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ORIGINAL ARTICLE

Main natural factors determining seasonal and long-term dynamics of zooplankton from Lake Kulundinskoye (Altai Krai)

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The paper presents the findings of studying the influence of main natural environmental factors on long-term (2000-2020) and seasonal (from April to October) dynamics of zooplankton from large hypergaline lake Kulundinskoye located in the Kulunda steppe (Altai Krai, Russia). We studied the relationship of 16 key indicators of zooplankton structure (its abundance and biomass as a whole and in major taxonomic groups, i.e., rotifers, paddleheads, branchipeds and gill- footed crustaceans as well as individual stages of a life cycle and a sex ratio in Artemia population) with 17 hydrophysical and hydrochemical indicators (temperature, density, pH, total salinity, hardness, alkalinity, Cl^-, NO_2^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, NH_4^+, Fe_2^{3+}, Ca^{2+}, Mg^{2+}, K^+, Na^+, monthly permanganate oxidizability (2017-2020) and average annual (for a growing season) data for 2000-2020. The influence of the studied factors on features of Artemia crustacean population (abundance, biomass, age and sex structure) dominated in zooplankton of this lake was analyzed as well. In different years, hydrophysical and hydrochemical regime of lake Kulundinskoye may vary significantly thus affecting zooplankton indicators. The statistical analysis of environmental factor impacts on zooplankton structure of the lake proves better results reliability when using monthly hydrophysical and hydrochemical data rather than averaged over the research period (April-October). The revealed man-induced changes in zooplankton structure are mainly due to the stimulating effect of increased salinity on Artemia population and its depressing influence on other taxa. Long-term dynamics of zooplankton is characterized by a complex cyclicity of water salinity and productivity of Artemia population (the 10-year and, possibly, shorter and longer cycles), which in turn depends on periodic changes in moisture content of the lake catchment.

Keywords: Zooplankton, environmental factors, limnology, hydrochemistry, salinity, brine shrimp, population, kulunda.

Introduction

Lake Kulundinskoye-the largest water body of the Kulunda Plain and Altai Krai, is situated in the south of Western Siberia in the closed Ob-Irtysh interfluve. Its water area in different years and seasons varies from 720.0 to 728.0 km^2; the average depth makes up 2.6-3.0 m, the maximum one reaches 3.5-4.0 m. The lake basin is rounded and slightly elongated of about 35 km long; the banks (in places, with salonetz-salonchak complexes) are flat. The lake is drainless with inflowing Rivers Kulunda and Suetka. The water is bitterly salty; its salinity is within 40.0-131.0 g/l (Solovov et al., 2001). Note that Roshydromet does not implement any hydrological, hydrochemical and hydrobiological observations of the lake.

Similar to some other hypergaline water bodies in this region, lake Kulundinskoye is of economic significance due to intensive extraction of aquatic biological resources, i.e., Artemia gill-footed crustacean cysts used as a starter feedstuff in aquaculture and valuable raw materials for cosmetic and pharmaceutical production (Lavens, Sorgeloos, 1996; Solovov et al., 2001; Litvinenko et al., 2009). However, Artemia productivity and biological resources extraction in the region under study are changeable and hardly predictable (Solovov, Studenikina, 1990; Vesnina, 2019).

According to S.V. Gerda biolimnological zoning (1959), the reservoirs of the Kulunda Plain belong to the Barabinsk-Kulunda lake district. A distinctive feature of lakes of this region is shallow basin depth and increased water salinity. Their ecosystems are subject to cyclic successions (Maksimov, 1989) because climate in the south of Western Siberia is characterized by alternating dry and wet periods with significant fluctuations in water levels and the area of drainless lakes (Shnitnikov, 1950, 1958). Strong fluctuations in water levels lead to pronounced changes in hydrochemical and hydrobiological regime of lakes (Pulsating Lake, 1982; Ecology, 1986).

Aquatic communities promptly respond to changes in environmental factors affecting lakes; their response time depends on the duration of life cycle of the species. For planktonic invertebrates from the south of the West Siberian Plain, life cycles usually last from a few days to several months. Despite rather long investigations of zooplankton from lake Kulundinskoye (Vesnina, 2002, 2019; Lisitsina, 2006, etc.), the dependences of its dynamics on environmental factors were previously studied mainly in the phenomenological aspect. Our goal was to study the composition, structure and dynamics of zooplankton of lake Kulundinskoye influenced by natural factors using up-to-date computer-based statistics programs.

Materials and Methods

The paper deals with analyzing field data obtained during the complex limnological and hydrobiological investigations of lake Kulundinskoye in 2017-2020 as well as similar archival and published (2000-2016) data. During this period, samples were collected monthly at the same 48 sampling stations (Fig. 1).

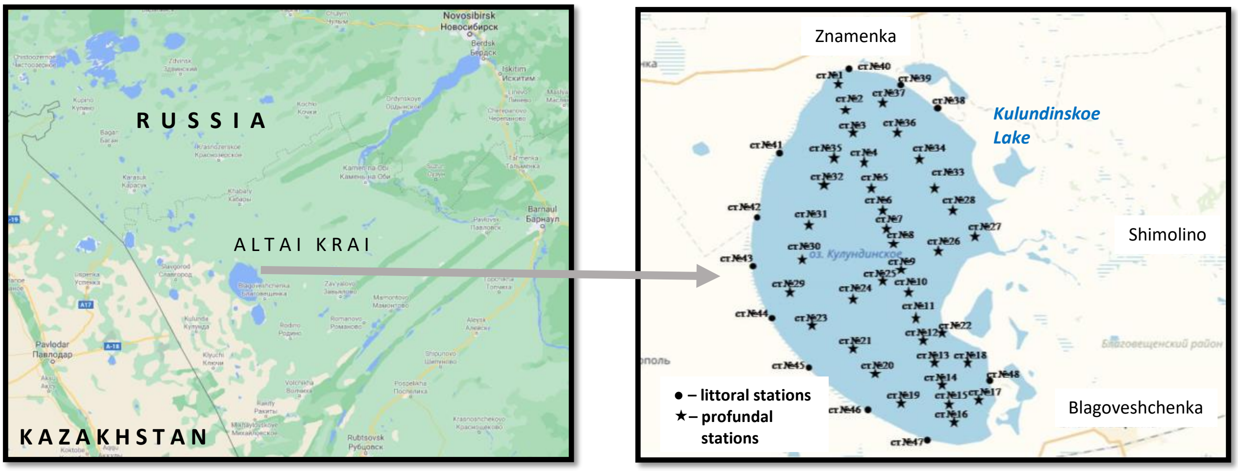


Fig. 1. The schematic map of location of lake Kulundinskoye and sampling stations (No.1-48).

The selection and processing of zooplankton samples were implemented by means of standard hydrobiological methods (Manual, 1992; Methodological instructions, 2002). 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 (Rylov, 1948; Manuylova, 1964; Kutikova, 1970; Key to, 1994, 1995, 2010). The chemical analysis of water samples was made by an accredited laboratory of JSC "Kuchuksulfat".

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

Results and Discussion

Key parameters of hydrochemical regime

Water temperature in the surface layer of lake Kulundinskoye in May 2020 was rather high-15.0^{o}C. In summer (July), it reached 29.4^{o}C and by October fell to 6.4^{o}C. Similar seasonal dynamics was typical for the average long-term data (2000-2019), except for summer temperatures of 2020, which were higher by 3.0-5.0^{o}C than the average long-term ones.

According to O.A. Alekin hydrochemical classification (1970), by salinity, lake Kulundinskoye refers to a hyperhaline reservoirs (Oksiyuk, Zhukinsky, 1993). In 2020, water salinity of lake ranged from 87.0 to 94.2 g/l. From long-term observations (2000-2019), it was within 32.0-115.4 g/l. An increase in salt concentrations in brine was marked by the end of the growing season. As for main ion composition, the lake water was chloride-sulfate of the sodium group, by pH-slightly alkaline (7.8 to 8.8). The concentration of nitrites (≤0.04 mg/l), nitrates (≤24 mg/l) and phosphates (≤0.7 mg/l) was low, whereas the content of ammonium ions (≤13 mg/l)-increased, and in 2017 they significantly exceeded the MPC standard (0.05 mg/l) for fishery reservoirs (Order, 2016). Over the long research period, dissolved oxygen in different months varied as 3.3-13.6 mg/l. Its minimum was recorded in October and the maximum-in April. The permanganate oxidizability of water ranged from 65.6 (in July) to 103.6 mgO_2/l (in April) showing the increased content of organic substances in the water.

Zooplankton of lake Kulundinskoye was represented by 9 species; Rotiphera (6), Cladocera (1), Copepoda (2) and Anostraca (1). All detected species are either halobionts (*Artemia* sp., *Cletocamptus retrogressus* Schmankevitsch, *Brachionus plicatilis* (O.F. Müller) or euryhalines (*Asplanchna priodonta* Gosse, Keratella cochlearis Gosse, K. quadrata (O.F. Müller), Hearthra ohuigis (Zernov*),* *Polyarthra dolichoptera* Idelson, *Moina macrocopa* (Straus)).

We cannot but touch upon the problem of taxonomic identification of Artemia crustacean. According to modern taxonomy, Artemia from the lakes of Western Siberia belongs to the order Anostraca, the family Artemiidae and the genus Artemia Leach, 1819. The specific name of the crustacean (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 (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, the role of Artemia in the community grows and the share of brackish-water species in the total biomass falls. In lake Kulundinskoye, brine salinity of 95-100 g/l is, probably, a barrier to the development of all accompanying Artemia species. In 2017-2020,

water desalination during the regression phase of water content brought to the loss of a dominant position of this species in the community, as it was noted previously during the periods of high water salinity (105.0-140.0 g/l) (Vesnina, 2002). In the last four years, the economic significance of the lake decreased because of the lack of bio-raw materials, i.e., commercial accumulations of Artemia cysts.

Assessment of natural factors effect on zooplankton structure

We studied the relationship of 16 key indicators of zooplankton structure (its abundance and biomass as a whole and in major taxonomic groups, i.e., rotifers, paddleheads, branchipeds and gill-footed crustaceans as well as individual stages of a life cycle and a sex ratio in Artemia population) with 17 hydrophysical and hydrochemical indicators (temperature, density, pH, total salinity, hardness, alkalinity, Cl^-, NO_2^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, NH_4^+, Fe_2^{3+}, Ca^{2+}, Mg^2+, K^+, Na^+, monthly permanganate oxidizability (2017-2020) and average annual (for the growing season) data for 2000-2020. The resultant calculations of the average annual data for a long-term period revealed several reliable (significance level $p < 0.05$) strong correlations (the Pearson correlation coefficient r=0.72-0.75) between the analyzed indicators (Table 1). All of them were associated solely with dominant zooplankton species, i.e., Artemia crustacean (the proportion of females in the population and the productivity of cysts) influenced positively by increased salinity and negatively by water temperature. At increased water salinity, water temperature, apparently, affects oxygen solubility through its decrease. Since sufficient data on dissolved oxygen content were not available, we excluded this indicator from the correlation analysis.

Table 1. Statistically significant correlations of major characteristics of zooplankton with indicators of the aquatic environment of lake Kulundinskoye based on the average annual (r-is the Pearson correlation coefficient, p-the significance level).

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

Previously published works report about both bisexual and parthenogenetic races of Artemia (Litvinenko et al., 2009). In Iranian lake Urmia, a parthenogenetic race coexists with a bisexual species Artemia urmiana (Takami, 1989). Change in reproduction type is feasible; for example, a sexual type of reproduction observed in spring and winter may turn into parthenogenetic in other seasons (Amat, 1983). Also it occurs under change of feeding conditions, i.e., parthenogenetic- when feeding by microalgae and separate-sex by mixed feeds.

Interestingly, current data are evidence of wrong interpretation of previously known facts about the sexual structure of Artemia populations (Boyer et al., 2021). It should be noted that fully parthenogenetic populations of this crustacean do not exist. In populations considered to be completely parthenogenetic, females also rarely reproduce sexually (on average ≈2%). Our data suggest that this indicator, probably, depends on water temperature and salinity in different seasons of the year.

The correlation analysis of monthly values of hydrochemical and hydrobiological indicators (2017-2020) was found to be more informative. 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 were revealed (Table 2). Almost half of them were associated with Artemia abundance and at certain stages of its life cycle (naupliuses and cysts). Their abundance positively correlated with water salinity, related concentrations of main salt ions (Cl^- and SO_4^{2-}) and nitrate ions as well. At the same time, abundance of brackish-water and euryhaline taxa (rotifers and copepods) negatively correlated with water salinity.

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

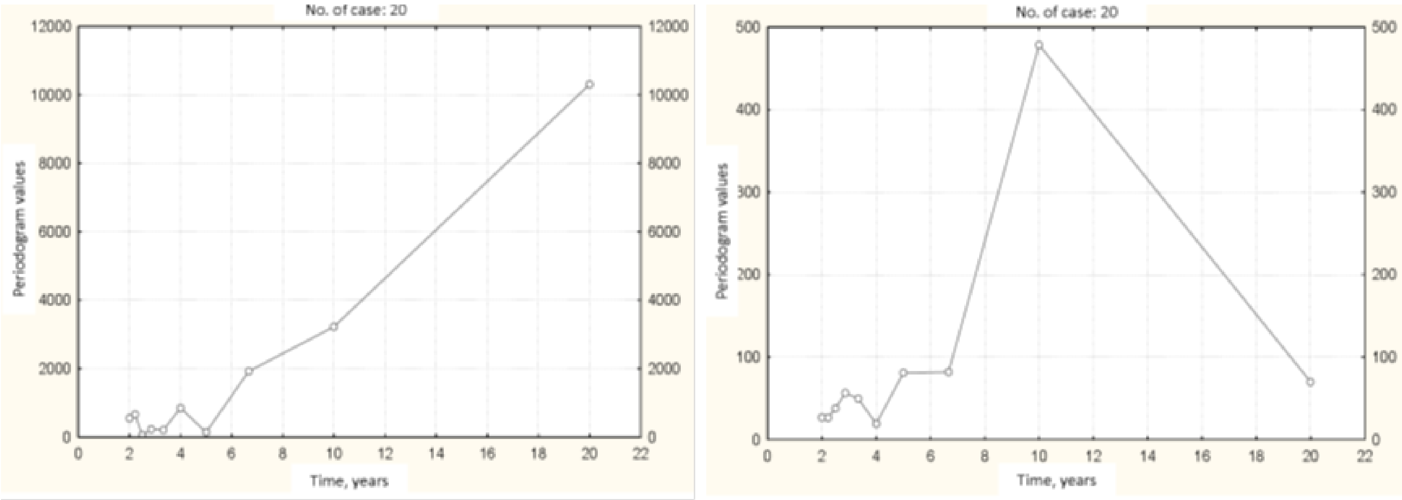
Pairs of indicators	*r*	*p*
Artemia abundance (total)-concentration of Cl^-	0.82	<0.01
Artemia abundance (total)-salinity	0.74	<0.01
Artemia abundance (total)-concentration of NO_3^{2-}	0.57	0.02
Artemia nauplius abundance-concentration of Cl^-	0.82	<0.01
Artemia nauplius abundance-salinity	0.75	<0.01
Artemia nauplius abundance-concentration of NO_3^{2-}	0.57	0.02
Artemia cysts abundance-concentration of Cl^-	0.64	<0.01
Artemia cysts abundance-concentration of SO_4^{2-}	0.56	0.02
Artemia cysts abundance-salinity	0.68	<0.01
Artemia cysts abundance-concentration of NO_3^{2-}	0.58	0.01
Rotifera abundance-Copepoda abundance	0.49	0.05
Rotifera abundance-Cladocera abundance	0.70	<0.01
Rotifera abundance-concentration of NO_3^{2-}	-0.50	0.04
Rotifera abundance-concentration of SO_4^{2-}	-0.65	<0.01
Rotifera abundance-salinity	-0.50	0.04
Copepoda abundance-concentration of SO_4^{2-}	-0.54	0.02
Copepoda abundance-salinity	-0.63	<0.01
Water salinity-concentration of Cl^-	0.73	<0.01
Water salinity-concentration of SO_4^{2-}	0.63	<0.01
Water salinity-concentration of NO_3^{2-}	0.76	<0.01

Concentrations of nitrates in water-temperature	-0.60	0.01

Obviously, among reliably identified correlation coefficients there are both true dependences of hydrobiological characteristics on hydrochemical factors (e.g., abundance of different taxa of hydrobionts on water salinity) and indirect ones, which depend on the concentration of individual basic ions, which is closely related to the total salinity.

As can be seen from the outcomes of the correlation matrice analysis, the indicators of zooplankton development correlate better not with the average annual characteristics of the aquatic environment, but with monthly values. This is due to the short duration of hydrobionts life cycles of zooplancton. As compared to zoobenthos, zooplankton is a more reliable indicator of environmental quality dynamics rather than chronic pollution (Bezmaternykh et al., 2006).

Clearly, prediction of variable aquatic biological resources of lake Kulundinskoye is better to conduct in the inter-annual aspect. To establish the data cyclicity in time series, we use the Fourier spectral analysis showing good correlation between water salinity of lake Kulundinskoye and the calculated productivity of Artemia per unit area of the lake. Both series have cycles lasting 6-7 years (Hamming weight-0.24); a 10-year cycle is most characteristic (Hamming weight-0.45), which is close in duration to the 11-year solar one. Moreover, the 10-year cycle is best related to salinity. We did not consider longer cycles due to limited sample size (20 years) and shorter ones (2-4 years) because of their poor statistical reliability (Fig. 2).



A B

Fig. 2. The findings of the Fourier analysis of water salinity (A) and productivity of Artemia (B) in lake Kulundinskoye (2000-2020).

The most studied reservoir of the closed Ob-Irtysh interfluve (lake Chany) is also characterized by pronounced intra-secular fluctuations of hydrological regime associated with changes in moisture content of the territory due to both solar activity and climate changes (Savkin et al., 2006). In the south of Western Siberia, fluctuations in water levels of lake Chany correlate well with those in annual precipitation (Galakhov, 2012). The data on long-term dynamics of macrozoobenthos biomass (Bezmaternykh, 2016) are well consistent with water level fluctuations of this lake: 1) intra-secular cycles-40 years or more; 2) presumably associated with solar activity-10-20 years; 3) high-frequency cycles-3-6 years (Vasiliev et al., 2006).

Conclusion

Lake Kulundinskoye is a hypergalinic reservoir with predominance of gill-footed crustacean Artemia in zooplankton structure. In different years, hydrophysical, hydrochemical and hydrobiological regime of the lake undergoes significant changes that affects its economic use, i.e., the extraction of crustacean cysts. The statistical analysis of environmental factors having effect on zooplankton structure of lake Kulundinskoye suggests that more reliable results are obtained when using monthly hydrophysical and hydrochemical data rather than the averaged over the research period (April-October). The revealed man-related variations in zooplankton structure are mainly due to a stimulating effect of increased salinity on Artemia population and its depressing impact on other taxa. The long-term dynamics of zooplankton is characterized by a complex cyclicity of water salinity and productivity of Artemia population (6, 10-year and, possibly, shorter and longer cycles), which in turn depends on periodic changes in moisture content of the lake catchment.

Conflict of Interest

The authors declare that they have no conflict of interest in this study.

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