Interannual and intra-annual changes in the Volga River water discharge in the alignment of the Zhigulevsk hydroelectric complex

V A Seleznev
Samara Federal Research Scientific Center RAS, Institute of Ecology of the Volga River Basin RAS, Togliatti, Russia
E-mail: seleznev53@mail.ru

Abstract. Interannual and intra-annual changes in river water flow play a decisive role in the formation of water quality and the functioning of aquatic ecosystems. For a quantitative assessment of long-term and seasonal changes in the water flow of the Volga River, an analysis of water discharge in the outlet section of the Kuibyshev reservoir (Zhigulevsky hydroelectric complex) for the period 1958-2019 was carried out. Almost the entire water flow of the Volga River passes through the bottom spillways of the hydroelectric power station and the overflow dam of the Zhigulevsky hydroelectric complex. The results of time series analysis showed that the average annual water discharge was 7.7×10³ m³/s, the highest water discharge was 10.4×10³ m³/s, and the lowest water discharge was 5.3×10³ m³/s. Over a long-term observation period (61 years), it was established that the water content of the river is characterized by a change in low water and high-water periods. Statistical analysis revealed a positive trend for an increase in the average annual water discharge of the Volga River by 700 m³/s. Extremely low-water (1996, 1977, 1976, 1975, 1973, 1967) and extremely high-water (1994, 1991, 1990, 1981, 1979, 1966) years have been identified. The regulation of water flow at the Zhigulevsky hydroelectric complex has formed the seasonal variability of water discharge, which is characteristic of technical water bodies. Within the year, three periods are distinguished: winter low-water period (December-March), spring high water (April-June), and summer-autumn low-water period (July-November). The highest water discharges were observed during the spring flood (8.7-19.6×10³ m³/s). During the winter and summer-autumn low-water period, the water discharge was 5.5-6.5×10³ m³/s. The amplitude of fluctuations in the average monthly water discharge for the entire observation period was 2.1-33.5×10³ m³/s.

1. Introduction
The water discharge of the Volga River in the outlet section of the Kuibyshev reservoir (Zhigulevsky hydroelectric complex) continuously changes over time. Interannual changes in water discharge mainly depend on natural and climatic factors, and intra-annual changes depend on the regime of regulation of water flow through the bottom spillways of the hydroelectric power station and the overflow dam of the Zhigulevsky hydroelectric complex. Almost all the water flow of the Volga River (97%) passes through the section of the Zhigulevsky hydroelectric complex [1]. Interannual and intra-annual changes in the Volga River water discharge at the section of the Zhigulevsky hydroelectric complex have a direct impact on the formation of water quality [2, 3] and the functioning of aquatic ecosystems of the Kuibyshev and Saratov reservoirs [4, 5]. The influence of water discharges can be
traced both in the Volgograd reservoir and in the unregulated section of the Volga River from Volgograd to the Caspian Sea [6].

Many articles [7-14] are devoted to the study of the water runoff of the Volga River, in which interannual changes in water runoff were analyzed since the beginning of the organization of instrumental observations. However, changes in water discharge since the creation of the Kuibyshev reservoirs have not been sufficiently studied, especially with regard to intra-anual changes in water runoff. With the development of the urbanization process, special attention is paid to assessing the influence of anthropogenic factors on the formation of water flow. The relevance of the study of changes in water runoff has increased in the context of global climatic changes that began in the seventies of the twentieth century.

Data on the water discharge of the Volga River are necessary for assessing and forecasting water quality and the ecological state of reservoirs, as well as for determining the anthropogenic load from point and diffuse sources of negative impact [15-17]. Therefore, the purpose of this work is to quantitatively estimate the interannual and intra-annual changes in the water discharge of the Volga River in the alignment of the Zhigulevsky hydroelectric complex since the creation of the Kuibyshev reservoir (1958–2019).

2. Materials and Methods
The section of the Zhigulevsky hydroelectric complex is simultaneously the closing section of the Kuibyshev reservoir, the largest in the Volga-Kama cascade [18]. It was formed in 1957 by the water retaining structures of the Zhigulevsky hydroelectric complex. The structure of the hydroelectric complex includes: a hydroelectric power station, combined with bottom spillways; concrete spillway dam; two-stage gateway (figure 1). The entrance sections for the Kuibyshev reservoir are the closing sections of the Cheboksary (Volga branch) and Nizhnekamsky (Kama branch) reservoirs.

![Figure 1. Zhigulevsky hydroelectric complex or the closing section of the Kuibyshev reservoir](image)

Currently, the water resources of the Kuibyshev reservoir are used for drinking and domestic water supply, energy, water transport, industrial and agricultural water supply. The reservoir is also used for fisheries and recreational purposes.

The length of the reservoir along the Volga direction is 510 km, and along the Kama direction - 270 km. The greatest width of the reservoir in the region of the Volga-Kamsky reach is 40 km. The average depth of the reservoir is 8.9 m, the greatest depth in the Pryplotinny reach area is 40.0 m. The total volume of the Kuibyshev reservoir at a normal backwater level is more than 57 km³. Before the
construction of the Zhigulevsky hydroelectric complex, the average volume of water flow for the period 1881-1957 was amounted to 255 km$^3$. The maximum annual water runoff was 389 km$^3$ and was observed in 1926, the minimum annual water runoff was –161 km$^3$ and was observed in 1937 [6].

The useful volume of the reservoir is about 31 km$^3$ and makes it possible to carry out seasonal, weekly and daily regulation of water flow in the interests of various water users. Interannual regulation of water flow is impossible, since the capacity of the Kuibyshev reservoir is insufficient. Seasonal regulation of water flow is carried out by the operating organization – the branch of JSC RusHydro – Zhigulevskaya HPP in accordance with the Basic Rules for the Use of Water Resources of the Kuibyshev Reservoir on the Volga", approved by the order of the Ministry of Land Reclamation and Water Management of the RSFSR dated November 11, 1983 No. 596.

To study changes in water discharge in the outlet section of the Kuibyshev reservoir, data obtained from the department of hydrology of the Zhigulevsky hydroelectric complex were used. Average monthly water discharge ($q$) for the period 1958-2019 were analyzed using the Statistica program.

3. Results and Discussion

The water flow of the river Volga in the outlet section of the Kuibyshev reservoir does not remain constant and is characterized by long-term and intra-annual changes. Changes in average annual water discharge mainly depend on climatic fluctuations in the Volga basin. The intra-annual distribution of water consumption is determined not only by natural causes, but also by the regulation of water flow at the structures of the Zhigulevsky hydroelectric complex.

3.1. Average annual changes in water discharge

We used two methods to analyze the interannual changes in water discharge: 1 - comparison of average annual water discharge ($Q$); 2 - analysis of "smoothed" changes by 5-year moving averaging (figure 2).

![Figure 2. Water discharge of the Volga River:](image)

**Reception 1.** Average annual water discharge of the Volga River ($Q$) for the period 1958-2019, was $7.7 \times 10^3$ m$^3$/s. The maximum average annual water discharge was observed in the high-water year 1990 and amounted to $10.4 \times 10^3$ m$^3$/s, the minimum discharge was observed in the low-water year 1975.
and amounted to $5.3 \times 10^3$ m$^3$/s. Consequently, the average annual water discharge changed by almost 2 times.

Based on the results of calculating the empirical provision of water discharge ($\delta$), low-water and high-water years were determined [8]. Over the 61-year period, there were 6 extremely high-water ($\delta \leq 10\%$) years: 1994, 1991, 1990, 1981, 1979, 1966 (Table 1). Among high-water years, water discharge varied from 9.2 to $10.4 \times 10^3$ m$^3$/s. Extremely dry years ($\delta \geq 90\%$) were observed: 1991, 1990, 1981, 1979, 1973, 1967. Among dry years, water discharge varied from 5.3 to $6.0 \times 10^3$ m$^3$/s. In extremely high-water years, the amplitude ($\Delta$) of fluctuations in intra-annual changes in water discharge is significantly greater than in extremely low-water years. The largest amplitude was observed in the high-water year 1979 and amounted to $26.9 \times 10^3$ m$^3$/s, and the smallest amplitude in the low-water year 1975 was $7.3 \times 10^3$ m$^3$/s.

**Table 1. Water discharge in extremely wet and dry years**

| Year   | $Q$, $\times 10^3$ m$^3$/s | $\Delta$, $\times 10^3$ m$^3$/s | Year   | $Q$, $\times 10^3$ m$^3$/s | $\Delta$, $\times 10^3$ m$^3$/s |
|--------|---------------------------|-------------------------------|--------|---------------------------|-------------------------------|
| 1966   | 9.3                       | 24.6                          | 1967   | 5.8                       | 9.8                           |
| 1979   | 10.1                      | 26.9                          | 1973   | 5.3                       | 13.4                          |
| 1981   | 9.2                       | 18.2                          | 1975   | 5.3                       | 7.3                           |
| 1990   | 10.4                      | 18.5                          | 1976   | 5.9                       | 9.4                           |
| 1991   | 10.1                      | 21.8                          | 1977   | 6.0                       | 11.1                          |
| 1994   | 10.4                      | 17.7                          | 1996   | 5.4                       | 8.5                           |

If we consider the earlier period from the beginning of systematic hydrological observations on the Volga (1898) to the creation of the Kuibyshev reservoir, then 1921, 1937 and 1938 should be attributed to extreme dry years, and 1916, 1926 and 1947 to extreme high-water years [8].

**Reception 2.** Analysis of "smoothed" changes in water discharge by means of 5-year moving averaging $Q$ shows the possibility of identifying three periods that differ in water content (Figure 1). The earliest 20-year period (1958-1977) is characterized by low water and includes five out of six extremely low-water years: 1977, 1976, 1975, 1973 and 1967. The next 22-year period (1978-1999) follows in chronological order. is characterized by high water content and includes five out of six extremely high-water years: 1994, 1991, 1990, 1981, and 1979. The current 20-year period (2000–2019) can be characterized as a period of average water availability. The highlighted long-term frequency of changes in the average annual water discharge is most likely due to the cyclical nature of climatic factors in the formation of water runoff in the drainage area of the Volga basin.

### 3.2. Intra-annual changes in water discharge

Within a year, the average monthly water discharge was characterized by intra-annual variability (Table 2, Figure 3), characteristic of reservoirs as natural and technical water bodies. Regulation at the hydroelectric complex leads to a redistribution of water flow between seasons. The hydrograph of reservoirs is being transformed, and connections between average ($q$), maximum ($q_{\text{max}}$) and minimum ($q_{\text{min}}$) water flows are disrupted. Compared to the natural regime of the Volga River, intra-annual regulation of water flow in the Kuibyshev reservoir reduces peak water consumption and increases the duration of the spring flood period. In the period of winter and summer-autumn low-water periods, regulation at the Zhigulevsky hydroelectric complex increases water discharge [2].
Table 2. Water discharge of the river Volga (section of the Zhigulevsky hydroelectric complex) for 1958–2019, $\times 10^3$ m$^3$/s

| Water discharge | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $q$             | 6.0 | 6.0 | 5.8 | 10.5| 19.6| 8.7 | 6.5 | 5.9 | 5.7 | 5.5 | 5.9 | 6.2 |
| $q_{\min}$     | 3.9 | 3.4 | 3.4 | 2.6 | 11.0| 1.3 | 3.6 | 2.1 | 3.6 | 3.7 | 3.1 | 3.4 |
| $q_{\max}$     | 8.6 | 9.0 | 9.7 | 21.8| 33.5| 16.8| 14.1| 9.9 | 8.6 | 11.9| 12.4| 9.0 |
| $q_{\max} - q_{\min}$ | 4.7 | 5.6 | 6.3 | 19.2| 22.5| 15.5| 10.5| 7.8 | 5.0 | 8.2 | 9.3 | 5.6 |

Analysis of intra-annual changes in water discharge allows us to distinguish three hydrological seasons: winter low water (December -March), spring high water (April-June), and summer – autumn low water (July-November). The shortest is the period of spring flood, when the greatest amplitude of fluctuations in water discharge was observed (8,7-18,3$\times 10^3$ m$^3$/s). At the beginning of the spring flood in April, an increase in water discharge was observed, in May there was a peak of flood, and in June, a decline in spring flood and a decrease in water discharge to minimum values during the spring flood. Steady water discharge was observed during the winter low-water period and amounted to 5,9-6,3$\times 10^3$ m$^3$/s. The period of the summer-autumn low-water period is the longest, when the water discharge is stable (5,3-6,5$\times 10^3$ m$^3$/s) and does not differ much from the discharge during the winter low-water period.

![Figure 3](image-url)  

Figure 3. Intra-annual changes in water discharge of the Volga River in the alignment of the Zhigulevsky hydroelectric complex

The boundaries and duration of hydrological seasons for each specific year depended on weather conditions and seasonal regulation of water flow at the Zhigulevsky hydroelectric complex. This was especially true during the spring flood period. For example, the spring flood season in 2002 lasted from April 16 to June 21 and amounted to 66 days, while in 2003 it lasted from April 19 to June 16 and amounted to 58 days. The longest period of summer-autumn low water in 2002 lasted from June 22 to November 25 and amounted to 157 days, and in 2003 it lasted from June 17 to December 8 and amounted to 175 days.
A more detailed idea of the intra-annual variability of water discharge is given by the average (q), maximum (q_{\text{max}}) and minimum (q_{\text{min}}) monthly water discharge (table 2). For the period 1958-2019 it was found that the average monthly water discharge ranged from 5.5 to 19.6×10^3 m^3/s, that is, the water discharge changes by 3.5 times. The maximum average monthly water discharge (q_{\text{max}}) ranged from 8.6 to 33.5×10^3 m^3/s, and the minimum (q_{\text{min}}) – from 1.3 to 11.0×10^3 m^3/s. The largest difference in average monthly water flow rates (q_{\text{max}} - q_{\text{min}}) was observed in May and amounted to 22.5×10^3 m^3/s. The smallest difference in average monthly water flow rates (q_{\text{max}} - q_{\text{min}}) was observed in January and amounted to 4.7×10^3 m^3/s.

4. Conclusion
The analysis of the observation data showed that the average annual water discharge of the Volga River in the section of the Zhigulevsky hydroelectric complex was 7.7×10^3 m^3/s. Over the long-term observation period (1958-2019), the average annual water discharge changed 2 times, mainly due to climatic fluctuations in the Volga basin. The maximum water discharge was observed in 1990 and amounted to 10.4×10^3 m^3/s. The minimum water discharge was observed in 1975 and amounted to 5.2×10^3 m^3/s.

Statistical analysis of the time series for 61 years revealed a positive trend for an increase in the average annual water discharge of the Volga River by 700 m^3/s. The periods of low water (1958-1977), high water (1978-1999) and average water content (2000-2019) are identified. Almost all observed extremely low-water years (1977, 1976, 1975, 1973, 1967) fell into a period of low water, and all extremely high-water years (1994, 1991, 1990, 1981, 1979) – into a period of high water.

The regulation of water flow at the Zhigulevsky hydroelectric complex has formed the seasonal variability of water discharge inherent in technical water bodies. The natural hydrograph was transformed into a natural and technical one. There are three periods within the year. The shortest (~90 days) is the period of spring flood, which lasts from April to June. The winter low-water period is ~120 days and lasts from December to March. The longest (~150 days) is the period of summer-autumn low water, which lasted from July to November. The highest water discharge was observed during the spring flood (8.7-19.6×10^3 m^3/s), and during the low-water period, the water discharge was 5.5-6.5×10^3 m^3/s. Over the entire observation period, the amplitude of fluctuations in the average monthly water discharge was 2.1-33.5×10^3 m^3/s, that is, the average monthly water discharge changed almost 16 times. The lowest monthly average flow was observed in August 2010, and the highest in May 1979.

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