lakes – a small number of species and, in general, low taxa diversity. Therefore, with an increased salt content, certain species and even divisions of algae can develop. Thus, some representatives of cyanobacteria withstand increased salinity in water bodies and even prefer lakes with an extremely high salt content, differing from representatives of other divisions in greater adaptability to extreme environmental conditions. It was noted above that almost all lakes contain *Jaaginema geminatum* and *Phormidium tenue* (Oscillatoriaceae). In the composition of green algae, *Dunaliella salina*, both in the vegetative state and in cysts and zoospores, belongs to such widespread species in all the studied lakes. This alga can withstand high salt concentrations, i.e. has outstanding salt tolerance. The phenomenal resistance of *D. salina* to abrupt osmotic shifts is not the result of isolating cells from the environment and maintaining homeostatic conditions in them but, on the contrary, the result of the easy permeability of a number of plasma membranes for water and some ions, which leads to a rapid balancing of the external and internal osmotic pressure. Many authors indicated that with an increase in the environment salinity, the pigment apparatus, respiratory and photosynthetic metabolism, and nucleic acid metabolism are reorganized in *Dunaliella* cells, which ensure the survival of these algae in extreme conditions of existence (Borovkov, 2005). Also, *Schroederia setigera*, which develops mainly in spring and summer plankton, can be attributed to frequently occurring species.

The ability of green alga *Cladophora glomerata* and cyanobacteria *Lyngbya aestuarii* to form “mats” is typical not only for Lake Kulundinskoye. For example, *L. aestuarii* forms similar “mats” on the rocky shores of the northwestern Atlantic coast of Morocco. The raw extract of this alga has antitumor, antioxidant and antimicrobial activity (Hassouani et al., 2017). It is interesting that *L. aestuarii* was absent in the phytoplankton of Lake Kulundinskoye in 2003 and 2013–2018, while *Heteroleibleinia kuetzingii* (Schmidle) Compère (=*Lyngbya kuetzingii* Schmidle) was present. *H. kuetzingii* colonies have been reported to occur around atolls, in lowlands flooded with sea water, as well as in freshwater bodies (Turner and von Aderkas, 2009).

There are various representatives of green algae in the phytoplankton of Lake Kulundinskoye. So, *Botryococcus braunii* forms large floating colonies, consisting of millions of microscopic (several tens of microns in diameter) rounded cells with very thick membranes. The most interesting ability of this alga is to synthesize various hydrocarbons, forming the so-called “algal oil”. This “oil” is very similar to oil in its chemical composition (Evseev, 2011). But it can be detected, of course, during the mass development of the species, that was not marked in Lake Kulundinskoye. In general, Lake Kulundinskoye is characterized by the development of algae from different divisions at any time of the year, while for other reservoirs, it is typical the development of one, two or several species in any particular period. For example, in Lake M. Yarovoye, the phytoplankton was monodominant in some years and months. In August 2005, only *Aphanocapsa salina*, a representative of cyanobacteria, was found in the phytoplankton samples; at other times – green chlamydomonad *Dunaliella salina*. Such a massive development of individual species in planktonocenoses with an increase in salinity under conditions when it is an extreme factor has already been noted for similar water bodies (Gorokhova and Zinchenko, 2014). In 2010, cyanobacteria *Dzensia salina* described by N. N. Voronikhin in 1929 was found in Lake Kuchukskoye. The species was found in a freshwater spring in Tajikistan (Shmeleva, Andrievskaya, 1987), but in the water of the spring, sulfate ions predominated as in Lake Kuchukskoye.

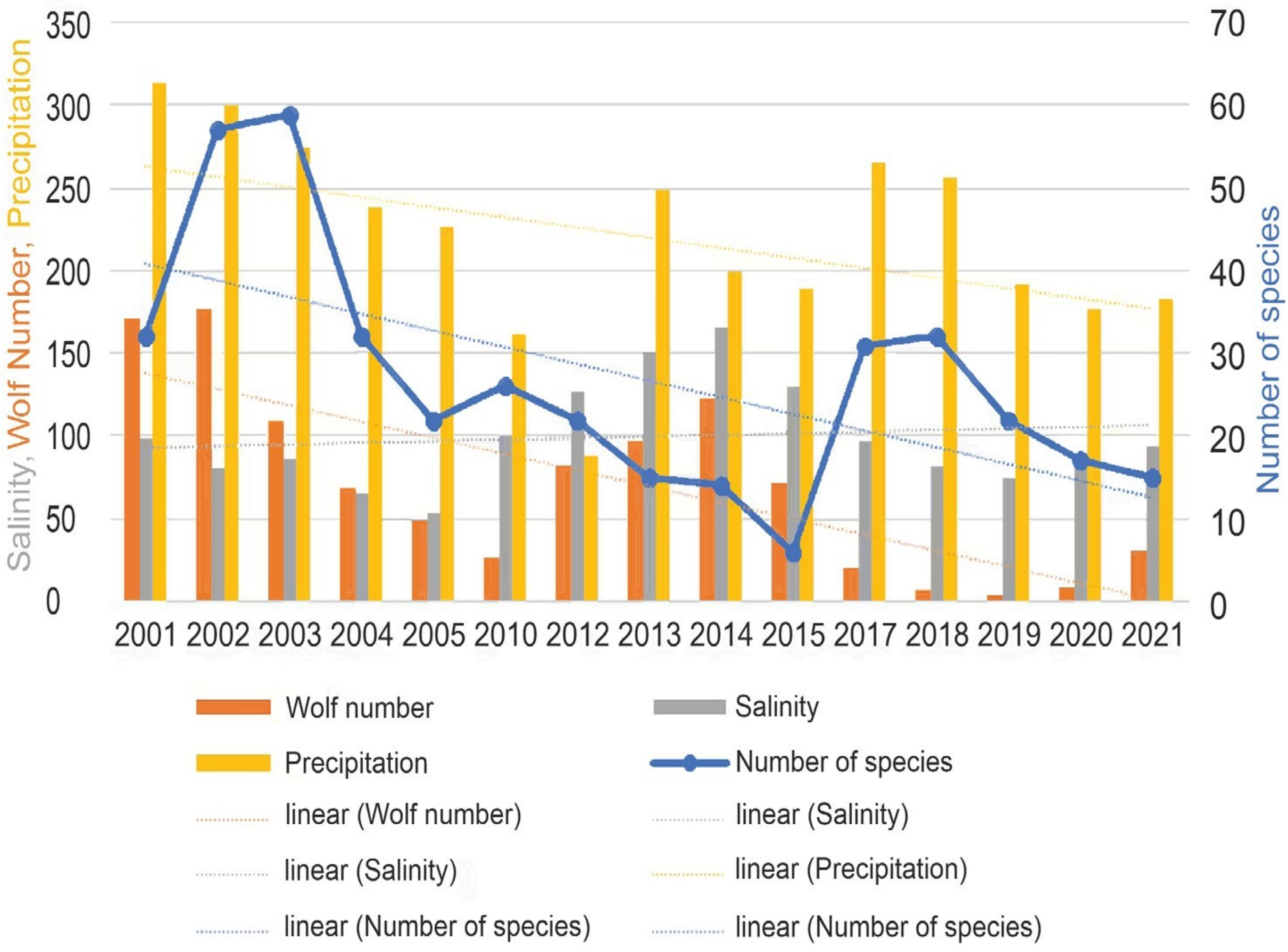

Figure 3. *Average values of salinity, Wolf number, amount of precipitation and the number of species in the phytoplankton of Lake Kulundinskoye in 2001–2021.*

Completely uncharacteristic representatives of highly mineralized lakes, such as, for example, *Scenedesmus quadricaudata* from green chlorococcal algae, a typical representative of freshwater flora, can be found in salt lakes. Chrysophycean alga *Chrysococcus rufescens* and euglenoids

Trachelomonas sp. were found in the lakes Kuchukskoye and Krivaya Puchina, although the species of these divisions are very sensitive to the impact of extreme factors. It was noted that species of the genus *Chrysococcus* are exclusively freshwater inhabitants, but some of them are also found in marine water bodies (Voloshko, 2017). *Trachelomonos* can be tolerated to low temperatures, drying up of water bodies, and changes in pH in the state of cysts (Moskalets, 2008). Sometimes *Chlamydopodium sieboldii* var. *simplex* and *Chlamydomonas anuraeae* were met in the lakes Malinovoye and Lomovoye, respectively. These algae can be developed on zooplankters (rotifers) and are able to switch to a free lifestyle. All these algae can be found in the plankton of the lakes, but they cannot be a true plankters and typical representatives of the plankton of the studied salt lakes. The atypical inhabitants of the plankton in salt lakes also include diatoms, which do not develop massively in salty continental water bodies, although this is the main component of algae in the sea water column. Diatoms *Halamphora coffeiformis*, *Epithemia argus*, *Encyonema ventricosum*, *Achnanthes adnata* were more diverse in Lake Krivaya Puchina. Occasionally, euglenoid *Lepocinclis ovum*, a mobile uniflagellate organism, that is ubiquitous in the Holarctic (Safonova, 1977) was found in the plankton. In Lake M. Shklo, green alga *Leptosira mediciana* was found, which can form small tufts with erect or abundantly branched filaments in water bodies (Moshkova and Gollerbakh, 1986).

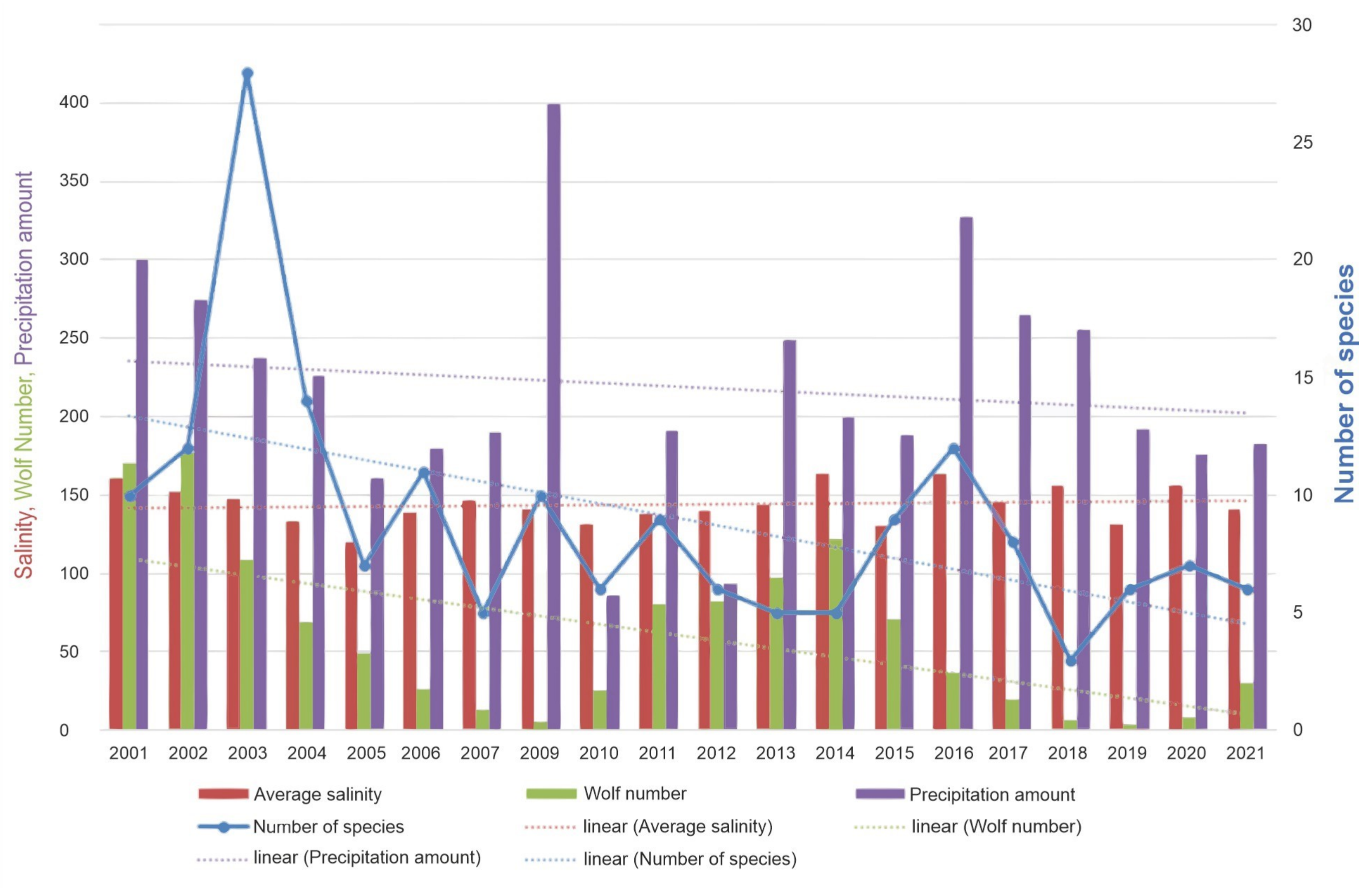

Figure 4. *Average values of salinity, Wolf number, precipitation amounts and the number of species in phytoplankton of Lake Bolshoye Yarovoye in 2001–2021.*

A distinctive feature of Lake Iodnoye is the massive development of algae in almost any period of the year, the so-called “bloom”, due to the development of the green alga *Chlorella vulgaris* or the cyanobacterium *Microcystis pulverea*. “Bloom”, as known, occurs as a response adaptive reaction of algae to an excess supply of nutrients, as a result of which complex, diverse, more stable communities are simplified, impoverished, and dominant taxa change (Akhmadullova, 2011). Probably, the discharging wastewater from the Mikhailovsky pine forest plants of chemical reagents into Lake Iodnoye contributes to the mass development of algae in it.

We analyzed the data on the number of species in phytoplankton and water salinity for the lakes Kuchukskoye, Kulundinskoye, B. and M. Yarovoye, for which there is the longest time series of concurring data (2010–2021). The trend of slight decrease in the average water salinity and an increase in the average number of species in phytoplankton during periods of open water each year were revealed for Lake Kuchukskoye (Fig. 5). At the same time, the correlation coefficient was -0.9, which may indicate a significant dependence of the phytoplankton development on the level of salinity in the reservoir in studied period. In Lake Kulundinskoe, the correlation coefficient for these values was only -0.5, therefore, the correlation between the number of species and salinity level was medium here (Fig. 3). The slight increase in salinity leads to a decrease in the number of species in phytoplankton of Lake B. Yarovoye, but no correlation was found (Fig. 4). A similar situation was observed in Lake M. Yarovoye. These lakes are distinguished by a consistently high level of salinity throughout the season, and by the end of the growing season, an almost uniform increase in salinity was observed (Ronzhina, 2008). Many species of algae cannot withstand extreme salinity. For a medium-deep Lake Malinovoye, data series was not long, but the differences from other medium-deep lakes are quite noticeable – the number of species decreases with a decrease of the level of salinity.

Weather conditions can also have a strong effect on salt lakes. The alternation of dry and rainy periods leads to a change in their morphometry, large seasonal and interannual fluctuations in salinity, and, as a result, to significant changes in the structural and functional organization of the biotic component (Balushkina, 2009). The level regime of most hyperhaline lakes is unstable, subject to significant fluctuations, up to the complete drying up of shallow water bodies and a noticeable reduction in areas and depths in large ones. When water conditions improve, watering of lakes occurs, and the reverse process of lake desalination begins (Permyakova, 2012). The noticeable correlation between the number of species and the amount of precipitation were observed in studied lakes (Figs 3–5): the number of species in phytoplankton decreases with a decrease in precipitation in the lakes Kulundinskoye (correlation coefficient 0.6) and M. Yarovoye (0.64). A weak inverse correlation (-0.2) between the amount of precipitation and the number of species was revealed in Lake Kuchukskoye, but there is no such correlation at all in Lake B. Yarovoye, although the trend lines show a significant decrease in the number of species with a slight decrease in precipitation. A very high positive dependence (0.9) of the number of species in phytoplankton on the amount of precipitation was found for small-area shallow-water lakes Iodnoye and M. Shklo (maximum depths from 0.6 to 1.2 m). Positive but medium correlation for the lakes Krivaya Puchina and Kurichye was quite understandable: Lake Kurichye is shallow-water self-sediment, and Lake Krivaya Puchina can generally dry up in summer period.

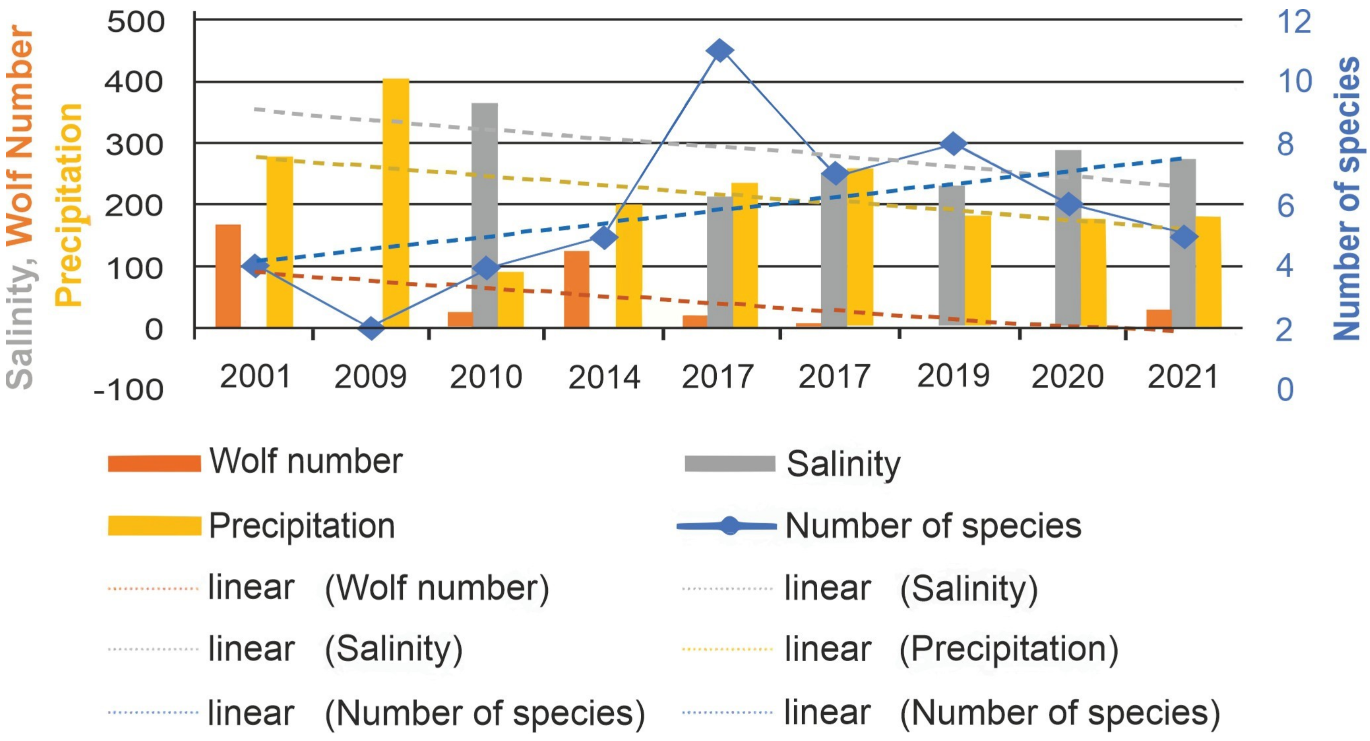

Figure 5. *Average values of the salinity, Wolf number, total precipitation and the number of species in the phytoplankton of Lake Kuchukskoye in 2001–2021.*

The acidity of water influences greatly on the biochemical and biological processes in algae cells. The hydrogen indicator is of great general biological importance, and therefore, in the process of evolution, most living organisms have developed mechanisms that ensure the relative constancy of this indicator in the cell. The role of this factor is determined primarily by its influence on the activity of enzymes and the state of other protein molecules. In addition, since most reactions in cells occur in an aqueous medium, an excess or deficiency of hydrogen ions can significantly affect the course of various non-enzymatic reactions as well (Zinovieva and Durnikin, 2012). Among the studied reservoirs, a very high positive correlation of pH values and the number of species in phytoplankton (0.9) was revealed only in Lake Iodnoye, which may be due to the discharging wastewater from the Mikhailovsky pine forest plants of chemical reagents. Practically the same correlation with pH (0.8) was also found in Lake Kuchukskoye, on the contrary, Lake Shukurtuz had a very high negative correlation (-0.9). The pH values in the lake can range from 7.12 to 8.4. A shift in pH to the acidic or alkaline side leads to the complete inhibition of photosynthesis and the absorption of oxygen in the light. It should be noted that algae themselves can drastically change pH in the course of their life activity, alkalizing and sometimes acidifying the environment (Sudnitsyna, 2005).

Thus, the phytoplankton of the lakes of the Kulunda basin consists of 241 species, 5 varieties, and 3 forms of algae from 7 divisions, 17 classes, 7 subclasses, 44 orders, 78 families, and 130 genera. The greatest taxonomic diversity was noted in the divisions Cyanobacteria, Chlorophyta, and Ochrophyta; the most classes (5) were in the division Ochrophyta; the most taxa with a rank above the family were in the subdivision Diatomeae (3 classes, 4 subclasses, 14 orders) and the division Chlorophyta (3 classes, 11 orders). In the family spectrum, 12 (out of 78) families are leading, accounting for 34.6% of the total number of genera and 48.5% of the total number of species. The taxa spectrum is characterized by one-, two- and threespecies families. The largest number of species in phytoplankton was found in most cases in deep-water and medium-deep brine lakes with a large variety of biotopes both horizontally and vertically. After the analysis of the dependence of the phytoplankton species number on various environmental factors and characteristics of water bodies (morphometric characteristics, water and air temperature, precipitation, salinity, pH, the Wolf number, some anions and cations), it was found that the higher correlation was for the water bodies with smaller area and volume, and the smaller one – for the larger and deeper lakes.

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