Трансформация экосистем
Ecosystem Transformation

ISSN 2619-0931 Online
www.ecosysttrans.com

DOI 10.23859/estr-220701
EDN TEDKZE
UDC 504.455+551.583+574.52

Article

Characteristic features of the dynamics of environmental parameters of the Saratov Reservoir in the beginning of the 21st century

Elena A. Shashulovskaya*, Svetlana A. Mosiyash

Saratov branch of the FSBSI "Russian Federal Research Institute of Fisheries and Oceanography", ul. Chernyshevskogo 152, Saratov, 410002 Russia

**shash.elena2010@yandex.ru*

Abstract. This study, conducted in the Saratov Reservoir in 2001–2020, investigates the dynamics of organic matter (OM), nutrients and phytoplankton under climate change conditions. A negative trend in the content of allochthonous OM and ammonium nitrogen is found. The reservoir water discharge, changes in phosphates and nitrates are associated with the dynamics of the North Atlantic Oscillation Index. A positive trend of iron concentrations in the reservoir is due to an increase in winter runoff caused by frequent winter thaws. The content of total and easily oxidized OM, as well as silicon is less associated with changes in hydrometeorological conditions. During the study period, the total biomass of phytoplankton and the biomass of green algae decreased, the proportion of cyanoprokaryotes increased, and the species composition of algae became simpler. The principal components method allowed us to identify the main factors combining the content of biogenic elements, the total biomass of phytoplankton and the main divisions of Bacillariophyta and Cyanoprokaryota, and the July water temperature.

Keywords: organic matter, biogenic elements, phytoplankton, climate change, North Atlantic Oscillation Index

Acknowledgements. The authors express their gratitude to their colleagues from the Saratov branch of the Russian Federal Research Institute of Fisheries and Oceanography, I.G. Filimonova, L.V. Grishina and E.G. Kuzina for their assistance in processing of hydrochemical material, and to all researchers and support staff who participated in sampling.

ORCID:
E.A. Shashulovskaya, https://orcid.org/0000-0003-1072-7046
S.A. Mosiyash, https://orcid.org/0000-0003-0875-6358

To cite this article: Shashulovskaya, E.A., Mosiyash, S.A., 2023. Characteristic features of the dynamics of environmental parameters of the Saratov Reservoir in the beginning of the 21st century. *Ecosystem Transformation* **6** (5), 11–28. https://doi.org/10.23859/estr-220701

Received: 01.07.2022
Accepted: 25.10.2022
Published online: 01.12.2023

DOI 10.23859/estr-220701
EDN TEDKZE
УДК 504.455+551.583+574.52

Научная статья

Особенности динамики экологических параметров Саратовского водохранилища в начале XXI века

Е.А. Шашуловская*, С.А. Мосияш

Саратовский филиал ФГБНУ «Всероссийский научно-исследовательский институт рыбного хозяйства и океанографии», 410002, Россия, г. Саратов, ул. Чернышевского, д. 152

**shash.elena2010@yandex.ru*

Аннотация. Показана динамика органического вещества (ОВ), биогенных элементов и фитопланктона Саратовского водохранилища в 2001–2020 гг. в условиях климатических изменений. Установлен отрицательный тренд содержания аллохтонного ОВ и аммонийного азота. Величина стока водохранилища, изменения фосфатов и нитратов были связаны с динамикой индекса североатлантического колебания. Положительный тренд концентрации железа в водохранилище обусловлен увеличением зимнего стока в результате частых зимних оттепелей. Содержание общего и легкоокисляемого ОВ, кремния в меньшей степени связано с изменением гидрометеорологических условий. За период исследования уменьшалась общая биомасса фитопланктона и биомасса зеленых водорослей, возрастала доля цианопрокариот, упрощалась видовая структура водорослей. Метод главных компонент позволил выделить главные факторы, объединяющие содержание биогенных элементов, общую биомассу фитопланктона и основных отделов Bacillariophyta и Cyanoprokaryota, июльскую температуру воды.

Ключевые слова: органическое вещество, биогенные элементы, фитопланктон, изменение климата, индекс североатлантического колебания

Благодарности. Авторы выражают благодарность коллегам Саратовского филиала ФГБНУ «ВНИРО» И.Г. Филимоновой, Л.В. Гришиной и Е.Г. Кузиной за помощь в обработке гидрохимического материала, а также всем сотрудникам, принимавшим участие в отборе проб.

ORCID:
Е.А. Шашуловская, https://orcid.org/0000-0003-1072-7046
С.А. Мосияш, https://orcid.org/0000-0003-0875-6358

Для цитирования: Шашуловская, Е.А., Мосияш, С.А., 2023. Особенности динамики экологических параметров Саратовского водохранилища в начале XXI века. *Трансформация экосистем* **6** (5), 11–28. https://doi.org/10.23859/estr-220701

Поступила в редакцию: 01.07.2022
Принята к печати: 25.10.2022
Опубликована онлайн: 01.12.2023

Introduction

Climatic changes, observed in recent decades, lead to a transformation of river and reservoir water flows, which ultimately hampers their water resource utilization and affects water quality. In most of Russia, in recent decades, there has been a tendency towards an increase in annual runoff, associated with a general increase in the country's territory wetness. However, in the basins of the Lower Volga, Dnieper and Don, on the contrary, a decrease in their annual runoff has been recorded, and low-water years have become more frequent (Cherenkova and Sidorova, 2021; Mnogoletnie kolebaniya..., 2021). For most rivers in the European part of Russia (ER), variations in their flow throughout the year have been reported: the proportion of the annual flow decreases during high-water and increases during low-water seasons (Cherenkova and Sidorova, 2021; Dmitrieva and Nefedova, 2018; Dzhamalov et al., 2015). Current changes in the thermal regime leads to frequent winter thaws, a decrease in soil freezing and a reduction in the duration of snow cover period. As a result, winter runoff of the rivers in ER increases and water storage in the snow cover decreases by early spring, which creates conditions for reduced spring flooding. A similar trend is also found for reservoirs, whose water flow is regulated, to a large extent, to suit the needs of different sectors of national economy.

In aquatic ecosystems, climate warming initiates a transformation of organic matter (OM) and nutrient flows, a decrease in transparency and dissolved oxygen content, an increase in mineralization, etc. (Linnik, 2020). Habitat change affects the structure of aquatic communities, trophic interactions between species and often leads to the intensification of eutrophication processes (Lazareva and Sokolova, 2013), indicated by changes in phytoplankton quantitative and structural characteristics.

Despite the general patterns of formation and development of organisms of different trophic levels, each particular reservoir has its specific features determined by the natural zone, terrain, degree of anthropogenic load, as well as the remoteness of the region from the main moisture-carrying streams. The above regional features of the catchment area are superimposed on changes in large-scale atmospheric circulation, which are quite clearly manifested in an increase in the rate of modern winter warming in northern Eurasia. The recorded anomalies in temperature and precipitation can lead to significant transformations of the heat and moisture supply regime in large regions and entail tangible environmental consequences (Popova et al., 2019).

Of the large-scale circulation systems, the North Atlantic Oscillation (NAO) is of the greatest interest for the climate of Russia. The essence of the NAO is the redistribution of atmospheric masses between the Arctic and the subtropical Atlantic. The alternation of positive and negative phases of NAO causes large changes in heat and moisture transfer, determines the temperature and intensity of water convective mixing, and the ice regime of European reservoirs (Lazareva and Sokolova, 2013; Nesterov, 2013). Over recent decades, the NAO has been studied as one of the possible sources of global warming (Malinin and Gordeeva, 2014). In this regard, some authors make an attempt to use statistical relationships with the NAO index to predict the direction of long-term changes in biotic characteristics of ecosystems (Kopylov et al., 2019; Lazareva and Sokolova, 2013; Mineeva, 2019).

Wolf numbers (W) (indicators of solar activity), along with the NAO, are markers of global processes associated with changes in weather and climatic conditions. Solar cycles regulate the distribution of phytoplankton biomass in seas and oceans through water circulation processes that change the light regime and nutrient availability (Mineeva, 2019).

The Volga basin, covering a significant territory of the ER, "integrates" the contribution of regional climatic parameters to the river flow variability. The Saratov Reservoir is the penultimate step in the huge Volga-Kama cascade. According to the hydrological regime, it is a river type reservoir with a high flow rate and coefficient of water exchange (18 times a year). The reservoir is mostly located in the forest-steppe zone (Gerasimova, 1996). Lateral inflow in the reservoir water balance averages 6%. The main flow regulator is the Kuibyshev Reservoir, which accumulates water during the spring flood and gradually releases the accumulated volumes during the low water period.

The aim of this work is to assess the dynamics of the main hydrochemical components determining the trophic level, and phytoplankton parameters in the Saratov Reservoir; to establish the relationship between their interannual fluctuations and the transformation of climatic factors in the early 21st century.

Materials and methods

Hydrochemical material was collected in 2001–2020 in the channel and coastal zones of the Saratov Reservoir at standard monitoring sections using a Ruttner bathometer (Fig. 1). Sampling was carried out during the growing season: in spring (May), summer (July – August) and autumn (October – November). Water samples in the channel zone were taken from the surface and near the bottom (0.5 m from the bottom) horizons, in the coastal area – only from the surface. Hydrochemical analysis included determination of organic matter content (color, permanganate (PO) and bichromate (BO) oxidizability, biochemical oxygen demand (BOD_5)) and biogenic elements (mineral forms of nitrogen and phosphorus, total iron, and silicon). Total mineral nitrogen was calculated as the sum of its mineral forms – ammonium ($N\text{-}NH_4$), nitrite ($N\text{-}NO_2$) and nitrate ($N\text{-}NO_3$). Generally accepted methods of titrimetric and photometric analyses were used (Rukovodstvo..., 1977). For comparison, we used data on the water chemical composition indicators measured at the Saratov Reservoir in 1969–1974, reported in the works by N.A. Gerasimova (1996) and S.G. Kotlyar (1978).

Phytoplankton samples were taken in 2001–2020 at permanent monitoring sections simultaneously with water samples collected for hydrochemical analysis (Fig. 1). Hydrobiological material was processed according to the unified methods (Dalechina and Dzhayani, 2014). The characteristics of phytoplankton in 1969–2020 were evaluated according to the works by N.A. Gerasimova (1996), I.N. Dalechina and E.A. Dzhayani (2012, 2014), and E.A. Shashulovskaya et al. (2021a).

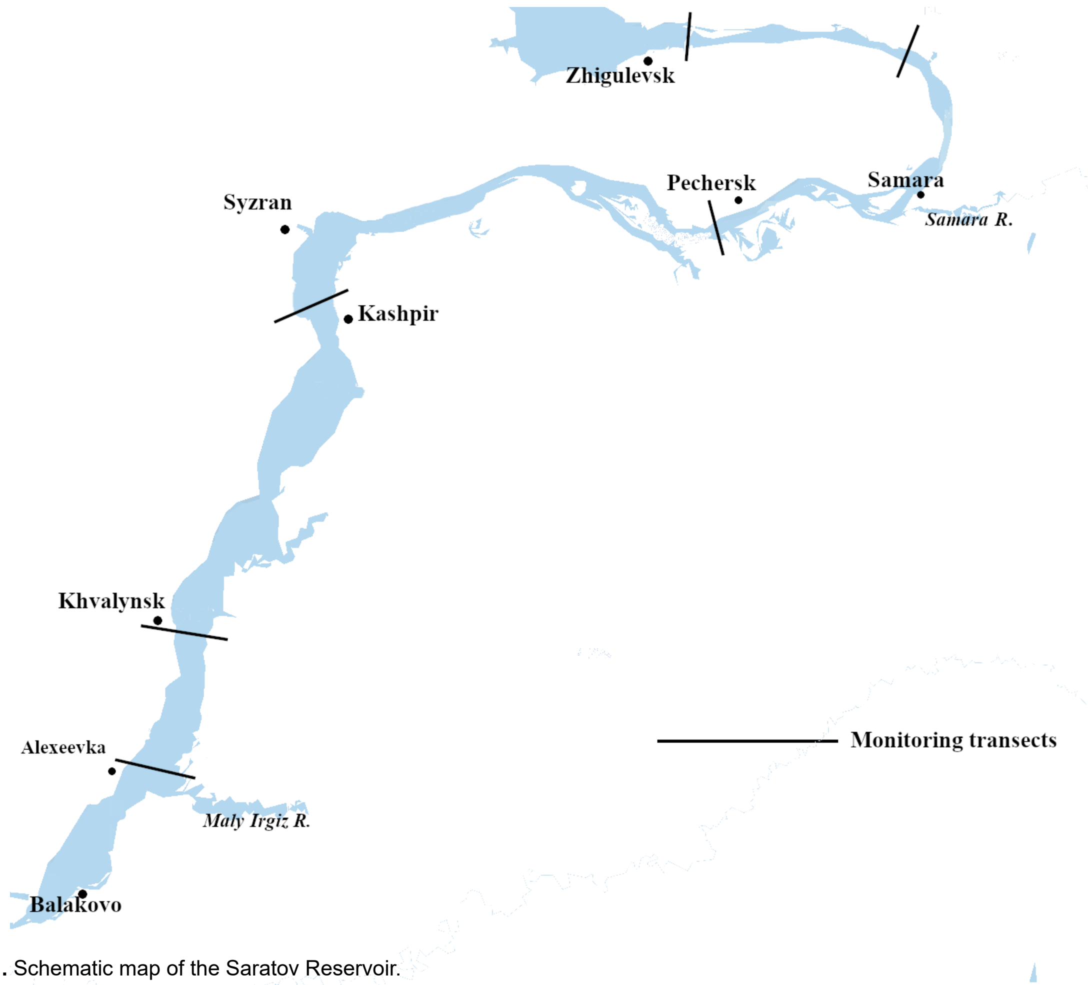

Fig. 1. Schematic map of the Saratov Reservoir.

The runoff volume was calculated according to the data of discharge through the Saratov hydroelectric plant, available on the website of PJSC «Rushydro»[1]. Transformed series of values of the NAO index and Wolf numbers were taken from websites of National Weather Service [2] and Space Weather Services[3]. Precipitation and air temperature data during the study period were obtained from the RIHMI WDC[4] resource and calculated as average values for sites located in the Middle Volga basin (the cities of Nizhny Novgorod and Kazan).

Statistical data were processed using the program of the Statgraphics Centurion XVI version 16.1.11 specialized software package. To analyze the results, the average concentrations of the parameters under study were used. The relationship between the parameters was determined using the Pearson correlation coefficient. The principal components analysis was used to structure a multidimensional array of initial hydrochemical parameters and phytoplankton biomass.

Results and discussion

Climatic and heliophysical features

The beginning of the 21st century is characterized by an increase in July water temperature in the Saratov Reservoir: since the 70s of the last century, it has increase by ~ 0.7 °C (Fig. 2**A**). Due to the high flow rate and geographical location of the Saratov Reservoir, its summer water temperatures were lower than in the Volgograd Reservoir (Shashulovskaya et al., 2021a). For example, the average July temperature during the study period was 2 °C lower and amounted to 20.8 °C. In the abnormally hot summer of 2010, the average water temperature in the Saratov Reservoir was 23.5 °C, while in the Rybinsk Reservoir it reached 24.5 °C (Kopylov et al., 2019), and 26.2 °C in the Volgograd Reservoir (Shashulovskaya et al., 2021a).

From 2001 to 2020, an increase in winter surface air temperatures was recorded in the Middle Volga region, especially noticeable starting from 2011 (Fig. 2**B**). This reflects the general trend of the early 21st century, characteristic of the larger territory of the ER (Cherenkova and Sidorova, 2021; Dzhamalov et al., 2015).

In 2001–2020, the annual runoff volume of the Saratov Reservoir varied from 195 to 299 km^3 (Table 1). The most high-water years were 2005, 2007 and 2017 (Table 1). In the first decade, a decrease in the runoff volume was recorded ($R^2 = 0.27$, $p = 0.12$), from 2011 to 2020 there was a tendency towards its increase ($R^2 = 0.29$, $p = 0.11$). Over the period from 2001 through 2020, intra-annual changes occurred: the winter discharge contribution to the total annual flow increased from 16 to 19%, and during the flood period, on the contrary, decreased by 5%.

The largest amount of precipitation fell in 2001, 2004, 2013, 2015, and the lowest – in 2008, 2018, 2020 (Table 1). During the study period, a slight decrease in the annual precipitation was recorded ($R^2 = 0.20$, $p = 0.05$). Due to regulation, the reservoir annual runoff and amount of precipitation are not related.

Markers of global processes affecting the hydrological, hydrophysical and biological characteristics of reservoirs are the NAO index and Wolf numbers (Kopylov et al., 2019; Lazareva and Sokolova, 2013; Mineeva, 2019).

The North Atlantic Oscillation Index is one of the most important characteristics of large-scale atmospheric circulation in the Northern Hemisphere. Over the current period of instrumental observations, two phases of the NAO index are distinguished in its inter-annual dynamics – positive and negative, for which significant trends with high coefficients of determination are found (Malinin and Gordeeva, 2014). In the period 2001–2010, there was a decrease in the annual NAO values ($R^2 = 0.34$, $p = 0.07$), which is a continuation of the NAO negative phase that began in 1993 (Malinin and Gordeeva, 2014). Since 2011, positive dynamics of the NAO index has been observed (Fig. 2**B**). The higher the values of this indicator, the more intense is the zonal transfer of air masses from the North Atlantic to the European

[1] Branch of PJSC "RusHydro" – Volzhskaya HPP. Web page. URL: http://www.volges.rushydro.ru (accessed: 16.11.2021).

[2] National Weather Service, Climate Prediction Center, USA. Web page. URL: https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml (accessed: 13.04.2022).

[3] Space Weather Services, Australian Space Weather Forecasting Centre, AUS. Web page. URL: https://www.sws.bom.gov.au/Solar/1/6 (accessed: 14.04.2022).

[4] All-Russian Research Institute of Hydrometeorological Information – World Data Center (RIHMI –WDC), RUS. Web page. URL: http://www.meteo.ru (accessed: 20.04.2022).

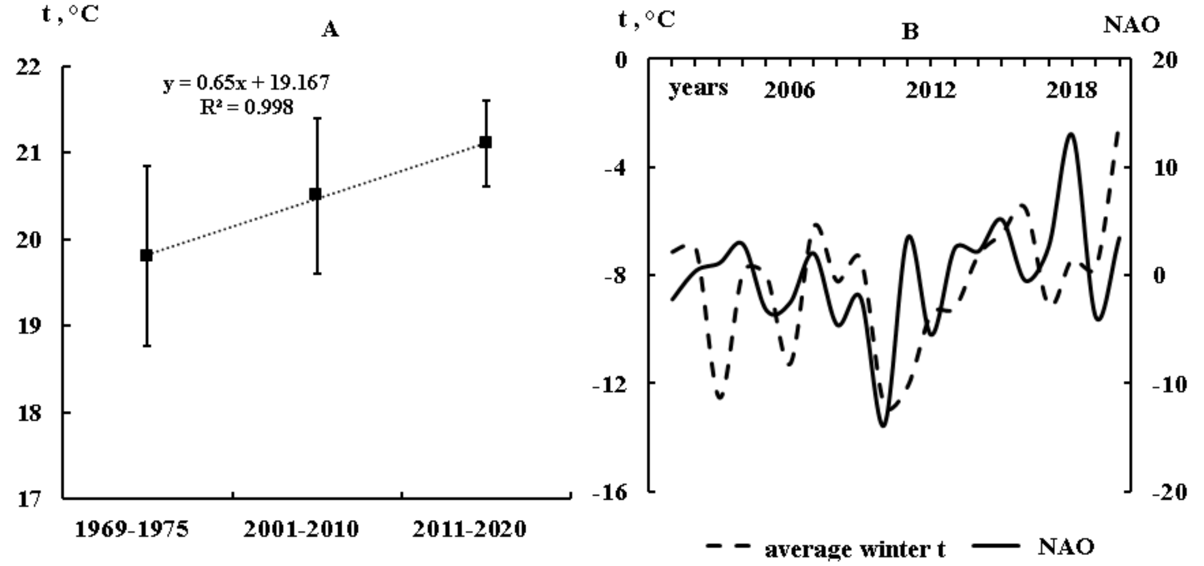

Fig. 2. Dynamics of the average July water temperature (95% confidence interval for the average) in 1969-2020 (**A**) and dynamics of the annual NAO index and winter air temperature in 2001-2020 (**B**).

Table 1. Hydroclimatic characteristics of the Saratov Reservoir in 2001–2020.

Year	T of July, °C	Precipitation, mm	Runoff volume, km³	NAO	W
2001	21.1	744	271	−2.19	170.2
2002	20.8	690	257	0.47	176.8
2003	19.5	650	242	1.17	109.0
2004	20.0	700	258	2.91	68.8
2005	19.9	635	283	−3.21	48.6
2006	20.0	679	209	−2.49	26.1
2007	20.0	662	286	2.08	12.7
2008	19.4	594	239	−4.54	4.6
2009	21.0	655	235	−2.02	4.9
2010	23.5	646	195	−13.83	25.4
2011	22.0	684	199	3.52	80.3
2012	21.7	659	242	−5.47	82.1
2013	20.9	707	273	2.52	96.9
2014	21.5	673	223	2.24	121.8
2015	19.5	709	197	5.20	70.5
2016	21.0	693	266	−0.46	36.9
2017	20.7	677	288	2.71	19.5
2018	21.4	589	272	13.00	6.6
2019	20.7	618	228	−3.82	3.6
2020	21.4	520	299	3.49	8.8

continent. Meanwhile, there is a significant increase in the amount of precipitation in the north and center of the ER. The alternation of positive and negative phases in the NAO frequency structure determines the thermal regime of reservoirs and the intensity of water mixing (Kopylov et al., 2019).

During the study period, two maximum (2001–2002 and 2011–2014) and two minimum (2008–2009 and 2018–2020) solar activity periods were observed in 11-year cycles, characterized by Wolf numbers (Table 1). A decrease in solar activity in 2001–2010 coincided with a decrease in the runoff volume of the reservoir and the NAO index to minimum values in 2010.

Organic matter

The quantitative content of organic matter is one of the most important factors determining the water quality of aquatic ecosystems, and, as a consequence, the conditions for aquatic life. Most of the OM enters the Saratov Reservoir from the Kuibyshev Reservoir located upstream. Allochthonous OM of humic nature is mainly characterized by water color and PO indices (Lozovik et al., 2017).

In 2011–2020, the water color in the Saratov Reservoir varied from 23 to 44degrees (Table 2). The average for the growing season values of this index changed synchronously with the reservoir runoff volume ($r = 0.84$, $p = 0.00$). The strongest correlation was noted between the water color and runoff volume in spring and, probably, in winter, by analogy with the Volgograd Reservoir (Shashulovskaya and Mosiyash, 2019). During heavy rain floods, increased values of the water color index were recorded in summer and autumn. In the first years of the reservoir operation, the water color varied almost within the same limits (15–42degrees) as it does now.

There is a significant correlation between water color and PO, since they characterize the same groups of OM. There is also a close relationship between the PO and the reservoir runoff values ($r = 0.70$, $p = 0.03$). During the period 2001–2010, a negative trend of changes in these indicators was observed (Fig. 3**A**). In 2011–2020, with increasing runoff volume, PO fluctuated in the same range (Fig. 3**B**). In spring, the water color and PO values are determined by humic substances delivered with flood terrigenous runoff. During the growing season, the processes of autochthonous OM formation contribute to the quantitative content of this group of substances.

With a decrease in the runoff volume during the NAO negative phase, the amount of allochthonous OM entering the reservoir decreases, and with an increase in the atmospheric circulation index, the reservoir runoff volume and the amount of OM of this group increase.

In the early 21st century, the bichromate oxidizability, which characterizes the content of the total organic matter, varied within a range of 21–45 mg/l and, on average, was somewhat lower than in the first years of the reservoir operation (Table 2). Fluctuations in this parameter are not associated with changes in runoff. In winter, the BO and PO values change synchronously (Shashulovskaya and Mosiyash, 2019). Probably, in winter, OM is mainly represented by humic and fulvic acids, which determine the color of water. In the growing season, with increasing abundance and biomass of planktonic organisms, the dynamics of organic matter in the reservoir is affected by bioproduction and mineralization processes. During this period, the nature of relationship between the indicators of the content of various groups of OM changes. Over the study period, no pronounced trends were found in the dynamics of the BO index in the water of the Saratov Reservoir.

Table 2. The content of organic matter in the water of the Saratov Reservoir in different periods of its operation. "–" – no data available; min–max – fluctuations range of indicator, M ± m – average value and its error.

Indicator	1969–1974		2001–2010		2011–2020	
	min–max	M ± m	min–max	M ± m	min–max	M ± m
Color, degree	15–42	25 ± 1	–	–	23–44	31 ± 2
PO, mgO/l	7.8–10.9	9.8 ± 0.3	6.3–10.5	8.8 ± 0.4	6.1–9.5	7.6 ± 0.3
BO, mgO/l	26–33	30 ± 1	21–45	28 ± 3	22–29	25 ± 1
BOD_5, mgO/l	1.1–1.8	1.3 ± 0.1	1.2–2.1	1.6 ± 0.1	1.1–2.5	1.6 ± 0.2
PO/BO, %	30–33	32 ± 1	30–37	33 ± 2	28–33	31 ± 2
BOD_5/BO, %	–	4.3 ± 0.4	–	5.8 ± 0.5	–	6.4 ± 0.7

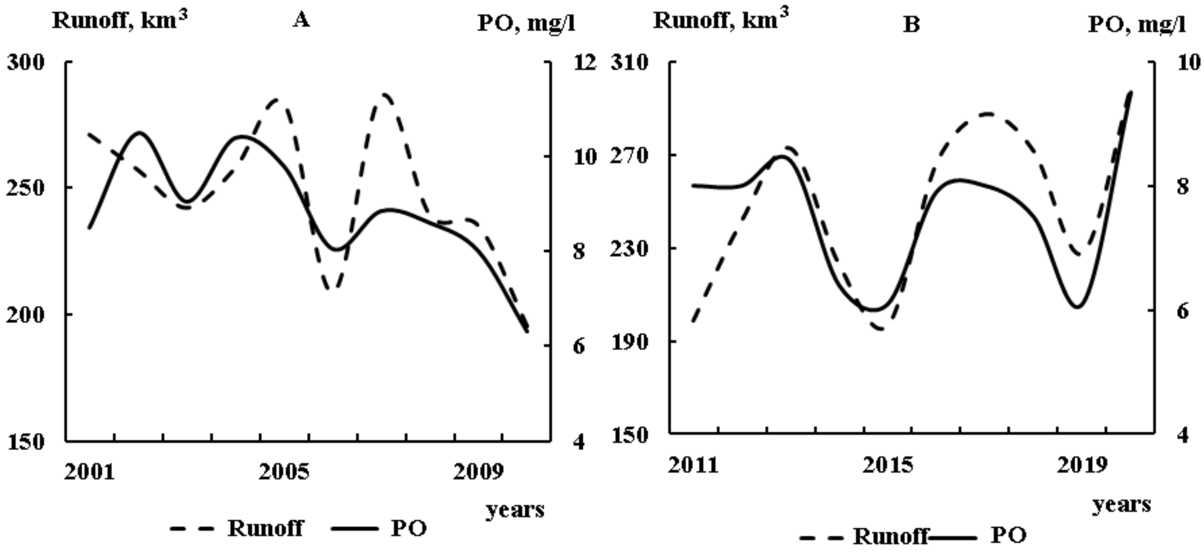

Fig. 3. Changes in the runoff volume and PO in 2001–2010 (**A**) and 2011–2020 (**B**).

The content of easily oxidizable OM during the study period varied from 1.1 to 2.5 mgO_2/l (Table 2). In 2001–2010, there was a decrease in the BOD_5 index but in the second decade of the 21st century it increased slightly with an increase in the fluctuation range of this indicator. The increased winter values of BOD_5 that we recorded in the Volgograd Reservoir (Shashulovskaya and Mosiyash, 2019) suggest that in the Saratov Reservoir, the catchment plays a significant role in the dynamics of this parameter, which makes it similar to allochthonous OM. However, during the study period, the BOD_5/BO ratio, which characterizes the proportion of labile OM, amounted to 5–6% showing a slight increase, compared to 1969–1974 (Table 2), obviously as a result of intensified bioproduction processes against the background of rising water temperatures.

Nutrients

In the early 21st century, the long-term dynamics of total mineral nitrogen – one of the two main biogenic elements affecting biological productivity – remained within a range of 0.41–2.32 mgN/l (Table 3). During the period of 2001–2020, there was a decrease in the content of all forms of mineral nitrogen, with the exception of nitrite nitrogen. The highest determination coefficients are characteristic of trend models of ammonium and total mineral nitrogen dynamics (R^2 = 0.62 and 0.37, respectively, at $p < 0.05$). Moreover, in the last decade the trend has been more clearly visible. A decrease in the content of ammonium nitrogen in the water of the Upper Volga Ivankovo Reservoir (Kirpichnikova et al., 2020), as well as in artificial water bodies of the Dnieper cascade (Zhezherya et al., 2021), in the beginning of the 21st century, has been reported. A possible reason for this phenomenon may be a decrease in the volume of spring inflow and a more active involvement of nitrogen in biogeochemical cycles with increasing temperature.

In 2001–2010, high coefficients of determination were found for ammonium nitrogen, nitrates, and, consequently, for the total mineral nitrogen (R^2 = 0.44–0.79 at $p < 0.05$) (Fig. 4**A**). During the period 2011–2020, there were no pronounced trends in the inter-annual changes in the ammonium content, and nitrate concentrations changed in accordance with the NAO index (Fig. 4**B**).

Nitrates are the dominant form of mineral nitrogen in the Saratov Reservoir. As a rule, their seasonal dynamics are well expressed and characterized by maximum concentrations in spring due to the presence of transformed winter waters and effects of terrigenous runoff with flood waters. In summer, the nitrate nitrogen concentrations decrease due to the consumption of this element by autotrophs for nutrition, and in autumn they increase as a result of mineralization processes (Shashulovskaya, 2022).

In the 70s of the last century and the first decade of the 21st century, the range of fluctuations and average values of ammonium and nitrates were close. However, in 2011–2020, the average concentration of ammonium, in contrast to nitrates, decreased by 2 times (Table 3).

Table. 3. The content of biogenic elements in the water of the Saratov Reservoir in different periods of its operation.

Biogenic elements	1969–1974		2001–2010		2011–2020	
	min–max	M ± m	min–max	M ± m	min–max	M ± m
N-NH_4, mg/l	0.14–0.72	0.36 ± 0.08	0.26–0.61	0.38 ± 0.04	0.09–0.27	0.19 ± 0.02
N-NO_2, µg/l	4–44	22 ± 6	5–22	12 ± 2	9–37	19 ± 4
N-NO_3, mg/l	0.29–0.86	0.48 ± 0.09	0.12–0.95	0.50 ± 0.08	0.16–0.64	0.40 ± 0.04
N mineral, mg/l	0.51–1.19	0.86 ± 0.11	0.41–2.32	0.98 ± 0.18	0.44–0.77	0.63 ± 0.04
Phosphorus mineral, µg/l	28–74	51 ± 9	37–75	54 ± 4	24–84	48 ± 6
Iron, mg/l	0.15–0.32	0.18 ± 0.03	0.07–0.22	0.15 ± 0.02	0.17–0.37	0.26 ± 0.02
Silicon, mg/l	1.5–3.4	2.3 ± 0.4	2.9–4.1	3.6 ± 0.5	2.9–3.8	3.3 ± 0.1

The nitrite nitrogen concentrations were low (6–25 µgN/l), but in some years (2011–2014 and 2019–2020) a significant increase in the amount of nitrite was recorded at some stations in the Saratov Reservoir, which may be associated with pollution .

In 2001–2020, the mineral phosphorus concentration ranged from 24–84 µg/L (Table 3). Changes in phosphorus content followed a cyclic pattern (Fig. 5**A**). During the period 2001–2011, a negative trend was observed in the average values of this parameter measured during the growing season, but an increase in the concentrations of mineral phosphorus were recorded in low-water years. In the first decade of the 21st century, a weak correlation with runoff was observed. Since 2012, maximum phosphorus concentrations have been recorded, as a rule, during high-water years. This indicates an increased role of hydrological factors in the genesis of this element. The seasonal dynamics of mineral phosphorus is characterized by an increase in concentrations of this element by autumn (Shashulovskaya, 2022), apparently due to internal nutrient load – hydrological, hydrophysical, chemical and biological intra-reservoir processes, closely related to the formation of anoxic zones in the bottom layers of the reservoir. In 2012–2020, the phosphate dynamics followed changes in the NAO (Fig. 5**A**). The range of fluctuations and average concentrations of phosphates in the early period of the reservoir operation and in recent decades are close (Table 3), which indicates the balance of intra-reservoir and hydrological factors in the genesis of this element in the reservoir ecosystem.

Over the growing season, the average concentrations of iron ranged from 0.07 to 0.37 mg/l (Table 3). During the study period, a significant positive trend in the content of this element was found ($R^2 = 0.77$, $p = 0.00$) (Fig. 5**B**). Maximum concentrations of iron were recorded in spring (Shashulovskaya, 2022), when a high correlation between this indicator and the water color was observed ($r = 0.85–0.88$, $p < 0.05$).

An increase in the number of thaws and liquid precipitation events in winter leads to increased volumes of water, rich in humic matter with a high content of natural iron, coming from the Upper Volga and Kama reservoirs (Shashulovskaya et al., 2021a). In recent decades, an increase in the concentration of this element has also been reported from other bodies of water located in wetland areas of the northern regions of the world, where a large amount of humic organic matter from drainage basin enters watercourses and water bodies. Thus, increased concentrations of iron have been recorded in many northern water bodies of Europe and America (Björnerås et al., 2017; Kalinkina et al., 2018).

The silicon content varied within narrow limits. At present, its average seasonal concentrations only slightly differ from the silicon content of water during the initial stage of the Saratov Reservoir operation (Table 3).

It is believed that when the NAO index is positive, winters become milder and the amount of precipitation increases. Negative phases of NAO, bring cooling and a decrease in precipitation (Kopylov et al., 2019). The period 2001–2010 is characterized by a decrease in precipitation and more severe winters (Fig. 2**B**). By 2010, the July water temperature increased to the maximum, and the NAO index and Wolf numbers decreased to their minimum values (Table 1). It should be noted that the most documented statistical relationship between the NAO and air temperature is most often observed in northwestern Europe (Kukushkin, 2020; Markovic et al., 2013; Ottersen et al., 2001). However, the relationship between the NAO and climate in different parts of Europe is unstable. In Austria, for example,

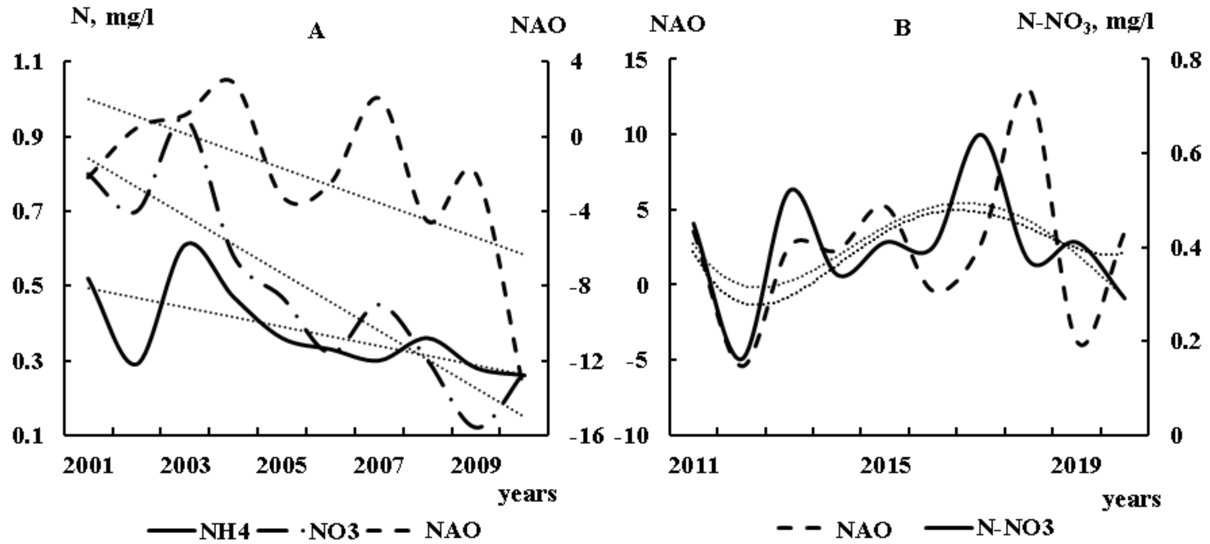

Fig. 4. Dynamics of mineral forms of nitrogen in the water of the Saratov Reservoir and the NAO index in 2001–2010 (**A**) and 2011–2020 (**B**). Dotted lines represent the main trends.

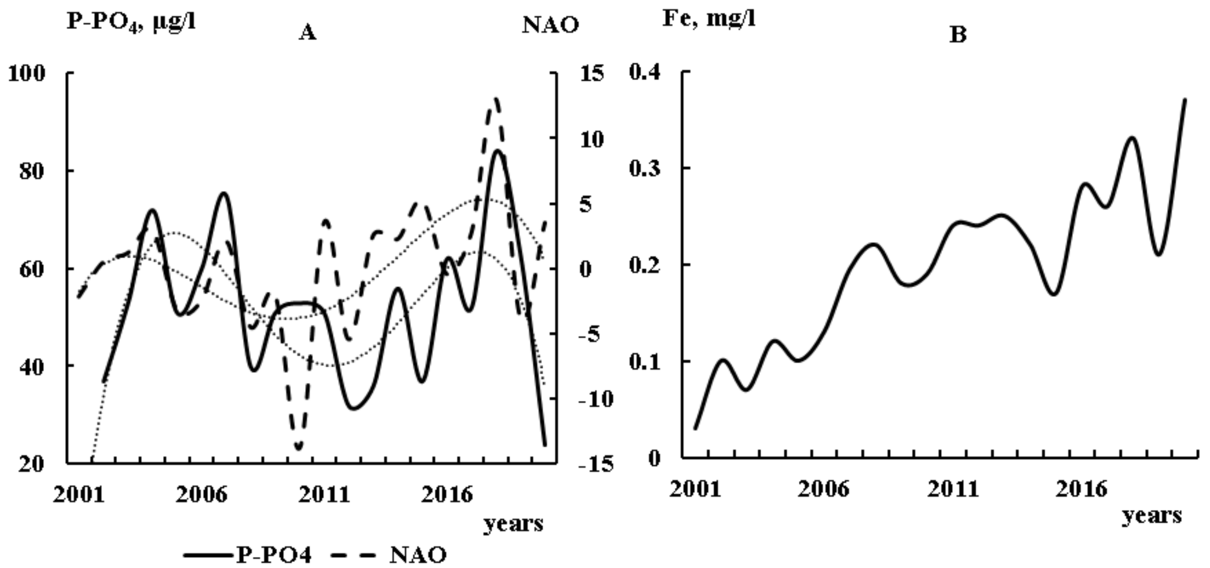

Fig. 5. Dynamics of phosphates, the NAO index (**A**) and total iron (**B**) in the water of the Saratov Reservoir in 2001–2020. Dotted lines represent polynomial trends.

the Danube water temperature was influenced by the NAO only during its positive phase (1981–1994). At lower latitudes (in Serbia), no relationship was found between water temperature in this river and NAO variability (Markovic et al., 2013). The study of large-scale environmental phenomena (NAO) and the underlying processes requires not only long-term data sets, but also an interdisciplinary approach (Báez et al., 2021; Ottersen et al., 2001).

Since 2011, according to the results of our studies, a weak trend of decreasing summer water temperature has been noted in the Saratov Reservoir. At the same time, the NAO index increases and a new 11-year cycle of solar activity begins. Such changes in global climatic factors, obviously, affected the strength of the relationship between the parameters under consideration. The water runoff volume increased, and the dynamics of nitrates and phosphates followed changes in the NAO index (Fig. 4**B**, Fig. 5**A**). The dynamics of total and easily oxidizable OM, as well as total iron and silicon were not associated with the fluctuations in the NAO index.

Phytoplankton

The microalgae community is one of the first to respond to changes in the hydrochemical and temperature regime. It is a criterion of the trophic state of the reservoir ecosystem. During the first years of the Saratov Reservoir operation (1969–1974), from 192 to 304 phytoplankton taxa below the rank of genus were found annually in the reservoir (Gerasimova, 1996). The largest number of species was recorded in the Bacillariophyta and Chlorophyta divisions. Biological summer was characterized by maximum values of phytoplankton abundance and biomass, the role of cyanoprokaryotes in plankton increased; more often they prevailed in number, less often in biomass. The greatest development was observed in intraspecific taxa from the genera *Microcystis, Anabaena* and *Oscillatoria*. In the summer of 1969–1974, the phytoplankton abundance varied from 0.71 to 10.36 million cells/l, the biomass – from 0.27 to 2.26 g/m^3 (Gerasimova, 1996).

Over the past two decades, the phytoplankton summer biomass has changed from 0.23 to 1.45 mg/dm^3, and negative trends in the biomass of Chlorophyta, Dinophyta, and Euglenophyta have been found (Shashulovskaya et al., 2021b). The phytoplankton species composition in the Saratov Reservoir has simplified to 112–182 taxa. During the summer period of 2000–2008, the average abundance of microalgae amounted to 5.6 million cells/l, the biomass – to 1.26 mg/l (Dalechina and Dzhayani, 2012). Species from the Cyanoprokaryota division were still most numerous accounting for 65–90% of the total abundance. Phytoplankton biomass was equally represented by Bacillariophyta, Cyanoprokaryota, Chlorophyta and Cryptophyta with the predominance of one or another division of algae in different years (Dalechina and Dzhayani, 2012).

At present, small-celled forms begin to make up a significant proportion of the phytoplankton abundance and biomass: of diatoms – species of the genera *Cyclotella*, *Stephanodiscus*, *Skeletonema subsalsum* (Cleve-Euler) Bethge, as well as *Nitzschia* sp., which was found in large quantities in colonies of cyanoprokaryotes *Microcystis aeruginosa* Kutz.; and of cryptophytes – *Chroomonas acuta* Uterm. (Dalechina and Dzhayani, 2014). Over the past two decades, an increase in the abundance of cryptophyte algae and small-celled species has also been recorded in other reservoirs of the Volga Cascade (Korneva et al., 2021).

During the first decade of the 21st century, summer biomass was formed by representatives of the divisions Bacillariophyta, Cryptophyta and Chlorophyta, and since 2010, Cyanoprokaryota has also become part of the dominant biomass groups (Fig. 6). Since 2003, there has been a significant long-term trend towards increasing biomass of cyanoprokaryotes ($R^2 = 0.80$, $p = 0.00$) (Dalechina and Dzhayani, 2014). An increase in the abundance and diversity of cyanoprokaryotes and their biomass alignment along the longitudinal axis of the Volga-Kama cascade from the Upper to the Lower Volga has also been reported by other researchers (Korneva et al., 2021).

During the study period, the ratio of the main systematic groups of phytoplankton in the Saratov Reservoir changed. If in 1969–1974 diatoms predominated, accounting for 60% of the biomass, then in 2003–2013 their percentage decreased to 20–30%. Amounting to 22% of the total biomass during the early period of the reservoir operation, the biomass of Cyanoprokaryota has increased up to 30% in recent decades (Fig. 6). In the 70s of the last century, other groups of phytoplankton (cryptophytes, dinophytes, euglenophytes) accounted for 9%, but currently their proportion has increased to an average of 40%.

Water temperature, along with the nutrient availability, is one of the main abiotic factors determining the level of phytoplankton development in water bodies. Evidently, global atmospheric processes and the level of solar activity, characterized by the NAO index and Wolf numbers, cannot but influence the development of phytoplankton. Some authors find a positive correlation between annual NAO values and primary phytoplankton production (Kopylov et al., 2019; Ottersen et al., 2001), as well as total chlorophyll concentrations (Mineeva, 2021). There is also a strong statistical relationship between the total chlorophyll, chlorophyll of diatoms and cyanoprokaryotes and Wolf numbers (Mineeva, 2021).

Multiple correlation analysis revealed no relationship between phytoplankton biomass and summer water temperature, annual NAO index, Wolf numbers and the hydrochemical parameters under consideration. Direct comparisons of water temperature and phytoplankton biomass, carried out over a long period in the Mozhaisk Reservoir, also showed a weak correlation between these parameters, which, according to the authors, is explained by complex patterns of internal water exchange and circulation of layers in the water column (Datsenko and Edelstein, 2021). Mineeva and co-authors (2021) point

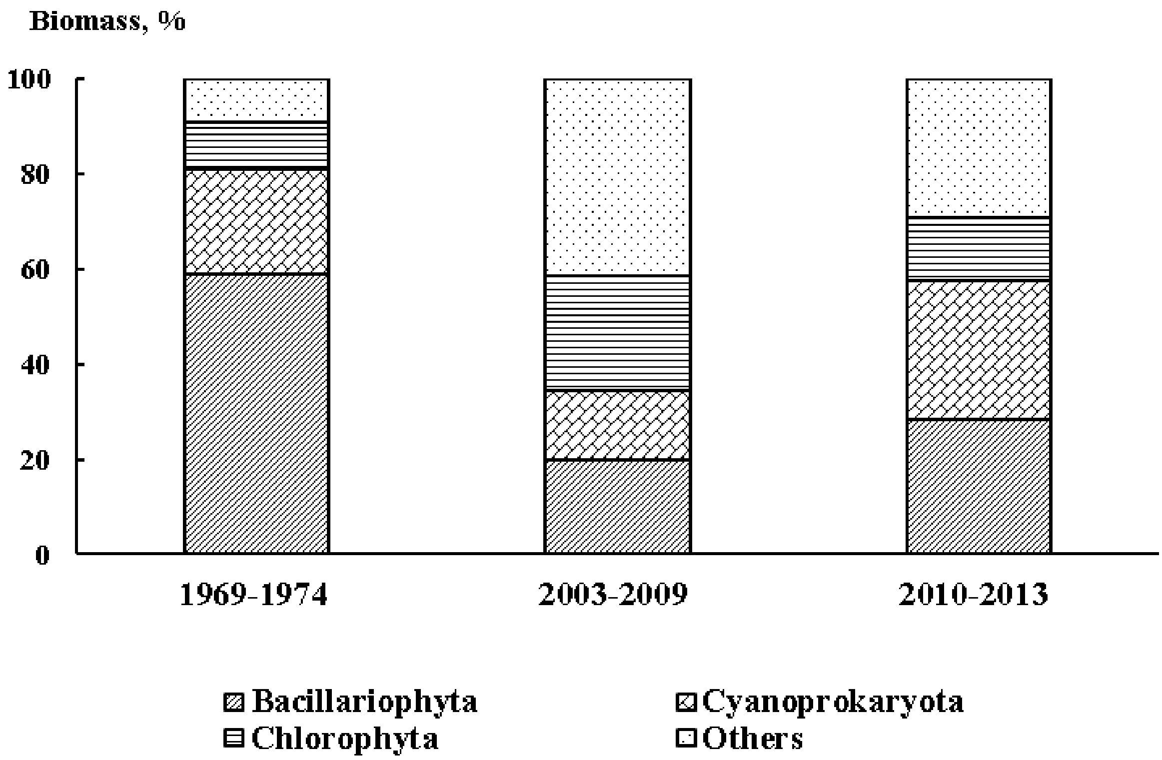

Fig. 6. The ratio of biomass of the main systematic groups of phytoplankton in the Saratov Reservoir in different periods of 1969–2013 (data for 1969–1974 are given according to Gerasimova, 1996; for 2003–2009 and 2010–2013 – according to Dalechina and Dzhayani, 2014).

out the absence of a close statistical relationship between phytoplankton biomass and nutrients, due to complex multifactorial effects on algal communities.

The use of the principal component analysis made it possible to identify four leading factors accounted for 82% of the total variance and combine the nutrient content, total biomass of phytoplankton and its main divisions (Bacillariophyta and Cyanoprokaryota). The total phytoplankton biomass, total mineral nitrogen and silicon are closely related to the first principal component. The second component integrates the iron content and the annual runoff volume, the third – mineral phosphorus and the N/P ratio. The fourth major factor is associated with the biomass of Bacillariophyta and Cyanoprokaryota and the July water temperature (Shashulovskaya et al., 2021b).

Conclusion

Thus, in the first two decades of the 21st century, the following features characterized the dynamics of environmental parameters of the Saratov Reservoir: negative trends in the content of allochthonous organic matter and ammonium nitrogen, a significant increase in the iron concentration, a decrease in the total biomass of phytoplankton and green algae, an increase in the proportion of cyanoprokaryotes, and simplification of the algal species composition.

This study allowed us to identify priority factors affecting the dynamics of the main hydrochemical components in the Saratov Reservoir in 2001–2020. The observed negative trend in the content of allochthonous OM and ammonium nitrogen is apparently caused by a decrease in the annual precipitation in the catchment area. Changes in phosphate and nitrate concentrations are, to a certain extent, associated with the NAO index dynamics. The positive trend in iron concentrations is likely due to an increased in winter runoff caused by increased temperatures during the cold season.

The principal component analysis made it possible to identify the main factors combining the nutrient content, the total biomass of phytoplankton and its main divisions Bacillariophyta and Cyanoprokaryota, and July water temperature. Obviously, a further increase in water temperature as a result of climate change will be a stimulating factor for the development of cyanoprokaryotes in the Saratov Reservoir.

References

Báez, J.C., Gimeno, L., Real, R., 2021. North Atlantic Oscillation and fisheries management during global climate change. *Reviews in Fish Biology and Fisheries* **31**, 319–336. https://doi.org/10.1007/s11160-021-09645-z

Björnerås, C., Weyhenmeyer, G.A., Evans, C.D., Gessner, M.O., Grossart, H.-P. et al., 2017. Widespread increases in iron concentration in European and North American freshwaters. *Global Biogeochemical Cycles* **31**, 1488–1500. https://doi.org/10.1002/2017GB005749

Cherenkova, E.A., Sidorova, M.V., 2021. On the impact of insufficient atmospheric moistening on the low annual discharge of large rivers in European Russia. *Water Resources* **48** (3), 351–360. https://doi.org/10.1134/S0097807821030064

Datsenko, Yu.S., Edelstein, K.K., 2021. Vliyanie temperatury vody na razvitie fitoplanktona v vodohranilishchah [Effect of water temperature on the development of phytoplankton in reservoirs]. *Tezisy dokladov Vserossiyskoi konferentsii, posvyashchennoi 65-letiyu IBVV RAN "Biologiya vodnykh ekosistem v XXI veke: fakty, gipotezy, tendentsii" [Collection of Abstracts of the All-Russian Conference Dedicated to the 65th Anniversary of the Institute for Biology of Inland Waters, Russian Academy of Sciences "Biology of Aquatic Ecosystems in the 21st Century: Facts, Hypotheses, Trends"*]. Yaroslavl, Russia, 57. (In Russian).

Dalechina, I.N., Dzhayani, E.A., 2012. Fitoplankton Saratovskogo vodohranilishcha v 2000–200 gg. [Phytoplankton of the Saratov Reservoir in 2000–2008]. *Materialy dokladov Vserossiiskoi konferentsii "Bassein Volgi v XXI veke: struktura i funktsionirovanie ekosistem vodokhranilishch" [Materials of reports of the All-Russian conference "The Volga basin in the 21st century: the structure and functioning of reservoir ecosystems"]*. Borok, Russia, 57–58. (In Russian).

Dalechina, I.N., Dzhayani, E.A., 2014. Dinamika vidovogo sostava i kolichestvennyh pokazatelej fitoplanktona v vodohranilishchah Nizhnej Volgi za 2003–2013 gg. [Dynamics of species composition and quantitative indicators of phytoplankton in the reservoirs of the Lower Volga for 2003–2013]. *Materialy mezhdunarodnoi nauchnoi konferentsii, posvyashchennoi 100-letiyu GosNIORH "Rybohozyajstvennye vodoemy Rossii: fundamentalnye i prikladnye issledovaniya" [Materials of the international scientific conference dedicated to the 100th anniversary of State Research Institute of Lake and River Fisheries "Fishery reservoirs of Russia: fundamental and applied research]*. St. Petersburg, Russia, 287–291. (In Russian).

Dmitrieva, V.A., Nefedova, E.G., 2018. Gidrologicheskaya reaktsiya na menyayushchiesya klimaticheskie usloviya i antropogennuyu deyatel'nost' v basseine Verkhnego Dona [Hydrological response to changing climatic conditions and anthropogenic activity in the Upper Don basin]. *Voprosy geografii [Questions of Geography]* **145**, 285–297. (In Russian).

Dzhamalov, R.G., Frolova, N.L., Telegina, E.A., 2015. Winter runoff variation in European Russia. *Water Resources* **42** (6), 758–765. http://www.doi.org/10.1134/S0097807815060032

Gerasimova, N.A., 1996. Fitoplankton Saratovskogo i Volgogradskogo vodohranilishch [Phytoplankton of the Saratov and Volgograd reservoirs]. Institute of Ecology of the Volga River Basin RAS, Tolyatti, 198 p. (In Russian).

Kalinkina, N.M., Filatov, N.N., Tekanova, E.V., Balaganskij, A.F., 2018. Mnogoletnyaya dinamika stoka zheleza i fosfora v Onezhskoe ozero s vodami r. Shuya v usloviyakh klimaticheskikh izmenenii [Long-term dynamics of iron and phosphorus runoff into Lake Onega with waters of the river Shuya in the conditions of climate change]. *Regional'naya ekologiya [Regional Ecology]* **2**, 65–73. (In Russian).

Kirpichnikova, N.V., Lapina, E.E., Kudryashova, V.V., 2020. Long-term dynamics of nitrogen and phosphorus concentration in subsoil water in Ivankovo reservoir drainage basin. *Water Resources* **47** (5), 721–730. http://www.doi.org/10.1134/S0097807820050103

Kopylov, A.I., Maslennikova, T.S., Kosolapov, D.B., 2019. Seasonal and year-to-year variations of phytoplankton primary production in the Rybinsk Reservoir: the effect of weather and climate variations. *Water Resources* **46** (3), 395–402. http://www.doi.org/10.1134/S0097807819030114

Korneva, L.G., Solovyeva, V.V., Mitropolskaya, I.V., Makarova, O.S., Sidelev, S.I., 2021. Mnogoletnyaya dinamika i raspredelenie fitoplanktona krupnykh ravninnykh vodohranilishch Evropeiskoi chasti RF [Long-term dynamics and distribution of phytoplankton in large lowland reservoirs of the European part of the Russian Federation]. *Tezisy dokladov Vserossiyskoi konferentsii, posvyashchennoi 65-letiyu IBVV RAN "Biologiya vodnykh ekosistem v XXI veke: fakty, gipotezy, tendentsii" [Collection of Abstracts of the All-Russian Conference Dedicated to the 65th Anniversary of the Institute for Biology of Inland Waters, Russian Academy of Sciences "Biology of Aquatic Ecosystems in the 21st Century: Facts, Hypotheses, Trends"*]. Yaroslavl, Russia, 102. (In Russian).

Kotlyar, S.G., 1978. Vliyanie zagryazneniya na gidrokhimicheskiy rezhim Saratovskogo vodohranilishcha [Influence of pollution on the hydrochemical regime of the Saratov reservoir]. *Trudy Saratovskogo otdeleniya GosNIORH [Proceedings of the Saratov branch of State Research Institute of Lake and River Fisheries]* **16**, 26–38. (In Russian).

Kukushkin, A.S., 2020. Effects of large-scale atmospheric oscillations on hydrometeorological conditions in the Danube River Basin in winter. *Russian Meteorology and Hydrology* **45**, 630–638. https://doi.org/10.3103/S1068373920090046

Lazareva, V.I., Sokolova, E.A., 2013. Dinamika i fenologiya zooplanktona krupnogo ravninnogo vodohranilishcha: otklik na izmenenie klimata [Dynamics and phenology of zooplankton in a large lowland reservoir: response to climate change]. *Uspekhi sovremennoi biologii [Advances in Modern Biology]* **133** (6), 564–574. (In Russian).

Linnik, P.M., 2020. Klimatichni zmini yak vazhlivij chinnik formuvaniya himichnogo skladu poverhnevih vod u suchasnih umovah (oglyad) [Climatic changes as an important factor in the formation of the chemical composition of surface waters in modern conditions (review)]. *Gidrobiologichnii zhurnal [Hydrobiological Journal]* **56** (5), 87–106. (In Ukrainian).

Lozovik, P.A., Zobkova, M.V., Ryzhakov, A.V., Zobkov, M.B., Efremova, T.A., Sabylina, A.V., Efremova, T.V., 2017. Allokhtonnoe i avtokhtonnoe organicheskoe veshchestvo prirodnykh vod: kineticheskie i termodinamicheskie zakonomernosti transformatsii, kolichestvennyi i kachestvennyi sostavy [Allochthonous and autochthonous organic matter of natural waters: kinetic and thermodynamic patterns of transformation, quantitative and qualitative compositions]. *Doklady akademii nauk [Reports of the Academy of Sciences]* **477** (6), 728–732. (In Russian).

Malinin, V.N., Gordeeva, S.M., 2014. Severoatlanticheskoe kolebanie i uvlazhnenie Evropeiskoi territorii Rossii [North Atlantic Oscillation and humidification of European Russia]. *Obshchestvo. Sreda. Razvitie [Society. Environment. Development]* **31** (2), 191–198. (In Russian).

Markovic, D., Scharfenberger, U., Schmutz, S., Voltaire, C., 2013. Variability and alterations of water temperatures across the Elbe and Danube River Basins. *Climatic Change* **119**, 375–389. https://doi.org/10.1007/s10584-013-0725-4

Mineeva, N.M., 2019. Content of photosynthetic pigments in the Upper Volga reservoirs (2005–2016). *Inland Water Biology* **2**–**1**, 161–169. https://doi.org/10.1134/S199508291902010X

Mineeva, N.M., 2021. Long-term dynamics of photosynthetic pigments in plankton of a large plains reservoir. *Biosystems Diversity* **29** (1), 10–16. https://doi.org/10.15421/012102

Mineeva, N.M., Stepanova, I.E., Semadeni, I.V, 2021. Biogenic elements and their significance in the development of phytoplankton in reservoirs of the Upper Volga. *Inland Water Biology* **14** (1), 32–42. https://doi.org/10.1134/S1995082921010089

Mnogoletnie kolebaniya i izmenchivost vodnykh resursov i osnovnykh kharakteristik stoka rek Rossiiskoi Federatsii: nauchno-prikladnoi spravochnik [Long-term fluctuations and variability of water resources and the main characteristics of the flow of rivers in the Russian Federation: scientific and applied handbook], 2021. Georgievsky, V.Yu. (ed.). RIAL, St. Petersburg, Russia, 190 p. (In Russian).

Nesterov, E.S., 2013. Severoatlanticheskoe kolebanie: atmosfera i okean [North Atlantic Oscillation: Atmosphere and Ocean]. Triada, Moscow, Russia, 144 p. (In Russian).

Ottersen, G., Planque, B., Belgrano, A., Post, E., Reid, Ph.C. Stenseth, N.C., 2001. Ecological effects of the North Atlantic Oscillation. *Oecologia* **128**, 1–14. https://doi.org/10.1007/s004420100655

Popova, V.V., Babina, E.D., Georgiadi, A.G., 2019. Klimaticheskie faktory izmenchivosti stoka Volgi vo vtoroi polovine XX – nachale XXI vv. [Climatic factors of Volga runoff variability in the second half of the 20th – early 21st centuries] *Izvestiya RAN. Seriya geograficheskaya [Bulletin of the Russian Academy of Sciences. Geographic Series]* **4**, 63–72. (In Russian).

Rukovodstvo po khimicheskomu analizu poverhnostnykh vod sushi [Guide to chemical analysis of terrestrial surface waters], 1977. Semenov, A.D. (ed.). Gidrometeoizdat, Leningrad, USSR, 542 p. (In Russian).

Shashulovskaya, E.A., 2022. O neobkhodimosti regional'noi reglamentatsii organicheskogo veshchestva i biogennykh elementov v nizhnevolzhskikh vodokhranilishchah [On the need for regional regulation of organic matter and biogenic elements in the Lower Volga reservoirs]. *Vodnoe hozyajstvo Rossii: problemy, tekhnologii, upravlenie [Water management in Russia: problems, technologies, management]* **1**, 25–38. (In Russian). https://doi.org/10.35567/19994508_2022_1_2

Shashulovskaya, E.A., Mosiyash, S.A., 2019. Gidrokhimicheskii rezhim Volgogradskogo vodokhranilishcha v podlednyi (zimnii) period [Hydrochemical regime of the Volgograd reservoir in the ice (winter) period]. *Sbornik statei mezhdunarodnoi nauchno-prakticheskoi konferentsii "Ekologicheskaya, promyshlennaya i energeticheskaya bezopasnost' – 2019" [Collection of articles of the international scientific and practical conference "Environmental, industrial and energy security – 2019"].* Sevastopol, Russia, 1768–1772. (In Russian).

Shashulovskaya, E.A., Mosiyash, S.A., Dalechina, I.N., 2021a. Long-term changes in the main indicators of the trophic state of the large plain reservoir under the influence of climatic transformation and successional processes. *Inland Water Biology* **14** (6), 627–637. https://doi.org/10.1134/S1995082921060110

Shashulovskaya, E.A., Mosiyash, S.A., Dzhayani, E.A., 2021b. Biogennye elementy i fitoplankton Saratovskogo vodokhranilishcha v sovremennykh usloviyakh [Nutrients and phytoplankton of the Saratov reservoir in modern conditions]. *Tezisy dokladov Vserossiyskoi konferentsii, posvyashchennoi 65-letiyu IBVV RAN "Biologiya vodnykh ekosistem v XXI veke: fakty, gipotezy, tendentsii" [Collection of Abstracts of the All-Russian Conference Dedicated to the 65th Anniversary of the Institute for Biology of Inland Waters, Russian Academy of Sciences "Biology of Aquatic Ecosystems in the 21st Century: Facts, Hypotheses, Trends"*]. Yaroslavl, Russia, 198. (In Russian).

Zhezherya, V.A., Zhezherya, T.P., Linnik, P.M., 2021. Biogenni rechovini u vodi vodoskhovishch Dniprovs'kogo kaskadu pislya zaregulyuvannya stoku Dnipra [Biogenic rivers near the water of the Dnieper cascade reservoirs after regulation of the Dnieper runoff]. *Gidrobiologichnii zhurnal [Hydrobiological Journal]* **6,** 89–109. (In Ukrainian).Báez, J.C., Gimeno, L., Real, R., 2021. North Atlantic Oscillation and fisheries management during global climate change. *Reviews in Fish Biology and Fisheries* **31**, 319–336. https://doi.org/10.1007/s11160-021-09645-z

Список литературы

Герасимова, Н.А., 1996. Фитопланктон Саратовского и Волгоградского водохранилищ. ИЭВБ РАН, Тольятти, Россия, 198 с.

Далечина, И.Н., Джаяни, Е.А., 2012. Фитопланктон Саратовского водохранилища в 2000–2008 гг. *Материалы докладов Всероссийской конференции «Бассейн Волги в XXI веке: структура и функционирование экосистем водохранилищ».* Борок, Россия, 57–58.

Далечина, И.Н., Джаяни, Е.А., 2014. Динамика видового состава и количественных показателей фитопланктона в водохранилищах Нижней Волги за 2003–2013 гг. *Материалы международной научной конференции, посвященной 100-летию ГосНИОРХ «Рыбохозяйственные водоемы России: фундаментальные и прикладные исследования».* Санкт-Петербург, Россия, 287–291.

Даценко, Ю.С., Эдельштейн, К.К., 2021. Влияние температуры воды на развитие фитопланктона в водохранилищах. *Тезисы докладов Всероссийской конференции, посвященной 65-летию ИБВВ имени И.Д. Папанина РАН «Биология водных экосистем в XXI веке: факты, гипотезы, тенденции»*. Ярославль, Россия, 57.

Джамалов, Р.Г., Фролова, Н.Л., Телегина, Е.А., 2015. Изменение зимнего стока рек Европейской части России. *Водные ресурсы* **15** (6), 581–588. http://www.doi.org/10.7868/S0321059615060036

Дмитриева, В.А., Нефедова, Е.Г., 2018. Гидрологическая реакция на меняющиеся климатические условия и антропогенную деятельность в бассейне Верхнего Дона. *Вопросы географии* **145,** 285–297.

Жежеря, В.А., Жежеря, Т.П., Линник, П.М., 2021. Біогенні речовини у воді водосховищ Дніпровського каскаду після зарегулювання стоку Дніпра. *Гідробіологічний журнал* **6**, 89–109.

Калинкина, Н.М., Филатов, Н.Н., Теканова, Е.В., Балаганский, А.Ф., 2018. Многолетняя динамика стока железа и фосфора в Онежское озеро с водами р. Шуя в условиях климатических изменений. *Региональная экология* **2,** 65–73.

Кирпичникова, Н.В., Лапина, Е.Е., Кудряшова, В.В., 2020. Многолетняя динамика содержания азота и фосфора в грунтовых водах водосбора Иваньковского водохранилища. *Водные ресурсы* **47** (5), 536–545. http://www.doi.org/10.31857/S0321059620050107

Копылов, А.И., Масленникова, Т.С., Косолапов, Д.Б., 2019. Сезонные и межгодовые колебания первичной продукции фитопланктона в Рыбинском водохранилище: влияние погодных и климатических изменений. *Водные ресурсы* **46** (3), 270–277. http://www.doi.org/10.31857/S0321-0596463270-277

Корнева, Л.Г., Соловьева, В.В., Митропольская, И.В., Макарова, О.С., Сиделев, С.И., 2021. Многолетняя динамика и распределение фитопланктона крупных равнинных водохранилищ Европейской части РФ. *Тезисы докладов Всероссийской конференции, посвященной 65-летию ИБВВ имени И.Д. Папанина РАН «Биология водных экосистем в XXI веке: факты, гипотезы, тенденции»*.Ярославль, Россия, 102.

Котляр, С.Г., 1978. Влияние загрязнения на гидрохимический режим Саратовского водохранилища. *Труды Саратовского отделения ГосНИОРХ* **16**, 26–38.

Лазарева, В.И., Соколова, Е.А., 2013. Динамика и фенология зоопланктона крупного равнинного водохранилища: отклик на изменение климата. *Успехи современной биологии* **133** (6), 564–574.

Линник, П.М., 2020. Кліматични зміни як важливий чинник формування хімічного складу поверхневих вод у сучасних умовах (огляд). *Гідробіологічний журнал* **56** (5), 87–106.

Лозовик, П.А., Зобкова, М.В., Рыжаков, А.В., Зобков, М.Б., Ефремова, Т.А., Сабылина, А.В., Ефремова, Т.В., 2017. Аллохтонное и автохтонное органическое вещество природных вод: кинетические и термодинамические закономерности трансформации, количественный и качественный составы. *Доклады академии наук* **477** (6), 728–732.

Малинин, В.Н., Гордеева, С.М., 2014. Североатлантическое колебание и увлажнение Европейской территории России. *Общество. Среда. Развитие* **31** (2), 191–198.

Минеева, Н.М., 2019. Содержание фотосинтетических пигментов в водохранилищах Верхней Волги (2005–2016 гг.). *Биология внутренних вод* **2-1,** 33–41. http://www.doi.org/10.1134/S0320965219020104

Минеева, Н.М., Степанова, И.Э., Семадени, И.В, 2021. Биогенные элементы и их роль в развитии фитопланктона водохранилищ Верхней Волги. *Биология внутренних вод* **1,** 21–34. http://www.doi.org/10.31857/S0320965221010095

Многолетние колебания и изменчивость водных ресурсов и основных характеристик стока рек Российской Федерации: научно-прикладной справочник, 2021. Георгиевский, В.Ю. (ред.). РИАЛ, Санкт-Петербург, Россия, 190 с.

Нестеров, Е.С., 2013. Североатлантическое колебание: атмосфера и океан. Триада, Москва, Россия, 144 с.

Попова, В.В., Бабина, Е.Д., Георгиади, А.Г., 2019. Климатические факторы изменчивости стока Волги во второй половине XX – начале XXI вв. *Известия РАН. Серия географическая* **4**, 63–72.

Руководство по химическому анализу поверхностных вод суши, 1977. Семенов, А.Д. (ред.). Гидрометеоиздат, Ленинград, СССР, 542 с.

Черенкова, Е.А., Сидорова, М.В., 2021. Оценка современных условий недостаточного увлажнения, влияющих на маловодность в бассейнах крупных рек Европейской части России. *Водные ресурсы* **48** (3), 260–269. http://www.doi.org/10.31857/S0321059621030068

Шашуловская, Е.А., 2022. О необходимости региональной регламентации органического вещества и биогенных элементов в нижневолжских водохранилищах. *Водное хозяйство России: проблемы, технологии, управление* **1,** 25–38. http://www.doi.org/10.35567/19994508_2022_1_2

Шашуловская, Е.А., Мосияш, С.А., 2019. Гидрохимический режим Волгоградского водохранилища в подледный (зимний) период. *Сборник статей международной научно-практической конференции «Экологическая, промышленная и энергетическая безопасность – 2019».* Севастополь, Россия, 1768–1772.

Шашуловская, Е.А., Мосияш, С.А., Джаяни, Е.А., 2021. Биогенные элементы и фитопланктон Саратовского водохранилища в современных условиях. *Тезисы докладов Всероссийской конференции, посвященной 65-летию ИБВВ имени И.Д. Папанина РАН «Биология водных экосистем в XXI веке: факты, гипотезы, тенденции»*. Ярославль, Россия, 198.

Báez, J.C., Gimeno, L., Real, R., 2021. North Atlantic Oscillation and fisheries management during global climate change. *Reviews in Fish Biology and Fisheries* **31**, 319–336. https://doi.org/10.1007/s11160-021-09645-z

Björnerås, C., Weyhenmeyer, G.A., Evans, C.D., Gessner, M.O., Grossart, H.-P. et al., 2017. Widespread increases in iron concentration in European and North American freshwaters. *Global Biogeochemical Cycles* **31**, 1488–1500. https://doi.org/10.1002/2017GB005749

Kukushkin, A.S., 2020. Effects of large-scale atmospheric oscillations on hydrometeorological conditions in the Danube River Basin in winter. *Russian Meteorology and Hydrology* **45**, 630–638. https://doi.org/10.3103/S1068373920090046

Markovic, D., Scharfenberger, U., Schmutz, S., Voltaire, C., 2013. Variability and alterations of water temperatures across the Elbe and Danube River Basins. *Climatic Change* **119**, 375–389. https://doi.org/10.1007/s10584-013-0725-4

Mineeva, N.M., 2021. Long-term dynamics of photosynthetic pigments in plankton of a large plains reservoir. *Biosystems Diversity* **29** (1), 10–16. https://doi.org/10.15421/012102

Ottersen, G., Planque, B., Belgrano, A., Post, E., Reid, Ph.C. Stenseth, N.C., 2001. Ecological effects of the North Atlantic Oscillation. *Oecologia* **128**, 1–14. https://doi.org/10.1007/s004420100655

Shashulovskaya, E.A., Mosiyash, S.A., Dalechina, I.N., 2021. Long-term changes in the main indicators of the trophic state of the large plain reservoir under the influence of climatic transformation and successional processes. *Inland Water Biology* **14** (6), 627–637. https://doi.org/10.1134/S1995082921060110