Influence of the water discharge of the Kuibyshev reservoir on the dynamics of the ecosystem of the Seredysh and Bakhilovsky islands, the Volga River, Russia

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Abstract. The state of the ecosystem of the protected islands Seredysh and Bakhilovsky (former Shalyga) is significantly affected by the water consumption in the power site of the Zhigulevskaya Dam. The 62-year dataset was analyzed to study the patterns of temporal variability of water discharge from the filling of the Kuibyshev Reservoir to the present. Long-term variability of the water discharge is due to climatic conditions in the Volga River basin, it follows to some extent the 22-year cycle of solar activity. Natural seasonal variability of the water discharge is altered by regulation at the Zhigulevskaya Dam, especially under unfavorable conditions for the formation of the water flow. The periods of low-water, high-water and medium water content were defined in regard to the annual water consumption. The low-water period lasted 19 years from 1958 to 1976, the high water period, 20 years from 1977 to 1998, and the period of medium water availability, 23 years from 1999 through 2019. Extreme high-water and low-water years, which had an adverse effect on the functioning of the islands’ ecosystem, were calculated using the empirical data on the water flow rate. During the spring flood of extremely high-water years, the water level in the reservoir increased sharply, so a part of the island was flooded. In the summer dry season of extremely dry years, the water level decreased, so the island area increased due to the shore retreat and appearing of sandbanks around the island. The negative impact of the water discharge on the ecological state of the islands may increase if the rules for regulating the water flow at the Zhigulevskaya Dam are violated.

1. Introduction
The methods of satellite imagery of the Earth made it possible to determine the influence of the hydrological regime on the ecological state of various territories and island systems of the coastal zone. Such large-scale studies are necessary, but insufficient if not taking into account the field data. It is extremely important to study the patterns of changes in water discharge and their impact on the state and dynamics of island ecosystems situated reservoirs near hydropower plants [1].

The Seredysh and Bakhilovsky (former Shalyga) islands are located on the Saratov Reservoir near the Zhigulevskaya Dam; these islands are the part of the I.I. Sprygin Zhiguli State Nature Biosphere Reserve. The islands resemble the silhouette of a giant fish, swimming against the current and hoping to overcome the dam on the Volga River (figure 1).

The Zhigulevskaya Dam locates only 12 km upstream the islands. The island relief is flat, the highest point is 5.0 m above the water level of the Saratov Reservoir. The island is about 5.5 km long,
the widest (central) part is 1.3 km. The Lake Kolchuzhnoe (Klyuchuzhino) is located on the island. The lake is connected with the reservoir through a channel during the spring flood [2].

This protected island is clearly visible from the Zhiguli Mountains near the village of Bakhilova Polyana. The sandy shores of the island welcome a large number of migratory birds, which use the island for rest and feeding. Half of the island is covered with woody vegetation, including pine forest. The island is not densely populated with animals. In winter, hares, roe deer, and elk appear on the island. During the years of high abundance of small rodents (mice), foxes also visit it [3].

The water discharge at the Zhigulevskaya Dam has a significant impact on the state of the ecosystem of the Bakhilovsky Island. The water level in the area of the island is significantly preconditioned by the flow rate. The water flow at the dam has been regulated for over 60 years. However, the patterns of interannual and seasonal fluctuations in water discharge have not been fully studied. As a result, it becomes difficult to study the dynamics of the ecosystem of the Bakhilovsky Island.

2. Materials and methods

Monthly data on the water discharge in the section of the Zhigulevskaya Dam were obtained from three main sources [4, 5]: (1) "Hydrological Yearbook", (2) "Annual data on the regime and resources of surface waters of the land", and (3) information on the Zhiguli hydroelectric power plant (courtesy of RusHydro PJSC).

The database on the water discharge in the outlet section of the Kuibyshev Reservoir (Zhigulevskaya Dam) was formed for the period from 1958 to 2019.

Figure 1. The Seredysh Island (1) and the Bakhilovsky (former Shalyga) Island (2).

The Bakhilovsky Island has a long history; initially, there were two islands, Seredysh and Shalyga, on the Volga River near the village of Bakhilova Polyana. The Seredysh Island was the first to form in
the middle of the river, later, the Shalyga Island appeared. For a long time, the Volga River moved the sandy shores of Shalyga Island towards the Seredysh Island. Gradually, a sand spit has appeared between the islands, and the two islands have connected by an isthmus [6-12]. This was possible due to extremely dry years in the 1920s-1930s. The natural period of development of the Bakhilovsky Island ended after the construction of the Zhigulevskaya Dam and establishing of the Kuibyshev Reservoir.

The anthropogenic period of the islands’ development begins in 1957; it is characterized by a sharp change in hydrological processes. Comparative analysis of the Volga River discharge in the natural and anthropogenic periods showed a significant decrease in the water runoff in the spring and an increase of the low-water period. The character of channel processes has changed significantly in the river sections located downstream of the Zhigulevskaya Dam. Due to the decreased water exchange rate, most of the river sediments retained in the Kuibyshev Reservoir. The water of the Saratov Reservoir, free of sediments, began to spend excess energy on the erosion of the island [13, 14].

As soon as the Bakhilovsky Island was downstream of the Zhigulevskaya Dam, the hydrological regime changed. The flow velocity its transport capacity has increased. The level of the spring flood has decreased, but its duration has increased. The river level has dropped significantly. The river has practically ceased to freeze along the entire coast of the reserve. Due to the periodic operation of the spillway dam during the spring flood, the northern shores of the islands began to erode, and the sandbanks have formed in the southwestern tip of the island. The islands’ area has increased significantly and amounted to 671 hectares.

A new stage in the island development began after the construction of the Saratov Dam. The water level near the town of Balakovo increased by 18 m comparing to the natural low-water level. The Bakhilovsky Island was caught to a zone of regressive accumulation. The water level has risen by 4 m in the area of the protected island. Almost complete flooding of all coastal sandbanks and vegetation of the southeastern coast of the Seredysh Island occurred. A large backwater has formed on the Shalyga Island. It exceeded the area of the remaining sandy shores. The area of the islands has decreased by 129 hectares in comparison with the previous period before the construction of the Saratov Dam. The flood period shifted towards the summer dry season. The water frees the island only in the second half of June.

The water flow of the Volga River in the alignment of the Zhigulevskaya Dam is mainly regulated in favor to the electricity demand. Meantime, such regulation violates the natural processes of the formation of the seasonal distribution of river water flow [15]. Therefore, it is very difficult to predict extreme low and high water discharge in the Saratov Reservoir, which primarily directs the channel processes and the state of the ecosystems of the Bakhilovsky Island.

3. Results

The average annual water discharge of the Kuibyshev Reservoir was 7,694 m$^3$ s$^{-1}$ for 62 years at the section of the Zhigulevskaya Dam. The lowest annual water discharge was 5,270 m$^3$ s$^{-1}$ in 1975. The highest water discharge was 10,431 m$^3$ s$^{-1}$ in 1990. The highest annual water consumption exceeded the lowest twofold.

3.1. Long-term changes

High-water and low-water years were defined based on the results of calculating the empirical water consumption for the period of 1958–2019. The dry years were low-extreme, middle, and highly extreme (very dry) [16]. During low-extreme dry year, the water scarcity is 50-75%, during middle dry year, 75-90%, and very dry year, over 90%. Low-extreme high-water year is characterized by the water scarcity of 50-25%, middle year, 25-10%, and extremely high-water year, less than 10%.

Over the period of the Kuibyshev Reservoir existence from 1958 to present, extremely high-water years ($P \leq 10\%$) were 1966, 1979, 1981, 1990, 1991, and 1994. The average annual water consumption for these years ranges as 9,193-10,431 m$^3$ s$^{-1}$. Very dry years ($P \geq 90\%$) were 1967, 1973, 1975, 1976, 1977, and 1996. The average annual water consumption for these years was 5,270-
5,984 m$^3$ s$^{-1}$. Over 62 years of observations, the number of extremely high-water and low-water years was the same, i.e. six years of each type (figure 2).

Since 1958, the listed extreme wet and dry years affected significantly the dynamics of the islands’ ecosystem. During the spring flood in extremely high-water years, the water level in the reservoir increased, and a part of the island was flooded. In the summer dry season of very dry years, the water level decreased, the islands’ area increased due to the drainage of sandbanks around the island. The negative impact of water consumption on the state of the islands may increase if the rules for regulating the water flow at the Zhigulevskaya Dam are violated.

Three periods with different water content were defined in regard to the dynamics of average annual water consumption: low-water, high-water, and medium years (figure 2). The dry period lasted 20 years from 1958 to 1977. This period includes five out of six extremely dry years: 1967, 1973, 1975, 1976, and 1977. The high-water period lasted 19 years from 1978 to 1996. This period was characterized by five out of six extremely high-water years: 1979, 1981, 1990, 1991 and 1994. The third period lasted 23 years from 1997 to 2019. Long-term changes in annual water consumption are due to natural and climatic conditions in the Volga River basin. The duration of periods with different water content averages 21.5 years and is close to the 22-year climatic cycle of solar activity.

3.2. Seasonal changes

Monthly water consumption is characterized by a significant variability comparing to that of the annual water consumption. Over 62 years, the average monthly water consumption of the Kuibyshev Reservoir was 7,694 m$^3$ s$^{-1}$ in the alignment of the Zhigulevskaya Dam. The lowest monthly water consumption was 2,127 m$^3$ s$^{-1}$ (August 2010), the highest, 33,500 m$^3$ s$^{-1}$ (May 1979). The highest water consumption exceeded the lowest one by 16 times.

![Figure 2. Average annual water consumption for the period of 1958-2019 in the area of the Bakhilovsky Island](image-url)

The difference of seasonal changes in the water consumption depended on the water content of a particular year. In high-water years, the range of fluctuations increased in comparison with the year of average water availability, in low-water years, decreased. The seasonal distribution of the water consumption in the most extremely high-water year (1990) and the most extremely low-water year (1976) are shown in figure 3.
year (1975) is shown on figure 3. The difference of fluctuations of the water consumption in 1990 was 4,110-22,600 m$^3$/s, in 1975, 3,700-11,000 m$^3$/s.

![Figure 3](image.png)

**Figure 3.** Seasonal variability of the water consumption in the extremely dry year of 1975 and the extremely wet year of 1990.

The seasonal variability of the water consumption in the extremely dry year of 1975 had one well-pronounced maximum during the spring flood, with a peak observed in May. Similar pattern is typical for natural conditions in the basin of the middle and lower reaches of the Volga River. The seasonal variability of the water consumption in the extremely high-water year of 1990 has two maxima due to the intensive regulation of water flow in the section of the Zhigulevskaya Dam. The first maximum is observed during the spring flood in May, the second, during the autumn dry season in October. During the winter low-water period, water discharge in dry and high-water years practically did not differ. Consequently, there is a question why they did large discharges in the winter of a dry year on the eve of the expected low water during the spring flood? Such seasonal regulation is due only to the interests of hydropower and does not take into account the natural regional features of the intra-annual distribution of water flow.

According to the correlation analysis, the natural ratio between the average value, maximum and minimum water consumption in a particular year is misbalanced in the Saratov Reservoir in the section of the Zhigulevskaya Dam. This pattern is observed most clearly in extremely dry and high-water years (Table 1).

Over 62 years of observations, year of 1990 was the most extreme high-water year with an empirical supply of 1.7%. However, at the peak of the spring flood, in May, its maximum average monthly water consumption was only 22,600 m$^3$/s, and the difference of the minimal and maximal water rates was 18,490 m$^3$/s. In the extremely high-water year of 1979, when the water scarcity was 6.4%, the maximum water consumption was much higher (33,500 m$^3$/s), and so was the difference (26,870 m$^3$/s). The Bakhilovsky Island was partially submerged during the spring flood of 1979. The water level in the area of the island has increased up to 30.76 m (Baltic system).

Over 62 years of observations, the year of 1975 was the most extremely dry year with an empirical supply of 99.5%. However, during the low-water period, in September, its minimum average monthly water consumption was 3,700 m$^3$/s, the difference, 7,300 m$^3$/s. In the extremely high-water year of 1973, when the water scarcity was 98.3%, the minimum discharge was significantly lower (3,050 m$^3$/s), but the difference exceeded that of the year of 1975 almost twofold (13,350 m$^3$/s). The year 2010,
which cannot be referred to extremely dry year, turned out to be unusual in terms of the seasonal distribution of water runoff. During the low-water period in August, the minimum average monthly water consumption dropped dramatically down to 2,010 m$^3$ s$^{-1}$. The area of the island has increased significantly, its shape has changed during the summer low-water period of 2010. In August, the average monthly water consumption dropped dramatically down to 2,127 m$^3$ s$^{-1}$, and the water level dropped to 27.75 m (Baltic system).

### Table 1. Mean, maximum, minimum, and difference of water consumption in extremely dry and wet years. $P$ is the water scarcity.

| Year | Mean annual consumption water (m$^3$ s$^{-1}$) | $P$ (%) | Maximum monthly water consumption (m$^3$ s$^{-1}$) | Month | Minimum monthly water consumption (m$^3$ s$^{-1}$) | Month | Difference (m$^3$ s$^{-1}$) |
|------|---------------------------------------------|--------|-----------------------------------------------|-------|-----------------------------------------------|-------|-----------------------------|
| 1990 | 10,431                                      | 1.7    | 22,600                                        | May   | 4,110                                         | March | 18,490                      |
| 1994 | 10,376                                      | 3.3    | 23,829                                        | May   | 6,178                                         | January | 17,651                    |
| 1979 | 10,076                                      | 6.4    | 33,500                                        | May   | 6,630                                         | December | 26,870                    |
| 1991 | 10,056                                      | 6.7    | 27,200                                        | May   | 5,360                                         | October | 21,840                     |
| 1966 | 9,274                                       | 8.3    | 29,100                                        | May   | 4,500                                         | September | 24,600                    |
| 1981 | 9,193                                       | 9.9    | 24,300                                        | May   | 6,060                                         | December | 18,240                     |
| 1977 | 5,984                                       | 91.7   | 14,500                                        | May   | 3,370                                         | March   | 11,130                      |
| 1976 | 5,944                                       | 93.3   | 12,800                                        | May   | 3,390                                         | March   | 9,410                       |
| 1967 | 5,785                                       | 95.5   | 14,000                                        | May   | 4,250                                         | October | 9,750                       |
| 1996 | 5,369                                       | 96.7   | 12,067                                        | May   | 3,598                                         | November | 8,469                      |
| 1973 | 5,290                                       | 98.3   | 16,400                                        | May   | 3,050                                         | November | 13,350                    |
| 1975 | 5,270                                       | 99.5   | 11,000                                        | May   | 3,700                                         | September | 7,300                      |

### 4. Conclusion

Our results evidence that the Saratov Reservoir is a natural-technical water body, where the natural ratio between the average value, maximum and minimum water consumption in a particular year is artificially misbalanced. Therefore, in the section of the Zhigulevskaya Dam, it is impossible to predict reliably the extreme low-water and extreme high-water average monthly water consumption, which changes the direction of the channel processes of the Volga River in vicinity of the Bakhilovsky Island and so the state of its ecosystem.

Long-term and seasonal changes in the water consumption of the Volga River in the alignment of the Zhigulevskaya Dam are a key factor in the dynamics of channel processes and the development of the ecosystem of the Bakhilovsky Island. Seasonal fluctuations in the average monthly water discharge of the Volga River have a more significant impact on the development of Bakhilovsky Island and the state of its ecosystems than the interannual fluctuations in the average annual water consumption. During the periods of extreme high-water and low water, the influence of seasonal variability of average monthly water consumption increases.

The conservation of the ecosystem of the protected Bakhilovsky Island needs a change in the system of seasonal regulation. Adjustment of the regulation system of the water consumption in the Saratov Reservoir should reduce the negative impact of regulation of water flow in extreme high-water and low-water years on the state of the island.

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