Long Periods of Increased/Decreased Runoffs of Large Russian Rivers

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Abstract. Long series of annual and seasonal runoffs of large Russian rivers (the Volga at Volgograd, the Don at Razdorskaya, the Yenisei at Igarka, and the Lena at Kyusyur) since the 1870s for the Russian Plain rivers and since the 1930s for the Siberian rivers have been analyzed. Long periods (phases) of increased and decreased water flow have been identified. The boundaries of contrast phases are determined with cumulative deviation curves in combination with Student’s test. The duration of the phases varies from 20–25 years to many decades (for runoff in low-water seasons of the Volga and Don). For the Volga and Don, the phases of decreased runoff are generally longer than increased flow phases (this is especially true for low-water seasons). The identified contrast phases show a statistically significant difference between the annual and seasonal runoffs, which varies from 10 to 65%. In the phases of increased flow, high-water years occur much more often than low-water years, and vice versa. In the period of current climate warming (since 1981), the changes in annual runoff relative to the calculated runoff of the reference period (from the 1930s to 1980) are opposing, i.e., the runoff decreased in the Don and increased in the Volga, Yenisei, and Lena. In this case, the changes are most significant in the Don. In the period of current climate warming, both the winter and snow-melt flood runoff has increased only for the Lena. At the same time, the contributions of climatic and anthropogenic factors to the changes in runoff differ significantly for each of the rivers under study.

1. Introduction

Studies show that the long-term changes of the annual and seasonal river flow are characterized by periods (phases, according to the terminology accepted in Russian hydrology) of decreased and increased values with different duration [1–3]. An important result, in particular for forecasting, is that long contrast phases with a duration of 10–15 years and more can be identified. They are observed against the background of corresponding climate changes. The anthropogenic factors can considerably transform both runoff values and the boundaries between contrast phases.

For several years, the authors have been studying the phases of decreased/increased flow in large rivers in Northern Eurasia [4–7].

This article presents the results of a comparison of the characteristics of the contrast phases of the largest rivers of the Russian Plain (the Volga and the Don) and Siberia (the Yenisei and Lena) over the period of observations (since the 1870s in the Russian Plain rivers and since the 1930s in Siberian rivers).

2. Methods to Analyze the Annual and Seasonal Runoff Data Sets

The approach to the analysis of long phases of multi-year variations of the annual and seasonal runoff caused by climate changes is based on its naturalization (the elimination of changes caused by the anthropogenic impact), the use of cumulative deviation curves, criteria of statistical homogeneity of the average flow values, and analysis of the characteristics of the identified contrast phases.

The cumulative deviation curves reflect the cumulative sum of deviations of a characteristic from its average value calculated for the entire observation period. In some cases, the deviations are normalized by
the coefficient of variation in order to compare the temporal changes of different types of characteristics. The cumulative deviation curves allow one to identify long-term periods (phases) during which the values of a characteristic below (or above) its long-term mean are predominant.

The boundaries of hydrological seasons (snow flood, low-water seasons) were determined using runoff hydrographs throughout the observation period. The data on the long-term dates of the beginning and the end of snow flood and winter freeze-up were also used.

The naturalization of the runoff assumes that the long-term hydrological series for the rivers under consideration are not homogeneous in terms of the impact of anthropogenic factors, and consist of two parts. The first part of the series included long-term data for the period before the effect of anthropogenic factors became appreciable. The second part consisted of a long-term series in which the annual runoff changed to a different extent under the effect of anthropogenic factors (primarily, reservoirs).

The flow for that period was reconstructed by two methods. One method [6], which has been used to reconstruct the Volga and Don flow, is based on the regression relationships between the flow of the main river and those of the rivers used as indicators of climate conditions (tributaries and the upper reaches of the main river), which show relatively weak anthropogenic perturbations in their water regime. The study of the phases of the Yenisei and Lena was based on long-term series of mean daily water discharges, naturalized in [8, 9] using a method for the transformation of runoff hydrograph, which is based on the influence function of G.P. Kalinin and P.I. Milyukov [10].

The part of the long-term runoff series reconstructed by one of the methods mentioned above was combined with the other part, in which the flow was not greatly affected by the anthropogenic impact. This is how the common series of conditionally natural runoff were constructed.

The time boundary of the change in the long-term phases of increased/decreased runoff values is determined by identifying the minimal and maximal values of the coordinates of cumulative deviation curves in combination with Student’s test. The long-term phases of the increased water flow correspond to a unidirectional tendency in an increase in the coordinates of the cumulative deviation curve, while the phases of the decreased flow correspond to a decrease in its coordinates. Short-period runoff changes can be seen against the background of such long-term trends.

3. Results and discussion

3.1. Long-Term Phases of Multi-Year Variations in the Conditionally Natural Annual and Seasonal Runoff
In the period of observations of the winter runoff (in all rivers under consideration), the summer–autumn runoff (in rivers on the Russian Plain), as well as the snow-flood runoff and the annual runoff of Siberian rivers, two major long-term phases can be identified. The phase of decreased flow is associated with the early observation period, and the following phase of increased flow begins in the 1970s–1980s (which is close to the beginning of the modern global climate warming) and continues up to the 2000s (Fig. 1). The snow-melt flood runoff of the Don also shows two long phases. However, the first phase (since the 1870s) showed an increased flow, followed by a phase of decreased flow (since 1972). In the Volga, a phase of increased snow flood runoff was also observed since the 1870, but as soon as the 1930s it was replaced by a phase of decreased water flow, with a new phase of increased runoff starting since the 1980s. And since the beginning of the 2000s again there is a phase of decreased snow flood flow. The number and sequence of replacement in the contrasting phases of the annual runoff on the Volga and Don is more complex than for the snow flood.

The time boundary of the change in the phases of contrast water flow varies appreciably for both the annual runoff and the runoff of hydrological seasons both for each river and between the rivers (Figure 1).

3.2. The Duration of Phases
The duration of the phases varies from 20–25 to 90 years (for the low water-season runoff in the Volga and Don). As a rule, the duration of the phases of decreased runoff is longer (and often, considerably) than the duration of increased flow phases, especially for the low water-season runoff of the Volga and Don. In the Lena and Yenisei, the duration of the contrast phases for the annual and winter runoff was similar. However, the phase of increased snow flood flow in these rivers was much shorter than the phase of its decreased flow.
| a | Volga | Don |
|---|---|---|
| I | ![Graph of Volga](image1) | ![Graph of Don](image2) |
| II | ![Graph of Volga](image3) | ![Graph of Don](image4) |
| III | ![Graph of Volga](image5) | ![Graph of Don](image6) |
| IV | ![Graph of Volga](image7) | ![Graph of Don](image8) |
3.3. Differences in the Runoff of Contrast Phases

The difference between the average runoff values in the phases of higher and lower flow is more than 12-18% for the annual runoff for both rivers; the same differences are 12 and 65% for the spring flood runoff, about 35% and 53% for the winter runoff, and 21 and 52% for the summer-autumn runoff in the Volga and Don, respectively.

In the Siberian rivers, the difference between the runoff in the phases of increased and decreased flow in winter is more than 40% in the Yenisei and about 20% in the Ob and Lena. The difference in the annual and spring flood runoff in these phases is smaller, varying within 10%.

Figure 1. Long-term changes in naturalized (I) snow flood flow, (II) winter water flow, (III) summer-autumn water flow, and (IV) mean annual water flow in: (a) the Volga at Volgograd and the Don at Razdorskaya, (b) the Yenisei River at Igarka and the Lena River at Kyusyur (blue and red) as deviations from their long-term mean values: (green) in the form of normalized cumulative deviation curves (CDCs). The vertical black lines show phase boundaries (shift points) of increased/decreased values of the naturalized water flow.
3.4. Runoff Frequency Structure in the Phases of Increased and Decreased Runoff

The numbers of high-water and low-water years in the long-term phases of the contrast water flow differ considerably. Thus, for the Volga and Don significant differences were found to exist between the ratios of the numbers of high-water and low-water years for the long-term phases of increased (PIR) and decreased (PDR) annual and seasonal water flow. A year was classified as high-water one if its annual and seasonal runoff values were not less than the runoff of 25% exceedance probability and as low-water if both the annual and seasonal runoffs were not greater than its value with 75% exceedance probability. In the phases of increased annual runoff, snow flood runoff, and the runoff of the winter and summer–autumn low-water seasons (Figure 2), the numbers of high-water years were 30, 26, 53, and 42% of the total number of years in the PIR, respectively; the respective numbers for the Don were 44, 35, 63, and 59%. The proportion of low-water years during the PIR was much lesser. In the Volga, it was 12, 19, 13, and 18%, and in the Don, 18, 7, 9, 10%, respectively. The situation at the PDR was inverse.

![Figure 2. Frequency structure of (I) annual, (II) snow flood, (III) winter, and (IV) summer-autumn runoff in the long-term phases of: (1) increased and (2) decreased runoff (a) Volga at Volgograd, (b) Don at Razdorskaya](image)

At the same time, the total proportion of low- and high-water years is relatively stable, varying mostly within the range of 40–60%. Accordingly, the proportion of the years with water discharges lying within the range of 25 and 75% exceedance probabilities is also relatively stable, varying within about the same limits (40–60%). For the annual runoff and the snow flood runoff, the proportion of such years is greater in the PIR than in the PDR (except for the annual runoff of the Don). Conversely, the proportion of the years falling within this range for the winter runoff and the runoff of the summer–autumn low-water season is greater in the PLR than in the PHR (except for the summer–autumn runoff of the Volga).

3.5. Runoff Changes in the Epoch of Modern Climate Warming

3.5.1. Overall changes in runoff caused by climate and anthropogenic factors. As one can see from Table 1, changes in the annual runoff in the rivers under consideration had different signs: in the period of current climate warming the runoff was decreasing in the Don and increasing in the Volga, Yenisei, and Lena. These changes were most significant in the annual Don runoff. Its decrease in that period was equal to more than five annual volumes of the runoff of the basic period, a fact that had a very adverse effect on the water-management and hydroecological situation in its basin and on the state of the Sea of Azov. At the same time, the total increase in the runoff of the Volga at Volgograd, the Yenisei at Igarka, and the Lena at Kyusyur over the period of current climate changes was approximately equal to the annual runoff volume of the basic period for the respective rivers.

Both the winter runoff and the runoff of the snow flood have increased over the period of modern climate warming only in the Lena River (Table 2). In the other rivers the changes in the runoff of the winter low-water season and the snow flood in this period had different signs. The relative increase in the winter runoff was greater than the decrease in the spring flood runoff.
Table 1. Changes in the average annual runoff under the effect of climate and anthropogenic factors in the period of modern climate warming relative to its naturalized values for the basic period (from the 1930s to 1980).

| River–gage         | Average annual runoff of the basic period | Period of modern climate warming | Changes in the average annual | on the average for | total over the period, km³ |
|--------------------|-------------------------------------------|---------------------------------|-------------------------------|--------------------|--------------------------|
|                    | years                                     | years                           | average annual runoff         | a year             |                          |
|                    | volume, km³/year                          | volume, km³/year                | average annual runoff on the  |                    |                          |
|                    |                                          |                                 | average for a year, km³       | %                  |                          |
| Volga–Volgograd    | 1930-1980                                 | 1981-2014                       | 255.1                         | 8.4                | 285.6                    |
|                    | 246.7                                     | 20.7                            | -4.7                          | -18.5              | -159.8                   |
| Don–Razdorskaya    | 1930-1980                                 | 1981-2014                       | 608                           | 30.4               | 729.6                    |
|                    | 25.4                                      | 20.7                            | -4.7                          | -18.5              | -159.8                   |
| Yenisei–Igarka     | 1936-1980                                 | 1981-2004                       | 608                           | 30.4               | 729.6                    |
|                    | 577.6                                     | 608                             | 30.4                          | 5.3                | 729.6                    |
| Lena–Kyusyur       | 1936-1980                                 | 1981-2007                       | 545.4                         | 24.9               | 672.3                    |
|                    | 520.5                                     | 545.4                           | 24.9                          | 4.8                | 672.3                    |

Table 2. Changes in the average winter runoff and the runoff of the snow flood under the joint effect of climatic and anthropogenic factors in the period of current climate warming relative to their naturalized values for the basic period (from the 1930s to 1980).

| River–gage         | Average annual runoff of the reference period, km³ | The period of modern climate warming | Changes in the average annual runoff |
|--------------------|----------------------------------------------------|------------------------------------|--------------------------------------|
|                    | winter                                             | snow flood                         | winter                               |
|                    | snow flood                                         |                                     | snow flood                           |
|                    | volume, km³                                        | %                                  | volume, km³                          | %                                  |
| Volga–Volgograd    | 27.2                                               | 66.9                               | 125.3                                | 39.7                              |
|                    | 166.3                                              |                                     | 146.0                                | -41                               |
| Don–Razdorskaya    | 2.5                                                | 4.7                                | 6.7                                  | 2.2                              |
|                    | 16.6                                               |                                     | 88.0                                | -9.9                             |
| Yenisei–Igarka     | 74.8                                               | 137.3                              | 389.6                                | 62.5                             |
|                    | 418.5                                              |                                     | 83.6                                | -28.9                           |
| Lena–Kyusyur       | 32.4                                               | 48.4                               | 397.1                                | 16                               |
|                    | 387.8                                              |                                     | 49.4                                | 9.3                             |

3.5.2. Contribution of climate warming and anthropogenic impact to the total runoff changes. The contributions of climate changes and anthropogenic impact to the total runoff changes over the period of modern climate warming were evaluated by comparing the naturalized average annual and seasonal runoff for the basic period (1930–1980) and the naturalized and actual runoff for the period since 1981. The boundaries of the periods in the rivers differ (see Table 1). This is a result of later start of observations at Siberian rivers and the lack of data on their naturalized runoff.

The difference between the naturalized runoff for the basic period and the following period characterizes the effect of climate changes (under the assumption that they are not caused by human activity). The runoff changes that are due to the anthropogenic impact were calculated by the difference between the estimates of climate-induced changes in the runoff and its changes caused by a joint effect of climatic and anthropogenic factors in the period of modern climate warming (see Tables 1 and 2).

The anthropogenic and climate-induced changes in the annual runoff were both directed toward its decrease only in the Don (Table 3). In this case, a much larger contribution to the decrease in the Don runoff was due to the anthropogenic factors, the most important among them being the construction of the Tsimlyansk Reservoir and consumptive water use for irrigation (Figure 3).

Table 3. Changes in the average annual runoff over the period of modern climate warming relative to their naturalized values for the basic period (from the 1930s to the 1980s).

| River–gage         | Anthropogenic changes | Climate changes over |
|--------------------|-----------------------|----------------------|
|                    | total over the period, km³ | average over year, km³ | total over the period, km³ | average over year, km³ |
| Volga–Volgograd    | -370.6                | -10.9                | 656.2                | 19.3                |
In the Lena, the changes in the annual runoff were due to climate changes, which caused its increase. The anthropogenic impact has not caused any appreciable changes in the Lena annual runoff. In the Volga and Yenisei, the effects of these factors were differently directed. Note that the climate-induced changes in the annual runoff in the Yenisei were larger, and the Volga runoff changes under the dominating effect of climate, the anthropogenic changes in the runoff were also significant. The contributions of the climate-induced and anthropogenic factors to the runoff changes in the seasons with contrast hydrological seasons (snow flood and winter low-water season) in the modern climate change period differed considerably. The changes in the winter runoff under anthropogenic and climatic factors were in one direction—toward its increase (Table 4, Figure 3). Their contributions to the changes in the Don winter runoff were nearly the same, while in the other rivers the contribution of climate changes to the increase in the winter runoff was twice as large as that of anthropogenic factors. The effects of these factors on the snow flood runoff were cardinaly different. The anthropogenic factors caused a decrease in the spring flood runoff in these rivers (the largest one in the relative characteristics in the Volga and Don) (Figure 3). Conversely, the climate changes contributed to an increase in the snow flood (except for the Don). Their effect in the Lena was much more considerable than that of the anthropogenic factors. In the Volga and Yenisei, conversely, the contribution of anthropogenic factors to the decrease in the spring flood runoff was much larger, resulting in its decrease in the period of current climate warming.

Table 4. Anthropogenic and climate-induced changes in the average annual runoff over winter season and snow flood on average over the season over the period of modern climate warming (km³) relative to their naturalized values for the basic period (from the 1930s to the 1980s).

| River–gage     | Winter        | Snow flood    |
|----------------|---------------|---------------|
|                | anthropogenic changes | climate-induced changes | anthropogenic changes | climate-induced changes |
| Volga–Volgograd | 27.4          | 12.3          | -43.4         | 2.4          |
| Don–Razdorskaya | 1             | 1.2           | -4.5          | -5.4         |
| Yenisei–Igarka | 40.3          | 22.2          | -37.2         | 8.3          |
| Lena–Kyusyur   | 10.7          | 5.3           | -10.6         | 19.9         |
4. Conclusions

During the periods of observations of winter runoff (for all above-considered rivers), summer–autumn runoff (for the rivers of the Russian Plain), spring flood and annual runoff for the Siberian rivers, two major long-term phases can be identified: the phase of decreased runoff at the beginning of the observation period, and the following phase of increased runoff that begins in the 1970–1980s (which is close to the onset of current global climate warming).

The snow-melt flood runoff of the Don also shows two long phases. The first phase (since the 1870s) showed higher runoff, and the following phase (since 1972) was a phase of lower runoff. In the Volga, first (since the 1870s) a phase of higher snow flood runoff was also observed; however, as soon as the 1930s it was replaced by a phase of lower runoff, which was followed again, since the 1980s, by a phase of higher runoff. Since the mid-1990s–early 2000s there was a tendency towards the passage to a phase of lower, spring flood, and summer–autumn runoff.

The time boundary between the higher and lower runoff phases varies appreciably for the annual runoff and the runoff of hydrological seasons, both for each single river and between the rivers. The phase duration is also very volatile and lies mostly within the range from 20–25 years to many decades (for the winter and summer–autumn runoffs of the Volga and Don). The average runoffs of contrast phases differ by 10–65%.

For the Volga and Don, the number of high-water years during increased runoff phases is much larger than the number of low-water years, and vice versa.

In the period of current climate warming (since 1981), compared with the calculated runoff of the basic period (from the 1930s to 1980), the changes in the annual runoff of the rivers under consideration were opposing: in the period of current climate warming the Don runoff was decreasing, and that of the Volga, Yenisei, and Lena is increasing. The changes were the largest in the annual runoff of the Don. Both winter and snow flood runoff increased in the period of current climate warming only for the Lena. In the other rivers in this period, the runoff of the winter low-water season and that of the snow flood changed in different directions. The relative increase in the winter runoff was more considerable than the decrease in the spring flood runoff. The anthropogenic and climate-induced changes in the annual runoff had the same direction (towards a decrease) only for the Don. The contribution of anthropogenic factors to the decrease in the Don runoff was much greater. In the Lena, the decrease in the annual runoff was caused by climate change. In the Volga and Yenisei, these factors acted in different directions. In the Yenisei, the climate-induced changes in the annual runoff were larger, and in the Volga, at the predominant effect of climate, its anthropogenic changes were considerable.

The contributions of climatic and anthropogenic factors to the changes in the runoff of contrast hydrological seasons (snow flood versus winter low-water season) in the period of current climate warming differed considerably. The winter runoff was steadily increasing under the effect of anthropogenic and climatic factors, and the contributions of these factors to the changes in the Don winter runoff were nearly the same, while the contribution of climate changes to the increase in the winter runoff of the other rivers was twice as much as that of the anthropogenic factors.

The effects of these factors on the snow flood runoff were cardinaly different. The anthropogenic factors caused a decrease in the spring flood runoff of these rivers (which was the largest in relative values for the Volga and Don), while climate changes contributed to an increase in the snow flood runoff in all rivers, except for the Don. Their effect on the Lena runoff was much more considerable than the effect of anthropogenic factors, while for the Volga and Yenisei, on the contrary, the contribution of anthropogenic factors to the decrease in spring flood runoff was much larger, resulting in its decrease in the period of current climate warming.

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