Assessing the effect of climatic and anthropogenic factors on the annual runoff of large rivers in European Russia and Siberia

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Abstract. This study presents the analysis of variations in the annual runoff of large rivers in European Russia (the Volga and Don) and Siberia (the Yenisei and Lena). Two methods used in the study assess the runoff changes under the effect of climate and economic activity. One method uses the data on water management statistics, and another is based on the reconstruction of the natural runoff in recent decades, during which its considerable anthropogenic changes have been taking place. We compare the obtained runoff estimates with the anthropogenically affected runoff over this period and the runoff for the previous (reference) period, in which the anthropogenic impact was negligible. The study shows that, in the period of considerable anthropogenic impact, the annual runoff of the Volga and Don decreased, and that of the Yenisei and Lena increased. In the case of the Volga and Don, the effect of anthropogenic factors is comparable with that of the climatic factors, whereas in the Yenisei and Lena, the former is much less than the latter. Both impacts on the runoff in the Volga and Don are directed towards its decrease. In the Yenisei and Lena, the effects of these factors were differently directed with the predominant effect of climatic factors.

1. Introduction

The assessment of the contributions of climatic and anthropogenic factors to the changes in river runoff is of extreme importance for the understanding of their genesis and developing measures aimed to decrease or even prevent the unfavorable effects. This problem is complicated by the close interrelation between the climatic and anthropogenic changes in the river runoff. Therefore, it is impossible to exactly distinguish their contributions to the formation and changes in river runoff; therefore, relative estimates should be used. Commonly, they are the values of runoff deviations from some reference values (e.g., its normal value, normal annual runoff, or the runoff for some other period) calculated by different methods. Estimates of the contributions of the climatic and anthropogenic factors to hydrological changes, primarily, the river runoff, are the focus of many studies, including our studies [1–4]. However, this problem requires further studies. This article presents an attempt to evaluate these contributions on the example of large European (the Volga and Don) and Asian (the Yenisei and Lena) Russian rivers.

2. Methods of study

Firstly, the boundaries of the reference periods (when the anthropogenic impact can be neglected) and
periods of considerable anthropogenic impact were determined for each river. For these periods, the average values of the annual runoff and their difference were calculated. This difference shows the overall changes in the runoff that took place under the effect of both anthropogenic impacts and climatic factors (table 1). These periods are different in the investigated rivers due to the different times when the considerable anthropogenic impacts began (for the beginning of each period), and the availability (lack) of data (for the end of the period).

**Table 1. Variations in the annual runoff under the joint effect of climatic and anthropogenic factors relative to the reference period.**

| River–gauge      | Reference period | Period of considerable anthropogenic impact | Runoff change |
|------------------|------------------|--------------------------------------------|---------------|
|                  | years            | years                                      |               |
|                  | runoff volume,   | runoff volume,                             | average annual| total, km³ |
|                  | km³/year         | km³/year                                   | km³, %        |            |
| Volga–Volgograd  | 1879-1929        | 1930-2014                                  | -30.2         | -2567      |
| Don–Razdorskaya  | 1876-1929        | 1930-2014                                  | -6.8          | -578       |
| Yenisei–Igarka   | 1936-1960        | 1961-2004                                  | 24.6          | 1082       |
| Lena–Kyusyur     | 1936-1967        | 1968-2007                                  | 21.3          | 852        |

The contributions of the anthropogenic and climatic factors to the observed total change in runoff shown in table 1 were evaluated by two methods. The first is based on the data on water management statistics available from various reference books [5, 6] as well as literary sources [1, 7], whereas the second uses the reconstruction of natural (more precisely, conditionally natural) runoff of the investigated river. In both cases, the estimates of the contributions of anthropogenic impact and climate changes to the overall changes in river runoff are based on the comparison of the runoff in a reference period, when the effect of economic activity was relatively low, with the actual and reconstructed (conditionally natural) runoff over the period of considerable anthropogenic impact. In this case, the difference between the reconstructed (conditionally natural) runoff for the period of intense anthropogenic impact and the runoff of the reference period reflects the effect of climate changes (under the assumption that they are not the result of human activity), and the difference between the reconstructed (conditionally natural) and the actual (observed) runoff in the period of intense anthropogenic impact reflects the contribution of anthropogenic impact on the total runoff changes.

The annual runoff was reconstructed by two methods. The first method is based on regression relationships between the runoff in the main river and that in rivers taken as indicators of climate conditions (tributaries and the upper reaches of the main river) and showing relatively low anthropogenic disturbances in their water regime. In this study, the rivers–indicators of climate conditions for the reconstruction of the annual and seasonal (winter and spring-flood) Volga runoff near Volgograd were the Oka near Kaluga, the Vyatka near Kirov, and the Belaya near Birsk. At the same time, the reconstruction of the Don runoff near Razdorskaya was based on the Don near Kazanskaya and the Khoper near Besplemyanovskoe. Notably, the basins of rivers–indicators also show some economic activity, which may have some effect on the results of the Volga and Don runoff reconstruction.

In the second method, the estimation of the Yenisei and Lena runoff changes was based on the long-term series of the average daily water discharges reconstructed by A.I. Shiklomanov et al. [8] using a method of transformation of annual runoff hydrograph. In this regard, a different reconstruction method was used, i.e., the method of transformation of the annual runoff hydrograph
using the influence function proposed by G.P. Kalinin and P.I. Milyukov [9]. The model parameters were calibrated against the data on parallel observations in years with no significant effect of anthropogenic factors in the upstream and downstream cross sections of the gage sections, considering the lateral inflow between them. The values of the Nash–Sutcliffe coefficient [10] to evaluate the accuracy of runoff reconstruction vary within the range of 0.82–0.98, suggesting sufficient reliability of calculations, and, according to the method used in hydrological forecasts [11], the reconstruction accuracy can be characterized as satisfactory or good.

The part of the long-term series of the annual and seasonal runoff reconstructed by one of the methods mentioned above was combined with its other part, which runoff had not been significantly disturbed by anthropogenic impact. In this way, the joint series of conditionally natural runoff were formed, which average values were compared with the reference and actual runoff during significant anthropogenic impact, which is typical of the recent decades.

3. Results and discussion

Table 1 indicates that changes in the annual runoff in the investigated rivers are differently directed, i.e. the total runoff in the Volga and Don decreased in the period of considerable anthropogenic impact, whereas that of the Yenisei and Lena increased. The largest relative changes were recorded in the Volga and Don runoff. Thus, the runoff of the Volga near Volgograd decreased by more than 2500 km$^3$ (more than 30 km$^3$/year) over 1930–2014, and this decrease in the Don near Razdorskaya in the same years was 600 km$^3$ (about 7 km$^3$/year); this had a serious adverse effect on the water-management and hydroecological situation in the southern parts of their basins and on the state of the Caspian Sea and the Sea of Azov.

Tables 2, 3 and the figure show the results of evaluating the contributions of climatic and anthropogenic factors to these changes, which were calculated using the data on water-management statistics and the method of conditionally natural runoff reconstruction. Table 3 indicates the anthropogenic and climatic changes in the annual runoff in the Volga and Don are directed similarly, i.e. towards its decrease. The share of the former in annual runoff changes is more than 36% in the Volga and more than 40% in the Don. The effects of reservoirs (especially, the Volga–Kama chain of reservoirs) and the consumptive water use for various economic needs are almost equal. In the Don, the effect of consumptive water use is 1.5 times higher than that of reservoirs (first of all, the Tsymlyansk Reservoir). In the Yenisei and Lena, the effects of anthropogenic and climatic factors have different directions with a predominant effect of climatic factors, which is almost 4 times greater than that of anthropogenic factors in the case of the Yenisei and more than 20 times greater in the case of the Lena. In the anthropogenic impact of Siberian rivers, the effect of reservoirs is predominant, primarily, due to the filling of the dead volumes of the Angara–Yenisei chain of reservoirs, as well as the Vilyuy Reservoir on the Vilyuy, a tributary of the Lena. The extent of anthropogenic impact in the Yenisei is by an order of magnitude greater than that in the Lena.

Table 2. Variations of the annual runoff during considerable anthropogenic impact, calculated from the data of water-management statistics relative to the reference period, km$^3$.

| River–gage | Anthropogenic changes | Climatic changes |
|------------|-----------------------|------------------|
|            | effect of reservoirs  |                  |                  |
|            | (dead-volume filling  |                  |                  |
|            | and additional        |                  |                  |
|            | evaporation)          |                  |                  |
|            | consumptive water use |                  |                  |
|            | total                 |                  |                  |
|            | average annual        |                  |                  |
| Volga–Volgograd | -450 | -476 | -926 | -10.9 | -1641 | -19.3 |
| Don–Razdorskaya | -94.3 | -146 | -240 | -2.8 | -338 | -4.0 |
| Yenisei–Igarka | -308 | -39.7 | -348 | -7.9 | 1430 | 32.5 |
| Lena–Kyusyur | -29.9 | -3 | -32.9 | -0.8 | 885 | 22.1 |
Table 3. Variations of the annual runoff during considerable anthropogenic impact, calculated from the reconstruction of its conditionally natural values, km³.

| River–gage        | Anthropogenic changes | Climatic changes |
|-------------------|-----------------------|------------------|
|                   | total over the period | average annual   |
|                   | total over the period | average annual   |
| Volga–Volgograd   | −1190                 | −14              |
| Don–Razdorskaya   | −230                  | −2.7             |
| Yenisei–Igarka    | −237.6                | −5.4             |
| Lena–Kyusyur      | −32                   | −0.8             |

The method of reconstruction of the conditionally natural runoff values has yielded the estimates of the contributions of the climatic and anthropogenic factors to the total runoff changes similar to those obtained from water-management statistics, especially for the Don and Siberian rivers, with the similar results obtained by the two methods for the Lena and Don (figure 1). The difference between the estimates for the Volga basin is somewhat greater, especially, the contributions of the anthropogenic impacts. This can be largely attributed to the landscape transformations in its basin, which effect on the runoff the water-management statistics does not reflect. It is also worth mentioning that the estimates of the anthropogenic changes in the Yenisei runoff obtained by these two methods significantly differ. This is most likely due to the somewhat overestimated consumptive losses of runoff caused by the additional evaporation from reservoir water areas in the region.

Figure 1. Changes in the annual runoff under the effect of anthropogenic and climatic factors as a percentage of the reference period runoff. (1) changes in runoff evaluated using water-management statistics data; (2) changes in runoff determined by reconstruction of its conditionally natural values.
4. Conclusion
We have assessed the contributions of anthropogenic and climatic factors to the changes in the annual runoff by two methods, using the data on water-management statistics and by the method of reconstruction of conditionally natural runoff, for the period of considerable anthropogenic impact on the river basins of the Volga, Don, Yenisei, and Lena, which differ in water content as well as natural and economic conditions. The estimates obtained by the two methods are similar. In this case, the shares of the anthropogenic factors in the annual runoff decrease estimated using the data on water-management statistics and the method of reconstruction of conditionally natural runoff are 36–46 and 40% for the Volga and Don, respectively; the same estimates for climatic factors are 54-64, and 60%, respectively.

In the Yenisei and the Lena, the effect of anthropogenic and climatic factors on the annual runoff is differently directed, with the dominating effect of climatic factors.

The further improvement of the proposed methods along with additional source data on recent years will improve the obtained estimates of the contributions of anthropogenic and climatic factors to changes in river runoff.

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