The impact of thermal regime on chlorophyll content in the southern part of the Kuibyshev reservoir

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Abstract. To assess the effect of water temperature on the concentration of chlorophyll "a", regular observations were carried out in the southern part of the Kuibyshev Reservoir in the period 2016-2022. It was found that there is an exponential relationship between the concentration of chlorophyll and water temperature. The growth rate of chlorophyll concentration with an increase in temperature in the range of 15-22 ºC was 0.5 μg / dm^3 per 1 ° C. With an increase in temperature above 22 ºC, the rate increased 5 times and was 2.5 μg / dm^3 per 1 ° C. The different growth rates of chlorophyll are explained by the fact that at temperatures below 22 ºC, *Bacillariophyta* and *Chlorophyta* dominated in the phytoplankton structure, and at higher temperatures - *Cyanophyta* algae, which caused the process of "blooming" of the water. For prognostic calculations, the correlation between air and water temperature was studied. A very strong correlation was found for August with a coefficient of 0.90. Using the Student criterion, a conclusion was made about the statistical significance of the obtained linear trend of water temperature. It was concluded that under conditions of global warming, the content of chlorophyll "a" will increase due to the rapid development of *Cyanophyta* algae, which will lead to a deterioration in the state of the ecosystem of the Kuibyshev Reservoir.

1 Introduction

In the context of global warming, the problem of assessing the impact of rising water temperatures on the content of chlorophyll "a" (hereinafter chlorophyll) is becoming increasingly important [1, 4, 6-7, 13]. One of the most important indicators of global warming is the regional trend towards rising air temperatures in the Volga region. Since the 1970s, each subsequent decade has been warmer than the previous one. In recent years (2015-2022), the increase in air temperature has been most intense, especially in the summer.

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Rising air temperatures in the Middle and Lower Volga cause an increase in the water temperature of the Kuibyshev Reservoir and an increase in the duration of the warm period [1]. Similar changes in the thermal regime are confirmed by studies of other Volga reservoirs.

In conditions of rising water temperatures, excessive development of phytoplankton is observed, primarily the group of blue-green algae (*Cyanophyta*), which causes the development of the process of "blooming" of water and negatively affects the ecological state and the formation of water quality in the reservoirs of the Volga-Kama cascade used for domestic and drinking water supply, fisheries, health recreation and water tourism.

The issue of the influence of thermal conditions on the dynamics of chlorophyll content has been actively discussed in the literature for several decades, but researchers have not yet been able to come to a consensus. A number of studies provide data on the independence of phytoplankton growth efficiency from temperature [2-3, 10]. However, other results have also been published in which the dependence of chlorophyll "a" on temperature is observed [8, 12, 14]. Therefore, temperature can be one of the factors determining the composition and dynamics of phytoplankton in a reservoir [5, 9]. Of particular interest is the assessment of the combined effect of water temperature and weather conditions on the growth rate of individual phytoplankton groups.

In the near future, further activation of mass development of *Cyanophyta* algae is expected due to climatic transformation of the thermal regime of reservoirs. The growth of absolute values of air and water temperature, an increase in the frequency of anticyclonic weather and the duration of the warm period activate the development of *Cyanophyta* algae in reservoirs [11]. Despite the successes achieved in the study of phytoplankton and the process of mass development of *Cyanophyta* algae, there is no consensus on the priority of the influence of certain abiotic factors on the state of phytoplankton.

Under these conditions, excessive development of phytoplankton, primarily the *Cyanophyta* group of algae, causes the development of the process of "blooming" of water, which negatively affects the ecological state and the formation of water quality in large Volga and Kama reservoirs. Almost all large reservoirs located in the Volga basin are used for drinking water supply, fisheries, recreation and tourism.

This article is devoted to the study of the combined effect of thermal regime and weather conditions on the content and dynamics of chlorophyll in the summer period of 2016-2022. The largest reservoir on the Volga, the Kuibyshev Reservoir, was chosen as the object of study. It is characterized by a slow water exchange, which contributes to the mass development of phytoplankton and, as a consequence, an increase in chlorophyll "a" in the summer. The expected results of studies to establish the relationship between water temperature and chlorophyll content will allow developing more reliable long-term forecasts of water quality and the ecological state of reservoirs.

2 Materials and methods

Comprehensive regular observations in the summer period of 2016-2022 were carried out in the southern part of the Kuibyshev Reservoir. The width of the reservoir at the survey site was 6 km. At the observation station, the depth during the summer period varied within the range of 14-16 m. Water temperature (t) was systematically measured and water samples were periodically taken to determine the chlorophyll content and determine the composition of phytoplankton at a depth of 0.5 m. Air temperature (T) was monitored at the Samara weather station. t was measured with a thermometer in a Spindler frame. Water samples for phytoplankton composition analysis and chlorophyll content determination were collected with a Molchanov GR-18 bathometer. The discreteness of chlorophyll content observations was 10 times a month. Biological samples for phytoplankton composition determination were taken once a month. The samples were processed in accordance with the methods accepted in hydrobiology. The error in measuring the water temperature was ±0.2 °C. The determination of chlorophyll "a" was determined in the laboratory using the spectrophotometric method. Chlorophyll is the main photosynthetic pigment quantitatively associated with the primary production of phytoplankton. A database was created to process the data array. Correlation and regression analyses were used to determine the relationship between air temperature and water temperature, and between chlorophyll and water temperature.

3 Results and Discussion

Comprehensive observations at the reservoir were carried out in years with different thermal regimes. The warmest years in terms of air temperature were 2021 and 2016, for which the average summer air temperature (T) was 23.8 °C and 22.7 °C, respectively. The coldest years were 2017 and 2019, for which the average summer T was 21.1 °C and 21.3 °C, respectively. Over seven years of observations at the Samara weather station, the daily average monthly T varied in the range of 20-27 ºC in June, 24-29 ºC in July and 22-31 ºC in August (Table 1). Nighttime air temperatures varied in the range of 13-18 ºC in June, 16-20 ºC in July and 15-21 ºC in August. Daily extreme T partially confirm the patterns established based on the average monthly air temperature data. In particular, maximum average daily T was usually observed in warm years (2021, 2016), and minimum - in cold years (2017, 2019).

Table 1. Average monthly (day, night), extreme (min, max) daily values of T, °C.

Year	June				July				August			
	average		extremes		average		extremes		average		extremes	
	day	night	min	max	day	night	min	max	day	night	min	max
2016	24	16	7	32	27	18	13	34	30	21	11	36
2017	20	13	6	28	25	17	12	36	26	17	13	35
2018	23	14	2	34	27	20	16	37	25	16	12	32
2019	25	16	11	34	24	16	13	35	22	15	7	36
2020	22	15	10	30	29	19	11	36	23	15	11	35
2021	27	18	12	38	28	18	15	36	31	20	13	38
2022	22	15	10	30	26	18	13	35	30	20	14	35

There is a correlation between T and t. The degree of correlation depends on the season. In spring, in April and May, the correlation is weak, the correlation coefficient is 0.24 and 0.28, respectively. In summer, in June, and in autumn, in September and November, the correlation is average (0.61, 0.50, and 0.57), and in July and October, the correlation is strong (0.70 and 0.76). August is characterized by a very strong correlation with a coefficient of 0.90. Using Student's criterion, a conclusion was made about the statistical significance of the obtained correlation coefficients for a significance level of 0.05 for July, August, and October. To predict the water temperature in August under various climate scenarios, a linear relationship was established between T and t (Figure 1). The obtained regression equations, in principle, allow, based on the specified values of the variable T, to predict the expected average values of t.

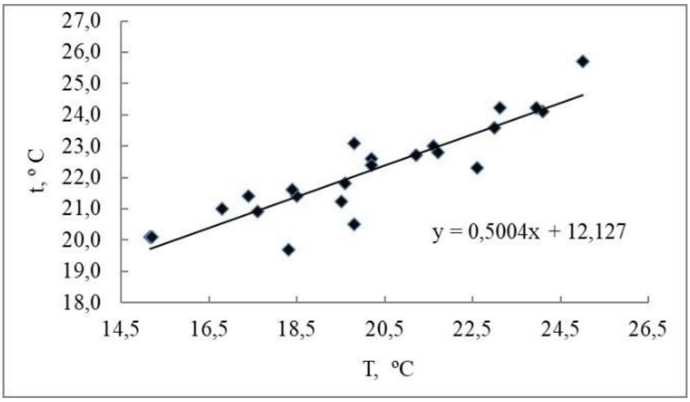

Fig. 1. Positive linear relationship between T and t.

According to long-term observations in 2016-2022, the average monthly water temperature (t) in June varied in the range of 15.2-20.7 ºC, the July water temperature - 21.2-26.5 ºC and the August t - 19.7-24.2 ºC. The amplitude of the average daily fluctuations in t was: 11.8-27.1 ºC in June, 17.6-26.5 ºC in July, 18.0-25.7 ºC in August.

The warmest summer was observed in 2021, when the summer air temperature was 23.8 °C, and the temperature of the surface water layer reached 23.1 °C. The coldest summer was observed in 2017, when summer T dropped to 21.1 °C, and t to 19.2 °C. The remaining years in the seven-year observation period occupied an intermediate position.

T in the summer of 2016 was 22.7 °C. During the summer, T gradually increased by 3.8 °C, starting from 20.3 °C in June to 24.1 °C in August (Table 2). The difference between day and night T was 8-9 °C. Day and night T were 24 °C and 16 °C in June, 27 °C and 18 °C in July, 30 °C and 21 °C in August.

In the summer of 2016, the average t was 22.1 °C. Over the summer, t increased by 4.6 °C, starting from 19.5 °C in June to 24.1 °C in August. If we use the water temperature of 22 °C as a criterion, then during the summer there were two periods when the average daily water temperature exceeded 22 °C. According to visual estimates, a short period of water "bloom" was observed from June 21 to 28, and the second long period - from July 5 to September 1. The total number of favorable days for the development of Cyanophyta algae was 66 days.

Table 2. Average monthly, maximum and minimum daily water temperature (t), °C.

Year	June			July			August		
	average	min	max	average	min	max	average	min	max
2016	19.5	15.8	23.8	22.6	21.2	23.8	24.1	22.8	25.0
2017	18.8	11.8	15.2	20.0	17.6	23.8	22.3	21.5	23.8
2018	16.2	11.9	21.9	23.4	21.6	24.6	22.8	21.2	25.6
2019	20.3	17.8	20.3	21.6	20.9	22.8	19.7	18.0	20.8
2020	17.9	14.4	21.1	23.0	21.2	25.0	21.2	19.8	24.2
2021	20.7	15.0	27.1	24.3	26.5	23.1	24.2	22.2	25.7
2022	16.8	12.1	22.3	21.4	20.7	22.5	24.2	22.7	24.9

The average chlorophyll concentration in the summer of 2016 was 6.2 μg/dm^3. In June, the chlorophyll concentration was 3.1 μg/dm^3, in July - 10.9 μg/dm3, and in August - 4.6 μg/dm^3 (Table 3). A sharp increase in chlorophyll concentration began on June 29. In July, the chlorophyll concentration was characterized by significant variability and fluctuated in the range of 5.1-21.9 μg/dm^3, which was due to changes in meteorological conditions. The highest chlorophyll concentration was observed on July 17 with an average daily temperature of 29.1 °C. Cyanophyta algae dominated in July and August, causing water bloom.

T in the summer of 2017 decreased by 1.6 °C compared to 2016 and was 21.1 °C. During the summer, T gradually increased by 4.1 °C, starting from 18.5 °C in June to 22.6 °C in August. The difference between day and night temperatures was 7-9 °C. Daytime and nighttime air temperatures were 20 °C and 13 °C in June, 25 °C and 17 °C in July, 26 °C and 17 °C in August.

In the summer of 2017, the average water temperature was 19.2 °C. Over the summer, t increased by 3.5 °C, starting from 18.8 °C in June to 22.3 °C in August. During the summer, there were two intervals when the average daily water temperature exceeded 22 °C. One interval was observed from July 29 to August 14, and the second short one - from August 20 to 28. In August, the night air temperature dropped below 17 °C, which did not contribute to the development of *Cyanophyta* algae.

In the cold summer of 2017, the chlorophyll concentration was low and amounted to 0.6 μg / dm^3. The range of chlorophyll concentration fluctuations was within 0.4 - 0.8 μg / dm^3 (Table 3). The water temperature exceeded 22 ° C only at the end of July. Therefore, even the maximum daily values of chlorophyll concentration remained extremely low 0.4-1.9 μg / dm^3. *Bacillariophyta* and *Chlorophyta* algae dominated in the phytoplankton composition in June-August. The process of "blooming" of water in the summer of 2017 was not observed.

Table 3. Average monthly and maximum concentration of chlorophyll, μg/dm^3.

Year	June		July		August	
	average	max	average	max	average	max
2016	3.1	6.9	10.9	21.9	4.6	7.1
2017	0.4	0.7	0.7	1.4	0.8	1.9
2018	2.5	4.1	8.4	11.6	3.1	6.7
2019	1.9	3.6	2.9	4.6	0.4	0.7
2020	3.9	4.9	9.3	12.3	0.4	0.7
2021	3.7	8.7	12.6	22.6	5.4	9.4
2022	1.5	3.2	2.1	4.4	10.1	11.3

The air temperature in the summer of 2018 increased by 1.0 °C compared to 2017 and was 22.1 °C. Daytime and nighttime T was 23 °C and 14 °C in June, 27 °C and 20 °C in July, 25 °C and 16 °C in August. In the summer of 2018, the average water temperature was 20.8 °C. It was 16.2 °C in June, 23.4 °C in July, and 22.8 °C in August.

In the summer, two intervals with t ≥ 22 °C were distinguished. One interval lasted from June 1 to 23, and the second from July 25 to August 21. The total number of favorable days for the development of *Cyanophyta* algae was 52.

The chlorophyll concentration in the summer of 2018 was 4.7 μg/dm^3. From June to July, the chlorophyll concentration increased from 2.5 to 8.4 μg/dm^3, and then decreased in August and was 3.1 μg/dm^3 (Table 3). In June, *Bacillariophyta* and *Chlorophyta* algae dominated in the phytoplankton composition. The chlorophyll concentration began to increase on June 27. In July, the chlorophyll concentration was characterized by significant variability, which was due to meteorological conditions. The highest chlorophyll concentration was recorded on July 11 in clear, calm weather and was 11.6 μg/dm^3. In July and August, *Cyanophyta* algae dominated, causing water "blooming".

T in the summer of 2019 decreased by 0.8 °C compared to 2018 and was 21.3 °C. During the summer, t initially increased from June to July from 22.2 to 23.1 °C, and then in August t sharply decreased to 18.8 °C. The difference between day and night temperatures was 7-9 °C. Day and night T were 25 °C and 16 °C in June, 24 °C and 16 °C in July, 22 °C and 15 °C in August.

Summer t was 20.5 °C. During the summer, the water temperature first increased from June to July from 20.3 to 21.6 °C, and then decreased to 19.7 °C in August. During the summer, there were two intervals when the average t per day exceeded 22 °C. One short interval lasted from June 23 to 27 and was 5 days. The second short interval was observed from July 21 to 26 and was 6 days. The total number of the most favorable days for the development of Cyanophyta algae was 11.

The chlorophyll concentration in the summer of 2019 was 1.8 μg / dm^3. From June to July, the chlorophyll concentration increased from 1.9 to 2.9 μg / dm^3, and then in August it sharply decreased to 0.4 μg / dm^3. The maximum chlorophyll value was 4.6 μg / dm^3 and was recorded on July 21 at a temperature of 22.6 ° C. Bacillariophyta and Chlorophyta algae dominated in the phytoplankton composition throughout the summer. The process of "blooming" of water in 2019 was not observed.

In 2020, the average summer T was 21.2 °C. The highest average monthly T was observed in July and was 29 °C, and the lowest in June - 22 °C. The average summer t was 20.7 °C (Table 2). In summer, there were 2 periods with t ≥ 22 °C: the first was observed for 9 days from July 4 to 11, and the second was observed for 27 days from July 13 to August 8. The total number of such days was 35 days. Of these, 10 days fell within the temperature range of 23 °C > t ≥ 22 °C, 18 days - 24 °C > t ≥ 23 °C, 6 days - 25 °C > t ≥ 24 °C and 1 day 26 °C > t ≥ 25 °C.

The chlorophyll concentration in summer 2020 was 4.6 μg/dm^3. From June to July, the chlorophyll concentration increased from 3.9 to 9.3 μg/dm^3, and then sharply decreased to 0.4 μg/dm^3 in August. The maximum chlorophyll concentration was 12.3 μg/dm^3 and was recorded on July 15 at a water temperature of 23.6 °C. *Bacillariophyta* and *Chlorophyta* algae dominated in the phytoplankton in June, *Cyanophyta* algae, which caused water "blooming", dominated in July, and *Bacillariophyta* and *Chlorophyt* algae dominated again in August.

In the warmest year of 2021, the air temperature increased by 2.6 °C compared to 2020 and was 23.8 °C. Daytime and nighttime T was 27 °C and 18 °C in June, 28 °C and 18 °C in July, 31 °C and 20 °C in August. In the summer of 2021, the average water temperature was 23.1 °C. It reached - 20.7 °C in June, 24.3 °C in July, and 24.2 °C in August. During the summer, two intervals with t ≥ 22 °C were distinguished. The first short interval lasted from June 21 to July 8, and the second long one - from July 9 to September 1. The total number of favorable days for the development of *Cyanophyta* algae was 72.

The chlorophyll concentration in the summer of 2021 reached its highest values and was 7.4 μg / dm^3. From June to July, the chlorophyll concentration increased from 3.7 to 12.6 μg / dm3, and then decreased to 5.4 μg / dm^3 in August. The maximum chlorophyll concentration was 22.6 μg / dm^3 and was recorded on July 15 at a water temperature of 24.6 ° C. In June, *Bacillariophyta* and *Chlorophyta* algae dominated in the phytoplankton. In July and August, *Cyanophyta* algae dominated, causing water "blooming".

In 2022, the average summer T was 22.1 ° C, 26.1 ° C during the day, and 17.7 ° C at night. The highest average monthly air temperature was observed in August and was 30 °C during the day and 20 °C at night, and the lowest was in June, 22 °C during the day and 15 °C at night. The average summer temperature was 20.8 °C (Table 2).

The chlorophyll concentration in the summer of 2022 was 4.7 μg/dm^3. From June to August, the chlorophyll concentration increased from 1.5 to 10.1 μg/dm^3. A significant increase in chlorophyll concentration began late on July 25. The maximum chlorophyll concentration was 11.3 μg/dm^3 and was recorded on August 15 in clear, calm weather and a water temperature of 24.9 °C. *Bacillariophyta* and *Chlorophyta* algae dominated in the phytoplankton in June and July, and *Cyanophyta* algae dominated in August, causing water "blooming".

The results of the studies showed that the chlorophyll concentration increased with increasing t. At the same time, the rate of chlorophyll growth increased significantly after reaching t ≥ 22 ºC. At this time, *Cyanophyta* algae begin to dominate in the phytoplankton composition. Significant and sharp fluctuations in chlorophyll concentration in July and August are due to the variability of meteorological conditions. During the presence of an anticyclone, clear and windless weather is observed. It contributes to the mass development of *Cyanophyta* algae. During the passage of a cyclone, cloudy and windy weather is usually observed and the activity of algae development decreases sharply. The increase in t observed in the modern period is the most important factor contributing to the spread and dominance of *Cyanophyta* algae in the reservoirs of the Middle and Lower Volga.

A correlation relationship has been established between the concentration of chlorophyll and t. The degree of relationship is determined by the correlation coefficient as strong and is 0.71. The exponential relationship between the concentration of chlorophyll and water temperature (Figure 2) is satisfactorily described by the equation:

$$Xl=0.0096\ e\ (0.2754\ t) \quad (1)$$

Equation (1) is an acceptable model for describing field observation data, since the determination coefficient is 0.48 and shows what part of the variability of the observed variable can be explained by the constructed equation.

Figure 2 shows that until the water temperature reaches 22 °C, the chlorophyll content increases relatively slowly by 0.5 µg/dm^3 per 1 °C, and then increases sharply (5 times) and is 2.5 µg/dm^3 per 1 °C. There is an objective explanation for this. In the structure of phytoplankton in June at t < 22 ºC, *Bacillariophyta* and *Chlorophyta* algae dominate, which do not cause water bloom. In July at t> 22 ºC, *Cyanophyta* algae dominate, which cause water bloom. In August, with a decrease in temperature, especially at night, *Bacillariophyta* and *Chlorophyta* algae begin to dominate again.

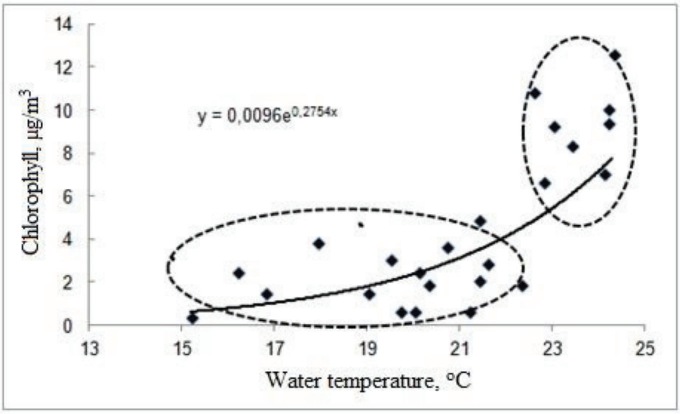

Fig. 2. Exponential relationship between chlorophyll and water temperature.

The obtained research results showed that, by assessing the current state, it is possible to predict the development of the water "bloom" process. The longer the warm period, the longer the water "bloom" process. The higher the water temperature, the higher the intensity of the water "bloom" process.

4 Conclusion

The results of the studies conducted in the summer period of 2016-2022 showed that water temperature and meteorological conditions (air temperature, wind and cloudiness) had a significant impact on the summer dynamics of chlorophyll concentration in the southern part of the Kuibyshev Reservoir. There is a correlation between air temperature and water temperature. The degree of correlation in June, July and August is inconsistent. In June, the correlation is average, in July it is strong, and in August it is very strong. The correlation coefficients were 0.61, 0.70 and 0.90, respectively. To predict the water temperature in August under various climate scenarios, a positive linear relationship was established between T and t. The resulting regression equation allows us to predict the expected average values of t based on the given values of the variable T.

As the water temperature increased, the chlorophyll concentration increased. In the interannual aspect, the highest concentration of chlorophyll was observed in warm years (2016, 2021) and amounted to 6.3 and 7.4 μg / dm^3, respectively, for the summer period. The lowest concentration of chlorophyll was observed in cold years. For example, in 2017 and 2019, the chlorophyll concentration was 0.7 and 1.8 μg / dm^3. In the seasonal aspect, the maximum concentration of chlorophyll was usually observed in July in clear weather and no wind. In the warm years of 2016 and 2021, the maximum concentration of chlorophyll reached 21.9 and 22.6 μg / dm^3, respectively.

Under the influence of the increase in water temperature, the change in chlorophyll concentration occurs according to an exponential dependence. At a water temperature of less than 22 ºC, the chlorophyll concentration increased relatively slowly at a rate of 0.5 μg/dm^3 per 1 °C, and then the rate sharply increased by 5 times and amounted to 2.5 μg/dm^3 per 1 °C. The reason for such dynamics is that the structure of phytoplankton in June (at $t < 22$ ºC) is dominated by *Bacillariophyta* and *Chlorophyta* algae, which do not create a "bloom" of water. In July, at $t > 22$ ºC, *Cyanophyta* algae mainly dominate, causing rapid growth of algae biomass. In August, with a decrease in daily t to a level of less than 22 ºC, especially at night, *Bacillariophyta* and *Chlorophyta* algae begin to dominate again.

The established influence of t on the content of chlorophyll and meteorological conditions. meteorological conditions. phylla allows us to state that under conditions of global warming, the chlorophyll content will increase, the process of water "blooming" will be activated and the tendency to deteriorate the ecological state and water quality of the Kuibyshev Reservoir will increase. A correlation has been established between the chlorophyll content and t. According to the correlation coefficient (0.71), the degree of connection is determined as strong. The established relationship between chlorophyll and t is supposed to be used as an acceptable model for describing the data of field observations. However, to improve modeling and increase the reliability of prognostic calculations, it will be necessary to continue detailed comprehensive studies aimed at assessing the influence of abiotic factors on the process of mass development of *Cyanophyta* algae under a wide range of meteorological conditions.

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