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Parameters of the temperature optimum for cyanobacteria in the Kuibyshev reservoir

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Abstract. Based on the results of hydrometeorological observations in the period 2016-2021, the parameters of the optimum temperature zone (TTO) for the process of mass development of cyanobacteria in the Kuibyshev reservoir were determined. Such parameters of the optimum zone as duration, intensity, upper and lower boundaries depend on the hydrometeorological conditions of a particular year. For the period 2016-2021, the average duration of the OST was 44 days, the longest - 72 days and was observed in 2021, and the shortest - 11 days and was observed in 2019. The highest intensity of OST was observed in 2021, when 10 days were characterized by low intensity, 15 days by moderate intensity, 23 days by strong intensity, 24 days by very strong intensity and 7 days by extreme intensity. The lowest intensity was observed in 2019, when 10 days were characterized by low intensity and 1 day by high intensity. The upper border of the WTO in 2021 was observed on June 21, and the lower border on September 1. In 2019, the upper limit was observed on June 23, and the lower limit on July 26. For the process of mass development of cyanobacteria, the most favorable year is 2021, and the unfavorable year is 2019. It was found that with the increase in air and water temperature, the duration and degree of intensity of the temperature optimum zone increased. Consequently, with a further increase in air temperature due to global warming, the duration and intensity of the optimum temperature zone will only increase, which will activate the process of mass development of cyanobacteria, which will negatively affect the ecological state and water quality of the Kuibyshev reservoir.

1 Introduction

The process of mass development of cyanobacteria (MDC) is a characteristic phenomenon for large lowland reservoirs with slow water exchange [1-8]. During the summer low-water period, the process of mass development of cyanobacteria negatively affects the formation of water quality. The water acquires an unpleasant odor and a specific color, the pH and content of organic substances in the water increases, the oxygen regime is disrupted [9-11],

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and the threat of toxic pollution appears [12-13]. Under these conditions, there are risks of using reservoirs for domestic and drinking water supply, fisheries and recreation.

The distribution, duration and intensity of the process of mass development of cyanobacteria significantly depends on hydrometeorological factors and, above all, on water temperature. With its increase, the process of mass development of cyanobacteria is activated, since an increase in water temperature promotes high activity and growth of cyanobacteria [14-15]. In addition, increasing water temperature can not only promote the growth of cyanobacteria, but also affect the formation of toxins. It is assumed that some species of cyanobacteria that do not produce toxins begin to synthesize toxins when the water temperature increases [16-17].

One of the most important indicators of global warming is the rising trend in the temperature of the surface layer of the atmosphere. According to Roshydromet, over the past 100 years, the overall increase in air temperature for the territory of Russia has been 1.0 °C, which is 0.4 °C higher than the average for the globe. Since the 70s of the last century, each subsequent decade has been warmer than the previous one. In recent years, the increase in air temperature has been most intense. According to the World Meteorological Organization, 2021 was the seventh year in a row that global temperatures were more than 1°C above industrial levels (1850-1900). A number of authors believe that the observed global warming and increase in surface water temperature [18] should be considered as the most important natural process contributing to the rapid spread and dominance of cyanobacteria in the reservoirs of the Middle and Lower Volga [19-21].

The process of mass development of cyanobacteria and its impact on the formation of actino water quality is being studied all over the world. Some progress has already been made, however, many issues that characterize the quantitative parameters of the process for specific reservoirs under different temperature conditions have not yet been sufficiently studied. This article is devoted to determining the duration and intensity of the temperature optimum zone for the process of mass development of cyanobacteria in the Kuibyshev reservoir, the largest in Europe.

The quantitative parameters of the temperature optimum zone depend on the hydrometeorological conditions of a particular year, so in the future it seems possible to predict them under various scenarios of global or regional climate change.

To assess these parameters, the last six years (2016-2021) were selected, which are of particular interest due to the increase in the temperature of the surface layer of atmospheric air in the Volga basin.

2 Object and methods of research

The Kuibyshev reservoir is the largest in Europe and is located in the central part of the Volga basin (Figure 1). The entrance point along the Volzhskaya branch is the Cheboksary HPP, along the Kama branch is the Nizhnekamsk HPP, and the closing point is the Zhigulevskaya HPP. The total length of the reservoir, taking into account the Volga and Kama branches, is 750 km, area - 6450 km^2, maximum width - 41 km, maximum depth - 50 m with a normal retaining level of 53 m BS.

For the mass development of cyanobacteria in a reservoir, the temperature factor is decisive, which is why it is so important to identify the temperature optimum zone (TOZ) of cyanobacteria and determine its parameters: the start and end time of the process, its duration and intensity, which depend on the hydrometeorological conditions of a particular year.

The thermal regime of the reservoir has been studied since its creation. Systematic measurements of surface water temperature at hydrological posts evenly spaced along the length of the reservoir are carried out in the coastal zone of the reservoir twice a day (8 and 20 hours).

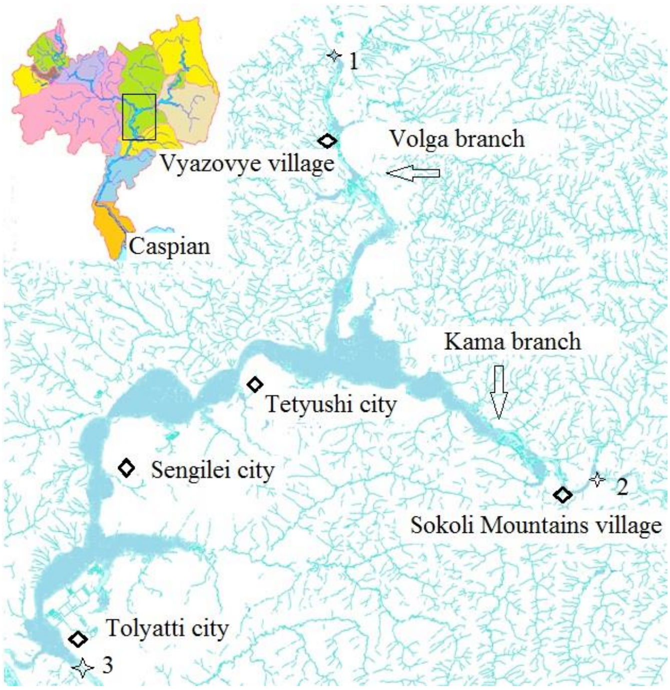


Fig. 1. Location of water temperature observation points at the reservoir (1 - Cheboksary HPP; 2 - Nizhnekamsk HPP; 3 - Zhigulevsk HPP).

According to observations at hydrological posts of Roshydromet [22], the average water temperature during the summer period (June-August) in different parts of the reservoir varies slightly within the range of 18.9-19.4 ºC. In the northern part of the reservoir on the Volga branch (Vyazovye village) the water temperature is 19.2 ºC, on the Kama branch (Sokoly Gory village) - 18.9 ºC, in the mixing zone of the Volga and Kama waters (Tetyushi) -19, 5 ºC and in the central part (Sengilei) - 19.4 ºC, in the southern part (Togliatti) - 19.1 ºC. Seasonally, the highest water temperature is observed in July - 20.8 ºC, and the lowest in June - 17.0 ºC. However, these data are clearly not enough to determine the parameters of the WTP; daily observation data on water temperature are needed.

To study the thermal optimum zone (TOZ) in relation to the process of mass development of cyanobacteria (MDC), data from hydrometeorological observations in the southern part of the reservoir during the period 2016-2021 were used. Surface air temperature measurements were carried out at the weather station in the city of Tolyatti. Air temperature values at 8 hours were used for analysis. Systematic observations of surface water temperature were carried out in the coastal zone of the reservoir (Tolyatti). Measurements were carried out daily at 8 o'clock with a surface (spring) thermometer in a Spindler frame at a depth of at least 1 m. The thermometer division value is 0.2 °C, therefore, the reading from the thermometer was taken with an accuracy of 0.1 °C.

To analyze the time series, an empirical method was chosen based on processing the available hydrometeorological observation data. As a criterion for determining the parameters of the thermal optimum zone, a water temperature of 22 °C was chosen. The number of days with water temperature ≥ 22 °C is considered as the duration of the temperature optimum zone. The number of days with different water temperatures characterizes the degree of intensity of the temperature optimum zone. The intensity of the temperature optimum is divided into gradations: weak (23 °C > t ≥ 22 °C), moderate (24 °C > t ≥ 23 °C), strong (25 °C > t ≥ 24 °C), very strong (26 °C > t ≥ 25 °C) and extreme (t ≥ 26 °C).

3 Results and Discussion

Analysis of observational data for the period 2016-2021 showed (Table 1) that the air temperature (T) in the summer period (June-August) in different years was 21.1-23.8 °C and was 2.0 higher than normal -4.7°C, established for the period 1952-1979 [23]. For the period 2016-2021, the warmest year was 2021, and the coldest year was 2017. Among the summer months, July was the warmest for 2018-2021, and August for 2016 and 2017.

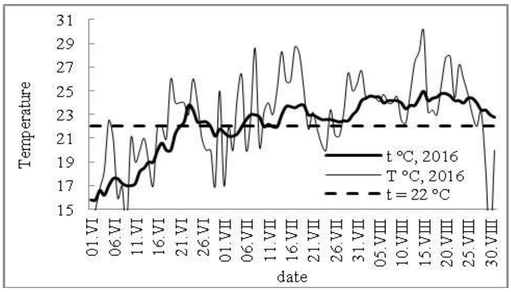
Water temperature (t) in summer in the period 2016-2021 varied within the range of 19.2-23.1 °C and exceeded the norm by 2.0-3.7 °C established for the period 1957-1980 [22], by 2.0-3.7°C. Thanks to this, favorable temperature conditions have developed for the process of mass development of cyanobacteria. However, parameters such as the duration and intensity of the temperature optimum zone (TOZ) differed significantly from year to year. 2021 turned out to be the warmest year.

Table 1. Air and water temperatures in summer 2016-2021.

Year	Month				Month			
	VI	VII	VIII	VI- VIII	VI	VII	VIII	VI- VIII
	Air temperature (T)				Water temperature (t)			
2016	20.3	23.6	24.1	22.7	19.5	22.6	24.1	22.1
2017	18.5	22.2	22.6	21.1	15.2	20.0	22.3	19.2
2018	20.3	24.2	21.7	22.1	16.2	23.4	22.8	20.8
2019	22.4	23.1	18.3	21.3	20.3	21.6	19.7	20.5
2020	18.9	25.3	19.5	21.2	17.9	23.0	21.2	20.7
2021	22.8	24.6	23.9	23.8	20.7	24.3	24.2	23.1
Norm	18.3	20.3	18.6	19.1	16.6	20.5	20.3	19.1

2016. During the summer period (June-August), the average air temperature (T) was 22.7 °C (Table 1) and exceeded the norm by 3.7 °C. The maximum average monthly temperature was observed in August and amounted to 24.1 °C. The excess of the norm for the average monthly air temperature was: in June - by 2.0 °C, in July - by 3.3 °C, in August - by 5.5 °C. The number of days with T ≥ 22 °C was 60. Of these, the number of days with temperatures in the range (23 °C > T ≥22 °C) was 8, in the range (24 °C > T ≥23 °C) - 11, in range (25 °C > T ≥24 °C) – 17, in the range (26 °C > T ≥25 °C) – 8, in the range (27 °C > T ≥26 °C) – 6, in the range (28 °C > T ≥27 °C) – 4, in the range (29 °C > T ≥28 °C) – 5, in the range (30 °C > T ≥29 °C) – 0, in the range (31 °C C > T ≥30 °C) – 1.

Over the summer period (June-August), the average water temperature (t) was 22.1 °C (Table 1) and exceeded the norm by 3.0 °C. The excess of the norm for the average monthly water temperature was: in June by 2.9 °C, in July – by 2.1 °C, in August – by 3.8 °C. In the summer, 2 temperature optimum zones were identified for the process of mass development of cyanobacteria, when a stable temperature transition through 22 °C was observed. The first optimum zone lasted only 8 days and was observed from June 21 to 28 (Figure 2). The second long (58 day) optimum zone was observed from July 5 to September 1. The combined optimum zone for the summer period was 66 days. Weak intensity of the optimum (23°C > t ≥ 22°C) was observed for 22 days, moderate (24°C > t ≥ 23°C) – 20 days, strong (25°C > t ≥ 24°C) – 23 days and very strong (26°C > t ≥ 25°C) – 1 day.



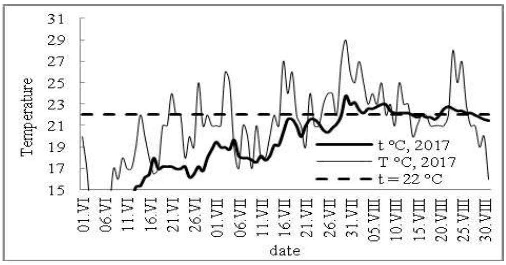


Fig. 2. Location of the temperature optimum zone (t ≥ 22°) in 2016 and 2017.

2017. In summer, the average air temperature (T) was 21.1°C (Table 1) and exceeded the norm by only 2.0°C. The maximum average monthly temperature was observed in August and amounted to 22.6°C. The excess of the norm for the average monthly air temperature was: in June - by 0.2°C, in July - by 1.9°C, in August - by 4.0°C. The number of days with T ≥ 22°C was 40. Of these, the number of days with temperature in the range (23°C > T ≥22°C) was 11, in the range (24°C > T ≥23°C) - 7, in range (25°C > T ≥24 °C) – 6, in the range (26°C > T ≥25 °C) – 7, in the range (27°C > T ≥26 °C) – 3, in the range (28°C > T ≥27°C) – 4, in the range (29°C > T ≥28°C) – 1, in the range (30°C > T ≥29°C) – 1, in the range (31° C > T ≥30 °C) – 0.

Over the summer period, the average water temperature (t) was 19.2°C (Table 1) and exceeded the norm by only 0.1°C. The average monthly water temperature was below normal: in June by 1.4°C, in July – by 0.5°C, and in August above normal by 2.0°C. In summer, 2 temperature optimum zones are identified. The first zone lasted 17 days and was observed from July 29 to August 14 (Figure 2). The second short zone was observed for 9 days from August 20 to 28. The total duration of the temperature optimum zone was 27 days. Of these, the number of days with the intensity of the temperature factor (with t ≥ 23°) was 5 days. A weak intensity of the optimum (23 °C > t ≥ 22 °C) was observed for 21 days and a moderate intensity (24 °C > t ≥ 23 °C) for 5 days.

2018. In summer, the average air temperature (T) was 22.1 °C (Table 1) and exceeded the norm by 3.0 °C. The maximum average monthly temperature was observed in July and amounted to 24.2 °C. The excess of the norm for the average monthly air temperature was: in June - by 2.0 °C, in July - by 3.9 °C, in August - by 3.1 °C. The number of days with T ≥ 22 °C was 52 days. Of these, the number of days with temperatures in the range (23°C > T ≥22 °C) was 5, in the range (24 °C > T ≥23 °C) - 7, in the range (25 °C > T ≥24 °C) – 9, in the range (26 °C > T ≥25 °C) – 10, in the range (27 °C > T ≥26 °C) – 13, in the range (28 °C > T ≥27 °C) – 4, in the range (29 °C > T ≥28 °C) – 3, in the range (30 °C > T ≥29 °C) – 0, in the range (31 °C > T ≥30 °C) – 1.

Over the summer period, the average water temperature (t) was 20.8 °C (Table 1) and exceeded the norm by 1.7 °C. In June, the water temperature was below the norm by 0.4 °C, and in July the excess of the norm was 2.9 °C, in August – 2.5 °C (Fig. 3). In summer, 2 temperature optimum zones were identified: the first was observed for 23 days from June

1 to June 23, and the second was observed for 28 days from July 25 to August 21 (Figure 3). The total duration of ZTO over the summer was 52 days. Of these, the number of days with the intensity of the temperature factor (with t ≥ 23 °C) was 25, with t ≥ 24 °C - 8, with t ≥ 25 °C - 1. Weak intensity of the optimum (23 °C > t ≥ 22 °C) was observed for 27 days, moderate (24 °C > t ≥ 23 °C) – 16 days, strong (25 °C > t ≥ 24 °C) – 28 days and very strong (26 °C > t ≥ 25 °C) - 1 day.

2019. In summer, the average air temperature (T) was 21.3 °C (Table 1) and exceeded the norm by 2.2 °C. The maximum average monthly temperature was observed in July and amounted to 23.1 °C. The excess of the norm in June was 4.1 °C, in July – 2.8 °C. In August, the air temperature was 0.3 °C below normal. The number of days with T ≥ 22°C was 48 days. Of these, the number of days with temperatures in the range (23°C > T ≥22 °C) was 9, in the range (24 °C > T ≥23 °C) - 11, in the range (25 °C > T ≥24 °C) – 4, in the range (26 °C > T ≥25 °C) – 9, in the range (27 °C > T ≥26 °C) – 5, in the range (28 °C > T ≥27 °C) – 6, in the range (29 °C > T ≥28 °C) – 2, in the range (30 °C > T ≥29 °C) – 2, in the range (31 °C > T ≥30 °C) – 0.

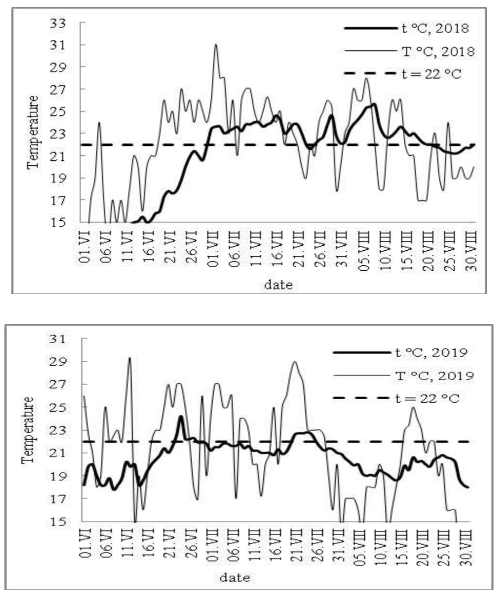


Fig. 3. Location of the temperature optimum zone in 2018 and 2019.

Over the summer period, the average water temperature (t) was 20.5 °C (Table 1) and exceeded the norm by 1.4 °C. The excess of the norm for the average monthly water temperature was: in June by 1.3 °C, in July – by 2.5 °C, in August – by 0.9 °C. In summer, 2 temperature optimum zones were identified: the first was observed for 5 days from June 23 to 27, and the second was observed for 6 days from July 21 to 26 (Figure 3). The total duration of the temperature optimum zone over the summer was 11 days. A weak intensity of the optimum (23 °C > t ≥ 22 °C) was observed for 10 days, a medium intensity (24 °C > t ≥ 23 °C) was absent, and a strong intensity (25 °C > t ≥ 24 °C) was observed for 1 day.

2020. In summer, the average air temperature (T) was 21.2 °C (Table 1) and exceeded the norm by 2.1 °C. The maximum average monthly temperature was observed in July and amounted to 25.3 °C. The excess of the norm for the average monthly air temperature was: in June - by 0.6 °C, in July - by 5.0 °C, in August - by 0.9 °C. The number of days with T ≥ 22 °C was 36 days. Of these, the number of days with temperatures in the range (23°C > T ≥22 °C) was 4, in the range (24 °C > T ≥23 °C) - 4, in the range (25 °C > T ≥24 °C) – 6, in the range (26 °C > T ≥25 °C) – 7, in the range (27 °C > T ≥26 °C) – 8, in the range (28 °C > T ≥27 °C) – 4, in the range (29 °C > T ≥28 °C) – 0, in the range (30 °C > T ≥29 °C) – 0, in the range (31 °C > T ≥30 °C) – 3.

Over the summer period, the average water temperature (t) was 20.7 °C (Table 1) and exceeded the norm by 1.6 °C. In June, the water temperature was below the norm by 0.4 °C, and in July the excess of the norm was 2.9 °C, in August – 2.5 °C. In summer, 2 temperature optimum zones were identified: the first was observed for 9 days from July 4 to July 11, and the second was observed for 27 days from July 13 to August 8 (Figure 4). The total duration of the temperature optimum zone over the summer was 35 days. Weak intensity of the optimum (23°C >t ≥ 22°C) was observed for 10 days, medium (24°C >t ≥ 23°C) – 18 days, strong (25°C >t ≥ 24°C) – 6 days and very strong (26 °C > t ≥ 25 °C) – 1 day (Figure 4).

2021. In summer, the average air temperature (T) was 23.8 °C (Table 1) and exceeded the norm by 4.7 °C. The maximum average monthly temperature was observed in July and amounted to 24.6 °C. The excess of the norm for the average monthly air temperature was: in June - by 4.5 °C, in July - by 4.3 °C, in August - by 5.3 °C. The number of days with T ≥ 22 °C was 64. Of these, the number of days with temperatures in the range (23 °C > T ≥22 °C) was 5, in the range (24 °C > T ≥23 °C) - 8, in range (25 °C > T ≥24 °C) – 8, in the range (26 °C > T ≥25 °C) – 8, in the range (27 °C > T ≥26 °C) – 10, in the range (28 °C > T ≥27 °C) – 5, in the range (29 °C > T ≥28 °C) – 12, in the range (30 °C > T ≥29 °C) – 3, in the range (31 °C C > T ≥30 °C) – 2, in the range (32 °C > T ≥31 °C) – 2, in the range (33 °C > T ≥32 °C) – 1.

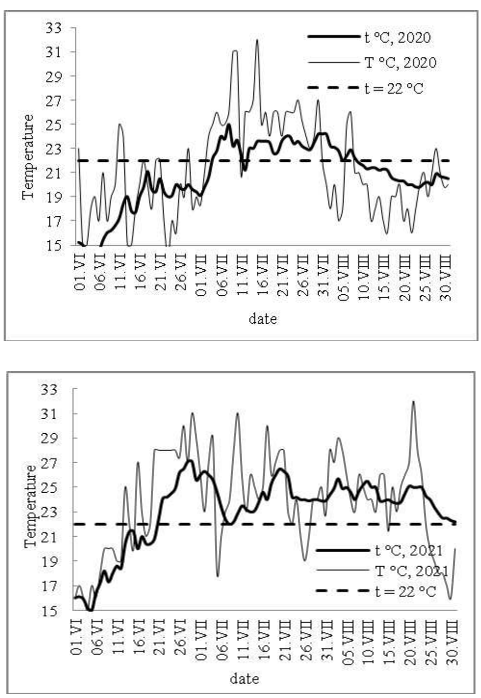


Fig. 4. Location of the temperature optimum zone in 2020 and 2021.

Over the summer period, the average water temperature (t) was 23.1 °C (Table 1) and exceeded the norm by 4.0 °C. The excess of the norm for the average monthly water temperature was: in June by 4.1 °C, in July - by 3.8 °C, in August - by 3.9 °C. In summer, 2 temperature optimum zones are identified. The first optimum zone lasted only 17 days and was observed from June 21 to July 8 (Figure 4). The second long (55th day) optimum zone was observed from July 9 to September 1. The combined optimum zone for the summer period was 72 days. Weak intensity of the optimum (23 °C > t ≥ 22 °C) was observed for 10 days, moderate (24 °C > t ≥ 23 °C) – 15 days, strong (25 °C > t ≥ 24 °C) – 23 days, very strong (26 °C > t ≥ 25 °C) – 24 days and extreme (t ≥ 26 °C) -7 days.

Analysis of observational data showed that the temperature optimum zone was observed annually in the Kuibyshev Reservoir during the period 2016-2021, when the summer temperature of the surface layer of water steadily passed through 22 °C. However, the degree of intensity, duration, start and end dates of the temperature optimum zone changed significantly and depended mainly on air temperature (Table 2).

Table 2. Temperature optimum zone parameters.

Year	Borders of the TOZ	TOZ period	Number of days with different intensities				
			23 > t ≥22	24 > t ≥23	25 > t ≥24	26 >t ≥25	t ≥26
2016	21.VI - 01.IX	66	22	20	23	1	-
2017	29.VII - 28.VIII	27	22	5	-	-	-
2018	01.VII - 21.VIII	52	16	25	8	1	-
2019	23.VI - 26.VII	11	10	-	1	-	-
2020	04.VII - 8.VIII	35	10	18	6	1	
2021	21.VI - 01.IX	72	10	15	23	24	7

The average duration of the temperature optimum for the process of mass development of cyanobacteria for 2016-2021 was 44 days. The longest duration was observed in 2021 and amounted to 72 days, and the shortest in 2019 and amounted to only 11 days. Consequently, the most favorable year for the process of mass development of cyanobacteria is 2021, and the most unfavorable year is 2019.

On average, July 1 is taken as the start date of the temperature optimum, and August 19 as the end date. The early start date of the temperature optimum is June 21 (2016 and 2021), and the late date is July 4 (2020). The early end date of the temperature optimum is July 26 (2019), the late date is September 1 (2021).

In terms of the intensity of the temperature optimum, the most favorable year for the development of the process of mass development of cyanobacteria is 2021, in which 15 days are characterized by moderate intensity, 23 days by strong intensity, 24 days by very strong intensity and 7 days by extreme intensity.

4 Conclusion

An analysis of joint observations of air and water temperatures at the Kuibyshev Reservoir in the period 2016-2021 showed that summer air temperature in the surface layer of the atmosphere forms a temperature optimum zone for the process of mass development of cyanobacteria.

The temperature optimum zone for the mass development of cyanobacteria was observed annually in the Kuibyshev Reservoir. Parameters such as the degree of intensity, duration, start and end dates of the temperature optimum changed significantly in the period 2016-2021 and depended on air temperature.

In terms of the duration and intensity of the temperature optimum, the most favorable year for the development of the process of mass development of cyanobacteria is 2021. The duration of the temperature optimum zone was 72 days, of which 10 days were characterized by low intensity, 15 days by moderate intensity, 23 days by strong intensity, 24 days by very strong intensity and 7 days by extreme intensity. 2019 is an unfavorable year for the development of mass development of cyanobacteria. The duration of the temperature optimum zone was only 11 days, of which 10 days were characterized by weak intensity and 1 day by strong intensity.

With increasing temperature, the duration and intensity of the temperature optimum zone increase. Consequently, with a further increase in air temperature due to global warming, the temperature optimum zone will expand. An increase in the duration and intensity of the temperature optimum activates the process of mass development of cyanobacteria, which will negatively affect the ecological state and water quality of the Kuibyshev Reservoir.

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