RESEARCH PAPER

WATER FLOW CHANGES IN THE DON RIVER (EUROPEAN RUSSIA) DURING 1891–2019

Alexander G. Georgiadi[1*], Irina P. Milyukova[1], Oleg O. Borodin[2], Artyom V. Gusarov[3]
[1]Institute of Geography, Russian Academy of Sciences, Staromonetny Alley, Moscow, 119017, Russia
[2]Water Problems Institute, Russian Academy of Sciences, Gubkin Street, Moscow, 117971, Russia
[3]Institute of Geology and Petroleum Technologies, Kazan Federal University, Kremlyovskaya Street, Kazan, 420008, Russia
***Corresponding author:** georgiadi@igras.ru
Received: May 1st, 2022 / Accepted: May 4th, 2023 / Published: July 1st, 2023
https://DOI-10.24057/2071-9388-2022-083

ABSTRACT. The Don River Long near Razdorskaya Village had long phases (lasting 33–86 years) of increased/decreased naturalized annual and seasonal water flow, and their properties for 1891–2019 were identified. Long-term changes in the annual and snow-melt flood flow occurred in the opposite phase relative to changes in the winter and summer-autumn flow. Annual hydrographs in the phase of decreased flow were characterized by an increase in water discharge during the low-water seasons of the year, but a noticeable decrease in daily flood water discharge and maximum water discharge. The share of high-water years (years with a flow exceedance probability equal to or less than 25%) in the phase of increased flow is significantly higher than the share of low-water years (years with a flow exceedance probability equal to or more than 75%). And on the contrary. At the same time the cumulative share of low- and high-water years remains relatively stable. The total changes in the annual and seasonal flow, caused by both anthropogenic and climatic factors, throughout the entire period of modern global warming (since 1989) consisted in a decrease of the annual and snow-melt flood flow and an increase of flow values during low-water seasons.

KEYWORDS: hydrological change, long-term phase, high- and low-water year, global warming, anthropogenic factor, hydrograph transformation, cumulative deviation curve

CITATION: Georgiadi A. G., Milyukova I. P., Borodin O. O., Gusarov A. V. (2023). Water Flow Changes In The Don River (European Russia) During 1891–2019. Geography, Environment, Sustainability, 2(16), 6-17
https://DOI-10.24057/2071-9388-2022-083

ACKNOWLEDGEMENTS: This research was funded by the Russian Science Foundation, project no. 20-17-00209; the methodological framework for contrasting phases analysis was developed under Governmental Order to the RAS Institute of Geography, AAAA-A19-119021990093-8 (FMGE-2019-0007). The work is also carried out in accordance with the Strategic Academic Leadership Program "Priority 2030" of the Kazan Federal University of the Government of the Russian Federation.

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

Studies relating to long-term changes in river water flow and other components of environmental flow which are regarded to be particularly susceptible to ongoing climate change, are given a great deal of attention due to current global warming began in the 1970s and 1980s (Hinzmann et al. 2005; Water Resources … 2008; Shiklomanov et al. 2013; Georgiadi et al. 2014; Magritsky 2015; Georgiadi et al. 2018; Shiklomanov et al. 2020; Scientific and applied reference … 2021; Georgiadi and Groisman 2022; Frolova et al. 2022; Zhuravlev et al. 2022). A large number of scientific publications is devoted to the evaluation of changes that happened in various hydrological characteristics during the global warming period compared to the relatively cooler baseline period (Shiklomanov and Georgievskii 2007; Water Resources … 2008; Georgiadi et al. 2019). As a rule, such estimates are made based on a comparison of the studied flow characteristic values for both periods of global warming and preceding baseline period. In addition, the problem of long-term periods (phases according to the terminology adopted in the former USSR (Andreyanov 1959; Kuzin 1979) and Russia (Georgiadi et al. 2014) of increased/decreased values of the river water flow characteristics and other geo-runoff (a term proposed by (Muraveysky 1960)) components (sediment, chemical, biological and heat fluxes from a catchment area) during XIX-XXI centuries is of considerable interest. The successive change of contrasting long-term phases is an important feature of the long-term dynamics of hydrological characteristics due to climate change. It should be noted that the deviation of values between such phases is considered statistically significant. The duration of these contrasting periods ranges from 10–15 years up to several decades (Georgiadi et al. 2014; Georgiadi et al. 2018; Georgiadi et al. 2019). In this regard, annual and seasonal changes in water flow in various regions of the world have recently been studied (Sharma and Singh 2017; Bolgov et al. 2018; Georgiadi et al. 2018; Shi 2019; Georgiadi et al. 2020). However, despite a rather wide range of studies on long-term phases of increased/decreased river water flow for various regions of the world, specifically for Russia's river basins, the spatial range of such studies still awaits significant enhancement.

One of the main problems in the development of this research topic is to determine the time boundaries between contrasting multi-year phases of water flow, as well as between the background (baseline) period and the period of global warming. In addition to various natural factors affecting the change in river flow (including factors associated with climate change), human activity in the channels and watersheds of rivers has a significant impact on the values under consideration (Water Resources … 2008; Georgiadi et al. 2014). At the same time, the set of acting anthropogenic factors, as well as their intensity, change over a long period. This raises the problem of identifying factors of change.

To determine the current changes in river water flow as a result of human impact, the authors developed two separate approaches (Georgiadi et al. 2014). The first of them concerns an integral assessment of the anthropogenic and climatic impact on the change in water flow by naturalizing the river water flow and its further comparison with the measured values. The naturalization procedure includes an analysis of the relationship between the hydrological characteristics of the studied river and its tributaries, which are in zones of slightly noticeable human impact and, thus, are indicators of climate change features. The other approach mainly includes various water balance methods and analysis of water management statistics. It allows assessing the influence of individual anthropogenic factors or their entire complex. Two approaches are used for naturalize river runoff. The regression model of the main river water flow based on river indicators of climate change features was used to naturalize long-term annual and seasonal water flow series (Georgiadi et al. 2014). In addition, daily water discharge values could be naturalized based on hydrograph transformation (Sokolovskii and Shiklomanov 1965; Georgievskii and Moiseenkov 1984; Shiklomanov et al. 2011; Stuefer et al. 2011) using travel time function (methods of unit hydrograph, isochrone lines, Kalinin-Milyukov, Muskingum, etc.). The concept and reliability of the second approach are similar to the method of river indicators of climate change features.

This research is devoted to studying long phases of increased and decreased naturalized annual and seasonal water flow as well the frequency structure of water flow time series for one of the largest rivers of Eastern Europe, namely the Don River, for the observation period of 1891–2019. In addition, the objective of this study was to assess the impact of current global warming and anthropogenic factors on river water flow characteristics including daily water discharge hydrographs.

MATERIALS AND METHODS

Study Area

One of the largest rivers of European Russia – the Don River – was chosen as the study object (Fig. 1). The total area of the Don River basin is 422,000 km^2, and 378,000 km^2 – at Razdorskaya village. The Don River basin is located mainly in the steppe (63%) and forest-steppe (32%) landscape zones.

Most of the annual water flow (62.4%) of the Don River occurs during the snow-melt flood (March-May), when there is an intensive melting of the snow cover. During the summer-autumn period, 25.4% of the annual water flow is formed. The winter period, which lasts from December to February, brings 12.4% of the annual water flow of this river. The calculation (as well as other estimations of the characteristics of the Don runoff presented in the paper) was made by authors based on the time series of naturalized daily average water discharge values (for naturalization methodology see below).

The natural landscapes of the Don River basin have changed significantly due to primarily agricultural activities in recent centuries (Arc Atlas: Our Earth 1996). Human-altered landscapes occupy more than 80% of the total area of the river's basin and are mainly used for non-irrigated

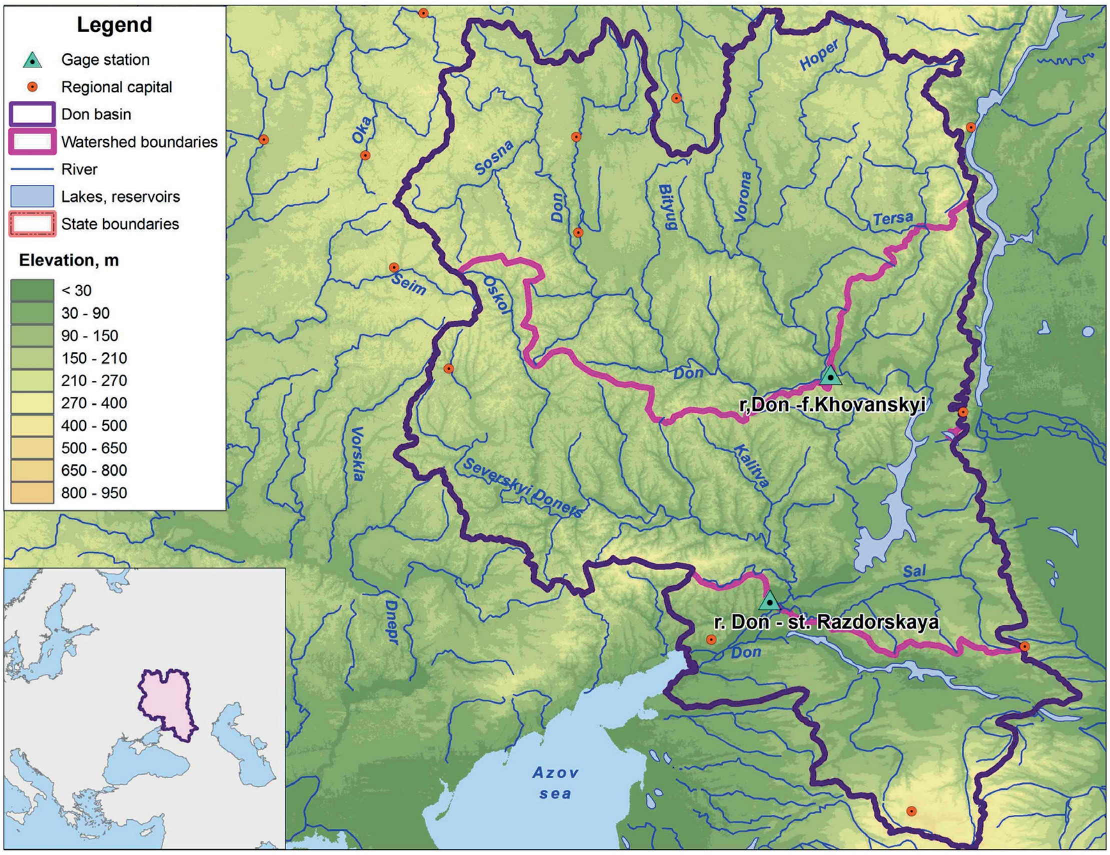

Fig. 1. Location of the Don River basin

agriculture. And since the 1980s no significant changes in the structure of land use within the Don basin have been revealed up to the present times (Kireeva et al. 2018).

Reservoirs, industry, agriculture (including irrigation), urban areas, as well as roads and pipelines, have a significant impact on the water regime of both the Don River and its tributaries, despite the fact that they occupy no more than 4% of the total basin area (Georgiadi et al. 2014; Varentsova et al. 2021). The cumulative anthropogenic impact (acting mainly through reservoir management, water withdrawal and subsequent discharge) is most noticeable when comparing hydrographs of water flow of the Don River, built according to data of periods before and after the construction of large hydraulic structures in its basin (see below). The most noticeable effect on the annual and especially seasonal water flow is exerted by the interannually regulated Tsimlyansk Reservoir which was filled in 1953. Its total volume is 23.9 km^3, including 11.5 km^3 of active storage. The long-term annual average water flow (for 1891–2019) of the Don River near Razdorskaya was found to be equal to 24.33 km^3.

Data

The research was based on a long-term series of daily average water discharge values of the Don River measured at Razdorskaya village and Khovansky farmstead (Fig. 1) between 1936 and 2019, and monthly average water discharge values at Razdorskaya from 1891 to 2019. These series were used to create a set of long-term naturalized water flow data (meaning that anthropogenic influence was excluded), as well as to calculate the observed flow values for main hydrological seasons (snow-melt flood, summer-autumn and winter low-flow seasons) and for the whole period within the designated time frame. The time limits of hydrological seasons were defined on the basis of information on the long-term average dates of the beginning and end of snowmelt floods and river freezing. Two separate periods stand out from the entire period of observation of the Don River's hydrological characteristics at Razdorskaya. The first is characterized by a rather low anthropogenic impact, while the second is characterized by significant changes in the flow of the Don River due to intense anthropogenic impact. The year 1951 was adopted as the dividing line between these two periods. At that point, the Tsimlyansk Reservoir started to fill.

Time series of air temperature and precipitation for the years 1936 to 2019 were obtained from measurements at a network of meteorological stations using the data array of the World Data Center of the Russian Institute of Hydrometeorological Information (RIHMI-WDC) dataset (http://meteo.ru).

Methodology

Method of naturalization of the hydrograph of daily average water discharge. To naturalize the values of the daily average water discharge of the Don River at Razdorskaya, a series of measured daily average discharge of the Don River at Khovansky (the basin area is 169,000 km^2) was used. The hydrological regime at Khovansky gauging station is characterized by considerably small changes due to anthropogenic factors mainly related to non-irrigated agriculture, urbanization, and water consumption by house-holds or industry. Furthermore, the anthropogenic impact is partly compensated by itself coming from different sources (Georgiadi et al. 2014).

The Kalinin–Milyukov method (Kalinin and Milyukov 1958) was used to naturalize a hydrograph with a small external impact on the hydrological regime. The Kalinin-Milyukov flow routing method conceptualizes a relation between the inflow and outflow of a river section as a linear function of water stored within the reach. According to this scheme, the water discharge at the lower boundary of the river section is calculated by the formula:

$$Q(t) = \int_0^t q(t) P(t-\tau) d\tau \quad (1)$$

where *Q(t)* is an outflow of a river section at time *t*, *q(t)* is an inflow of a river section at time *t*; *P(t)* is the water travel time curve function:

$$P(t) = \frac{1}{\tau(n-1)!}\left(\frac{t}{\tau}\right)^{n-1} e^{-\left(\frac{t}{\tau}\right)} \quad (2)$$

where *n* is the number of characteristic sites with an identical travel time value equal to *τ*.

J. Nash (Nash 1959), independently of G. Kalinin and P. Milyukov (1958), derived the same equation for the lag-curve. The parameters used in the travel time function were determined based on the daily average water discharge series for the Don River at Razdorskaya and Khovansky for the years 1938 to 1950. This time frame was chosen due to the lack of a significant anthropogenic impact on the flow values of the Don River. In order to maintain a water balance between the above-mentioned stations, the flow hydrograph at Razdorskaya was calculated as the sum of the transformed discharge at Khovansky and the lateral inflow. The overall volume of the lateral inflow was calculated based on the difference in the flow volume of the Don between the Razdorskaya and Khovansky stations. Then it was distributed among the period of interest daily in accordance with empirical coefficients selected for the low water period, rising, and recession of the flood wave. The estimated travel time (*n*t*) between the Khovansky and Razdorskaya stations was found to be equal to 21.6 days, and for the lateral inflow – 16.8 days. The quality of the performed analysis was recognized as sufficient according to the Nash-Sutcliffe performance criteria–NSE (Nash and Sutcliff 1970; Moriasi, et al. 2007). The NSE value for daily water discharge for annual and snowmelt flood periods was found equal to 0.91, for the summer-autumn period–0.97, and for winter–0.89.

Hydrological regime shift (change) point detection for annual and seasonal water flow. The time boundaries between individual long phases of increased and decreased values of annual and seasonal water flow were determined using normalized cumulative deviation curves (Andreyanov 1959; Georgiadi et al. 2018) in combination with the statistical homogeneity of the average values of the series using the Student t-test (Stepanek 2008; Lemeshko et al. 2018) and Mann-Whitney-Pettitt (MWP) test (Pettitt 1979) in the AnClim software for analysis time series. The estimates of the shift points of the contrasting phases, determined by different methods, mostly coincided with the conclusions made earlier for Russian rivers (Georgiadi et al. 2018).

Normalized CDCs represent the cumulative sum of deviations of a certain characteristic (variable) from its long-term annual average value, calculated for the entire observation period (Andreyanov 1959; Georgiadi et al. 2018). Often deviations are normalized to the coefficient of variation so that the temporal variability of dissimilar characteristics can be compared. Normalized CDCs were calculated using the following formulas:

$$CDC_{\tau} = \frac{1}{C_v} \sum_{i-1}^{\tau} (K_i - 1) \quad (3)$$

$$K_i = {}^{E}i / E_m \quad (4)$$

$$C_v = \frac{\sigma}{E_m} \quad (5)$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (E_i - E_m)^2} \quad (6)$$

where CDC_{τ} is the coordinate value of the cumulative deviation curve at time moment *τ*; E_i is the value of the *i*-th term of the series (*i* = 1, 2 … *n*); *n* is the number of terms in the time series; E_m is the long-term annual mean of the time series; K_i is the modular coefficient of the *i*-th term of the time series; C_v is the coefficient of variation of the time series; *σ* is the standard deviation of the time series.

Normalized CDCs are used to identify long-term phases (10–15 years or more) of values that have steadily increased or decreased compared to the time series averages over the entire observation period. In most of the cases considered, the necessary change points between long-term phases could be determined from the extreme (minimum or maximum) CDC values. They provide a graphical representation of the transition between different long-term phases of long-term averages for each of the hydrological characteristics.

The Student t-test and Mann-Whitney-Pettitt (MWP) test were used to identify the statistical heterogeneity of time series data, to assess the statistical significance of these deviations from the average values of the series for contrasting long-term phases of hydrological characteristics (variables), and also to determine the years in which changes occurred (change points). The MWP test and Student's t-test examined whether the average values in two different phases were the same or different.

The MWP test is a nonparametric rank-based test for identifying changes in a of a series'average. It uses cumulative sums to test the null hypothesis of no change. It divides data into two groups and investigates whether they come from the same distribution (Xie et al. 2014). It is a commonly used test primarily because it is distribution-free and insensitive to outliers and skewness in the data (Hedberg 2015; Yeh et al. 2015; Sharma and Singh 2017). The well-known Student's t-test is a parametric test based on a comparison of the mean values of two samples with unknown but equal variances (Lemeshko et al. 2018). This equality is confirmed by the results of Fisher criterion calculations for most characteristics considered in this paper for the rivers under study.

Estimation of the frequency of occurrence of low-, medium- and high-water years. A year was classified as high-water one if its annual and seasonal water flow values were not less than the flow of 25% exceedance probability and as low-water if both the annual and seasonal flow were not greater than its value with 75% exceedance probability. Accordingly, the medium-flow years were the ones with flow between 25% and 75% exceedance probability.

The assessment of the frequency of the specific water flow value was carried out based on the empirical curves of the frequency of the naturalized annual and seasonal water flow, constructed from their series for the years 1891 to 2019. The empirical value of the exceedance probability of water flow in year *i (Qi)*, PQ_i, was calculated using the following formula:

$$PQ_i = \left(\frac{m_i}{(n+1)} \right) * 100\% \quad (7)$$

where mi is the rank position of the year in the list of discharge values in descending order, and n is the total number of water discharge values in the series.

Assessment of annual and seasonal changes in water flow in the Don River basin upstream of Razdorskaya due to climate change and anthropogenic impact. The assessment of the climate change and anthropogenic impact effects on the overall change in water flow value during the ongoing global warming period is based on a comparison of naturalized long-term annual and seasonal average water flow values for the baseline period with observed and naturalized water flow values for the modern global warming period. The time limit between the baseline period and the current period of global warming was determined using the cumulative deviation curves of the long-term air temperature values averaged over the territory of the Don River basin (Georgiadi et al. 2014). The assessment of the contribution of anthropogenic impact and global warming towards the total runoff changes is based on comparing the runoff for the base period (which was either relatively poorly affected by economic activity or, as in our case, anthropogenic changes were excluded from it) with the actual (anthropogenic-modified) and restored (conditionally natural) runoff for the period of active global warming and significant anthropogenic impact within the catchment area and the river channel itself. Furthermore, the difference between the restored (virtually natural) runoff of the second period and the quasi-natural runoff of the baseline period characterizes the effect of global warming (and related climatic changes), while the difference between the restored (conditionally natural) and actual (observed) runoff of the second period defines the contribution of anthropogenic influence on the total changes in runoff.

RESULTS

Long-term phases of annual and seasonal water flow

The annual and seasonal water flow series of the Don River at Razdorskaya are characterized by two long-term phases (Fig. 2). Moreover, a phase of increased water flow was observed at the start of the studied period (since 1891) for snowmelt flood season and annual flow values while for the summer-autumn and winter low-water seasons started with a phase of decreased flow (since 1891 and 1898, respectively).

These phases were changed in 1965 for the values of annual and melted flood flow, and in 1977 and 1979 – for values of winter and summer-autumn water flow. Apparently, they will persist for some time in the future. The duration of the identified contrasting long-term phases ranges from 30 years for the phase of increased summer-autumn flow to 86 years for the phase of reduced winter flow (Table 1).

At the same time, the duration of increased flow periods for annual and snowmelt flood flow was found to substantially exceed the duration of the opposite phases. As was previously mentioned, the opposite was true for long contrasting phases of winter water flow. The situation for the summer-autumn low-water period flow values, however, was somewhat more complex. Within the long-term reduced phase of summer-autumn flow (1898–1978), two shorter incorporated phases could be distinguished. The first one was characterized by enlarged flow values

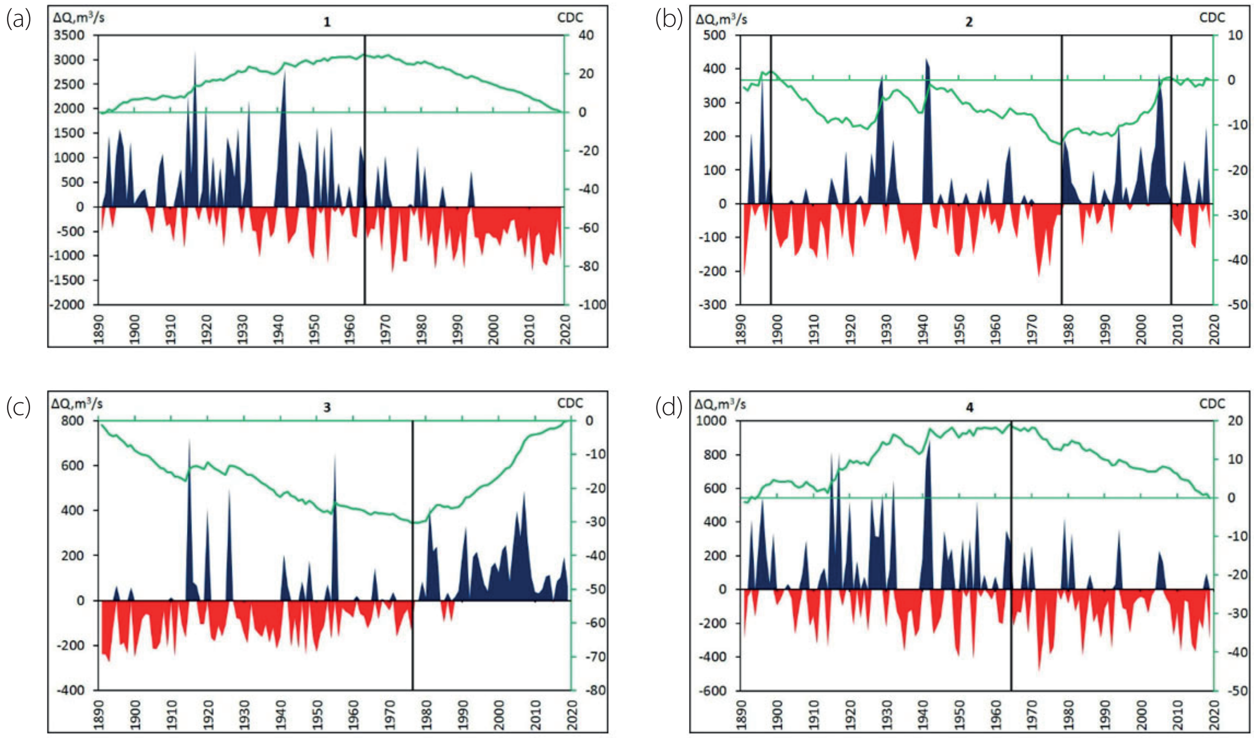

Fig. 2. Long-term changes in naturalized (a) snowmelt flood flow, (b) summer-autumn water flow, (c) winter water flow, and (d) annual average water flow of the Don River at Razdorskaya. Blue and red fields are positive and negative deviations relative to long-term averages, respectively; the green line is normalized cumulative deviation curves (CDC)

Table 1. Characteristics of contrasting phases of naturalized water flow of the Don River at Razdorskaya

Long-term phase	Water flow, km^3			
	Annual (January-December)	Snow-melt flood (March-May)	Summer-Autumn (June-November)	Winter (December-February)
	Phase boundaries/phase duration (years)/average value of characteristics			
DV[a]	1965–2019/55/21.22	1965–2019/55/11.11	1899–1978/80/5.76	1891–1976/86/4.03
IV[a]	1891–1964/74/26.65	1891–1964/74/18.24	1979–2008/30/7.23	1977–2019/33/2.5
IVav[a]	26.65	18.24	7.23	4.03
DVav[a]	21.22	11.11	5.76	2.5
(IVav – DVav)	5.43	7.13	1.55	1.53
(IVav – DVav), % relative to DVav	25.6	64.2	26.9	61.2

[a] DV, IV – decreased and increased values, respectively; DVav, IVav – hydrological characteristics averaged over long-term phases of their decreased and increased values.

and observed in 1926–1933. The consequent short phase of decreased water flow was identified between 1934 and 1940.

The most noticeable difference between the flow values of different contrasting phases is observed for the winter and flood periods, where it reaches more than 60% (Table 1). The least significant deviation between phases is observed for annual flow (~25%) and the summer-autumn low-water period (27%). However, considering the shorter phase of increased summer-autumn flow, the deviation value for this season reaches 37%.

Shift point analyses of multi-year changes of annual and seasonal water flow.

Comparison of the determined shift points obtained using normalized CDCs (Fig. 2) and using criteria of statistical homogeneity (Table 2) confirmed the previously drawn conclusion (Georgiadi et al. 2018) about the similarity of the results of these methods.

Long-term changes in daily water discharge annual hydrograph.

Annual hydrographs produced based on the naturalized water discharge values and averaged over long-term phases of increased (1951–1964) and decreased (1965–2019) water flow found for annual and snow-melt flood flow data vary drastically between each other (Fig. 3). Moreover, the total volume of water coming with snow-melt as well as peak discharge values are reducing significantly during the long phase of decreased runoff. However, the time limits of snow-melt floods remain almost the same. The values of water discharge for low-water seasons (winter and summer-autumn) increase in the phase of decreased annual and flood water flow especially during the winter low-water season.

Table 2. Shift points for contrasting phases of naturalized water flow of the Don River at Razdorskaya

The direction of the change of contrasting phases	Methods				
	Cumulative deviations curve anomalies	Student - *t* test		MWP Test	
	Shift point	Shift point	*p*-Value	Shift point	*p*-Value
Snow-melt flood water flow					
Increased→Decreased	1965	1972	0.05	1972	0.01
Summer-Autumn water flow					
Decreased→Increased	1979	1979	0.05	1978	0.01
Winter water flow					
Decreased→Increased	1977	1979	0.05	1977	0.01
Annual water flow					
Decreased→Increased	1965	1965	0.05	1965	0.05

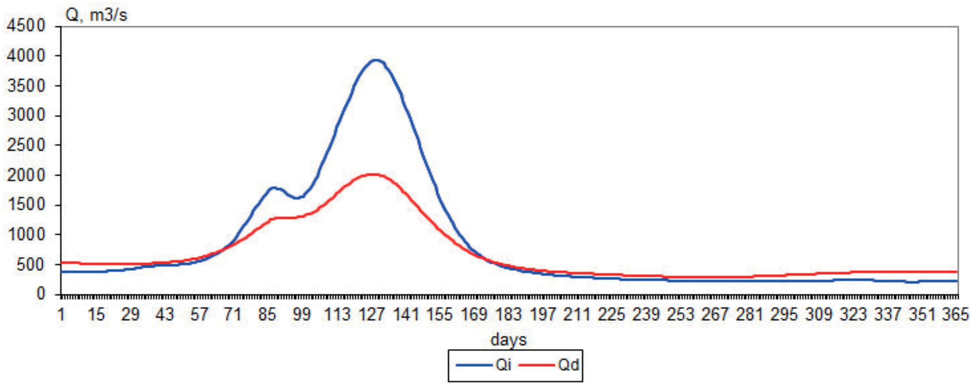

Fig. 3. Annual hydrographs of naturalized daily average water discharge (Q) of the Don River at Razdorskaya for contrasting phases of annual and snowmelt flood flow. Q_d and Q_i are water discharge values for decreased and increased water flow phases, respectively

A comparison of annual hydrographs averaged over the long-term phases of increased (for the period from 1979 to 2019) and decreased (for the period from 1945 to 1976) flow for the long-term phases of lower-water hydrological seasons shows that the hydrographs characteristic of them are close to the hydrographs of the contrasting phases of annual and flood flow considered above. The differences between them are largely explained by the mismatch of the boundaries of their contrasting phases.

River water flow frequency structure in the phases of increased and decreased annual and seasonal water flow. It was found that the number of high-water years (years with a probability of flow exceeding equal to or less than 25%) and low-water years (years with a probability of exceeding 75% or more) vary drastically during contrasting long-term phases of increased or decreased flow (Fig. 4). In this regard, the relative number of high-water years observed during the long-term increased flow phase according to the annual flow values, as well as depending on the flow rate of snow-melt flood, winter, and summer-autumn low-water seasons, has reached 35, 36, 55, and 42%, respectively.

At the same time, the proportion of low-water years during this phase was found to be significantly smaller reaching 22%, 11%, 0%, and 11%, respectively. The reverse pattern was observed for the long-term decreased flow phase (Fig. 4). Meanwhile, the total proportion of both low- and high-water years remains relatively stable changing from 40% to 52% for decreased flow phase and even less, between 47% and 56%, for increased flow phase. Thus, the proportion of years with a probability of flow exceeding from 25% to 75% (mid-water years) is also considered fairly stable and fluctuates within similar limits. It varies from 44% to 54% for the increased flow phase and between 45% and 60% for the decreased flow phase.

Changes in annual and seasonal flow values during the modern global warming period The starting point of the modern period of global warming in the Don River basin. An analysis of the curves of cumulative deviations showed that the onset of increased warming (according to air temperature values) in the study area can be attributed to 1988 (Fig. 5). Thus, the period from 1939 to 1988, characterized by relatively lower air temperatures, was taken as the base period in this study. In the Don River basin, there are significant discrepancies between the average long-term climate variables for the initial and subsequent (warmer) periods: the annual average air temperature was 6.0°C and 7.4°C, and the annual precipitation was 423 mm and 476 mm, respectively.

Annual and seasonal river water flow changes. The variability in annual and seasonal flow values due to both climate change and anthropogenic influence effect has shown ambiguous patterns (Table 3). It can be seen that during the period of modern global warming, snow-melt flood flow has noticeably decreased, while the values of winter and summer-autumn low-water flow have increased significantly. Thus, although the annual water flow for the study period decreased, but to a lesser extent than in the snowmelt flood period.

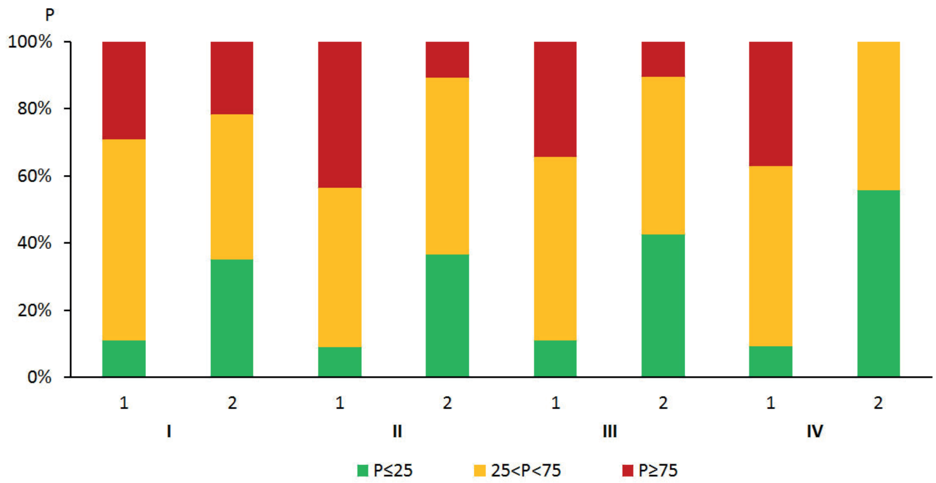

Fig. 4. Frequency structure of (I) annual, (II) snow-melt flood, (III) summer-autumn, and (IV) winter water flow in the Don River at Razdorskaya during the long-term phases of (1) increased and (2) decreased water flow. The proportion of years with water flow: red – equal to or less than that corresponding to 75% exceedance probability; yellow – greater than that corresponding to 75% and less than that corresponding to 25% exceedance probability; green – equal to or greater than that corresponding to 25% exceedance probability

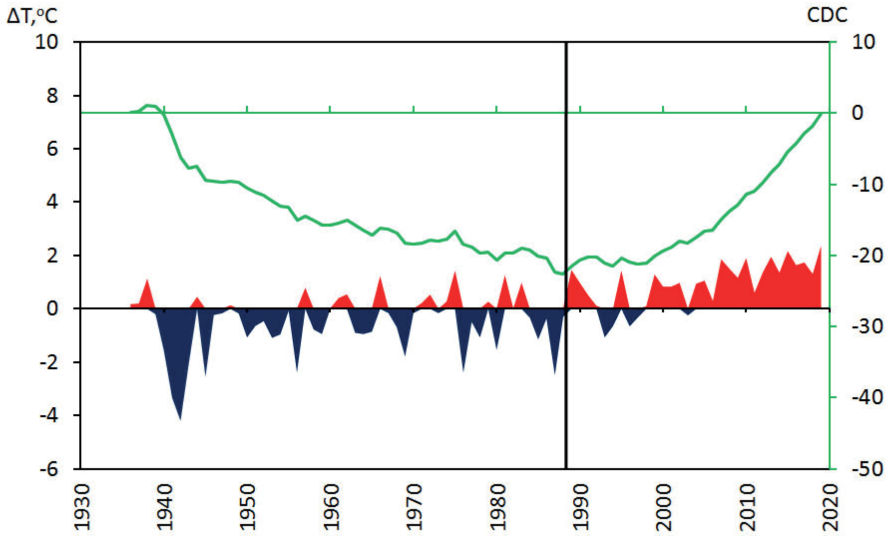

Fig. 5. Long-term changes of the annual average air temperatures in the Don River basin, expressed in the coordinates of the normalized cumulative deviation curves (CDC) and deviations from their long-term average values (red and blue fields)

Table 3. Total annual and seasonal water flow changes during the modern global warming period (1989–2019) due to cumulative climate change and anthropogenic influence effect compared to values naturalized from the baseline period (1939–1988)

Period	Naturalized long-term average flow for baseline period, km³/year	Modern global warming period		
		Actual long-term average flow, km³/year	Long-term average flow changes	
			km³/year	%
Year	24.17	19.58	–4.59	–19.0
Snow-melt flood	15.43	6.21	–9.22	–59.7
Summer-autumn low-water period	5.94	8.91	2.97	50.0
Winter low-water period	2.87	4.48	1.61	56.1

However, anthropogenic and climatic factors that caused changes in annual and seasonal water flow were unidirectional (Table 4). They resulted in a significant flow decrease during the snow-melt flood period (up to 24% and 36%, respectively). The flow during summer-autumn and winter low-water periods, in their turn, have increased due to the influence of anthropogenic and climate change-related factors. It is important to note that the respective contribution of both factors varied for winter and summer-autumn periods. If the summer-autumn flow was mainly influenced by anthropogenic causes, then the winter flow was largely influenced by factors associated with climate change.

Changes in daily water discharge annual hydrograph. The sudden transformation of annual hydrographs for observed daily water discharge values (with anthropogenic changes included) in the Don River at Razdorskaya has happened as a result of global warming influence compared to the cooler baseline period (Fig. 6).

Table 4. Anthropogenic and climate-related changes in long-term annual and seasonal average water flow over the modern global warming period (1989–2019) compared to their naturalized values for the baseline period (1939–1988)

Period	Anthropogenic changes		Climate-induced changes	
	km^3/year	%	km^3/year	%
Year	–1.45	–6.0	–3.14	–13.0
Snow-melt flood	–3.64	–23.6	–5.58	–36.2
Summer-autumn low-water period	1.92	32.3	1.05	17.7
Winter low-water period	0.25	8.7	1.36	47.4

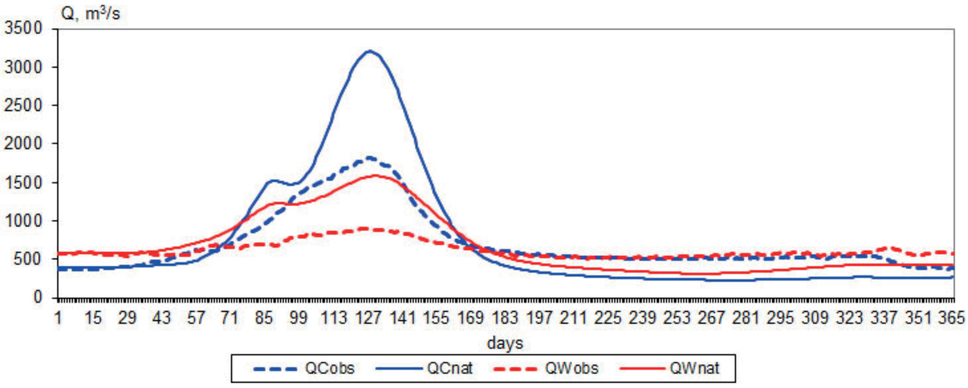

Fig. 6. Annual hydrographs of naturalized and measured (with anthropogenic influence included) daily water discharge values in the Don River at Razdorskaya for the baseline period and the period of modern global warming. QW_{nat} and QW_{obs} are naturalized and measured (with anthropogenic influence included) water discharge values, respectively, for the global warming period (1989–2019); QC_{nat}, QC_{obs} are naturalized and measured (with anthropogenic influence included) water discharge values, respectively, for the baseline period (1939–1988)

A significant reduction in both naturalized and measured snow-melt flood daily water discharges is observed during the period of intensified global warming influence. At the same time, the water discharge was found to noticeably rise in low-water seasons within the same period. On the other hand, the measured water discharges for the summer-autumn low-water season were found to almost coincide with the baseline period water discharge values while the winter flow discharges have shown a substantial increase. This irregularity was mainly caused by the Tsimlyansk Reservoir management procedure.

Changes in frequency structure of annual and seasonal river water flow. A character of deviations in the number of high-water (with the flow equal to or less than 25% exceedance probability) and low-water (with the flow equal to or more than 75% exceedance probability) years between the baseline period and the period of modern global warming considering seasonal low-water periods does not differ significantly from the ones observed for respective contrasting long-term phases of increased/decreased flow values (Fig. 7). This is due to the relatively small-time gap between these contrasting phases and the manifestation of global warming processes in the region. Consequently, the features of long-term variability between the compared periods for both cases do not vary significantly. The period of global warming almost coincided with the phase of increase in the flow of low-water seasons (winter and summer-autumn) relative to their time limits.

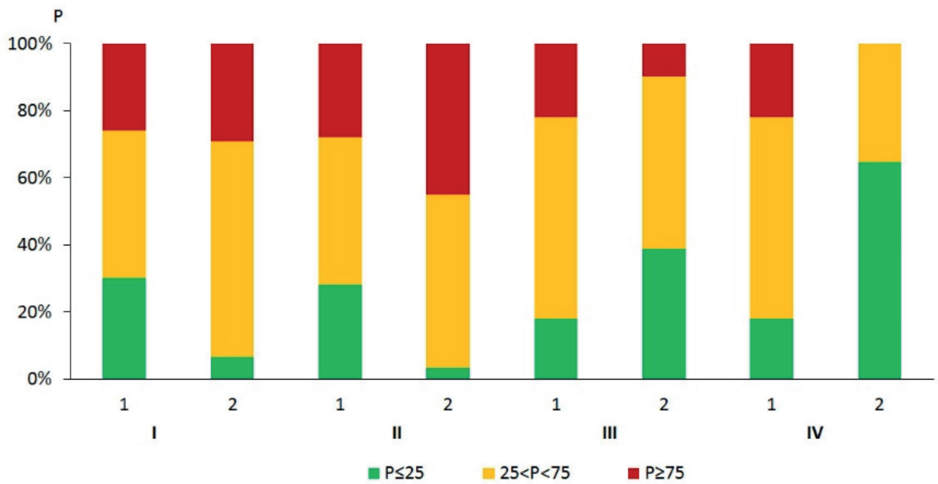

Fig. 7. Frequency structure of (I) annual, (II) snow-melt flood, (III) summer-autumn, and (IV) winter water flow of the Don River at Razdorskaya during (1) the baseline period (1939–1988) and (2) the global warming period (1989–2019). The proportion of years with water flow: red – equal to or less than that corresponding to 75% exceedance probability; yellow – greater than that corresponding to 75% and less than that corresponding to 25% exceedance probability; green – equal to or greater than that corresponding to 25% exceedance probability

The mismatch of the global warming period, starting from the shift point between the contrasting phases of annual and snow-melt flood flows, is considered to be much more significant and reaches a range of 25 years. The global warming period overlaps the part of the long-term phase of reduced annual and snow-melt flood flow values. The period before the beginning of the global warming effect on the Don River basin has incorporated phases of both increased and decreased annual and snow-melt flood flow values to an equal extent. This is the main reason for the noticeable discrepancy in the number of low-, medium- and high-water years between the contrasting phases, as well as between the background (baseline) period and the period of global warming intensification.

DISCUSSION

The time series of daily water discharge annual hydrograph in the Don River at Razdorskaya for the period of intensified anthropogenic influence (1951–2019) was naturalized using the annual hydrograph transformation method. As a result, a unique long-term series of natural annual and seasonal water flow values for 1891–2019 was obtained. This also made it possible to identify and analyze the features of the hydrological regime of the Don River, including long-term phases of increased/decreased annual and seasonal flow, the annual hydrograph of daily water discharge, as well as differences in the number of low-, medium- and high-water years. Finally, it has enabled an estimation of modern global warming on these characteristics. Thus, a sufficient contribution was made to the development of a modern methodology for studying changes in river water flow.

It is important to note that the characteristics of contrasting phases of both annual and seasonal water runoff values for the Don near Razdorskaya, as well as the contribution of climatic and anthropogenic factors to their interannual changes observed during global warming, were estimated close to the results obtained by the authors while using another method of runoff naturalization (Georgiadi et al. 2014; Georgiadi et al. 2019). That method was based on a regression model built between annual and seasonal runoff of the Don near Razdorskaya and corresponding values for the Don River at Kazanskaya and the Khoper River at Besplemyanovsky.

In contrast to estimates based on regression analysis of annual and seasonal runoff, the approach, which uses the transformation of the annual hydrograph of daily water discharges, also creates the basis for a detailed analysis of long-term changes in genetic components of seasonal and annual river runoff taking into account long-term changes in the seasonal boundaries. However, this approach also has limitations, the most serious of which is related to the limited extent of simultaneous observations during the period of the conditionally natural water regime.

Evidently, the naturalization procedure for water flow should include a set of methods, including hydrological models that describe hydrological processes with various level of detail (Motovilov et al. 1999; Kalugin 2022).

One of the main problems in studying long-term flow changes is related to the determination of shift points between contrasting multi-year phases or between the period of global warming and the base period. Generally, specialized statistical criteria for long-term series homogeneity are used (Frolova et al. 2022). Our experience of previous studies shows that the optimal set of methods for identifying the time boundary between heterogeneous periods includes the mentioned criteria (parametric and non-parametric), as well as the analysis of the cumulative deviation curve (Georgiadi et al. 2018; Georgiadi and Groisman 2022). This makes it possible to determine the shift points with a high degree of certainty.

Although there is some progress in studies of long-term phases of hydrological characteristics, including those made for the territory of Russia, many issues still require further investigation. This covers specifically the spatial distribution patterns of characteristics of long-term contrasting flow phases. At the same time, promising results have been presented already concerning the synchronism of long-term contrasting phases of seasonal runoff on the rivers of the Russian Plain (Georgiadi et al. 2014) and the regionalization of the territory of Russia with respect to the boundaries of the change of long-term periods of increased/decreased annual and maximum runoff (Frolova et al. 2022) and changes in the pattern of the intra-annual distribution of runoff on the rivers of the Russian Plain during the period of global warming (Ivanov et al. 2022).

One of the important methodological problems while assessing the impact of global warming on river runoff is to determine both its spatial boundaries, as well as temporal boundaries of the baseline period with which the characteristics of river runoff are compared. The shift points between the long-term phases of decreased and increased values of annual air temperature averaged for the Don basin over the 1939–2019 period was used as the starting point of global warming effects in the Don basin in this study (1989). It should be noted that, in order to assess the scale of modern changes in river flow associated with global warming, the characteristics of two periods with different climate conditions were compared. The choice of a time boundary between them was not always justified. Therefore, it was often suggested to use different years (1978, 1980, etc.). The study area's spatial coverage, meanwhile, covered extremely large areas. Occasionally, the main reason for choosing certain years as the time limits of the compared periods was lying in the need to have a sufficient duration of each of the compared periods so that statistically reliable estimates could be obtained (Georgiadi and Kashutina 2016). Often, the transition between long periods (phases) of decreased and increased flow, which are evidently related to global warming, has served as justification for choosing a specific year as the boundary. However, it turned out that the boundaries between contrasting flow phases differ significantly not only for rivers of different regions but also for annual and seasonal flow volumes of the same river (Georgiadi 2014; Georgiadi et al. 2019; Milyukova et al. 2020; Georgiadi et al. 2020; Georgiadi and Groisman 2022; Frolova et al. 2022, etc.).

The points of contrasting phases shifting, in general, do not coincide for river flow and air temperature and may differ very significantly. Due to differences in estimates of both the global warming and baseline period boundaries, the results of runoff variation assessment differ as well. However, in most cases, those differences are not so significant. For instance, the estimates for the Don given in this article compared to our previous publications (Georgiadi et al. 2014; Georgiadi et al. 2019) differed considerably only for winter runoff although other boundaries for the compared periods and different methods of naturalizing annual and seasonal runoff were used there.

CONCLUSIONS

The long-term series of naturalized natural monthly water flow values of the Don River at Razdorskaya from 1891 to 2019 was obtained by the exclusion of human-induced flow changes (mainly those explained by interannual and seasonal water flow regulation of the Tsimlyansk Reservoir in 1951–2019). This was done based on the transformation of the annual hydrograph of daily water discharge of the river. The described procedure allowed determining and analyzing features of the Don River's hydrological regime such as annual hydrograph of daily water discharge, long-term phases of increased/decreased annual and seasonal flow, and differences in the number of low-, medium-, and high-water years between these phases. In addition, an analysis of modern global warming was carried out on the basis of this.

Two long-term phases of annual and seasonal flow were identified. The shift points obtained using the normalized cumulative deviation curve analysis and statistical homogeneity tests were almost identical, which means a high level of reliability of these methods. The comparison between the distinguished contrasting phases has shown significant differences in values between both periods. Annual and snowmelt flood flow values have entered a phase of increased flow since the 1890s, while the phase of decreased flow was observed for the winter and summer-autumn low-water seasons. In the 1960s and 1970s these phases changed. The duration of contrasting phases for different seasons varied from 30 to 86 years. The most recognizable deviation between flow values in different phases were observed during the winter low-water season and snow-melt flood when it has reached over 60%. Significantly smaller variation was typical for the annual (~25%) and summer-autumn period (27%).

The annual hydrographs of daily average naturalized water discharge averaged over long-term phases of increased and decreased water flow found based on annual and snow-melt flood flow values series have shown noticeable dissimilarity. Peak and volume of snow-melt water runoff were noticeably reduced in the long phase of decreased water flow. However, the time limits of the snow-melt flood in contrast long phases does not differ significantly. On the contrary, during low-water seasons, especially in winter, the water flow increases.

The share of high-water years in the phase of increased flow is significantly higher than the share of low-water years, although the cumulative share of low- and high-water years remains relatively stable. Thus, the proportion of medium-water years (25–75% exceedance probability) is also considered sufficiently stable during any contrasting phase.

During the modern global warming period (which was observed in the region through increased air temperatures since 1989) the changes in annual and seasonal flow was caused by both anthropogenic and climate change-related factors, and thus, has shown an ambiguous nature. It could be seen that snow-melt flood flow has been reduced noticeably during the modern global warming period while the flow in winter and summer-autumn low-water periods have risen substantially. Thus, even though the annual water flow has decreased over the studied period, the reduction was to a lesser extent than that of the snow-melt flood period.

Anthropogenic and climate change-related changes in annual and seasonal flow during the global warming period was unidirectional. They resulted in a significant decrease in the snow-melt flood flow. At the same time, the flow increased in the summer-autumn and winter low-water seasons under their influence. It should be noted that the corresponding contribution of both factors were different for the winter and summer-autumn seasons. If the summer-autumn water flow was mainly influenced by anthropogenic causes, then the winter flow was largely influenced by factors associated with climate change.

The sudden transformation of annual hydrographs for observed (with anthropogenic changes included) and naturalized daily average water discharge values has happened under the influence of global warming compared to the cooler baseline period. A significant decrease in values of both measured and naturalized snow-melt flood water discharge was observed, while the low-water seasons were characterized by a noticeable rise in river water flow. Despite a significant increase in winter flow, water discharge in the summer-autumn season did not significantly exceed baseline values. This unevenness is mainly caused by the peculiarities of the management of the Tsimlyansk Reservoir.

Since the shift points for the global warming period and long-term phase of increased naturalized flow for low-water seasons almost coincide, the deviation in frequency of low-, medium-, and high-water years occurrence does not differ significantly. However, the substantial discrepancy between the time boundaries of phases of both reduced annual and snow-melt flood flow and of the global warming period results in noticeable differences in the number of low-, medium-, and high-water years.

REFERENCES

Andreyanov V.N. (1959). Cyclic fluctuations of annual water flow and their accounting for hydrological calculations. Proc. SHI. Flow calculations. Gidrometeoizdat: Leningrad, USSR, 686 3-50 (in Russian).

Arc Atlas: Our Earth (1996). MacOdrum Library – Carleton University [online]. Available at: https://library.carleton.ca/find/gis/geospatial-data/arc-atlas-our-earth [Accessed 29 Oct. 2021].

Bolgov M.V., Filippova I.A., Osipova N.V., Korobkina E.A. and Trubetskova M.D. (2018). Current features of the hydrological regime of rivers in the Volga Basin. Hydrological Changes. Problems of Geography, 145, 206-221 (in Russian).

Frolova N.L., Magritskii D.V., Kireeva M.B., Grigor'ev V.Y., Gelfan A.N., Sazonov A.A. and Shevchenko A.I. (2022). Streamflow of the Russian rivers under current and forecasted climate chfnges. A review of publications. 1. Assessment of changes in the water regime of Russian rivers by observation data. Water Resources, 49(3), 333-350, DOI: 10.1134/S0097807822030046.

Georgiadi A.G. and Groisman P.Ya. (2022). Long-term changes of water flow, water temperature and heat flux of two largest arctic rivers of European Russia, Northern Dvina and Pechora. Environmental Research Letters, 17(8), DOI: 10.1088/1748-9326/ac82c1.

Georgiadi A.G. and Kashutina E.A. (2016). Long-Term Runoff Changes of the Largest Siberian Rivers. Izvestiya Rossiiskoi Akademii Nauk, Seriya Geograficheskaya, 5, 70-81 (in Russian).

Georgiadi A.G., Kashutina E.A. and Milyukova I.P. (2019) Long periods of increased/decreased runoffs of large Russian rivers. IOP Conf. Ser.: Earth Environ. Sci., 386, 012-048, DOI: 10.1088/1755-1315/386/1/012048.

Georgiadi A.G., Koronkevich N.I., Milyukova I.P., Kashutina E.A. and Barabanova E.A. (2014). Contemporary and Scenario Changes in River Runoff in the Basins of the Largest Russian Rivers. Part 2. Basins of the Volga and Don. Maks Press: Moscow, Russia (in Russian).

Georgiadi A.G., Kashutina E.A. and Milyukova I.P. (2018). Long-term changes of water flow, water temperature and heat flux of the largest Siberian rivers. Polarforschung, 87(2), 167-176, DOI: 10.2312/polarforschung.87.2.167.

Georgiadi A.G., Milyukova I.P. and Kashutina E.A. (2020). Contemporary and scenario changes in river runoff in the Don Basin. Water Resources, 47, 913-923, DOI: 10.1134/S0097807820060068.

Georgievskii V.Yu. and Moiseenkov A.I. (1984). Restoration of natural hydrographs of the flow of large rivers, regulated by a cascade of reservoirs (the example of the Volga River). Proc. SHI, 291, 54-61 (in Russian).

Hedberg S. (2015). Regional Quantification of Climatic and Anthropogenic Impacts on Streamflows in Sweden. Institutionen för geovetenskaper: Uppsala, Sweden.

Hinzmann L.D., Bettez N.D., Bolton W.R., Cyapini F.S., Dyurgerov M.B., Fasti C.F., Griffith B., Hollisters R.D., Hope A., Hantington H.R., et al. (2005). Evidence and implications of recent climate change in Northern Alaska and other Arctic regions. Climatic Change, 72, 251–298, DOI: 10.1007/s10584-005-5352-2.

Ivanov A.M., Gorbarenko A.V., Kireeva M.B. and Povalishnikova E.S. (2022). Identifying climate change impacts on hydrological behavior on large-scale with machine learning algorithms. Geography, Environment, Sustainability, 3(15), 80-87, DOI: 10.24057/2071-9388-2022-087.

Kalinin G.P. and Milyukov P.I. (1958). Approximate Calculation of Unsteady Motion of Water Masses. Proceedings of the Central Institute of Forecasts. Gidrometeoizdat: Leningrad, USSR, 66, 72 p. (in Russian).

Kalugin A. (2022). Hydrological and meteorological variability in the Volga River basin under global warming by 1.5 and 2 degrees. Climate, 10, 107, DOI: 10.3390/cli10070107.

Kireeva M.V., Ilich V.P., Sazonov A.A. and Mikhaylyukova P.G. (2018). An assessment of changes in land use and their impact on Don River basin runoff using satellite imagery. Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa (Current problems in remote sensing of the Earth from space), 15(2), 191-200 (in Russian).

Kuzin P.S. (1979). Cyclic fluctuations in the water flow of rivers of the Northern hemisphere. Gidrometeoizdat: Leningrad, USSR (in Russian).

Lemeshko B., Lemeshko S., Veretelnikova I. and Novikova A. (2018). On the application of checking criteria for homogeneity of means. Bulletin of Siberian State University of Telecommunications and Informatics, 1, 41-55 (in Russian).

Magritsky D.V. (2015). Factors and trends of the long-term fluctuations of water, sediment and heat flux in the lower reaches of the Lena River and the Vilyui River. Moscow University Bulletin. Series 5, Geography, 6, 17-30 (in Russian).

Milyukova I.P., Georgiadi A.G. and Borodin O.O. (2020). Long-term changes in water flow of the Volga basin rivers. E3S Web of Conferences, 163(2), 05008, DOI: 10.1051/e3sconf/202016305008.

Motovilov Y.G., Gottschalk L., Engeland K., and Rodhe A. (1999). Validation of a distributed hydrological model against spatial observations. Agricultural and Forest Meteorology, 98, 257-277.

Moriasi D.N., Arnold J.G., Van Liew M.W., Bingner R.L., Harmel R.D. and Veith T.L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50(3), 885-900, DOI: 10.13031/2013.23153.

Muraveisky S.D. (1960). Rivers and lakes, Hydrobiology. Runoff. Geografgiz: Moscow, USSR, 388 p. (in Russian).

Nash J.E. (1959). Systematic determination of unit hydrograph parameters. Journal of Geophysical Research, 64, 111-115.

Nash J.E. and Sutcliff J.V. (1970). River flow forecasting through conceptual models. Part I—A Discussion of Principles. Journal of Hydrology, 10, 282-290.

Pettitt A.N. (1979). A non-parametric approach to the change-point problem. Journal of the Royal Statistical Society. Series C (Applied Statistics), 28, 126-135.

Sharma S. and Singh P.K. (2017). Long term spatiotemporal variability in rainfall trends over the state of Jharkhand. India Climate, 5, 2-18.

Shi X., Qin T., Nie H., Weng B. and He Sh. (2019). Changes in major global river discharges directed into the ocean. Int. J. of Environ. Res. And Public Health, 16(8), 1-19, DOI: 10.3390/ijerph16081469.

Shiklomanov I.A. and Georgievskii V.Yu. (2007). Effect of climate changes on the hydrological regime and water resources of Russian rivers. Proc. British–Russian Conf. "Hydrological Effects of Climate Changes", Novosibirsk, Russia, 143–151 (in Russian).

Shiklomanov A.I., Golovanov O., Lammers R.B., Tretjyakov M. and Yang D. (2011). Dam/Reservoir-Induced Hydrological Changes in Large Siberian Rivers. Amer. Geophys. Union, Fall Meeting 2011, Abstract C31B-06.

Shiklomanov A.I., Lammers R.B., Lettenmaier D.R., Polischuk Yu., et al. (2013). Hydrological changes: historical analysis, contemporary status, and future projections in Regional Environ. In: Changes in Siberia and Their Global Consequences, Ch. 4, Editor 1, Groisman, P.Ya., Editor 2, Gutman, G. Springer Sci.+Business Media: Dordrecht, Netherlands, 111–154.

Shiklomanov A., Déry S., Tretiakov M., Yang D., Magritsky D., Georgiadi A. and Tang W. (2020). River Freshwater Flux to the Arctic Ocean. In: Arctic Hydrology, Permafrost and Ecosystems. Editor 1, Yang, D., Editor 2, Kane, D.L. Springer: Cham, Switzerland, 703-738, DOI: 10.1007/978-3-030-50930-9_24.

Scientific and applied reference: Long-term fluctuations and variability of water resources and the main characteristics of the flow of rivers of the Russian Federation (2021). REAL: St. Petersburg, Russia, 190 p. (in Russian).

Sokolovskii D.L and Shiklomanov I.A. (1965). Calculations of flood hydrographs using electronic modeling devices. Proc. LGMI, 23, 65-79 (in Russian).

Stepanek P. (2008). AnClim–software for time series analysis [online]. Department of Geography, Faculty of Sciences, Masaric University, Brno, Czech Republic. Available at: http://www.climehom.eu [Accessed 29 Oct. 2021]

Stuefer S., Yang D. and Shiklomanov A. (2011). Effect of stream flow regulation on mean annual discharge variability of the Yenisey River. IAHS Publ., 346, 27-32.

Varentsova N.A., Grechushnikova M.G., Povalishnikova E.S., Kireeva M.B., Kharlamov M.A. and Frolova N.L. (2021). Influence of climatic and anthropogenic factors on spring runoff in the Don basin. Bulletin of the Moscow University. Series 5. Geography, 5, 91-108.

Water Resources of Russia and their Use (2008). State Hydrological Institute: St. Petersburg, Russia (in Russian).

Xie H., Li D. and Xiong L. (2014). Exploring the ability of the Pettitt method for detecting change point by Monte Carlo simulation. Stochastic Environmental Research and Risk Assessment, 28, 1643-1655, DOI: 10.1007/s00477-013-0814-y.

Zhuravlev S.A., Georgievsky V.Yu., Balonishnikova Zh.A. and Shamin S.I. (2022). Water management / Third assessment report on climate change and its consequences on the territory of the Russian Federation / Edited by V. M. Kattsov; Rosgidromet: St. Petersburg, Russia, 344-356 (in Russian).

Yeh C.-F., Wang J., Yeh H.-F., Lee C.-H. (2015). Spatial and temporal streamflow trends in Northern Taiwan. Water, 7(2), 634-651, DOI: 10.3390/w7020634.