ISSN 1995-0829, Inland Water Biology, 2024, Vol. 17, No. 6, pp. 985–996. © Pleiades Publishing, Ltd., 2024.

PHYTOPLANKTON, PHYTOBENTHOS, PHYTOPERIPHYTON

Studies of the Seasonal Dynamics of Planktonic Algae in the Volzhsky Reach of the Kuibyshev Reservoir in 2017

L. Y. Khaliullina[a, *] **and I. I. Khaliullin**[a]

[a] *Kazan (Volga Region) Federal University, Institute of Fundamental Medicine and Biology, Kazan, Russia*

**e-mail: liliya-kh@yandex.ru*

Received February 12, 2024; revised June 8, 2024; accepted July 3, 2024

Abstract—Studies were carried out on the seasonal dynamics of phytoplankton in the Volga reach of the Kuibyshev Reservoir in 2017. At the same time, the seasonal values of the main abiotic environmental factors influencing the dynamics of phytoplankton (level regime, intensity of incident solar radiation, some basic hydrochemical and hydrophysical indicators, etc.) were analyzed. The dominant phytoplankton complex consists of blue-green, green volvox, centric diatoms, and dinophytes. The study area is subject to the extremely intense processes of blooming of water due to the mass reproduction of *Microcystis, Aphanizomenon,* and *Anabaena* blue-green algae species, and the waters of the studied area during most of the growing season corresponds to the mesosaprobic type and a moderately polluted zone.

Keywords: phytoplankton, structure, biomass, abundance, algae, seasonal and interannual changes, Volga River, Kama River, Kuibyshev Reservoir, water level

DOI: 10.1134/S1995082924600091

INTRODUCTION

Kuibyshev Reservoir, the largest in Europe in regards to area and the sixth stage of the Volga-Kama cascade of reservoirs, currently has many hydrological and environmental problems. Since the Volga reservoirs are artificially regulated systems, it is possible to influence their condition. The most significant factors that can be controlled and that determine the processes within a reservoir are the regimes of water inflow and regulation of flow by the hydraulic structure.

To manage these factors, multivariate predictive calculations are needed under different scenarios of river-flow regulation. This requires data on a number of parameters that can only be obtained through monitoring over several years (Datsenko, 2007; Rakhuba, 2023).

The most important biological agent in the reservoir ecosystem is phytoplankton. The mass reproduction of some of its species causes extremely negative consequences in the form of water bloom. When organizing the monitoring of planktonic algae, it is necessary to focus on the average frequency of changes in synoptic weather cycles. In the climatic conditions of the Middle Volga, it is approximately 1 week, since the indicators of phytoplankton and biogens of reservoirs are very labile. Their qualitative and quantitative indicators, depending on many factors that are difficult to take into account technically, can fluctuate greatly even within a few hours and be unrepresentative. Based on this, the minimum recommended frequency of observations of the state of reservoir ecosystems during the growing season should be at least once a week (Datsenko, 2007; Datsenko et al., 2017).

One of the most significant sections of the reservoir is the Volga reach, located in the upper part of the reservoir, which has retained the Volga River regime to a greater extent than the lower sections of the reservoir: high flow rates and sandy soils, especially oxygen regime and biogenic substances (Water ..., 2006; Kuibyshevskoe ..., 2008; Khamitova and Kalaida, 2017). There is quite a lot of information on planktonic algae in this section of the reservoir (Ecology ..., 1989; Pautova and Nomokonova, 1994; Phytoplankton ..., 2003; Korneva, 2015; Kuzmina and Medyankina, 2019; Mineeva et al., 2022, etc.). Most often, the data were obtained as a result of large expeditions that studied the spatial distribution of aquatic organisms over a short period of time in different years.

The aim of this work is to identify the most significant factors that influence the processes of eutrophication and the mass development of phytoplankton, leading to the blooming of water by cyanobacteria in the reservoir.

MATERIALS AND METHODS

Studies of planktonic algae were conducted from May to October 2017 in the middle part of the Volga reach of the Kuibyshev Reservoir. The permanent

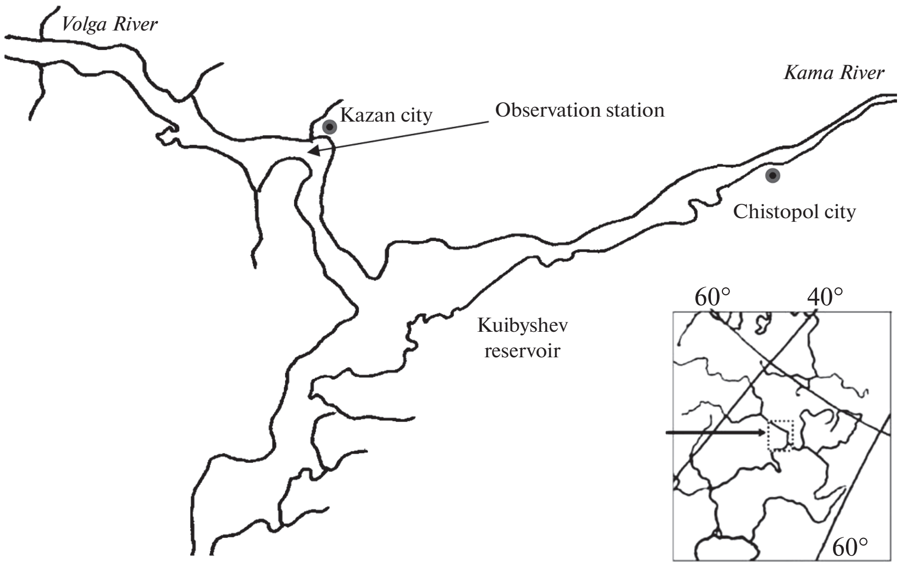

Fig. 1. Map of the Volga reach of the Kuibyshev Reservoir, where the research area was located in 2017 (indicated by the arrow).

observation station was located on the Volga River bed (fairway) in the area of the river port of Kazan (Fig. 1). The main supply of the studied section of the reservoir is provided by snow (60% of the annual runoff), groundwater (30%), and rainwater (10%). The waters are calcium hydrocarbonate, with a mineralization of 120–130 mg/L. The water level in the Kuibyshev Reservoir varies due to annual, seasonal, and daily regulation by the hydroelectric dam; water level fluctuations reach 5–6 m (Vodnye ..., 2006; Kuibyshevskoye ..., 2008).

Samples were collected at intervals of once a week from a small vessel using a Molchanov GR-18 bathometer (with a volume of 4 L) at a depth of 15–20 m. Surface and integrated samples were studied—samples from the surface and up to 0.5 m were mixed from a depth of triple transparency measured using a Secchi disk (the lower boundary of the photosynthesis zone) and 0.5 m from the bottom.

The collection and processing of samples was carried out in accordance with generally accepted hydrobiological methods (Gollerbach et al., 1953; Methodology ..., 1975; Algae ..., 1989; Sadchikov, 2003).[1] For a quantitative and qualitative recording of monadic and amoeboid forms that are destroyed or deformed during fixation, samples were filtered through a membrane filter on the day of collection and examined in a live state. To thicken the phytoplankton, a PVF-35/NB vacuum filtration device was used. To concentrate phytoplankton, Vladipor membrane filters of the MFAS–OS-2 and MFAS–OS-3 types with pore sizes of 0.45 and 0.8 μm, respectively, were used. Alongside that, 0.5 L samples were collected and fixed with 4% formalin. Fixed samples were concentrated by the sedimentation method to 7–10 mL for a qualitative and quantitative assessment of phytoplankton. To study the algae, an Axio imager 2 microscope was used (Carl Zeiss). Diatoms were identified in permanent preparations using a MERLIN field emission microscope (Carl Zeiss). The counting of organisms was carried out in Goryaev's chamber. The volumetric counting method was used to determine the biomass. Species with abundance or biomass ≥10% of total indicators were considered dominant.

For each sample, the trophic index (TSI) was calculated for the Milius block using the formula (Isachenko et al., 1993)

$$Ib = 44.87 + 23.22 \log B.$$

To determine the degree of saprobity, the saprobity index (S_B) of Pantle and Bukka as modified by Sladecek was calculated (1973).

During the entire research period, meteorological conditions and hydrological features of the sampling area were recorded daily. Also, during weekly observations, the chemical composition of the water was recorded and analyzed (analyses were performed by employees of the hydrochemical laboratory of Sredvolgavodkhoz), and the level of illumination and solar radiation (data was obtained at the meteorological observatory of Kazan Federal University) and the temperature and transparency of the water were measured.

During the work, a statistical analysis of primary data was carried out. The Shapiro–Wilk (W) test was used to check the normality of the data. It was revealed that in both surface and integrated samples the sapro-

[1] AlgaeBase is a database of information on algae that includes terrestrial, marine, and freshwater organisms. 2000. Access mode: http://algaebase.org. Cited July 16, 2021.

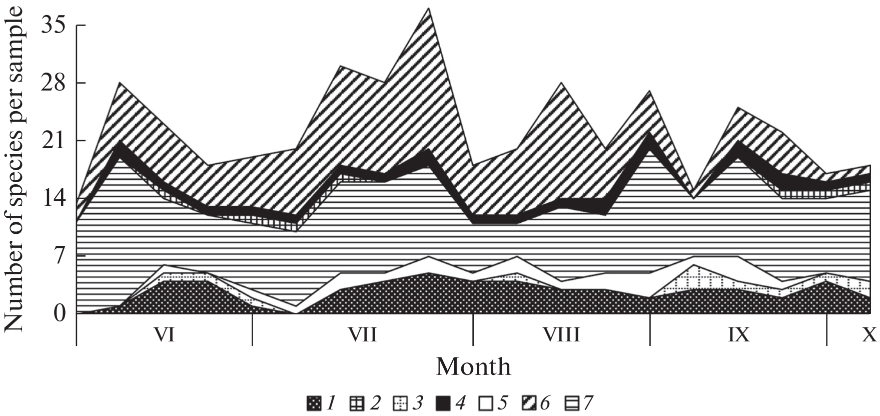

Fig. 2. Seasonal dynamics of the number of phytoplankton taxa in the Volga reach of the Kuibyshev Reservoir in 2017. (*1*) Cyanophyta, (*2*) Cryptophyta, (*3*) Euglenophyta, (*4*) Chrysophyta, (*5*) Dinophyta, (*6*) Chlorophyta, and (*7*) Bacillariophyta.

bity indices (W = 0.96, $p = 0.56$) and trophicity (W = 0.96, $p = 0.59$), obtained from phytoplankton biomass, have a normal distribution. The following chemical and physical parameters of water also had a normal distribution: water level (W = 0.91, $p = 0.07$), water temperature (W = 0.95, $p = 0.40$), hydrogen index (W = 0.96, $p = 0.52$), dissolved oxygen (W = 0.98, $p = 0.88$), ammonium nitrogen (W = 0.96, $p = 0.60$), nitrate nitrogen (W = 0.92, $p = 0.05$), hydrocarbonates (W = 0.94, $p = 0.22$), total phosphorus (W = 0.96, $p = 0.49$), COD (W = 0.97, $p = 0.83$), and total rigidity (W = 0.97, $p = 0.72$).

Since the remaining quantitative characteristics did not have a normal distribution, when studying the relationship between the characteristics under study, in most cases nonparametric methods and criteria were used for the statistical processing of the results. Calculations were performed using the analysis package in Microsoft Excel and Statistica v. 12.

RESEARCH RESULTS

The characteristics of the reservoir water regime, combined with weather conditions, have a significant impact on the development of phytoplankton. The hydrodynamic factor limits the increase in algae biomass if the rate of doubling of biomass is less than the rate of water exchange in the reservoir (Datsenko, 2007; Rakhuba, 2020). In 2017, which turned out to be a cold and high-water year, the conditions for the development of phytoplankton in the Kuibyshev Reservoir in the summer months were not very favorable due to the high water flow at the Zhiguli Hydroelectric Complex (Review ..., 2018). The rise in water level during spring filling began in March from the 48.92 m BS mark and, with minor fluctuations, remained at the 53.5 m mark until the end of July. Later, gradually decreasing, by the end of September, it reached 52.1 m. From the beginning of October, the water level began to rise, and it remained high throughout the winter months. This hydrological regime during most of the summer was due to the actual lateral inflow, which was caused by heavy precipitation in the Upper Volga and Kama river basins. As a result, in 2017, the average water consumption during the summer low-water period increased and exceeded the long-term norm by >50%. Idle water discharge was carried out for 4 months, from April 21 to August 24, as a result of which water consumption during the summer low water period increased significantly (Review ..., 2018; Khaliullina and Khaliullin, 2022).

The average values of abiotic parameters and results of hydrochemical analysis for the season are given in Table 1.

During the research period, 237 species, varieties, and forms of algae were identified in the phytoplankton of the Volga River: Cyanophyta, 31; Chrysophyta, 8; Bacillariophyta, 67; Xanthophyta, 5; Cryptophyta, 5; Dinophyta, 7; Euglenophyta, 13; and Chlorophyta, 100. The largest number of species were in the divisions of green algae (42% of the total list) and diatoms (28). The specific species richness of phytoplankton varied from 13 to 37 species and intraspecific taxa in the sample (Fig. 2). The maximum values of floristic richness were observed at the end of July.

An increase in species diversity occurred with significant fluctuations in water levels, as well as after heavy rains and thunderstorms. During these periods, benthic diatoms, which are not typical for the riverbed part, appeared in the water, as did flagellate algae from the divisions of euglenophytes, dinophytes, golden, and green, which usually live in shallow and macrophyte-overgrown bays of the reservoir (Khaliullina and Yakovlev, 2015; Khaliullina and Demina, 2015).

During periods when the water level was more or less stable, the water mainly contained planktonic species of centric diatoms, cyanobacteria, volvox, and sphaeroplethus green algae. Many species were encountered singly and were identified only in qualitative samples.

Table 1. Physicochemical parameters of water in the Volga reach of the Kuibyshev Reservoir in 2017

Indicator	$M \pm SE$	min–max	*m*
Component composition of the main ions			
Hydrocarbonates, mg/L	147.71 ± 6.45	103.73–195.30	28.10
Total hardness, mg-eq/L	2.94 ± 0.11	2.00–3.80	0.50
Physical indicators			
Color, degree	54.49 ± 4.79	8.30–88.35	20.88
Suspended solids, mg/L	4.72 ± 0.61	5.00–14.00	2.67
Transparency, cm	208.68 ± 12.86	150.00–370.00	56.07
Air temperature, °C	18.05 ± 2.31	1.00–31.00	10.07
Water temperature, °C	18.68 ± 0.93	10.60–24.10	4.03
Hydrogen index	7.89 ± 0.09	7.10–8.51	0.38
Gas mode			
Dissolved oxygen, mg/L	8.38 ± 0.34	5.56–12.67	1.46
Biogenic and organic substances			
Ammonium nitrogen, mg/L	0.65 ± 0.03	0.42–0.88	0.14
BOD 5, mg O_2/L	1.72 ± 0.33	1.00–6.65	143
COD, mg O_2/L	42.93 ± 2.40	21.00–61.40	10.48
Manganese, mg/L	0.05 ± 0.02	0.00–0.31	0.09
Nitrate nitrogen, mg/L	1.76 ± 0.15	0.27–2.60	0.67
Nitrite nitrogen, mg/L	0.05 ± 0.01	0.02–0.13	0.03
Total phosphorus, mg/L	0.07 ± 0.01	0.02–0.12	0.03

M, average value for the sampling period; *SE*, standard error of the mean; and *m*, standard deviation of the indicators.

Although integrated samples are more informative for phytoplankton studies, surface water samples were also collected and analyzed at the same time. When cyanobacteria accumulate on the surface of the water, their quantitative indicators in integrated samples may be of little information (Table 2), and one can miss the periods of their water blooming.

The average total quantity of phytoplankton during the study period reached 4.60 ± 1.54 million cells/L and varied within the range of 0.14–24.01 million cells/L. The average total biomass was 1.81 ± 0.44 mg/L, and minimum and maximum values fluctuated within the range of 0.39–7.38 mg/L (Fig. 3). In quantitative terms, cyanobacteria, diatoms, and green and dinophyte algae dominated.

Cyanobacteria appeared in the samples from the beginning of June and dominated in numbers throughout the summer and autumn, periodically causing water blooms everywhere due to the mass reproduction of *Microcystis aeruginosa* emend. Elenk. and *Aphanizomenon flos-aquae* (L.) Ralfs. Periodically, species *Anabaena flos-aquae* (Lyngb.) Breb., *A. affinis* Lemm., and *A. planctonica* Brunnth became subdominants, in different proportions. Species *Oscillatoria planctonica* Wołosz., *Gomphosphaeria lacustris* Chodat., *Gloeocapsa turgida* (Kütz.) Hollerbach, and *G. limnetica* (Lemm.) Hollerbach were discovered sporadically, although the content of these species was insignificant.

In terms of biomass, centric diatoms and volvox green algae predominated most often, yielding to cyanobacteria only during periods of intense water bloom. The centric diatoms *Aulacoseira subarctica* (O. Müll.) Haworth, *A. granulata* (Ehr.) Sim., *A. islandica* (O. Müll.) Sim., *A. ambigua* (Grun.) Sim., *Cyclotella meneghiniana* Kütz., *C. atomus* Hust., *Stephanodiscus astraea* (Kütz.) Grun., *S. hantzschii* Grun., and *Asterionella formosa* Hass, typical of the Kuibyshev Reservoir, were in the lead. *Achnanthes* sp. clusters were often visible in Cyanobacteria *Microcystis aeruginosa* colonies. Among the pennate diatoms, subdominants included *Diatoma tenuis* C. Agardh., *Synedra acus* Kütz., *S. ulna* (Nitzsch.) Ehrenb., *Nitzschia acicularis* (Kütz.) W. Smith, *N. palea* (Kütz.) W. Smith. Fouling species *Melosira varians* C. Agardh., *Diatoma vulgaris* Bory, and *Fragilaria construens* (Ehrenb.) Grun. were found in phytoplankton.

Volvoxes *Chlamydomonas* spp., *Phacotus lenticularis* (Ehrenb.) Diesing, and *Pandorina morum* (Müll.) Bory dominated among green algae, and quite often there were species *Carteria* spp., *Pteromonas aculeata* Lemm., and *Tetraselmis cordiformis* (Cart.) Stein. The number of spheroplethians *Coelastos microporus* Näg., *Dictyosphaerium pulchellum* Wood, *Monoraphidium*

Table 2. Average abundance and biomass of phytoplankton the Volga reach of the Kuibyshev Reservoir in 2017

Indicator	$M \pm SE$	min–max	m
Integrated samples			
$N_{general}$, million cells/L:	4.60 ± 1.54	0.14–24.01	6.69
Cyanophyta	3.53 ± 1.43	0.00–21.99	6.22
Euglenophyta	0.01 ± 0.00	0.00–0.06	0.01
Dinophyta	0.03 ± 0.01	0.00–0.11	0.04
Bacillariophyta	0.54 ± 0.11	0.08–1.68	0.47
Cryptophyte	0.01 ± 0.00	0.00–0.05	0.02
Chrysophyta	0.04 ± 0.01	0.00–0.11	0.03
Chlorophyta	0.45 ± 0.15	0.00–2.01	0.63
$B_{general}$, mg/L:	1.81 ± 0.44	0.39–7.38	1.93
Cyanophyta	0.28 ± 0.11	0.00–1.71	0.49
Euglenophyta	0.02 ± 0.02	0.00–0.28	0.07
Dinophyta	0.32 ± 0.10	0.00–1.42	0.45
Bacillariophyta	0.69 ± 0.14	0.13–2.39	0.60
Cryptophyte	0.01 ± 0.00	0.00–0.05	0.02
Chrysophyta	0.02 ± 0.00	0.00–0.06	0.02
Chlorophyta	0.46 ± 0.20	0.00–2.88	0.87
S_B	1.74 ± 0.07	1.07–2.16	0.29
TSI	46.44 ± 2.16	35.31–65.02	9.41
Surface tests			
$N_{general}$, million cells/L:	7.16 ± 2.61	0.17–36.30	11.40
Cyanophyta	5.51 ± 2.41	0.00–35.10	10.49
Euglenophyta	0.00 ± 0.00	0.00–0.02	0.01
Dinophyta	0.04 ±0.01	0.00–0.16	0.05
Bacillariophyta	0.60 ± 0.24	0.00–3.55	1.03
Cryptophyte	0.00 ± 0.00	0.00–0.03	0.01
Chrysophyta	0.04 ± 0.01	0.00–0.15	0.04
Chlorophyta	0.96 ± 0.62	0.00–11.79	2.70
$B_{general}$, mg/L:	2.38 ± 0.67	0.16–12.10	2.93
Cyanophyta	0.45 ± 0.20	0.00–2.75	0.86
Euglenophyta	0.01 ± 0.01	0.00–0.08	0.02
Dinophyta	0.49 ± 0.15	0.00–2.06	0.66
Bacillariophyta	0.98 ± 0.38	0.00–6.23	1.65
Cryptophyte	0.00 ± 0.00	0.00–0.03	0.01
Chrysophyta	0.02 ± 0.01	0.00–0.08	0.02
Chlorophyta	0.42 ± 0.18	0.00–2.89	0.78
S_B	1.79 ± 0.07	1.17–2.28	0.32
TSI	46.63 ± 2.96	26.24–70.02	12.89

S_B, saprobity index by phytoplankton biomass; TSI, trophic index by phytoplankton biomass; $N_{general}$, total number; $B_{general}$, total biomass; M, average value for the sampling period; SE, standard error of the mean; m, standard deviation of the indicators.

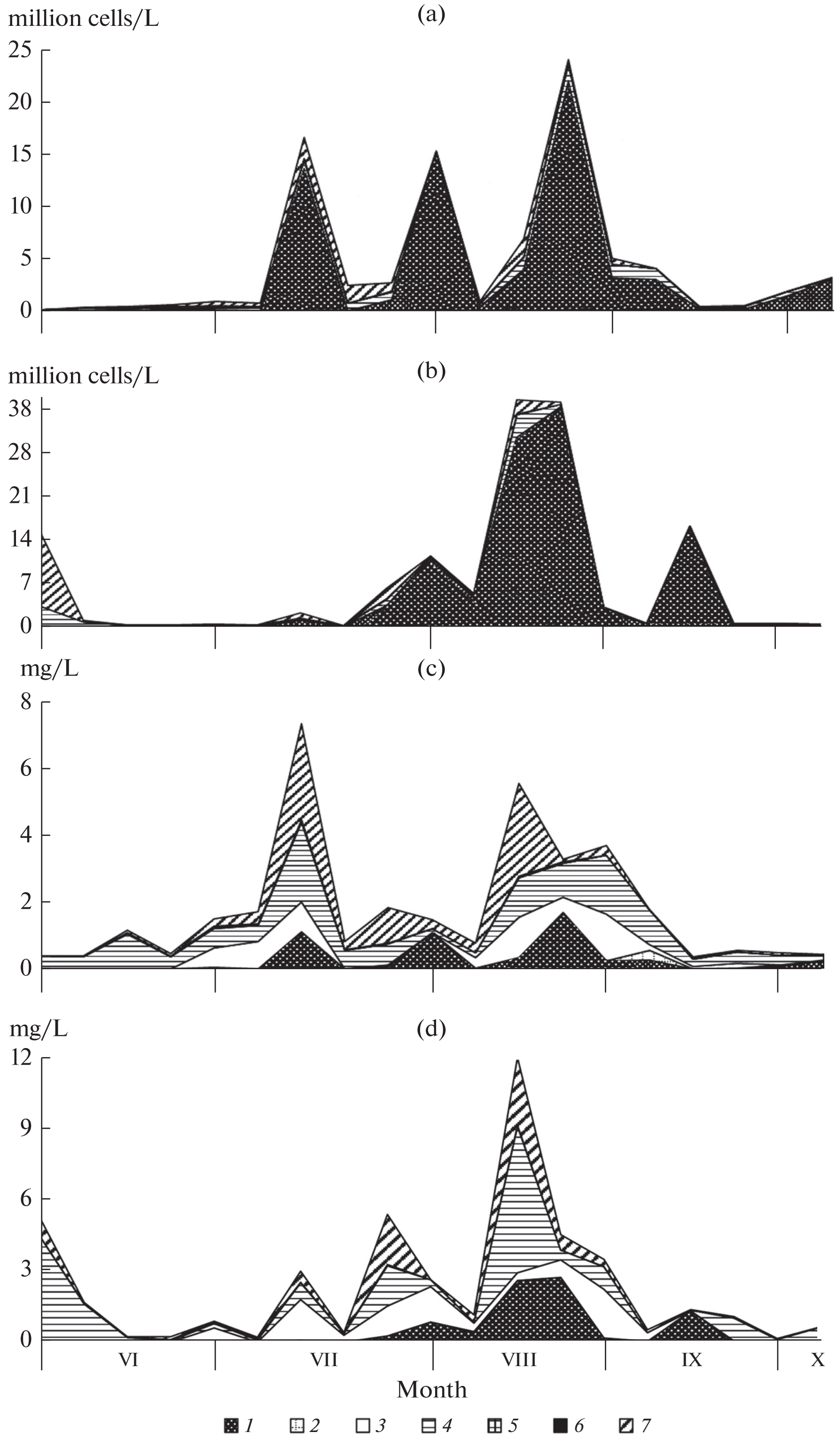

Fig. 3. Seasonal dynamics of abundance (a, b) and biomass (c, d) of phytoplankton in the Volga reach of the Kuibyshev Reservoir in 2017: (a, c) integrated samples and (b, d) surface samples. (*1*) Cyanobacteria, (*2*) euglenophytes, (*3*) Dinophytes, (*4*) diatoms, (*5*) cryptophytes, (*6*) golden algae, and (*7*) green algae.

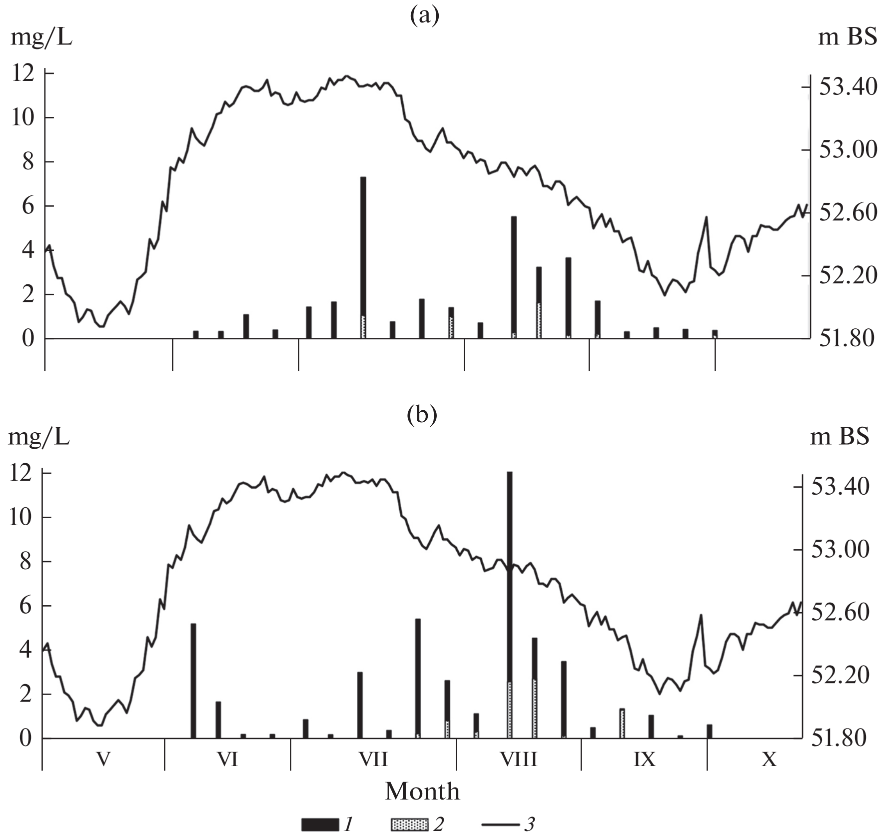

Fig. 4. Dynamics of biomass (mg/L) of phytoplankton depending on the water level (m) of the Volga reach of the Kuibyshev Reservoir in 2017: (a) integrated samples and (b) samples from the water surface. (*1*) Total biomass, mg/L; (*2*) biomass of cyanobacteria, mg/L; and (*3*) water level, mBS.

arcuatum (Korsch.) Hind., *Scenedesmus acuminatus* (Lagerh.) Chodat., *S. denticulatus* Lagerh., *S. discusformis* (Chodat.) Fott and Komarek, *S. quadricauda* (Turp.) Breb., *S. brasiliensis* Bohl., *Crucigeniella rectangularis* (Neg.) Komarek, *C. tetrapedia* (Kirch.) Kuntze, *Pediatric Duplex* Meyen, *Oocystis natans* Smith, and *Kirchneriella lunaris* (Kirhn.) Moeb. increased periodically.

Among other groups, cryptophytes *Cryptomonas ovata* Ehrenb. and *Cryptomonas* spp.; dinophyte algae of the genera *Peridinium*, *Gymnodinium*, and *Glenodinium*; species *Ceratium hirundinella* (Müll.) Dujard.; and euglenophytes *Euglena viridis* Ehrenb. and *Trachelomonas* spp. predominated.

Seasonal dynamics of the number and biomass of phytoplankton during the research period are presented in Figs. 3 and 4. During June and the first half of July, their content in the water was low and consisted mainly of centric diatoms and volvox green algae. At the very beginning of June, there were numerous small, colorless, heterophyllous, yellow-green, and cryptophyte algae that were difficult to identify, but their numbers had sharply decreased by the end of June. The weather was mostly rainy; the water level remained high and stable, close to 53.5 m, which did not contribute to the intensive reproduction of phytoplankton. By the end of the first 10 days of June, a period of clean water was established, caused by an outbreak of reproduction of zooplankton organisms, which could be seen in large quantities in water samples. Phytoplankton consisted of diatoms and isolated *Microcystis aeruginosa* colonies.

The highest numbers and biomass of phytoplankton were observed from the second half of July to September. The intensive reproduction of cyanobacteria *Microcystis aeruginosa* and *Aphanizomenon flos-aquae* began in mid-July, forming spots of blooming water.

In the middle of the second 10-day period of July, the water level in the reservoir began to drop quite sharply, and in a few days it fell from 53.5 to 52.8 m BS, while a strong current was observed in the river. Under the current circumstances, the processes of water blooming have intensified due to the development of *Aphanizomenon flos-aquae*; due to the accumulation of its colonies, the water turned into a green mush in shallow bays. During these days, a large number of dead fish could be seen floating along the shores. Also, in the water of the channel part, along with cyanobacteria, the content of flagellated volvox green algae sharply increased. Over the week, their numbers and biomass increased from 0.33 million cells/L and 0.36 mg/L to 2.01 million cells/L and 2.88 mg/L, respectively.

There were also many specimens of common polyrhizome *Spirodela polyrhiza* (L.) Schleid. on the surface of the water, as well as fragments of other higher plants, which is not at all typical for the open water area of the reservoir. The powerful thunderstorm with heavy rain that occurred on July 31 helped clear the water of cyanobacteria in the riverbed for a short time; however, this did not affect the nature of the bloom in the bays.

The hot weather and calm on the water that had set in by the beginning of August, as well as the steady decrease in the water level, again led to an extreme bloom of the water, dominated by *Microcystis aeruginosa*.

By mid-August, there was a short-term decline in the number and biomass of all phytoplankton groups, although the weather and hydrological conditions did not change and all the circumstances that developed continued to contribute to the blooming of the water. *Microcystis aeruginosa* colony clusters formed small spots on the surface, mostly located in the water column and at the bottom. The oxygen content in the water decreased several times compared to the previous week, while the BOD5 levels in the water column, on the contrary, increased four times. Mass fish deaths were observed on these days.

After a few days, the blooming processes resumed with even greater intensity, and by the beginning of the third 10 days of August, the number and biomass of cyanobacteria reached their maximum for the season. By this time, the dominant species had become *Aphanizomenon flos-aquae*. There were also many green flagellate algae *Chlamydomonas* spp., *Phacotus lenticularis*, *Pandorina morum*, and *Carteria* spp.; dinophyte genera *Peridinium*, *Gymnodinium*, *Glenodinium*, and *Ceratium*; euglena genera *Euglena* and *Trachelomonas*; and diatoms.

The heavy rainfall on August 29 and windy weather led to a decrease in the cyanobacteria *Aphanizomenon flos-aquae* bloom in the water that was present during this period. The content of diatoms and dinoflagellates in the water increased sharply (Fig. 3). However, later, with the establishment of windless weather and a steady rapid decrease in the water level by the end of the first 10 days of September, the processes of blooming caused by the mass reproduction of *Microcystis aeruginosa* and *Aphanizomenon flos-aquae* resumed. A significant quantity of euglena and green flagellate algae were also observed in the water.

By the end of September, the water level began to rise sharply, the reproduction processes of all types of planktonic algae began to decline, the water began to clear, transparency increased, and the blooming of the water stopped for some time. A few days later, the water level dropped sharply by almost half a meter and calm set in, which immediately led to the intensive reproduction of *Microcystis aeruginosa* and *Aphanizomenon flos-aquae*. There were also many euglena and volvox algae.

In the beginning of October, the water level in the reservoir began to rise and the content of algae in the water decreased, but a moderate amount of cyanobacteria in the water was observed until the end of October.

RESULTS AND DISCUSSION

In 2017, the seasonal dynamics of phytoplankton in the studied area of the Volga reach was characterized by two peaks in abundance and biomass—in the summer and summer–autumn periods. Cyanobacteria dominated in numbers, periodically causing water blooms, which were caused by the mass development of genera *Microcystis*, *Aphanizomenon*, and *Anabaena*. Moreover, representatives of these three genera are rarely found simultaneously. Centric diatoms, green volvox, and dinoflagellates dominated in terms of biomass. Also, the waters of the studied section of the Volga River are characterized by high concentrations of flagellate heterotrophic species of planktonic algae.

The Volga reach in the study area is extremely susceptible to water blooms caused by cyanobacteria. Although climatic conditions determine the intensity of water bloom processes, these phenomena depend not least on changes in hydrodynamic processes occurring in the reservoir water area. During the work, the main hydrochemical and hydrophysical indicators of the waters of the reach were analyzed (Figs. 5–7), and calculations of the Spearman correlation coefficient between the phytoplankton indicators and the hydrochemical and hydrophysical indicators of the water were carried out.

One of the most important factors influencing the structure of phytoplankton and water quality is the reservoir level regime (Datsenko et al., 2017). This is confirmed by the Spearman correlation coefficients. In particular, water transparency is negatively related to water level ($r = -0.7$), hydrogen index ($r = -0.8$), total hardness ($r = -0.8$), nitrate nitrogen ($r = -0.7$), and total phosphorus ($r = -0.7$) and positively related to suspended matter ($r = 0.7$) and hydrocarbonates ($r = 0.7$). The number and biomass of cyanobacteria also negatively correlate with the water level, especially in samples from the surface layer ($r = -0.5$), and euglena algae in integrated samples ($r = -0.6$). The increase in water level is not conducive to the intensive reproduction of these representatives of phytoplankton, which prefer low-flow water bodies with a high content of biogens.

The number of cryptophyte algae, on the contrary, increased with increasing water level ($r = 0.6$), at which transparency decreases. According to our observations, cryptophyte algae preferred lower tem-

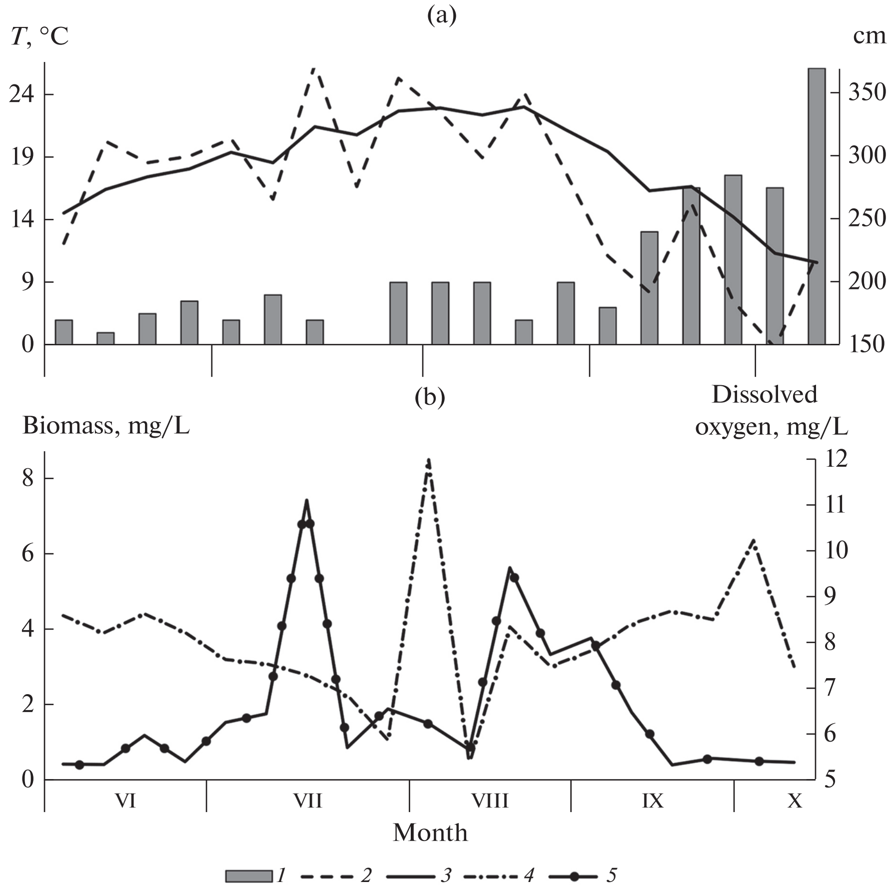

Fig. 5. Dynamics of the main hydrochemical and hydrophysical indicators of the Volga reach of the Kuibyshev Reservoir in 2017: (a) transparency (*1*), air temperature (*2*) and water temperature (*3*); (b) dissolved oxygen in water (*4*) and phytoplankton biomass (*5*) in integrated samples.

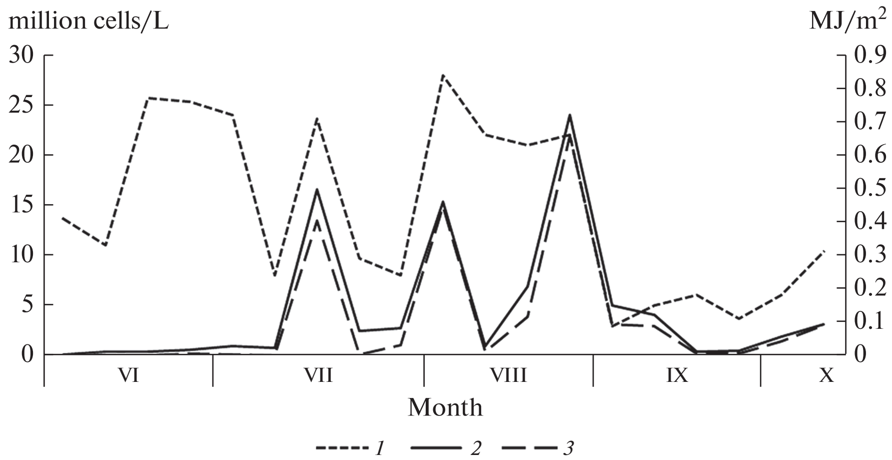

Fig. 6. Dynamics of total solar radiation (MJ/m^2) (*1*), the total number of phytoplankton (*2*), and the number of cyanobacteria (*3*) (million cells/L) in integrated samples of the Volga reach of the Kuibyshev Reservoir in 2017.

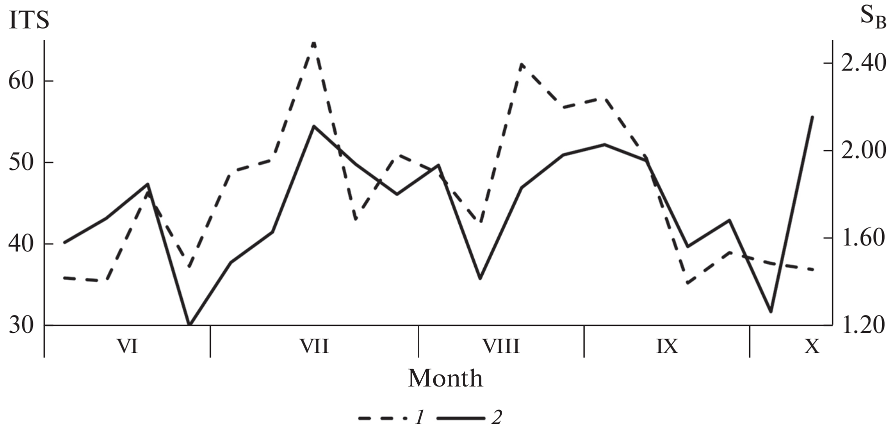

Fig. 7. Dynamics of the trophic index (TSI) (*1*) and saprobity index (S_B) (*2*) on the biomass of phytoplankton in integrated samples of the Volga reach of the Kuibyshev Reservoir.

peratures ($r = -0.5$) and increased content of hydrocarbonates in water ($r = 0.6$), the concentration of which increased with increasing water level. These organisms prefer waters with higher color and low transparency (Korneva, 2009). Compared to other algae, cryptophytes are also extremely sensitive to excess light and temperatures of >20°C (Belyakova et al., 2006; Wirth et al., 2019).

The main environmental factors that determine the growth and development of algae also include solar radiation, water temperature, and the concentration of biogenic elements (Algae, 1989; Mineeva et al., 2022). According to our data, warming of air and water had a particularly positive effect on the development of cyanobacteria ($r = 0.5$), dinophytes ($r = 0.8$), and green algae ($r = 0.8$). Quantitative indices of algae of all divisions were positively correlated with nitrite nitrogen ($r = 0.5$) and total phosphorus content ($r = 0.5$). With an increase in the biomass of cyanobacteria in water, the chemical oxygen demand increases ($r = 0.6$) and the hydrogen index increases ($r = 0.5$).

The dynamics of daily measurements of total solar radiation was analyzed (Fig. 6). The graph describing the dynamics of phytoplankton abundance generally follows that of solar radiation, but no statistically significant relationship (with $r < 0.05$) between the studied parameters was revealed. In nature, cause-and-effect relationships of this kind can be difficult to trace in such small samples with a wide variability as observations from one season (Vyruchalkina et al., 2016). The reaction of phytoplankton, like other aquatic organisms, to changing environmental conditions does not manifest itself immediately, but after a fairly long period of time (Korsak et al., 2009); it can be difficult to establish statistically reliable relationships between the studied parameters of this kind.

According to the results, the waters of the studied section of the Volga reach during most of the growing season corresponded to the mesosaprobic type and moderately polluted zone (Fig. 7). The trophic status of the waters, determined by the biomass of phytoplankton, water transparency, and total phosphorus content, mostly corresponded to the mesotrophic type and, during periods of maximum development of planktonic algae, it was often eutrophic.

CONCLUSIONS

During the period under study, the structural and quantitative indicators of phytoplankton, in general, correspond to the indicators obtained by other researchers in different years for the phytoplankton of the study area. The dominant complex of the phytoplankton of the Volga reach of the Kuibyshev Reservoir at the present stage consists of cyanobacteria, green volvox, centric diatoms, and dinoflagellates. This area is subject to extremely intense processes of water blooming due to the mass reproduction of cyanobacteria species *Microcystis*, *Aphanizomenon*, and *Anabaena*. The waters of the study area during most of the growing season correspond to the mesosaprobic type and moderately polluted zone.

Detailed studies of the seasonal dynamics of phytoplankton with short intervals (no more than a week) between sampling allowed us to determine with great certainty that the main influence on the development of planktonic algocenoses is exerted, first and foremost, by changes in the water level regime, weather conditions, and the nature of precipitation. Also, the factors determining the rate of development of a number of algae groups include air temperature, water temperature, and the content of dissolved substances in the water; the amount and distribution of dissolved substances largely depend, in turn, on the dynamics of the water level regime.

ABBREVIATIONS AND NOTATION

BS Baltic Height System

TSI	Trophic Index
S_B	saprobity index for phytoplankton biomass
W	Shapiro–Wilk criterion (when checking data for normal distribution)

ACKNOWLEDGEMENTS

We sincerely thank the staff of the Sredvolgavodkhoz hydrochemical laboratory (Kazan) for assistance in processing hydrochemical samples, as well as the staff of the meteorological observatory at Kazan Federal University for providing data.

FUNDING

This work was partially carried out using funds from the Strategic Academic Leadership Program of Kazan (Volga Region) Federal University (PRIORITY-2030).

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any human or animal studies.

CONFLICT OF INTEREST

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

REFERENCES

Belyakova, G.A., D'yakov, Yu.T., and Tarasov, K.L., *Botanika (Botany)*, Moscow: Akademiya, 2006, vol. 2.

Datsenko, Yu.S., *Evtrofirovanie vodokhranilishch: gidrologo-gidrokhimicheskie aspekty* (Eutrophication of Water Reservoirs. Hydrological and Hydrochemical Aspects), Moscow: GEOS, 2007.

Datsenko, Yu.S., Puklakov, V.V., and Edel'shtein, K.K., Analysis of the influence of abiotic factors on phytoplankton growth in a low-flow stratified storage reservoir, *Tr. Karel'sk. Nauch. Tsentra Ross. Akad. Nauk*, 2017, no. 10, p. 73.

Ekologiya fitoplanktona Kuibyshevskogo vodokhranilishcha (Ecology of Phytoplankton of the Kuibyshev Reservoir), Leningrad: Nauka, 1989.

Fitoplankton Nizhnei Volgi. Vodokhranilishcha i nizov'e reki (Phytoplankton of the Lower Volga. Reservoirs and Lower Reaches of the River), St. Petersburg: Nauka, 2003.

Freshwater Phytoplankton), Moscow: Univ. Shkola, 2003.

Gollerbakh, M.M., Kossinskaya, E.K., and Polyanskii, V.I., *Blue-green algae, Opredelitel' presnovodnykh vodoroslei SSSR (Key to Freshwater Algae of the USSR)*, Moscow: Sov. Nauka, 1953, vol. 2.

Isachenko, A.G., Bovykin, I.V., Rumyantsev, V.A., et al., *Teoreticheskie voprosy klassifikatsii ozer* (Theoretical Issues of Lake Classification), St. Petersburg: Nauka, 1993.

Khaliullina, L.Y. and Demina, G.V., Seasonal dynamics of phytoplankton communities residing in different types of shallow waters in the Kuibyshev Reservoir (Russia), *Int. Aquat. Res.,* 2015, vol. 7, no. 4, p. 315.

Khaliullina, L.Y. and Khaliullin, I.I., Features of the seasonal dynamics of phytoplankton in the Kama River (Kuibyshev Reservoir) in 2017, *Inland Water Biol.*, 2022, vol. 15, p. 760. https://doi.org/10.1134/S1995082922060086

Khaliullina, L.Yu. and Yakovlev, V.A., *Fitoplankton melkovodii v verkhov'yakh Kuibyshevskogo vodokhranilishcha* (Phytoplankton of Shallow Waters in the Upper Reaches of the Kuibyshev Reservoir), Kazan: Akad. Nauk RT, 2015.

Khamitova, M.F. and Kalaida, M.L., *Issledovanie izmenenii gidrobiologicheskikh kharakteristik v usloviyakh lokal'nykh zagryaznenii v regione Srednei Volgi* (Study of Changes in Hydrobiological Characteristics under Conditions of Local Pollution in the Middle Volga Region), LAP LAMBERT Academic, 2017.

Korneva, L.G., Formation of phytoplankton in the Volga basin under the influence of natural and anthropogenic factors, *Cand. Sci. (Biol.) Dissertation*, St. Petersburg, 2009.

Korneva, L.G., *Fitoplankton vodokhranilishch basseina Volgi* (Phytoplankton of Reservoirs of the Volga River Basin), Kostroma: Kostrom. Pechatn. Dom, 2015.

Korsak, M.N., Mosharov, S.A., Skorobogatov, A.M., et al., The influence of total solar radiation on the spring "bloom" of phytoplankton in the Uchinskoye reservoir, *Vestn. Mosk. Univ., Ser. 16: Biol.*, 2009, no. 1, p. 41.

Kuibyshevskoe vodokhranilishche (Nauchno-informatsionnyi spravochnik), Tolyatti: Inst. Ekol. Volzhsk. Basseina Ross. Akad. Nauk, 2008.

Kuz'mina, K.A. and Medyankina, M.V., About phytoplankton of the Volga reach of the Kuibyshev reservoir, *Samarskaya Luka*, 2019, vol. 28, no. 1, p. 18.

Metodika izucheniya biogeotsenozov vnutrennikh vodoemov (Methodology for Studying Biogeocenoses of Inland Water Bodies), Moscow: Nauka, 1975.

Mineeva, N.M., Poddubny, S.A., Stepanova, I.E., and Tsvetkov, A.I., Abiotic factors and their role in the development of phytoplankton in reservoirs of the Middle Volga, *Inland Water biol.*, 2022, no. 6, p. 640. https://doi.org/10.31857/S0320965222060158

Pautova, V.N. and Nomokonova, V.I., *Produktivnost' fitoplanktona Kuibyshevskogo vodokhranilishcha* (Phytoplankton Production in the Kuibyshev Reservoir), Tolyatti: Samar. Nauchn. Tsentr Ross. Akad. Nauk, 1994.

Rakhuba, A.V., Assessment of the Influence Exercised by the Hydrodynamic Regime on the Phytoplankton Development and the Water Quality of the Kuibyshev reservoir, *Uch. Zap. Kazan. Univ., Ser. Estestv. Nauki,* 2020, vol. 162, no. 3, p. 430.

Rakhuba, A.V., Modeling of water blooms in the Kuibyshev reservoir in years with different flow regulation regime, *Geogr. Vestn.,* 2023, vol. 2, no. 65, p. 92.

Sadchikov, A.P., *Metody izucheniya presnovodnogo fitoplanktona* (Methods for Studying Sladecek, V., System of water quality from the biological point of view, *Arch. Hydrobiol.,* 1973, vol 7.

Vodorosli. Spravochnik (Algae. Handbook), Kiev: Nauk. Dumka, 1989.

Vyruchalkina, T.Yu., Filatov, N.N., Dianskii, N.A., and Gusev, A.V., On forecasting long-term variations of water level of large lakes, *Tr. Karel'sk. Nauchn. Tsentra Ross. Akad. Nauk*, 2016, no. 9, p. 3.

Water bodies of the Republic of Tatarstan, in *Gidrograficheskii spravochnik (Hydrographic Handbook)*, Kazan: Idel-press, 2006, p. 35.

Weather conditions review in Kazan according to the Kazan University weather station, KFU Meteorological Observatory, 2018. https://kpfu.ru/ecology/struktura/otdelenie-ecologyafii-i-turizma/kafedra-meteorologii-klimatologii-i-ekologii/meteorologicheskaya-observatoriya/obzor-po-gody. Cited March 08, 2018.

Wirth, C. and Limberger, R., Temperature light interaction and tolerance of high water temperature in the planktonic freshwater flagellates Cryptomonas (Cryptophyceae) and Dinobryon (Chrysophyceae), *J. Phycol.*, 2019, vol. 55, no. 2, p. 404.

Publisher's Note. Pleiades Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
AI tools may have been used in the translation or editing of this article.

SPELL: OK