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Articles

Long-term and seasonal dynamics of zooplankton in hypergaline lake Kulundinskoye (Kulunda Steppe, Russia)

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The paper investigates the effects of natural environmental factors on the long-term (2000–2020) and seasonal (April–October) dynamics of zooplankton in the hypergaline Lake Kulundinskoye, located in the Kulunda steppe of Altai Krai, Russia. Sixteen key indicators of zooplankton structure, including abundance and biomass of major taxonomic groups such as Rotifera, Cladocera, Copepoda, and Anostraca, as well as individual stages of a life cycle and sex ratio in *Artemia* population, were studied in relation to 17 hydrophysical and hydrochemical indicators such as temperature, density, pH, total salinity, hardness, alkalinity, and other parameters. Monthly data for 2017–2020 and average annual data for 2000–2020 were analyzed to identify the impact of environmental factors on zooplankton structure. The study also examined the influence of these factors on the *Artemia* crustacean population, which dominates the zooplankton in this lake. The hydrophysical and hydrochemical regime of Lake Kulundinskoye can vary significantly from year to year, which affects the zooplankton indicators. Statistical analysis showed that monthly hydrophysical and hydrochemical data are more reliable than averaged data for the research period (April-October) in determining the impact of environmental factors on zooplankton structure. The results indicate that the changes in zooplankton structure are mainly due to the stimulating effect of increased salinity on the *Artemia* population and its depressing influence on other taxa. The long-term dynamics of zooplankton is characterized by a complex cyclicity of water salinity and productivity of the *Artemia* population, which is influenced by periodic changes in the moisture content of the lake catchment.

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Keywords

Zooplankton, environmental factors, limnology, hydrochemistry, salinity, *Artemia*, population, Kulunda

Introduction

The paper focuses on the study of Lake Kulundinskoye, the largest water body in the Kulunda Plain and Altai Krai, located in the south of Western Siberia. The lake's water area varies from 720 to 728 km2 depending on the year and season, with an average depth of 2.6–3.0 m and a maximum depth of 3.5–4.0 m. The lake is drainless, with inflowing rivers Kulunda and Suetka. Its bitter saltwater has a salinity level of 40–131 g l-1 (Solovov et al. 2001). It is important to note that Roshydromet does not conduct any hydrological, hydrochemical, and hydrobiological observations of the lake.

Lake Kulundinskoye is economically significant due to the extraction of aquatic biological resources, specifically *Artemia* crustacean cysts, which are used as a starter feedstuff in aquaculture and for cosmetic and pharmaceutical production (Lavens, Sorgeloos 1996; Litvinenko et al. 2009). However, the productivity of *Artemia* and biological resource extraction in the region is unpredictable and changeable (Solovov, Studenikina, 1990; Vesnina et al. 2022, 2023).

The lake belongs to the Barabinsk-Kulunda Lake district, according to biolimnological zoning by Gerd (1959). Lakes in this region are characterized by shallow basin depth and increased water salinity. The lake ecosystem is subject to cyclic successions due to the alternating dry and wet periods (Shnitnikov 1968; Maksimov 1989), significant fluctuations in water levels, and the area of drainless lakes in the south of Western Siberia (Johansen, Krivoshchekov 1986; Smirnova, Shnitnikov 1982). These fluctuations cause changes in hydrochemical and hydrobiological regimes, affecting the aquatic communities promptly.

Despite previous investigations of zooplankton from Lake Kulundinskoye (Vesnina 2002; Lisitsina 2006), its dynamics in response to environmental factors were studied mainly in a phenomenological aspect. The paper aims to study the composition, structure, and dynamics of zooplankton of lake Kulundinskoye, influenced by natural factors, using modern computer-based statistics programs.

Materials and methods

The article deals with the analysis of field data obtained during complex limnological and hydrobiological investigations of Lake Kulundinskoye (Lake Kulunda, 53°0′N 79°30′E) in 2017–2020 as well as similar archival and published data (2000– 2016). During this period, samples were collected monthly at the same 48 sampling stations (Fig. 1).

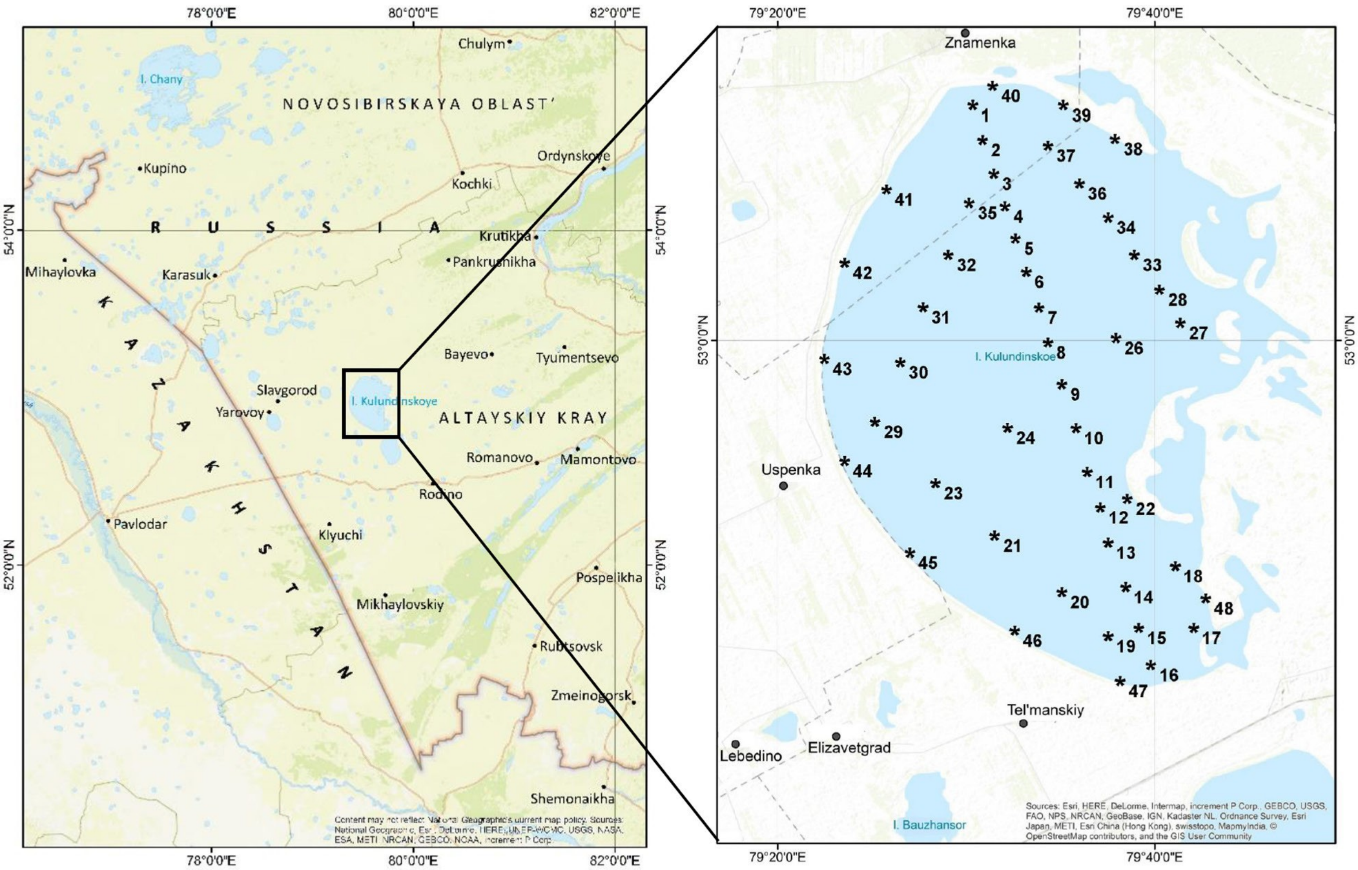

Figure 1. *Lake Kulundinskoye and sampling station locations.*

Selection and processing of zooplankton samples were implemented by means of standard hydrobiological methods (Wetzel Likens 2000). Samples were taken monthly in the period from April (or May) to October using a small Apstein plankton net (with a mesh size of 64 microns), fixed with formalin (up to 4%), and processed using a Bogorov camera and an MBS-10 stereomicroscope. For taxonomic determination, we consulted a number of manuals (Key to freshwater invertebrates of Russia and adjacent territories, 1994, 1995). The chemical analysis of the water samples was performed by an accredited laboratory of the JSC "Kuchuksulfat".

For the statistical processing of the obtained data, we used MS Excel-2017 and Statistica 10 software. Since the data generally had a normal distribution, Pearson’s linear correlation coefficient matrices were constructed to identify the impact of natural factors on zooplankton. One-dimensional Fourier spectral analysis was performed to isolate the oscillation periods of long-term data (Borovikov 2013).

Result

Key parameters of hydrochemical regime

The hydrochemical regime of Lake Kulundinskoye is determined by key parameters such as water temperature, salinity, pH, and dissolved oxygen levels. In May 2020, the water temperature in the surface layer of the lake was 15.0 °C, which rose to 29.4 °C in July and fell to 6.4 °C by October. These seasonal dynamics were consistent with long-term data from 2000–2019, except for summer temperatures in 2020, which were 3.0-5.0 °C higher than the long-term average.

Based on Alekin's (1970) hydrochemical classification, Lake Kulundinskoye is a hyperhaline lake

(Oksiyuk et al. 1993) with a salinity range of 87.0–94.2 g L-1 in 2020. The long-term observations (2000–2019) show that the salinity range was 32.0–115.4 g L-1. An increase in salt concentration in brine was observed at the end of the growing season. The lake water's main ion composition was chloride-sulfate of the sodium group, with a slightly alkaline pH range of 7.8–8.8. Nitrite, nitrate, and phosphate concentrations were low, whereas ammonium ion levels were elevated, exceeding the MPC standard (0.05 mg L-1) for Russian fishery reservoirs in 2017. Dissolved oxygen levels in different months ranged from 3.3–13.6 mg L-1 over the long-term research period, with the minimum recorded in October and the maximum in April. The permanganate oxidizability of water ranged from 65.6 mgO L-1 in July to 103.6 mgO L-1 in April, indicating an increase in organic substance content in the water.

Key parameters of zooplankton

Lake Kulundinskoye's zooplankton community comprises nine species: six Rotifera (*Brachionus plicatilis* Müller, 1786, *Polyarthra dolichoptera* Idelson,1925, *Asplanchna priodonta* Gosse, 1850, *Keratella cochlearis* (Gosse,1851), *K. quadrata* (Müller, 1786), *Hexarthra oxyuris* (Zernov, 1903)), one Cladocera (*Moina macrocopa* (Straus, 1820)), one Copepoda (*Cletocamptus retrogressus* Schmankech, 1875), and one Anostraca (*Artemia* sp.). The identified species are either halobionts or euryhalines.

The name *Artemia salina* Linnaeus, 1758) is recognized as taxonomically invalid. Six species have been described for bisexual races (consisting of males and females), and populations consisting of only females are conventionally designated as *Artemia parthenogenetica* Bowen & Sterling, 1978 (Litvinenko et al. 2009). The identification of these species is still incomplete. In this paper, we designate it as *Artemia* sp.

With increasing water salinity, the number of species decreases, and the role of Artemia in the community increases. However, brine salinity of 95–100 g L-1 in Lake Kulundinskoye is likely a barrier to the development of all accompanying *Artemia* species. In 2017–2020, water desalination during the transgression phase of water content caused a loss of a dominant position of this species in the community, as noted during the periods of high water salinity (105–140 g L-1) in previous studies (Vesnina 2002).

Assessment of natural factors effect on zooplankton structure

To assess the effect of natural factors on zooplankton structure, we studied the relationship between 16 key indicators of zooplankton structure and 17 hydrophysical and hydrochemical indicators. We found several reliable (significance level $p<0.05$) strong correlations (the Pearson correlation coefficient $r=0.72–0.75$) between the analyzed indicators. These correlations were associated solely with the dominant zooplankton species, *Artemia* crustacean. The proportion of females in the population and the productivity of cysts were positively influenced by increased salinity and negatively by water temperature. At increased water salinity, the water volume and *Artemia* cyst productivity increased. Conversely, a decrease in water temperature resulted in lower productivity of cysts.

Pairs of indicators	r	p
Productivity of *Artemia cysts*– temperature in August	-0.75	0.02
Female proportion in *Artemia* population – salinity in spring	0.73	0.03
Female proportion in *Artemia* population – temperature in October	-0.74	0.02
Female proportion in *Artemia* population – fertility of Artemia females	-0.72	0.03

Table 1. *Statistically significant correlations of the main characteristics of zooplankton with indicators of the aquatic environment of Kulundinskoye Lake based on the average annual (r – the Pearson correlation coefficient; p – the significance*

level)

In 2009, Litvinenko et al. reported on both bisexual and parthenogenetic races of *Artemia*. In Lake Urmia, Iran, a parthenogenetic race coexists with a bisexual species known as *Artemia urmiana* Günther, 1899, as documented by Takami (1989). The change in reproduction type is possible and has been observed where a sexual type of reproduction, seen in spring and winter, may turn into parthenogenetic in other seasons due to changes in feeding conditions, such as when feeding on microalgae versus mixed feeds.

Recently, Boyer et al. (2021) published data that challenges the previous understanding of the sexual structure of *Artemia* populations. It is important to note that fully parthenogenetic populations of this crustacean do not exist. Even in populations that are considered to be completely parthenogenetic, females rarely reproduce sexually (on average ≈2%). Our data suggest that this indicator may depend on water temperature and salinity in different seasons of the year.

To gain more insight into this phenomenon, we performed a correlation analysis of monthly values of hydrochemical and hydrobiological indicators from 2017 to 2020. We found a total of 22 pairs of reliable (significance level $p<0.05$ and $p<0.01$) medium and strong correlations (Pearson correlation coefficient $r=0.49–0.82$) between the analyzed indicators (Table 2). Almost half of these correlations were associated with *Artemia* abundance at different stages of its life cycle, including nauplii and cysts. Their abundance positively correlated with water salinity and related concentrations of main salt ions (Cl- and SO42-) and nitrate ions as well. Conversely, the abundance of brackish-water and euryhaline taxa, such as rotifers and copepods, negatively correlated with water salinity.

Pairs of indicators	r	p
Artemia abundance (total) – concentration of Cl-	0.82	<0.01
Artemia abundance (total) – salinity	0.74	<0.01
Artemia abundance (total) – concentration of NO32-	0.57	0.02
Artemia nauplius abundance – concentration of Cl-	0.82	<0.01
Artemia nauplius abundance – salinity	0.75	<0.01
Artemia nauplius abundance – concentration of NO32-	0.57	0.02
Artemia cysts abundance – concentration of Cl-	0.64	<0.01
Artemia cysts abundance – concentration of SO42-	0.56	0.02
Artemia cysts abundance – salinity	0.68	<0.01
Artemia cysts abundance – concentration of NO32-	0.58	0.01
Rotifera abundance – Copepoda abundance	0.49	0.05
Rotifera abundance – Cladocera abundance	0.70	<0.01
Rotifera abundance – concentration of NO32-	-0.50	0.04
Rotifera abundance – concentration of SO42-	-0.65	<0.01
Rotifera abundance – salinity	-0.50	0.04
Copepoda abundance – concentration of SO42-	-0.54	0.02
Copepoda abundance – salinity	-0.63	<0.01
Water salinity – concentration of Cl-	0.73	<0.01

Water salinity – concentration of SO42-	0.63	<0.01
Water salinity – concentration of NO32-	0.76	<0.01
Concentrations of nitrates in water – temperature	-0.60	0.01

Table 2. *Statistically significant correlations of the main characteristics of zooplankton with indicators of the aquatic environment of Lake Kulundinskoye based on monthly data (see Table 1)*

The previously identified correlation coefficients include both direct relationships between hydrobiological characteristics and hydrochemical factors (such as the abundance of different hydrobiont taxa and water salinity), as well as indirect relationships that are influenced by the concentration of individual ions that are closely related to overall salinity.

The correlation analysis revealed that monthly values of aquatic environment indicators are more informative than annual averages, especially for zooplankton development. This is because the short life cycles of zooplankton make them a better indicator of dynamic changes in environmental quality, rather than chronic pollution (Bezmaternykh et al. 2006).

When predicting variable aquatic biological resources in Lake Kulundinskoye, it is best to consider inter-annual cycles. Using Fourier spectral analysis, we found a good correlation between water salinity and the calculated productivity of *Artemia* per unit area of the lake. Both series have cycles lasting 6–7 years, with the most characteristic being a 10-year cycle that is similar in duration to the 11-year solar cycle. The 10-year cycle is also most closely related to salinity. However, the 10-year cycle is equal to half of our sample, so it cannot be considered as reliably proven. Longer cycles were not considered due to limited sample size, while shorter cycles (2–4 years) were found to have poor statistical reliability (see Fig. 2).

A
B

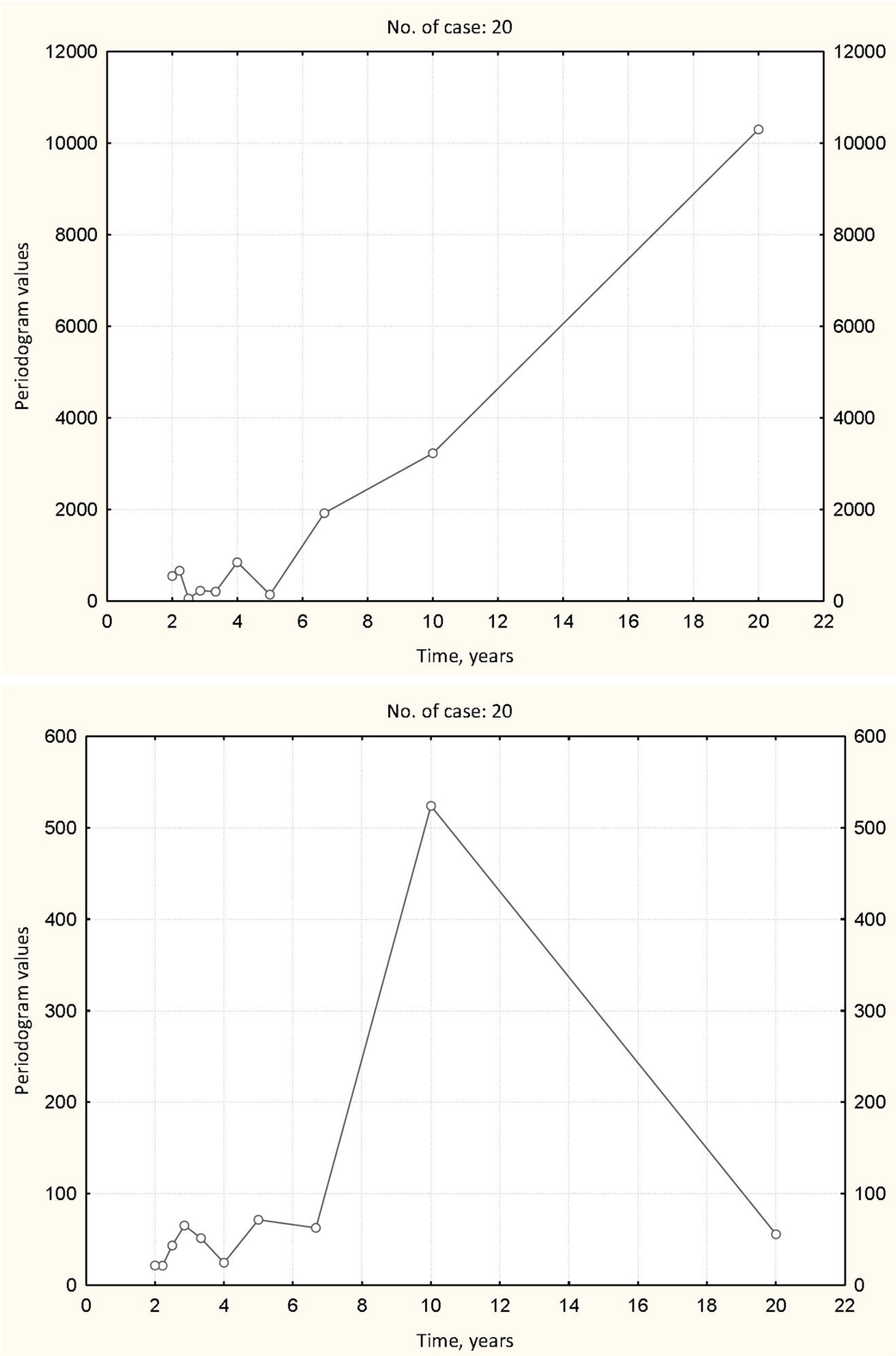
No. of case: 20
Periodogram values
Time, years
No. of case: 20
Periodogram values
Time, years

Figure 2. *Fourier analysis of water salinity in Lake Kulundinskoye* ***(A)*** *and productivity of Artemia* ***(B)****, 2000–2020.*

Lake Chany, the most extensively studied lake in the closed Ob-Irtysh interfluve, experiences significant fluctuations in its hydrological regime due to changes in the moisture content of the territory, which are caused by both solar activity and climate changes (Savkin 2006). In the southern part of Western Siberia, the water level fluctuations of Lake Chany are well correlated with those of annual precipitation (Galakhov 2012). The long-term dynamics of the biomass of macrozoobenthos in this lake, as reported by Bezmaternykh in 2016, are in good agreement with its water level fluctuations. These fluctuations can be categorized into three types: intra-secular cycles lasting 40 years or more, cycles that are presumably associated with solar activity and last 10–20 years, and high-frequency cycles that last 3–6 years (Vasil'ev et al. 2006).

Conclusions

Lake Kulundinskoye is a hypergalinic reservoir dominated by the crustacean Artemia in its zooplankton composition. However, the hydrophysical, hydrochemical, and hydrobiological regimes of the lake undergo significant changes every year, which have implications for its economic use, particularly the extraction of crustacean cysts.

The statistical analysis of environmental factors that influence the zooplankton structure of Lake Kulundinskoye suggests that monthly hydrophysical and hydrochemical data are more reliable for obtaining accurate results than averages calculated over the entire research period (April–October). The variations observed in the zooplankton structure are mainly due to the positive impact of increased salinity on the *Artemia* population and the negative impact it has on other taxa.

The long-term dynamics of zooplankton in Lake Kulundinskoye is characterized by a complex cyclicity of water salinity and productivity of the *Artemia* population. These cycles, which last 6 and 10 years and possibly include shorter and longer cycles, depend on periodic changes in the moisture content of the lake catchment.

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