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PHYTOPLANKTON, PHYTOBENTHOS, AND PHYTOPERIPHYTON

Chlorophyll Content and Factors Affecting Its Spatial Distribution in the Middle Volga Reservoirs

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Abstract—On the basis of the data obtained during field observations in the summer low water period of 2001, the patterns of chlorophyll distribution and its relation to hydrological and hydrochemical factors in two eutrophic reservoirs of the Middle Volga are studied. The hydrological structure of the Gorky Reservoir, where the Volga water mass dominates, is homogeneous, while in the Cheboksary Reservoir along with the eutrophic Volga waters, the mesotrophic Oka water masses can be distinguished keeping their abiotic and biotic features over a long distance. Phytoplankton in the two contiguous reservoirs with different flow regimens and anthropogenic loads responds differently to the external influence. An autotrophic community in the Gorky Reservoir is more stable and depends little on abiotic factors which account for ~63% of the explained chlorophyll variation. In the Cheboksary Reservoir under maximal for the Volga cascade flow velocity and anthropogenic load, the development and distribution of phytoplankton are almost completely ($R^2 = 0.93$) controlled by these factors. The trophic state of the reservoirs has not changed as compared to the beginning of the 1990s.

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INTRODUCTION

Algae are the main producers of organic matter in large lakes and reservoirs and the complex approach to the problem of the aquatic ecosystem state assessment requires the study of an autotrophic link. Among indices of abundance and functioning of phytoplankton, the priority position is held by photosynthetic pigments. The content of chlorophyll (Chl) *a* as the main pigment of green plants is considered to be a universal ecologic functional characteristic for assessment of abundance and temporal and spatial algae dynamics as well as the trophic state of a waterbody and the water quality.

Different water masses are formed in reservoirs—large artificial waterbodies [4]. Their properties affect phytoplankton development and distribution. Having influence on light and gas regimen and water pH, the phytoplankton, in turn, is of great importance in an ecosystem for environmental conditions formation. The study of the relationship between biotic and abiotic factors is necessary for assessment of the state of aquatic ecosystems, a consideration of the problem of biological productivity formation and changes in the trophic state of waterbodies.

The purpose of this study is to elicit and analyze possible relations of chlorophyll content to parameters identifying different water masses in large manmade lakes with Gorky and Cheboksary reservoirs serving as reference waterbodies. The data collected in a broadened network of stations characterize patterns of phytoplankton spatial distribution and are supplementing the observations of the previous years [13–15] providing a basis for long-term monitoring of the ecosystem in reservoirs.

MATERIALS AND METHODS

The material was collected on 31 stations in the Gorky Reservoir and 16 stations of the Cheboksary Reservoir from July 31 to August 14, 2001. Most stations listed in Table 1 are located along the transsection: the right bank–the center (the Volga riverbed)–the left (Gorky Reservoir) or near the right and left banks (Cheboksary Reservoir). The coordinates of stations were determined using GPS 12 XL.

Samples were collected from surface to bottom using a 1-m long bathometer. The pigments were determined by the spectrophotometric method [17, 19]. The routine methods [2, 3, 5] were used to determine abiotic parameters (water temperature, transparency, color, electroconductivity, pH, content of suspended matter (SM), dissolved oxygen and biogenic elements, and flow velocity). Statistical data processing was made using standard PC programs. Variability of characteristics was estimated using the coefficient of variation (C_v). Its

Table 1. Chlorophyll content at stations in Gorky and Cheboksary reservoirs in August 2001

Section	Coordinates		Chlorophyll, μg/l			
	N	E	right bank	riverbed	left bank	mean
			Gorky Reservoir			
tail water of Rybinsk hydroelectric power station	58°02′	38°57′	–	12.7 (1)	–	–
downstream the town of Rybinsk			–	5.9 (2)	–	–
upstream the city of Yaroslavl	57°41′	39°51′	12.4	11.6 (3)	14.4	12.8
downstream the city of Yaroslavl	57°33′	39°59′	–	10.3 (4)	13.0	11.7
opposite settlement of Krasnyi Profintern	57°45′	40°28′	16.4	16.7 (5)	28.0	20.4
upstream the city of Kostroma	57°46′	40°53′	13.9	20.6 (6)	18.8	17.8
downstream the city of Kostroma	57°44′	40°58′	12.9	11.9 (7)	15.6	13.5
downstream the town of Ples	57°28′	41°32′	23.2	7.6 (8)	15.4	15.4
upstream the city of Kineshma	57°29′	42°05′	6.3	8.9 (9)	14.8	10.0
downstream the city of Kineshma	57°27′	42°17′	10.5	8.6 (10)	10.8	10.0
downstream the town of Yur'evets	57°17′	43°07′	12.0 (11)	–	19.5 (12)	15.7
upstream head water of Gorky hydroelectric power station	56°43′	43°18′	9.7 (15)	10.1 (14)	16.5 (13)	12.1
			Cheboksary reservoir			
tail water of Gorky hydroelectric power station	56°37′	43°28′	–	9.5 (1)	–	–
downstream the settlement of Balakhna	56°28′	43°38′	–	4.2 (2)	–	–
Sormovo industrial center	56°21′	43°57′	–	34.0 (3)	–	–
outlet of treatment plants of the city of Nizhniy Novgorod	56°17′	44°08′	72.4 (4)	–	27.4 (5)	49.9
downstream the town of Kstovo	56°10′	44°16′	41.7 (6)	–	24.5 (7)	33.1
downstream the village of Bezvodnoe	56°09′	44°23′	31.0 (8)	–	22.5 (9)	26.7
downstream the settlement of Vasilsursk	56°08′	46°01′	6.2 (10)	–	6.2 (11)	6.2
downstream the town of Kozmodem'yansk	56°21′	46°38′	5.8 (12)	–	5.8 (13)	5.8
downstream the settlement of Il'inka	56°09′	47°15′		7.8 (14)	–	–
head water of Cheboksary hydroelectric power station	56°11′	46°51′	–	6.1 (15)	–	–
tail water of Cheboksary hydroelectric power station	56°07′	47°35′	–	5.8 (16)	–	–

Note: In brackets, numbers of stations on dendrograms, see Figure.

values (<0.3, 0.3–0.7, and >0.7) reflected low, moderate, and high variability, respectively. The correlation analysis was used to demonstrate a degree of the relationship between characteristics. In the Gorky Reservoir, the content of total nitrogen and total phosphorous was determined on 15 stations located in the Volga riverbed (Table 1). The obtained data were used in the cluster analysis.

Clustering of stations was made according to chlorophyll content and totality of abiotic parameters.

Gorky and Cheborsary reservoirs occupying an internal part in the cascade according to the classification of A.B. Avakyan and coworkers [1] belong to "very large" (surface area 1591 and 1270 km^2, reservoir capacity 8.70 and 12.60 km^3, respectively) and rather "shallow" (average depths of 3–6 m) manmade lakes. Water masses in the Gorky Reservoir are mainly formed by the Volga water inflowing from Rybinsk Reservoir located upstream and, only in its lower part, they are transformed being affected by tributaries. In the Cheboksary Reservoir at a long distance downstream the Oka River inflow, more mineralized Oka water masses not being mixed with water from the Volga River are observed close to the right bank [9]. The trophic states of both reservoirs are classified as eutrophic. Of all the Volga reservoirs, the Cheboksary Reservoir is subjected to the highest anthropogenic load [10].

RESULTS

During the study period conducted at the height of summer hydrological and hydrochemical water periods, the characteristics in Gorky and Rybinsk reservoirs had differed significantly (Table 2). Water temperature was higher in the Gorky Reservoir. Water transparency increased in stations located near the river

Table 2. Abiotic characteristics of the water column in Gorky and Cheboksary reservoirs in August 2001

Characteristic	Reservoirs			
	Gorky		Cheboksary	
	Range	Mean	Range	Mean
Water temperature, °C	19.7–21.9	20.7 ± 0.1 (3.4)	19.9–24.0	22.1 ± 0.3 (5.0)
Transparency, cm	100–170	137 ± 4 (14.7)	65–170	113 ± 7 (26.8)
Color, deg	40–55	47 ± 1 (13.0)	30–60	42 ± 2 (19.0)
Electroconductivity, μS/cm	184–198	190 ± 1 (2.3)	195–502	298 ± 23 (31.3)
SM, mg/l	3.2–11.3	6.2 ± 0.5 (39.8)	3.0–18.3	7.6 ± 0.9 (49.5)
pH	7.8–8.2	8.0 ± 0.02 (1.6)	7.6–8.4	8.0 ± 0.05 (2.5)
Dissolved O_2, mg/l	7.2–10.8	8.9 ± 0.2 (11.6)	6.3–9.2	7.5 ± 0.2 (9.4)
N_{total}, μg/l	760–1020	860 ± 10 (8.2)	860–1650	1070 ± 50 (20.3)
P_{total}, μg/l	40–70	60 ± 2 (16.9)	50–190	100 ± 10 (41.1)
N_{total}/P_{total}	12–19	15 ± 0.4 (13.9)	7–21	12 ± 1 (37.3)
Current velocity, m/s	0.00–0.68	0.19 ± 0.03 (90.7)	0.13–0.62	0.29 ± 0.04 (56.5)

Note: Here and in Tables 3 and 6: mean with a standard error, in brackets—coefficient of variation.

channels and decreased downstream large cities, lands subject to floods and in regions subjected to the highest anthropogenic loads. Water color varied insignificantly and, judging by average values, was somewhat higher in the Gorky Reservoir, water pH ~8.0, and content of dissolved oxygen was lower in the Cheboksary Reservoir. Values of water conductivity (characterizing the water mineral content) were rather stable in the Gorky Reservoir but varied in a wide range in the Cheboksary Reservoir.

The content of suspended matter was the most variable water quality characteristic. The maximal current velocities in both reservoirs were similar but the average velocity was much higher in the Cheboksary Reservoir compared to the Gorky Reservoir (Table 2). Distribution of total nitrogen (N_{total}) and total phosphorous (P_{total}) in the water area of the Gorky Reservoir was rather uniform, but in the upper part, receiving waters from the Rybinsk Reservoir, the content of N_{total} and P_{total} was lower than in other parts. In the Cheboksary Reservoir, concentrations of both elements varied in a wide range and were higher than in the Gorky Reservoir: maximal was 1.6 and 2.7 times, average was 1.2 and 1.6 times, and average N_{total}/P_{total} ratio was 12–15 in both reservoirs (Table 2).

The Chl *a* content in the Gorky Reservoir was variable (Table 1). Differences between minimal and maximal values ranged from 20 to 70% and, only on two stations (downstream the town of Ples and upstream the city of Kineshma), they increased 2–3 times. High phytoplankton abundances were registered, as a rule, near the left shore, and low abundances were observed in the central river channel stations. The abovementioned stations stood against a background of other stations. On the first station, the maximal content of a pigment was recorded near the right shore, and on the second station, in the center. Downstream the dam of the Rybinsk hydroelectric power station, a high abundance of phytoplankton (average Chl *a* content in the reservoir section) was recorded in the part from settlement of Krasnyi Profintern to the town of Ples and in the upper part of the near dam (Yur'evets) expansion (Table 1).

In the Cheboksary Reservoir Chl *a* concentrations had a wider range of variations as compared to the Gorky Reservoir (Table 1). The highest content of the pigment was recorded in the mid part of the reservoir from Sormovo industrial center to Bezvodnoe Village. In the upper part of the reservoir and in its lower part from the settlement of Vasil'sursk to the dam, the phytoplankton abundance was low. Slight differences between stations along transverse sections were recorded only in the central part of the reservoir and had the same values as in the Gorky Reservoir—from 40–70% up to 2.6 times. Phytoplankton was mainly observed at stations on the right bank.

An average ratio between chlorophyll concentrations and nutrient concentration values (phytoplankton "response") [6] was similar in both reservoirs, but maximal values of the characteristics were higher in the Cheboksary Reservoir (Table 3). A similar tendency was observed for the chlorophyll *a* contribution to suspended matter (SM). But judging by Chl/SM ratio in some parts of the Cheboksary Reservoir (downstream Sormovo industrial center and downstream the site of Nizhniy Novgorod waste waters discharge) at chlorophyll *a* content 34 and 72 μg/l, respectively, planktonic suspension was mainly found in the water.

The correlation analysis demonstrates the presence of moderate (r = 0.3–0.7) positive correlation between chlorophyll content and water pH, dissolved oxygen,

Table 3. The correlation between chlorophyll content, biogenic elements, and suspended matter (SM)

Characteristic	Reservoir			
	Gorky		Cheboksary	
	Range	Mean	Range	Mean
Chl *a*, μg/l	5.9–28.0	13.6 ± 0.9* (36.3)	4.2–72.4	18.8 ± 4.5 (98.1)
	5.9–20.6	12.2 ± 1.1** (35.4)	–	–
Chl/N_{total}	0.008–0.024	0.014 ± 0.009 (33.8)	0.005–0.044	0.016 ± 0.003 (75.3)
Chl/P_{total}	0.11–0.34	0.21 ± 0.01 (34.4)	0.04–0.68	0.21 ± 0.05 (89.9)
Chl/SM, %	0.09–0.34	0.21 ± 0.02 (34.8)	0.05–1.13	0.28 ± 0.07 (107.5)

* For 30 stations.
** For 15 stations.

and suspended matter and moderate negative correlation between Chl *a* and water transparency in the reservoirs (Table 4). In the Cheboksary Reservoir, the Chl *a* content was strongly dependent on water conductivity and content of nutrients, primarily on total nitrogen. The effect of water color, current velocity, and N_{total}/P_{total} ratio on the phytoplankton in the reservoirs was not observed.

Using multivariate regression analysis, low coefficients of the relationship between Chl *a* and nitrogen and phosphorus were also obtained (Table 4). Values of R^2 increase when N_{total}/P_{total} ratio, as well as transparency, are used in calculations. The effect of these characteristics was more pronounced in the Cheboksary Reservoir where water color and temperature played a sufficient role along with nutrient contents. Water conductivity and current velocity did not influence R^2 values.

DISCUSSION

The study was conducted during the summer low water period when relatively stable abiotic conditions were formed in a waterbody and negative changes could be distinctly manifested against their background. Ambient conditions in the reservoirs were close to typical for a summer low water period. Low coefficients of variations of mean values testify to stability or insignificant variability of abiotic parameters.

In both reservoirs variability of water transparency and color, the content of dissolved oxygen and total nitrogen was low ($C_v < 30\%$), temperature and pH of water was minimal ($C_v < 5\%$), and the content of suspended matter was moderate ($C_v <$ 40–50%). The Gorky Reservoir was characterized by a stable water conductivity and low variability of the content of total nitrogen and phosphorous and their ratio. These factors corresponded to the features of the hydrological structure of the reservoir and testified to domination of the Volga water masses.

Abiotic parameters in the Cheboksary Reservoir were more variable because of the presence of different water masses (Table 5) with their pronounced peculiar properties. Most characteristics of the Volga waters (color, conductivity, pH, content of SM, and P_{total}, N_{total}/P_{total} ratio) differed slightly from such characteristics in the Gorky Reservoir (Table 2). A moderate increase in water temperature was probably due to a more southern location of the Cheboksary Reservoir and consequent decline of transparency, the content of dissolved oxygen, and increase in the concentration of total nitrogen. All these were caused by a high anthropogenic load in the reservoir. The Oka waters as compared to the Volga waters were characterized by a considerable increase in water conductivity and P_{total} content and low content of N_{total}. Transparency of the Oka water masses formed in the zone of carbonate and karstic deposits was lower and color was higher as compared to the Volga water masses.

The areas near large wastewater outlets (Table 5) were characterized by peculiar conditions influencing negatively the state of the reservoirs. In such areas an increase in water temperature and mineralization, concentration of suspended matter and biogenic elements, and decrease in water transparency were observed.

The Chl *a* content was in the range marked in the previous years during formation of the phytoplankton summer peak. In a seasonal cycle, spring values did not exceed 13–18 μg/l; at the beginning of the summer, the values of Chl *a* content decreased, and at the peak of the summer, they reached their maximum (60–88 μg/l). In autumn the content of the pigment decreased (to 15–20 μg/l) that was typical for the autumn peak (Table 6). During the periods of the previous observations (1989–1992), maximal and average summer concentrations of the pigment were higher [14] and, in July of 1996, were lower [15]. However, these differences were associated with interannual variations of phytoplankton abundance indices peculiar to the other Volga reservoirs. Thus, during 20 year observations in the Rybinsk Reservoir, maximal summer concentrations of Chl *a* ranged from 8 up to 127 μg/l [10]. On the whole the chlorophyll content in the Gorky Reservoir, as in the previous years [14], corresponded to its eutrophic state. No statistical differences were found between values cal-

Table 4. The characteristic of the relationship between chlorophyll content and abiotic parameters

Parameter	Reservoirs	
	Gorky	Cheboksary
	Coefficients of paired correlation (r)	
Temperature (t, °C)	–0.12	0.57
Transparency (Transp.)	–0.44	–0.69
Color (Col.)	0.06	0.06
Electroconductivity (Ec.)	–0.21	0.36
pH	0.60	0.40
Dissolved O_2	0.45	0.60
SM	0.55	0.37
Current velocity	–0.22	0.10
N_{total}	0.28	0.88
P_{total}	0.26	0.36
N_{total}/P_{total}	–0.22	0.17
	Coefficients of multivariate correlation (R^2)	
N_{total}, P_{total}	0.12	0.10
N_{total}, P_{total}, N_{total}/P_{total}	0.22	0.60
N_{total}, P_{total}, Ec.	0.16	0.10
N_{total}, P_{total}, Transp.	0.39	0.78
N_{total}, P_{total}, t	0.19	0.78
N_{total}, P_{total}, Col.	0.08	0.66
N_{total}, P_{total}, current velocity	0.10	0.11
N_{total}, P_{total}, N_{total}/P_{total}, Transp.	0.53	0.80
N_{total}, P_{total}, N_{total}/P_{total}, Ec.	0.17	0.67
N_{total}, P_{total}, N_{total}/P_{total}, t	0.19	0.78
N_{total}, P_{total}, N_{total}/P_{total}, Transp., t	0.63	0.83
N_{total}, P_{total}, N_{total}/P_{total}, Transp., t, Ec.	0.48	0.90
N_{total}, P_{total}, N_{total}/P_{total}, Transp., t, Ec., Col.	0.48	0.90
N_{total}, P_{total}, N_{total}/P_{total}, Transp., t, Ec., Col., current velocity	0.49	0.93

culated for a different number of stations (Table 3): the Student's test ($t = 1.05$) was lower than its table value.

Chlorophyll concentrations on stations along sections reveal a mesoscale spatial (horizontal) distribution of phytoplankton. In the Gorky Reservoir, such distribution formed under effect of hydrodynamical conditions and morphometrical properties of the sites was homogeneous. Differences between Chl *a* concentrations within the section amount to 20–70% increasing two–threefolds in the central part downstream cities of Kineshma and Ples.

Higher indices of phytoplankton development were recorded on right-shore stations, the minimal, on central channel stations. At Chl *a* content 12.9 ± 1.4 μg/l on right-shore stations, 16.7 ± 1.5 μg/l on left-shore, and 11.5 ± 1.4 μg/l on channel stations; the coefficients of variations of means are low (9–12%). Such differences were marked earlier [14].

At the macroscale level of phytoplankton distribution, water areas with its different abundance can be distinguished as moving downstream. Lower indices are usually recorded in the upstream river part with a complex hydrodynamical regimen where water masses of the Volga and Main reaches of the Rybinsk Reservoir inflow through lock chambers. A large volume of water discharge determines high and multidirectional current velocities [8]. In spring and autumn when diatom algae prevail in the phytoplankton, the values of chlorophyll content are the same as in the Rybinsk Reservoir, but in summer when mass development of blue-greens occurs along with diatoms, the chlorophyll content decreases [12].

High phytoplankton abundance (mean concentrations of Chl *a* concentrations for sections) was observed from the settlement of Krasnyi Profintern to the town of Ples and in the upstream part of near dam

Table 5. Parameters of different water masses in the Cheboksary Reservoir

Parameter	Water mass		Zone of wastewater inflow*
	the Volga	the Oka	
Chlorophyll, μg/l	21.9 ± 4.2	6.3 ± 0.3	57.0 ± 15.4
Temperature, °C	21.7 ± 0.4	22.1 ± 0.4	23.4 ± 0.6
Transparency, cm	116 ± 10	123 ± 11	70 ± 5
Color, deg	47 ± 3	37 ± 2	38 ± 3
Dissolved O_2, mg/l	7.6 ± 0.1	7.2 ± 0.3	8.3 ± 1.0
SM, mg/l	6.5 ± 1.0	7.0 ± 1.0	13.4 ± 4.9
pH	7.9 ± 0.1	8.0 ± 0.1	8.4 ± 0.1
Electroconductivity, μS/cm	196 ± 5	316 ± 3	477 ± 14
Current velocity, m/s	0.30 ± 0.05	0.15 ± 0.01	0.49 ± 0.14
N_{total}, μg/l	1020 ± 60	980 ± 30	1570 ± 90
P_{total}, μg/l	60 ± 10	120 ± 10	180 ± 10
N_{total}/P_{total}	16 ± 1	8 ± 1	9 ± 1
Chl/N_{total}	0.021 ± 0.004	0.006 ± 0.0004	0.036 ± 0.008
Chl/P_{total}	0.35 ± 0.08	0.05 ± 0.01	0.31 ± 0.07

* Average for right-shore stations located near discharge sites of treatment plants of the city of Nizhniy Novgorod and downstream (region of the town of Kstovo).

(Yur'evets) expansion (Table 1). Formation of such highly productive zones can be determined by anthropogenic impact. An increase of chlorophyll concentration was registered in sites located near industrial centers (cities of Rybinsk, Yaroslavl, Kostroma, and Kineshma) and downstream the discharge of heated water of Kostroma hydroelectric power station during the previous years too [14]. Furthermore, the Chl *a* content increased in the lakelike near dam expansion, that could be caused by decrease of the current velocity and inflow of rivers Elnat', Nemda, and Unzha into the upstream part of the expansion.

On the whole it can be stated that the macroscale phytoplankton distribution in the Gorky Reservoir is characterized by a moderate variability: the coefficient of variation of the average content of Chl *a* (Table 3) amounts to 36%, and minimal and maximal concentrations of Chl *a* differ 4.7 times. Such distribution can be more inhomogeneous as was observed in the previous years: coefficients of variations of the average content of Chl *a* amounted to ~60% during the summer peak [10]. It can be explained by a great extension of the reservoir, presence of parts of different morphometry and inflow of waters of different genesis.

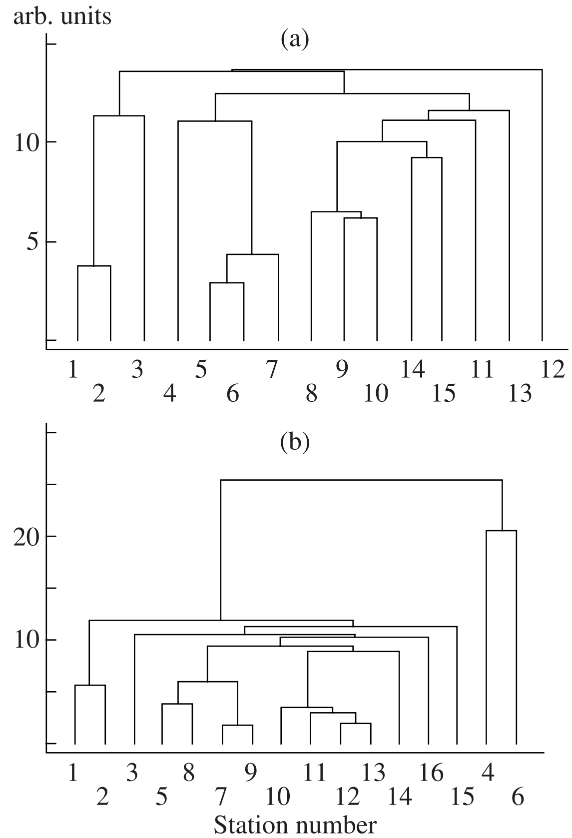
Results of the cluster analysis show (see figure) that stations in the reservoir form a group within which they take place corresponding to their localization in the reservoir. Small clusters are formed by stations in the river part from Rybinsk hydroelectric power station to the city of Kineshma (st. 1–3, 4–7, 8–10) and stations 14 and 15 upstream the dam of Gorky hydroelectric power station. On the dendrogram only stations 11–13 located in a transitional zone between a riverine part and a lacustrine expansion near the dam receiving left-bank tributaries are isolated.

Seasonal dynamics of phytoplankton in the Cheboksary Reservoir as distinct from the Gorky Reservoir demonstrate no early summer decline and Chl *a* concentrations increase from spring to summer reaching their maximum in August (Table 6). The distribution of phytoplankton in water area of the Cheboksary Reservoir is marked by a macroscale heterogeneity. The minimal and maximal values of Chl *a* differ 17 times and the coefficient of variations of the mean is close to 100% (Table 3).

Differences in the mesoscale distribution of phytoplankton (according to Chl *a* content on stations along cross sections) are less expressed. They were recorded only in the middle part of the reservoir at high

Table 6. Seasonal changes in chlorophyll content (μg/l) in Gorky and Cheboksary reservoirs in 1989–1992 (according to [10])

Season	Reservoirs			
	Gorky		Cheboksary	
	Range	Mean	Range	Mean
Spring	7.5–18.5	11.8 ± 0.4	3.2–16.8	9.1 ± 0.4
Early summer	2.7–14.3	5.9 ± 0.4	3.2–28.5	12.5 ± 0.8
Summer	5.5–88.3	27.0 ± 2.3	3.0–77.9	19.8 ± 1.7
Autumn	5.9–19.5	12.6 ± 1.1	6.0–18.8	11.1 ± 0.3



Cluster analysis of the relationship between stations in the Gorky (a) and Cheboksary (b) reservoirs: ordinate axis—Euclidian distance.

concentrations of the pigment and the values were the same values as in the Gorky Reservoir—from 40–70% up to 2.6 times. The part from Sormovo industrial center to the settlement of Bezvodnoe receiving waters of the Oka, one of the two largest tributaries of the Volga, and sewages from large industrial plants of Nizhniy Novgorod district is subjected to a strong anthropogenic load. In the previous years, high concentrations of the pigment were observed in the middle part of the reservoir downstream the city of Nizhniy Novgorod and inflow of the main tributaries—rivers Oka, Vetluga, Kerzhenets, and Sura—and near the dam the values decreased [13].

Most of abiotic parameters and content of Chl *a* differ in the Volga and Oka water masses of the Cheboksary Reservoir. The content of Chl *a* in the Volga water is much higher (Table 5). Thus, in the eutrophic by Chl *a* content Cheboksary Reservoir, mesotrophic Oka waters with their abiotic and biotic features are distinctly expressed. In spite of a decrease of Chl *a* concentrations in the upper part of the Cheboksary Reservoir, on the whole its values in the Volga water mass are 1.6 times higher than in the Gorky Reservoir. It can be due to a markable increase in the content of N_{total} (Tables 2 and 5) that is closely connected with Chl *a* (Table 4). The maximal content of the pigment was observed in the parts receiving wastewaters and characterized by the highest concentrations of biogenic elements. During the summer period, the mass development of blue-green algae causing water “blooming” deteriorates water quality and poses the threat of secondary pollution of the reservoir.

Two groups of station were distinguished within the reservoir using cluster analysis (see figure). One of them is formed by two right-bank stations (st. 4 and 6) with the highest water electroconductivity located in the site of discharge of wastewaters of Nizhniy Novgorod and near the industrial center of the town of Kstovo. Within the second cluster, three groups of two–four stations were distinguished: the upper riverine part (st. 1 and 2), left-bank stations near sites of wasterwaters discharge from cities of Nizhniy Novgorod and Dzerzhinsk (st. 5 and 7–9), the part from settlement of Vasil’sursk to the town of Koz’modem’yansk receiving waters of rivers Sura and Vetluga (st. 10–13).

Besides, four stations are isolated on the dendrogram. The first of them (st. 3) is located downstream the Sormovo industrial center, two stations (st. 14 and 15) are upstream the dam of Cheboksary hydroelectrical power station, and st. 16 is in its tail water.

The analysis of the relationship between the index of Chl *a* development and abiotic characteristics testifies to an important role of algocenoses in formation of the ambient medium in ecosystems of the Gorky and Cheboksary reservoirs during the summer period. Negative coefficients of the paired correlation between Chl *a* and water transparency and positive coefficients of the correlation between Chl *a* and content of suspended matter (Table 4) testify to the role of algae in formation of the light regimen in the water column. The contribution of Chl *a* to the composition of suspended matter (Table 3) is large, which is typical for eutrophic reservoirs in the cascade [11]. The positive relationship of Chl *a* and the content of dissolved oxygen and pH evidences intensive photosynthetic processes and water aeration as a result.

Among ecological aspects of phytoplankton development, special attention is paid to the analysis of the relation between the content of chlorophyll as an indicator of biomass and biogenic elements that is important for assessment of the trophic state of a reservoir and its changes. The effect of biogenic elements on phytoplankton in the Volga reservoirs was considered in the works [13, 14]. All of the Volga reservoirs are characterized by a high content of N_{total} and P_{total} typical for eutrophic waters, which should meet the requirements of algocenoses [20]. But total nitrogen and phosphorous is not fully available for algae, so in some cases biogenic limitation is observed. It is validated by the results of experiments [7] and by analysis of N_{total}/P_{total} ratio applied in ecological studies of algocenoses for assessment of the algae development control by one or another element [16].

In summer of 2001, the content of total nitrogen and total phosphorous in Gorky and Cheboksary reservoirs was the same as in the previous years [13, 14]. Judging by the ratio of concentrations, it can be suggested that, in the upper part of the Gorky reservoirs with untransformed waters from the Rybinsk Reservoir, the phytoplankton is subjected to limitation of phosphorous ($N_{total}/P_{total} > 15$). On the stations with values of $N_{total}/P_{total} = 12–15$, the algae are supplied with balanced biogenic feeding. Such a situation is not stable as in some years the phytoplankton in the reservoir can be subjected either to nitrogen (August of 1990) or phosphorous (May and August of 1992) limitation [14]. In the Cheboksary Reservoir, the phytoplankton development in the Volga water is limited by phosphorous (the mean $N_{total}/P_{total} = 16$) in the Oka water, and it may seem strange, in sites of wastewater discharge from the city of Nizhniy Novgorod, the limitation of nitrogen ($N_{total}/P_{total} = 8–9$ (Table 5)) takes place. The latter is, probably, the reason for a high value of the coefficient of correlation between N_{total} and Chl *a* content (Table 4).

The provision of phytoplankton with biogenic elements and their efficient use is reflected by Chl/N_{total} and Chl/P_{total} ratios discussed in publications of the past years [6, 10]. Values of both parameters vary in waters of different trophy level. High values of chlorophyll per unit of N_{total} and P_{total} were recorded in eutrophic waters (Table 3 and 5) and minimal values were typical for mesotrophic Oka waters.

An insignificant effect of N and P on phytoplankton in both reservoirs is confirmed by multivariate correlation analysis. According to R^2 values, presence of both N and P explains a low percent of Chl *a* variability (Table 4). The fact that no correlation was found between Chl *a* and biogenic elements in the Volga reservoirs does not indicate the absence of their effect on phytoplankton. This effect can be of more complex character and may be disguised by many factors including water dynamics, effect of zooplankton, presence of available forms of biogenic elements, their ratio, turnover, and direction of flows [18]. In fact the share of explained variation of Chl *a* increases (especially in the Cheboksary Reservoir) at using N_{total}/P_{total} ratio for calculations. When water transparency characterizing light regimen in the water column is taken into account, the correlation between Chl *a* with environmental factors increases. The effect of transparency on phytoplankton is more pronounced in the Cheboksary Reservoir, where one more hydrooptical parameter—water color—and temperature play a significant role along with biogenic elements. Electroconductivity depending on water mineralization and current velocity do not influence R^2 values.

The results of the analysis allow us to suggest that, in the height of summer, the phytoplankton in two contiguous reservoirs of the cascade with different flow regimen, structure of water masses, and anthropogenic load responds differently to the external influence. In the Gorky Reservoir, a stable autotrophic community is formed with close indices of abundance depending little on the environmental factors. Only ~63% of the explained Chl *a* variation is dependent on content and relationship between the main biogenic elements, water temperature, and transparency. The account of the other analyzed parameters yields lower values of R^2. As the main abiotic factors have been considered in the paper, we can suggest that biotic relations play an important role in planktonic algae development in the ecosystem of the Gorky Reservoir.

The other situation is observed in the Cheboksary Reservoir, where under conditions of the maximal flow velocity and anthropogenic load [8, 10], the community is developed depending to a greater extent on hydrological and hydrochemical conditions. The combined effect of the considered abiotic parameters almost completely ($R^2 = 0.93$) control the phytoplankton development in the reservoir.

CONCLUSIONS

In the summer period of 2001, the level of phytoplankton development and the pattern of its distribution in water area of the Gorky and Cheboksary reservoirs were typical for both studied reservoirs. As assessed by chlorophyll content, the reservoirs, of which trophic state has not changed during the 1990s, can be considered as the eutrophic water bodies.

In the Cheboksary Reservoir, the mesotrophic Oka River water mass can be distinguished preserving its abiotic and biotic properties over a long distance. The phytoplankton in the contiguous reservoirs responds in different ways to the effect of external factors. A stable autotrophic community in the Gorky Reservoir depends little on abiotic factors. Only ~63% of the explained variation of Chl *a* is dependent on the content and ratio of the main nutrients, temperature, and transparency. In the Cheboksary Reservoir under conditions of the maximal for the Volga cascade flow and anthropogenic load, the phytoplankton development is almost completely controlled ($R^2 = 0.93$) by hydrological and hydrochemical regimens' factors.

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REFERENCES

1. Avakyan, A.B., Saltankin, V.P., and Sharapov, V.A., *Vodokhranilishcha* (Reservoirs), Moscow: Mysl, 1987.
2. Alekin, O.A., Semenov, A.D., Skopintsev, B.A., *Rukovodstvo po khimicheskomu analizu vod sushi* (A guide to Chemical Analysis of Inland Waters), Leningrad: Gidrometeoizdat, 1973.

3. Bikbulatov, E.S., On the Method of Determination of Total Phosphorus Distribution in Natural Waters, *Hydrokhimicheskie Materialy*, 1974, vol. 60, pp. 167–174.
4. Butorin, N.V., *Gidrologicheskie protsessy i dinamika vodnykh mass v vodokhranilishchakh volzhskogo kaskada* (Hydrological Processes and Dynamics of Water Masses in Reservoirs of the Volga Cascade), Leningrad: Nauka, 1969.
5. Gapeeva, M.V., Razgulin, S.M., and Skopintsev, B.A., An Ampoule Persulfate Method for Determination of Total Nitrogen in Natural Waters, *Hydrokhimicheskie Materialy*, 1984, vol. 87, pp. 67–70.
6. Vinberg, G.G., *Sravnitelnye biolimnologicheskie issledovaniya, ikh vozmozhnosti i ogranicheniya* (Comparative Biolimnetic Studies, Their Capabilities and Restrictions), in *Produktsionnye i hydrobiologicheskie issledovanya na vnutrennikh vodoemakh* (Productional and Hydrobiological Studies in Inland Waterbodies) Leningrad, Hydrometeoizdat, 1986, pp. 4–18.
7. Elizarova, V.A., Koroleva, M.B., *Intensivnost' rosta fitoplanktona v Rybinskom vodokhranilishche v svyazi s nebol'shimi dobavkami fosfora i azota* (The Rate of Phytoplankton Growth in the Rybinsk Reservoir Depending on Small Additions of Phosphorus and Nitrogen), in *Flora i produktivnost' pelagicheskikh i litoral'nykh fitotsenozov v vodoemakh basseina Volgi* (Flora and Productivity of Pelagic and Littoral Phytocenoses in the Volga Basin Waterbodies), Leningrad: Nauka, 1990, pp. 189–199.
8. Litvinov, A.S., *Energo- i massoobmen v vodokhranilishchakh Volzhskogo kaskada* (Energy and Mass Exchange in the Volga Cascade Reservoirs), Yaroslavl: Yaroslavl St. Tech. Univ., 2000.
9. Litvinov, A.S. and Zakonnova, A.V., Description of Hydrological Conditions in the Cheboksary Reservoir during the First Years of Its Fill up, *Vodnye Resursy*, 1994, vol. 21, no. 3, pp. 365–374.
10. Mineeva, N.M., *Rastitel'nye pigmenty v vode volzhskikh vodokhranilishch* (Plant Pigments in Water of the Volga Reservoirs), Moscow: Nauka, 2004.
11. Mineeva, N.M., *Formirovanie podvodnogo svetovogo rezhima vodokhranilishch Volgi* (Formation of Lighting Regimen in Water of the Volga Reservoirs), in Current Problems of Efficient Use of Biological Resources of Reservoirs. Yaroslavl: Yaroslavl State Technical University, 2005, pp. 213–223.
12. Mineeva, N.M. and Mitropolskaya, I.V., Structural and Functional Characteristics of Planktonic Algocenoses as Indicators of the Ecological State of the Upper Volga Reservoirs, *Biology of Inland Waters*, 2003, no. 1, pp. 39–48.
13. Okhapkin, A.G., *Fitoplankton Volgi. Fitoplankton Cheboksarskogo vodokhranilishcha* (Phytoplankton of the Volga. Phytoplankton of the Cheboksary Reservoir), Togliatti, Institute of Ecology of the Volga Basin, RAS, 1994, 275 p.
14. Okhapkin, A.G., Mikulchik, I.A., Korneva, L.G., and Mineeva, N.M., *Fitoplankton Volgi. Fitoplankton Gorkovskogo vodokhranilishcha* (Phytoplankton of the Volga. Phytoplankton of the Gorky Reservoir), Togliatti, Institute of Ecology of the Volga Basin, RAS, 1997, 224 p.
15. Sigareva, L.E. and Timofeeva, N.A., The Study on the Relationship between the Content of Vegetative Pigments in Bottom Sediments and Indices of the Trophic State of the Gorky Reservoir, *Wodnye Resursy*, 2001, vol. 28, no. 6, pp. 742–751.
16. Claesson, A., Research on Recovery of Polluted Lakes. Algal Growth Potential and the Availability of Limiting Nutrients, Acta Univ. Uppsala, 1978, no. 461, pp. 1–27.
17. Jeffrey, S.W. and Humphrey, G.F., New Spectrophotometric Equations for Determining Chlorophylls a, b, c_1 and c_2 in Higher Plants, Algae and Natural Phytoplankton, *Biochem. Physiol. Pflanz.*, 1975, vol. 167, pp. 191–194.
18. Pridmore, R.D., Vant, W.N., and Rutherford, J.C., Chlorophyll-nutrient Relationships in North Island Lakes (New Zealand), *Hydrobiologia*, 1985, vol. 121, no. 2, pp. 181–189.
19. SCOR-UNESCO Working Group no. 17. Determination of Photosynthetic Pigments in Sea Water, in *Monographs on Oceanographic Methodology*, Paris: UNESCO, 1966, pp. 9–18.
20. Vollenweider, R.A., Das Nahrstoffbelastungsconzept als Grundlage fur den eutrophierungs-prozess stehender Gewasser und Talsperren, Z. Wasser- und Abwasser-Forsch., 1979, vol. 12, no. 2, pp. 46–56.