water

MDPI

Article

Extreme Low Flow during Long-Lasting Phases of River Runoff in the Central Part of the East European Plain

Aleksandr G. Georgiadi [1,*] and Pavel Y. Groisman [2]

[1] Institute of Geography, Russian Academy of Sciences, 119017 Moscow, Russia
[2] Hydrology Science & Services Corporation, Asheville, NC 28804, USA; groismanp@bellsouth.net
* Correspondence: georgiadi@igras.ru

Abstract: In the rivers of the central part of the East European Plain (the Volga at Staritsa, the Oka at Kaluga, and the Don at Stanitsa Kazanskaya), long phases (10–15 years or more) of increased/decreased annual and seasonal runoff have occurred, as well as differences in the frequencies of extremely low flow conditions from the late 19th century to 2020. Phase boundaries were identified by cumulative deviation curves and statistical homogeneity. The frequencies of specific water flow values were estimated using the empirical curves of the exceedance probability of annual and seasonal water flows based on their long-term time series. In the century-long changes of rivers considered, two long contrasting phases were revealed. These phases are characterized by increased and decreased runoff of hydrological seasons. Near simultaneously, a phase of increased runoff was first observed for the freshet season. On the contrary, phases of decreased runoff were first observed for low-water seasons. The runoff phases differ significantly in duration and differences in flow. Significant differences were revealed in the frequency of low-water years for a low runoff with an exceedance probability above or equal to 75% and above or equal to 95%.

Keywords: central part of the East European Plain; annual and seasonal river runoff; long-lasting phases; extreme low flow

check for updates

Citation: Georgiadi, A.G.; Groisman, P.Y. Extreme Low Flow during Long-Lasting Phases of River Runoff in the Central Part of the East European Plain. *Water* **2023**, *15*, 2146. https://doi.org/10.3390/w15122146

Academic Editors: Vittorio Di Federico and Renato Morbidelli

Received: 24 April 2023
Revised: 23 May 2023
Accepted: 30 May 2023
Published: 6 June 2023

1. Introduction

Much research has been devoted to various aspects of long-term contrasting phases in long-term changes in annual and seasonal river flow and extremely low streamflow [1–7]. However, the question of how the frequency of low-water years changes during the long-term phases of increased/decreased runoff has not been sufficiently investigated. This article examines long periods (phases) of increased and decreased annual and seasonal runoff, as well as abnormally low runoff (when the water flow was less than or equal to the exceedance probability 75 and 95%) of three rivers (the Volga at Staritsa, the Oka at Kaluga, and the Don at Stanitsa Kazanskaya) in the central part of the Eastern European Plain for the period from the late 19th century to 2020. This region encompasses the upstream areas of three major rivers of central European Russia located before the major reservoirs and water-withholding channels built downstream. During the past century, these parts of the river basins have been affected by anthropogenic activities, but, summarily, these activities did not significantly impact the water regime of the rivers [2,3]. On the contrary, the changes in extreme streamflow of these rivers, especially the frequency and magnitude of floods and hydrological droughts, affect many aspects of human activity in this densely populated agricultural and industrial region. In this respect, it would be enough to mention one of the major water supply routes to the Moscow metropolitan area, with a population of 21.5 million via the Volga–Moskva Channel.

Extreme low flow in the low-flow period of the year (here, these are the summer–autumn and winter seasons) endangers water supply to population, industrial, and agriculture consumption and may detrimentally affect the regional ecosystems. Moreover, extreme low flows during the snowmelt flood period and during the year as a whole affect fisheries and hydropower production downstream. The purpose of our study was to quantify the extremely low-flow events on the rivers of the Central Part of European Russia during all hydrological seasons within the year and to assess the long-term dynamics of these events while keeping in mind the ongoing and projected climatic changes.

The problem of studying long periods ("phases," фазы, in the terminology of the USSR and Russia [8]) of increased/decreased runoff and other components of geo-runoff [9], as well as other environmental components, including the ecosystem conditions of rivers, lakes and marine waters [1,10], receives considerable attention. Interest has been motivated largely by global warming since the 1970s [11,12] and the accompanying changes in river runoff characteristics. These contrasting phases are characterized by specific, relatively steady river water regimes. They are important in the long-term dynamics of hydrological characteristics caused by climate changes. Differences in the mean flow during such contrasting phases are, most often, statistically significant. The phases commonly last 10–15 years but can extend over several decades [2,3,7]. The annual and seasonal river runoff has already been studied in many regions worldwide [2–6,13–17], as well as the fluxes of heat, suspended sediments, and chemicals within the river streams [5,18–20].

Additionally, extremely low flows of varying intensity can be formed against the background of long-term fluctuations in annual and seasonal runoff. Extreme low-flow conditions may cover not only low-water seasons of the year (which, in the northern extratropics, are summer–autumn, and winter) but also the snowmelt (freshet season) and the year as a whole [21]. In recent years, interest in extremely low streamflow has increased significantly [22]. Much attention has been paid to various aspects of low flow in low-water seasons [23–26] because they are a key limit to water consumption [27]. Extreme low flow conditions often cover large areas, especially in years with severe atmospheric and agricultural droughts [21,28,29]. Such droughts form over vast areas of the East European Plain, mainly in the steppe, forest–steppe, and the southern part of the forest zone [7,21]. The relationship between changes in the frequency of extremely dry hydrological years and the variations of the mean flow during the main hydrological seasons of the year remains a topic in need of further study.

2. Materials

2.1. Study Area

Our study area includes three upstream drainage basins of the major rivers in the center of European Russia (the Volga, Oka, and Don Rivers). These basins lie in the mixed-forest zone (Volga, Oka) and the forest–steppe and steppe zones (Don) of the southern macroslope of the East European Plain (Figure 1 and Table 1).

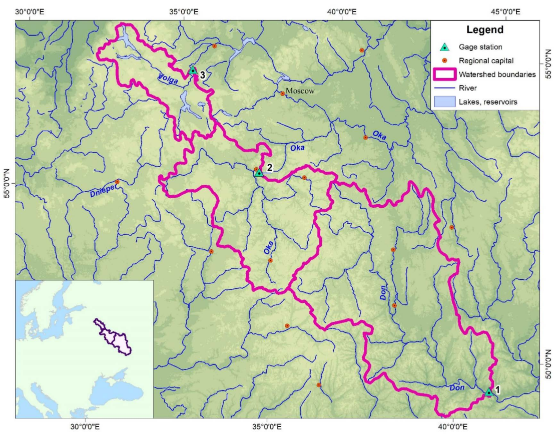

Figure 1. Three studied upstream river basins and river gauge locations at their closures. 1—the Don River at Stanitsa Kazanskaya, 2—the Oka River at Kaluga, 3—the Volga River at Staritsa. Major map projection is Lambert Azimuthal Equal Area projection (central meridian 20° E, latitude of origin 45° N).

Table 1. Major characteristics of river basins.

River—Gage	Basin Area, 10^3 km^2	Natural Zone	Period of Observation	Mean Water Discharge, m^3/s			
				Annual	Snowmelt Flood	Summer-Autumn	Winter
Volga—Staritsa	21,100	MBF *	1891–2020	160	399	129	89
Oka—Kaluga	54,900	MBF	1882–2020	289	702	157	140
Don—Stanitsa Kazanskaya	102,000	3/4 Forest–steppe 1/4 Steppe	1882–2020	317	788	158	170

Note(s): * MBF-mixed and broad-leaved forest.

The considered river basins are located within the Atlantic Continental climatic region of the temperate climatic zone of the Northern Hemisphere. It is characterized by moderately cold winters and rather warm summers. The annual surface air temperatures in the basins under consideration averaged over the period between 1936 and 2021 are 4.5 °C (Volga), 5.4 °C (Oka), and 6.5 °C (Don), respectively. In all seasons, westerly winds prevail, bringing into the river basins the humid air of the Atlantic origin. The average annual precipitation totals are about 630 mm in the Volga and Oka River basins and approximately 100 mm less in the Don River basin.

More than half of the annual runoff of the Oka and Don (61–62%, respectively) passes in the period of the spring snowmelt flood (March–May); while in the upper Volga, about 42% of the annual runoff forms in this hydrological season (i.e., in April–May). The runoff fraction during the summer–autumn period, in its annual volume for the Volga River, is about the same as that of the spring flood (about 42%), while in the Oka and Don Rivers, it accounts for about a quarter of annual runoff (27 and 25%, respectively). The winter runoff of the Volga River accounts for as little as 18% of the annual value and those in the Oka and Don Rivers account for 12% and 13%, respectively. The average annual water runoff over the entire observation period is 5.1 km^3 in the Volga, 9.1 km^3 in the Oka, and 10 km^3 in the Don.

The anthropogenic factors that exercise the most effect on the runoff and water regime of the Oka and, especially, the Don River basins are agriculture and urbanization. For example, in the Don River Basin, urbanized territories occupy up to 4% of the area. Water is withdrawn for irrigation and various industrial and domestic uses. Overall, the total effect of anthropogenic factors on the runoff of the rivers under consideration is not significant because those effects are mutually compensated [3].

2.2. Data

This study is based on the long-term time series of mean monthly water discharges during the period between 1882 and 2020 (Oka–Kaluga and Don–Stanitsa Kazanskaya) and between 1891 and 2020 (Volga–Staritsa). These time series were used to calculate the long-term mean annual and seasonal values over periods of snowmelt flood as well as winter and summer–autumn low-water seasons. The boundaries of hydrological seasons, which were assumed constant for the entire observation period, were determined from long-term data on the mean monthly values of water discharge as well as the mean long-term data on river freezing and ice cover destruction within the river basins.

The river gauge stations selected for this study belong to the State System of river level and discharge observations, which is the oldest in Russia. While the gauge types changed with time, their calibration and intercomparison have always been secured. The hydrological station positions have been selected according to fixed official criteria. Among these criteria are the riverbed stability and the absence of direct anthropogenic impact on the river partition that was selected for monitoring. In addition to regular measurements of the water level at the river gauge stations, special discharge measurements are being made at the river intersections collocated with the gauge stations. Using these two types of measurements (discharge and water level), formulae that link them are being developed to define discharge using daily water level data. These formulae are annually tested and adjusted (if necessary). This laborious routine has not changed since its introduction in the late 19th century. It secures the homogeneity of the century-long discharge time series with an accuracy of about 5%. In the cold season, when the rivers are covered by ice, this accuracy is somewhat reduced. During extremely high snowmelt flood days, when the rivers run over their banks, the discharge estimates become approximations based on the observers' skills and experience.

3. Methods

3.1. Hydrological Regime Shift (Change) Point Detection for Annual and Seasonal Water Flow

The boundaries between long phases of decreased and increased values of the annual and seasonal water flow were determined using cumulative deviation curves (CDC) [5,8] in combination with the assessment of the statistical homogeneity of the mean values within these long phases. Homogeneity was tested using parametric and non-parametric homogeneity criteria.

3.1.1. Cumulative Deviation Curves

CDCs represent a cumulative sum of a characteristic's deviations from its mean value, calculated over the entire observation period [5,8]. Such deviations are often standardized by the coefficient of variations to enable comparison of time variations in characteristics of different kinds. The values of standardized cumulative deviation curves are calculated as

$$\boldsymbol{CDC_{\tau}} = \frac{\mathbf{1}}{\boldsymbol{C_v}} \sum\nolimits_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{\tau}} (\boldsymbol{K_i} - \mathbf{1})$$

$$K_i = E_i / E_m$$

$$C_v = \frac{\sigma}{E_m}$$

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

where CDC_{τ} is the coordinate value of the cumulative deviation curve at time 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 entire 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; and σ is the standard deviation of the entire time series.

Cumulative deviation curves are used to identify long phases (10–15 years and more) in long-term variations of the characteristics under consideration, within which the characteristics were steadily increasing or decreasing relative to the mean long-term value of the series over the entire observation period. In most cases considered, the points (years) of the change of long contrast phases are signaled by extreme (whether minimal or maximal) values of the CDC. Thus, the CDC provides a vivid graphical representation of the passage between long phases of lower and higher values of the characteristics.

3.1.2. Criteria for Statistical Homogeneity of Long-Term Time Series of River Water Flow Based on Their Mean Values

The parametric Student's t-test [30] and the non-parametric Mann–Whitney–Pettitt (MWP) test [31], run in the AnClim software package [32], were used to evaluate the statistical significance of differences between the mean values of potentially contrasting phase series of hydrological characteristics in order to determine the years in which changes took place. The rank non-parametric MWP test is widely used primarily because it does not depend on the distribution type, and it is insensitive to outliers and asymmetry in the data [4,13,14].

The contrast-change years identified by these means were in general agreement with those reported elsewhere [5]. In our opinion, using a set of such or similar methods results in a more reliable identification of changes between contrast phases.

3.2. Estimation of the Frequency of Occurrence of Low Flow Years

The extremely low water flow years were defined as those in which the monthly, seasonal (for summer–autumn and winter low-water seasons and the snowmelt flood), and annual flow were less than or equal to the runoff corresponding 75 and 95% exceedance probability of water flow.

The assessment of the specific water flow value frequency was based on the empirical curves of the exceedance probability for the annual and seasonal water flows constructed from their series for the entire periods of observation for each considered river. The empirical value of the exceedance probability of water flow in the year i (Q_i), PQ_i, was calculated using the following formula:

$$\boldsymbol{PQ_i} = \left({}^{m_i}/_{(n+1)}\right) * \mathbf{100\%} \quad (1)$$

where m_i 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.

4. Results

4.1. Long-Lasting Phases of Annual and Seasonal Water Flow

In the century-long changes of three rivers considered, two long contrasting phases for each hydrological season (snowmelt flood, summer–autumn, and winter low-water seasons) were revealed (Figure 2). These phases are characterized by increased and decreased runoff during hydrological seasons.

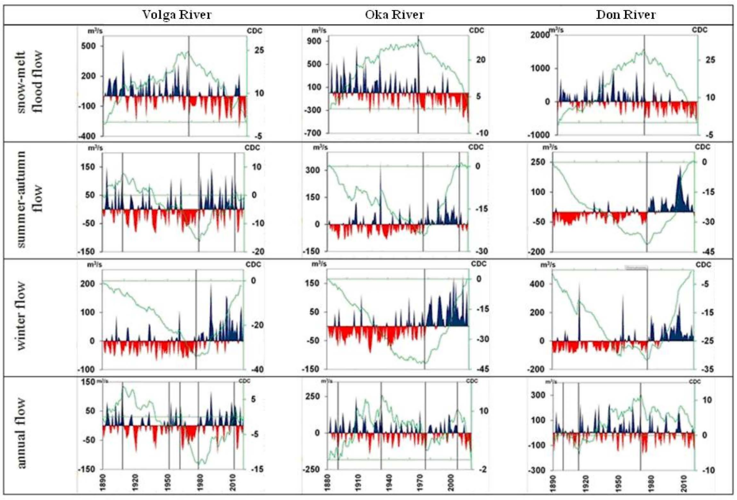

Figure 2. Long-term changes in snowmelt flood flow, summer–autumn water flow, winter water flow, and mean annual water flow in the Volga River at Staritsa, the Oka River at Kaluga, and the Don River at Stanitsa Kazanskaya. Blue and red fields indicate positive and negative deviations relative to long-term averages, respectively; the green line is the normalized cumulative deviation curve (CDC). The vertical black lines show phase boundaries (shift points) of increased or decreased values of the water flow.

A nearly simultaneous phase of increased runoff was first observed for the freshet season, which was replaced by the phase of decreased runoff in 1968–1970–1971 (on the Volga near Staritsa, the Oka near Kaluga, and the Don near Stanitsa Kazanskaya, respectively). On the contrary, phases of decreased runoff were first observed for low-water seasons. Thereafter, almost synchronously (between 1976 and 1979), a phase of increased runoff occurred at all these rivers. For the Volga River, an additional phase of increased summer–autumn flow between 1891 and 1909 was revealed at the beginning of the observation period.

For the annual runoff (Figure 2), three (in the Volga and Don Rivers) to four (in the Oka River) contrast phases were identified. For the Volga River, the dynamics of the phases of annual flow are similar to the series of changes in the contrast phases of the summer–autumn runoff. For the Oka and Don Rivers, the phase dynamics of annual flow proceed in a similar way but differ from the dynamics of the runoff phase changes of the snowmelt flood and flow of low-water seasons.

4.1.1. Shift Point Analyses of Multi-Year Changes of Annual and Seasonal Water Flow

Comparing the contrast phase years revealed by the cumulative deviations (Table 2 and Figure 2) against those obtained via statistical homogeneity confirmed the understanding [5] that these methods give similar results. The methods disagree in only a few cases (one for the MWP criterion for determining the year of the change of contrasting phases in the summer–autumn runoff of the Volga and four cases for Student's test in determining the year of phase changes in the Oka annual runoff). Even in those cases, however, the criteria (which also exceed their critical values corresponding to the significance levels indicated in the table) are still rather close to each other (Table 2).

Table 2. Shift points for river water flow characteristics of the Volga, Oka, and Don Rivers.

River Gauge Station	**Volga at Staritsa**		**Oka at Kaluga**		**Don at Stanitsa Kazanskaya**	
Method	**Shift Point**	***p* Value**	**Shift Point**	***p* Value**	**Shift Point**	***p* Value**
			snowmelt flood flow			
CDC	I→D 1968/1969	-	I→D 1970/1971	-	I→D 1971/1972	-
Student's test	1969	0.05	1971	0.05	1972	0.05
MWP test	1963	0.01	1971	0.01	1972	0.01
			summer-autumn water flow			
CDC	I→D 1909/1910 D→I 1979/1980	-	I→D 1976/1977	-	D→I 1977/1978	-
Student's test	1910 1980	0.05 0.05	1978	0.05	1978	0.05
MWP test	1935; 626 [a] (1911; 610) [b] 1980	0.05 0.01	1973	0.01	1978	0.01
			winter water flow			
CDC	D→I 1977/1978	-	D→ I 1977/1978	-	D→I 1978/1979	-
Student's test	1989; 8129 [a] (1981; 7811) [b]	0.05	1979	0.05	1981	0.05
MWP test	1978	0.01	1970	0.01	1977	0.1
			annual water flow			
CDC	I→D 1909/1910 D→I 1952/1953 I→D 1962/1963 D→I 1979/1980 I→D 2012/2013	-	I→D 1933/1934 D→I 1976/1977 I→D 2007/2008	-	D→I 1914/1915 I→D 1971/1972	-
Student's test	1910 1953 1963 1977	0.05 0.05 0.05 0.05	1918; 2500 [a] (1934; 2440) [b] 1998; 2758 [a] (1978; 2752) [b] 2014; 4767 [a] (2008; 4223) [b]	0.05 0.05 0.05	1915 1972	0.05 0.05
MWP test	1910 1952 1963 1980	0.05 0.1 0.01 0.01	1934 1977 2008	0.1 0.05 0.01	1915 1972	0.1 0.05

Note(s): I—Increased river runoff and D—Decreased river runoff with the arrows showing the direction of runoff shift; [a]—the value of the MWP test criterion; [b]—the closest additional shift points and their corresponding values of the MWP test criterion (presented in parentheses).

4.1.2. Characteristics of Contrasting Phases of Water Flow

The runoff phases differ significantly between rivers (Table 3). The duration of long phases of different annual runoff components is within the following limits (in years): in the Volga River, from 10 (the increased winter runoff phase) to 86 (the decreased winter runoff phase); in the Oka River, from 13 (decreased winter runoff, which is still ongoing) to 96 (decreased winter flow); and in the Don River, from 14 (decreased annual runoff) to 88 (decreased winter runoff). The duration of long phases of different annual runoff components on these rivers are within the following limits: in the Volga River, from 10 (increased winter runoff) to 86 (decreased winter runoff) years; in the Oka River, from 13 (decreased winter runoff, which is still ongoing) to 96 (decreased winter flow) years; and in the Don River, from 14 (decreased annual runoff) to 88 (the decreased winter runoff) years. The phase durations of increased spring snowmelt flood runoff in these three rivers and the annual runoff in the Oka and Don exceeded the durations of their opposite phases. The Volga River, as well as the winter and summer–autumn runoff on all three rivers, showed an inverse relationship with the duration of the phases of decreased runoff exceeding the duration of their opposite phases.

Table 3. Characteristics of contrasting phases of water flow of the Volga—Staritsa, Oka—Kaluga, and Don—Stanitsa Kazanskaya.

River Gauge	Volga–Staritsa		Oka–Kaluga		Don–Kazanskaya	
Long Phase	**Mean Water Discharge, m^3/s**	**Length of Phase/Years**	**Mean Water Discharge, m^3/s**	**Length of Phase/Years**	**Mean Water Discharge, m^3/s**	**Length of Phase/Years**
Snow–melt flood flow						
I	444	1891–1968/78	784	1882–1970/89	910	1891–1971/81
D	332	1969–2020/52	554	1971–2020/30	587	1972–2020/49
$I_{average}$–$D_{average}$, m^3/s	112		230		323	
$I_{average}$–$D_{average}$, in % relative to $D_{average}$	33.7		41.5		55	
Summer–Autumn flow						
I	151	1891–1909/19	191	1977–2012/36	201	1978–2020/43
I	158	1980–2012/33	-		-	
$I_{average}$	155					
D	109	1910–1979/70	142	1882–1976/95	133	1891–1977/87
$I_{average}$–$D_{average}$, m^3/s	46		49		78	
$I_{average}$–$D_{average}$, in % relative to $D_{average}$	42.2		34.5		58.7	
Winter flow						
I	130	1978–2020/43	196	1978–2020/43	210	1979–2020/42
D	69	1892–1977/86	115	1882–1977/96	132	1891–1978/88
$I_{average}$–$D_{average}$	61		81		78	
$I_{average}$–$D_{average}$, in % relative to $D_{average}$	88.4		70.4		59.1	
Mean annual flow						
I	180	1891–1909/19	312	1892–1933/42	344	1915–1971/57
I	183	1953–1962/10	308	1977–2007/31	-	
I	179	1980–2012/33	-		-	
$I_{average}$	180		310			
D	147	1910–1952/43	270	1934–1976/43	308	1901–1914/14
D	122	1963–1979/17	233	2008–2020/13	295	1972–2020/49
$D_{average}$	140		261		299	
$I_{average}$–$D_{average}$	40		49		45	
$I_{average}$–$D_{average}$, in % relative to $D_{average}$	28.6		18.8		15.1	

Note(s): Abbreviations for I and D are the same as in Table 2. In the table, the symbol '-' means that phases have not been revealed.

The flow differences (as a percentage of the phase of decreased flow) for contrasting phases on the Oka River vary from 19% for the annual runoff to 70% (for the winter runoff). For the Don River, these differences vary from 15% for the annual runoff to 59% for the winter and summer–autumn runoff. Finally, for the Volga River, these differences vary from 29% for the annual runoff to 88% (for the winter runoff). As a rule, the differences in runoff reach their greatest values in the low-water seasons of the year and are the smallest for the annual runoff.

4.2. Extreme Low Flow during Long-Lasting Phases of Water Flow

Very significant differences were revealed in the frequencies of low-water years for a low runoff with exceedance probability ≥75% and ≥95% (Table 4). These differences were observed at all rivers of the region and for both annual and seasonal runoff phases (i.e., for snowmelt freshet, as well as for the summer–autumn and winter low flow seasons). For the summer–autumn and winter seasons on the Oka and the Don Rivers during the increased runoff phases, extremely low-water flows were not observed at all. However, in the same seasons but in contrasting phases, there were more significant differences in the frequency of low-water years than during snowmelt freshet and annual runoff. The range of changes in the frequency of low-water years, the runoff of which was lower than the runoff of 75 and 95% exceedance probability, is different for the phases of increased and decreased runoff. Table 4 shows that the range of changes in the frequency of low-water years, the runoff of which was lower than the runoff of 75 and 95% exceedance probability, is different for the phases of increased and decreased runoff.

Table 4. The number and proportion of low-water years (with exceedance probability ≥75 and ≥95%) in long-lasting phases of increased and decreased annual and seasonal water flow in the Volga River at Staritsa, the Oka River at Kaluga, and the Don River at Stanitsa Kazanskaya.

Phase	Volga River—Staritsa		Oka River—Kaluga		Don River—Kazanskaya	
	≥75%	**≥95%**	**≥75%**	**≥95%**	**≥75%**	**≥95%**
	Phase Period/Phase Length/Number and Percent of Low–Water Years					
	Snowmelt flood flow					
I	1891–1968 [a]/78 [b]		1882–1970/89		1891–1971/91	
	8 [c]/16.7 [d]	2 [c]/2.6 [d]	10/11.2	1/1.1	8/8.8	0
D	1969–2020/52		1971–2020/40		1972–2020/49	
	16/30.8	4/7.8	23/57.5	5/12.5	24/50	7/14.3
	Summer–Autumn flow					
I	1893–1909/17 1980–2013/34		1977–2013/37		1978–2020/43	
	3/5.9	1/2	0	0	0	0
D	1910–1979/70		1882–1976/95		1891–1977/87	
	22/31.4	4/5.7	33/34.7	6/6.3%	30/34.5%	6/6.9%
	Winter flow					
I	1978–2020/43		1979–2020/42		1979–2020/42	
	2/4.7	0	0	0	0	0
D	1892–1977/86		1882–1978/97		1891–1978/88	
	23/26.7	5/5.8	32/33	6/6.2	31/35.2	5/5.7
	Mean annual flow					
I	1892–1909/18 1952–1962/11 1980–2013/34		1891–1933/43 1978–2007/30		1915–1970/56	
	3/4.8	1/1.6	10/13.7	3/4.1	11/19.6	2/3.6
D	1910–1951/42 1963–1979/17		1934–1977/44 2008–2020/13		1900–1914/15 1971–2020/50	
	24/40.7	3/5.1	21/36.8	4/7	20/30.8	4/6.1%

Note(s): Abbreviations for I and D are the same as in Tables 2 and 3. For each river and each phase, the table shows four streamflow characteristics for each exceedance. These characteristics are as follows: [a]—phase length; [b]—number of years within the phase; [c]—the number of low-water years for each exceedance; and [d]—the proportion (percent) of low-water years for each exceedance. For clarity, the characteristic indicators ([a, b, c], and [d]) are shown only for the first I phase of the Volga River.

5. Discussion

Since the 1970–1980s, global warming has caused considerable changes in river flow characteristics, as well as other environmental components. Reid et al. [11] identified a shift in the early 1980s for various characteristics within the Earth's biophysical systems from the upper atmosphere to the depths of the ocean and from the Arctic to the Antarctic that occurred at slightly different times around the world. The available studies show that the current global warming leads to differently directed changes in river runoff in different parts of the Earth [3,5,6,33]. In the rivers considered here, in the period of the ongoing global warming (the boundaries of which coincided with the appropriate long phases of seasonal runoff changes), decreased snowmelt flood runoff and, at the same time, increased runoff of the summer–autumn and winter hydrological seasons, are observed. However, in the previous period, phases of increased snowmelt flood runoff and decreased runoff of the low-water seasons of the year were also observed. Only in the upper reaches of the Volga River, in the early observation period, did we find a relatively short phase of higher flow. Such behavior of the long runoff phases in the main hydrological seasons of the year and their alternation are common across most of the East European Plain, which contains the right-side tributaries of the Volga, the Don basin, and the Dnieper basin [2,17,34]. The long-term dynamics of the annual flow phases in the Oka and Don Rivers are more complex than that of the runoff of the hydrological seasons of the year.

Though the long phases of increased/decreased runoff of rivers have already been studied for various regions of the world, particularly in Russia [2,3,5,6,35], the geography of such studies requires a considerable extension. Of great interest is the correlation between the long phases of the annual and seasonal runoff and the zoning of a territory by the level of synchronicity between runoff phases. As to the study of the correlation between the long phases in multi-year variations of hydrological characteristics and macroscale atmospheric circulation, there is already considerable attention [7,36–43].

Many studies focus on the methodological approaches for determining the boundaries and properties of contrast phases in long-time series of river runoff. These include various criteria for assessing the statistical homogeneity of series with the aim of identifying transitions from one phase to another, referred to as "shift points" [4,5,7,14,44–50]. An important problem in such studies is choosing the boundaries between long, contrasting phases of river water flow. The optimal set of methods for determining the time boundary between the long-lasting phases with different water regimes includes criteria (parametric and non-parametric) of the statistical homogeneity of the series in terms of their mean values, as well as the use of the cumulative deviation curves [5,7]. This makes it possible to determine the boundary between contrasting phases with sufficient accuracy.

Unlike the severest droughts, which are quite frequent in summer over the East European Plain, the extreme low-water flow in rivers in these and other years was observed in different hydrological seasons or in the annual flow. Our study, for the first time, revealed a radical change in the frequency of low-water years in contrasting long phases of river flow, both in the main hydrological seasons of the year and over the year as a whole. Earlier, a correlation had been found between the extremely low flow observed in different hydrological seasons of the year and over the year as a whole in the largest and medium-sized rivers of the region and the extreme draughts in the East European Plain observed during the period of ongoing global warming [21]. Since the late 19th to the early 21st centuries, the proportion of years in which extremely low flow was recorded (in at least one or within several seasons of the year) has varied across the major rivers in the region (the Volga, Don, Dnieper, and Western and Northern Dvina Rivers). It varied from 46 to 57% of the length of the entire observation period [51].

Among the years of the most severe drought (1891, 1921, 1931, 1946, 1972, and 1975), extremely low flow was observed in territories of all river basins mentioned above only in 1921 and 1972. In 1921, the lowest flow was recorded in practically all hydrological seasons of the year as well as annually in all rivers (except for winter in the Don and summer–autumn in the Northern Dvina).

Currently, the exceedance probabilities for runoff of low-water years are calculated on the basis of multi-year time series for the entire observation period. That is, they operate with the frequency of the "average" low-water years over the entire period. These years constitute (in our study) 25 cases out of a hundred for runoff of low-water years with 75% probability exceedances and 5 cases for low-water runoff with 95% probability exceedances. Our analysis reveals, from more than a century of observation periods, long phases of increased/decreased runoff. During these phases, the frequencies of low-water years differ significantly from their "average" values calculated for the entire observation period. At the same time, in the phase of decreased runoff, the "average" frequencies of low-water years are significantly exceeded, and in the phases of increased runoff, their frequency is significantly lower than the "average" frequencies of low-water years (or they are not observed at all). This property of differences between opposite phases of streamflow has an important practical consequence for environmental and human activities in the river basins. By definition, phases are prolonged periods, and their duration can reach many decades (cf. Table 3). Both ecosystems and human activities adjust to the current flow phase. Bridges, canalization, and the entire water supply infrastructure have been built under the assumption that the river flow and its extreme manifestations will not significantly change. However, then the runoff phase changed, and the flow outliers began to behave differently. "The old-timers do not recall." How frequently did we hear this sentence in the past decade?

6. Conclusions

We investigated the long-lasting phases of increased and decreased water flow as well as an abnormally low flow (when the water flow was less than or equal to 75 and 95% exceedance probability levels) of three rivers (the Volga at Staritsa, the Oka at Kaluga, and the Don at Stanitsa Kazanskaya) in the central part of the East European Plain over a period from the late 19th century to 2020.

The contrasting phases are characterized by statistically significant differences in mean values of the river runoff characteristics with prolonged duration of these phases, usually 10–15 years or more (up to 96 years in the winter low-flow period at the Oka River, Table 3). These phases represent a characteristic feature of the long-term variability in the regional rivers' flow.

In the century-long changes of three rivers considered, two main long contrasting phases for each hydrological season (snowmelt flood, summer–autumn, and winter low water seasons) were revealed. These phases characterize increased and decreased runoff during hydrological seasons. Nearly simultaneously, a phase of increased runoff was first observed for the freshet season, which was replaced by the phase of decreased runoff in 1968–1970–1971 (on the Volga near Staritsa, the Oka near Kaluga, and the Don near Stanitsa Kazanskaya, respectively). On the contrary, phases of decreased runoff were first observed for low-water seasons. Thereafter, almost synchronously (between 1976 and 1979), a phase of increased runoff occurred in all three rivers. For the annual streamflow, during the past 100+ years, we have identified three (at the Volga and Don Rivers) to four (at the Oka River) contrast phases.

Comparing the transition years identified by the cumulative deviation method and statistical homogeneity criteria confirmed that these methods deliver similar results.

The duration of long-term phases of different annual runoff components on these rivers is within the following limits: on the Volga River from 10 to 86 years, the Oka River from 13 to 96 years, and the Don River from 14 to 88 years. The flow differences (as a percentage of the phase of decreased flow) for contrasting phases are:

- On the Oka: from 19% for the annual flow and up to 70% for the winter flow;
- On the Don: 15% for the annual flow and up to 59% for the winter and summer-autumn flow, and;
- On the Volga: 29% for the annual flow and up to 88% for the winter flow.

The differences in the runoff, as a rule, reach the greatest values in the low-water seasons of the year and are the smallest for the annual runoff.

Very significant differences in the frequency of low-water years for low runoff, with exceedance probability ≥75 and ≥95%, were revealed for all rivers of the region and for both long phases of annual and seasonal runoff. For the summer–autumn and winter seasons on the Oka and the Don Rivers during the phases of increased runoff, extreme low-water flows were not observed at all. However, in the same seasons but during the phases of decreased runoff, there were more significant differences in the frequency of low-water years compared with the snowmelt freshet and annual runoff. Thus, to avoid surprises, water management in these river basins should account for the current long-term water flow phase as well, as should be done in all other river basins where distinctive streamflow phases occur.

Author Contributions: Conceptualization, methodology and validation: A.G.G.; investigation and writing: A.G.G. and P.Y.G. All authors have read and agreed to the published version of the manuscript.

Funding: The article is based on the results of studies that were carried out under the Governmental Order of the Institute of Geography, Russian Academy of Sciences, the state assignment FMGE-2019-0007 (AAAA-A19-119021990093-8).

Data Availability Statement: The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author upon reasonable request.

Acknowledgments: This investigation is based on the materials of studies supported by Governmental Order No. to the RAS Institute of Geography, AAAA-A19- 119021990093-8 (FMGE-2019-0007). The work of Pavel Groisman is partially supported by the U.S. NSF Grants # 2020404 'Belmont Forum Collaborative Research: Coastal OceAn SusTainability in Changing Climate' and # 2127343 'NNA Collaborative Research: Frozen Commons: Change, Resilience and Sustainability in the Arctic' and by NOAA through the Cooperative Institute for Satellite Earth System Studies under Cooperative Agreement NA19NES4320002.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rodionov, S.N.; James, E. Overland application of a sequential regime shift detection method to the Bering Sea ecosystem. *ICES J. Mar. Sci.* **2005**, *62*, 328–332. [CrossRef]
2. Shiklomanov, I.A. *Water Resources of Russia and Their Use (WRRU)*; State Hydrological Institute: St. Petersburg, Russia, 2008; p. 600. (In Russian)
3. Georgiadi, A.G.; Koronkevich, N.I.; Milyukova, I.P.; Kashutina, E.A.; Barabanova, E.A. *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, 2014; p. 214. (In Russian)
4. Yeh, C.F.; Wang, J.; Yeh, H.F.; Lee, C.H. Spatial and temporal streamflow trends in Northern Taiwan. *Water* **2015**, *7*, 634–651. [CrossRef]
5. Georgiadi, A.G.; Kashutina, E.A.; Milyukova, I.P. Long-term changes of water flow, water temperature and heat flux of the largest Siberian rivers. *Polarforschung* **2018**, *87*, 167–176.
6. Shi, X.; Qin, T.; Nie, H.; Weng, B.; He, S. Changes in major global river discharges directed into the ocean. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1469. [CrossRef]
7. Georgiadi, A.G.; Groisman, P.Y. Long-term changes of water flow, water temperature and heat flux of two largest arctic rivers of European Russia, Northern Dvina and Pechora. In *Environmental Research Letters*; IOP Publishing: Bristol, UK, 2022; Volume 17, pp. 1–14. [CrossRef]
8. Andreyanov, V.G. Cyclical fluctuations of annual runoff and their accounting in hydrological calculations problems of runoff calculations. *Proc. State Hydrol. Inst.* **1959**, *68*, 3–50. (In Russian)
9. Muraveisky, S.D. *Rivers and Lakes, Hydrobiology, Runoff*; Geografgiz: Moscow, Russia, 1960; p. 387. (In Russian)
10. North, R.P.; Livingstone, D.M.; Hari, R.E.; Köster, O.; Niederhauser, P.; Kipfer, R. The physical impact of the late 1980s climate regime shift on Swiss rivers and lakes Inland. *Waters* **2013**, *3*, 341–350.
11. Reid, P.C.; Hari, R.E.; Beaugrand, G.; Livingstone, D.M.; Marty, C.; Straile, D.; Barichivich, J.; Goberville, E.; Adrian, R.; Aono, Y.; et al. Global impacts of the 1980s regime shift. *Glob. Chang. Biol.* **2016**, *22*, 682–703. [CrossRef]
12. AR6 Synthesis Report: Summary for Policymakers Headline Statements. Available online: www.ipcc.ch (accessed on 16 April 2023).

13. Hedberg, S. *Regional Quantification of Climatic and Anthropogenic Impacts on Streamflows in Sweden*; Institutionen Geovetenskaper, Uppsala University: Uppsala, Sweeden, 2015; pp. 1–35.
14. Sharma, S.; Singh, P.K. Long term spatiotemporal variability in rainfall trends over the state of Jharkhand, India. *Climate* **2017**, *5*, 18. [CrossRef]
15. Bolgov, M.V.; Filippova, I.A.; Osipova, N.V.; Korobkin, E.A.; Trubetskova, M.D. Current features of the hydrological regime of rivers in the Volga Basin. Hydrological Changes. *Probl. Geogr.* **2018**, *145*, 206–221. (In Russian)
16. Georgiadi, A.G.; Koronkevich, N.I.; Barabanova, E.A.; Kashutina, E.A.; Milyukova, I.P. Contribution of climatic and anthropogenic factors to changes in the flow of large rivers of the Russian Plain and Siberia. *Dokl. Earth Sci.* **2019**, *488*, 1211–1216. [CrossRef]
17. Geordiadi, A.G.; Milyukova, I.P.; Kashutina, E.A. Current and scenario changes in river runoff in the Don basin. *Water Resour.* **2020**, *47*, 651–662. [CrossRef]
18. Georgiadi, A.G.; Kashutina, E.A. Long-term changes of suspended sediment discharges in the largest Arctic rivers of Russia. In Proceedings of the V All-Russian Scientific Conference with International Participation and the XXXIV Plenary Meeting of the Interuniversity Research Coordination Problem Council on Soil Erosion and Fluvial Processes, Moscow, Russia, 3–6 September 2019; Lomonosov Moscow State University: Moscow, Russia, 2019; pp. 157–158. (In Russian)
19. Tsyplenkov, A.; Golosov, V.; Belyakova, P. How Does the Suspended Sediment Yield Change in the North Caucasus During the Anthropocene? *Hydrol. Process. Spec. Issue* **2021**, *35*, 1–20. [CrossRef]
20. Georgiadi, A.G.; Danilenko, A.O. Northern Dvina River: Long Periods of Increased and Decreased Water and Ionic Runoff in the 19th–21st Centuries. *Geogr. Nat. Resour.* **2022**, *43*, 149–155. [CrossRef]
21. Georgiadi, A.G.; Milyukova, I.P.; Borodin, O.O. Spatial and temporal correlation between severe droughts and extreme low flow. Ninth International Symposium "Steppes of Northern Eurasia". In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2021; Volume 817, p. 012034. [CrossRef]
22. Hasrul, H.H.; Siti, F.M.; Nur, S.M.; Asmadi, A. Research Trends of Hydrological Drought: A Systematic Review. *Water* **2019**, *11*, 2252. [CrossRef]
23. Vladimirov, A.M. *River Runoff in Low Flow Season*; Gidrometeoizdat: Leningrad, Russia, 1976; p. 295. (In Russian)
24. Beran, M.A.; Rodier, J.A. *Hydrological Aspects of Drought. A Contribution to the International Hydrological Programme*; Unesco-WMO Presses Universitaires de France: Vendôme, France, 1985; p. 149, ISBN 92-3-102288-1.
25. Filippova, I.A. Probabilistic regularities of minimum runoff variations: Case study of the rivers of the Central Black Earth Region. *Water Resour.* **1996**, *23*, 357–363. (In Russian)
26. Smakhtin, V.Y. Low flow Hydrology: A review. *J. Hydrol.* **2001**, *240*, 147–186. [CrossRef]
27. Alekseevsky, N.I.; Frolova, N.L. Safety of water use under low-water conditions. *Water Resour.* **2011**, *6*, 6–17. (In Russian)
28. Georgiadi, A.G.; Kashutina, E.A. Hydroclimate Characteristics of Extreme Droughts Observed on the Russian Plain since the 1970s. *Arid Ecosyst.* **2021**, *11*, 117–123. [CrossRef]
29. Zolotokrylin, A.N.; Vinogradova, V.V.; Meshcherskaya, A.V.; Strashnaya, A.I.; Cherenkova, E.A. *Second Appraisal Report of Roshydromet on Climate Changes and Their Effects in the Russian Federation Territory*; Roshydromet: Moscow, Russia, 2014; pp. 551–587. (In Russian)
30. Cramer, H. *Mathematical Methods of Statistics*; Princeton University Press: Princeton, NJ, USA, 1946; p. 575.
31. Pettitt, A.N. A non-parametric approach to the change-point problem. *J. R. Stat. Soc.* **1979**, *C 28*, 126–135. [CrossRef]
32. Stepanek, P. AnClim-Software for Time Series Analysis. Department of Geography Fakulty of Sciences Masaric University Brno. 2008. Available online: www.climehom.eu (accessed on 16 April 2023).
33. Hall, J.; Arheimer, B.; Borga, M.; Brázdil, R.; Claps, P.; Kiss, A.; Kjeldsen, T.R.; Kriauciunien, J.; Kundzewicz, Z.W.; Lang, M.; et al. Understanding flood regime changes in Europe: A state-of-the-art assessment. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 2735–2772. [CrossRef]
34. Milyukova, I.; Georgiadi, A.; Borodin, O. Long-term changes in water flow of the Volga basin rivers. *E3S Web Conf.* **2020**, *163*, 05008. [CrossRef]
35. Frolova, N.L.; Magritskii, D.V.; Kireeva, M.B.; Grigor'ev, V.Y.; Gelfan, A.N.; Sazonov, A.A.; Shevchenko, A.I. Streamflow of the Russian rivers under current and forecasted climate changes. A review of publications. 1. Assessment of changes in the water regime of Russian rivers by observation data. *Water Resour.* **2022**, *49*, 333–350. (In Russian) [CrossRef]
36. Pekarova, P.; Miklanek, P.; Pekar, J. Spatial and temporal runoff oscillation analysis of the main rivers of the world during the 19th–20th centuries. *J. Hydrol.* **2003**, *274*, 62–79. [CrossRef]
37. Laurens, M.; Bouwer, L.B.; Vermaat, J.E.; Aerts, J. Winter atmospheric circulation and river discharge in northwest Europe. *Geophys. Res. Lett.* **2006**, *33*, 1–4. [CrossRef]
38. Babkin, V.I. Volga runoff during periods of weakening and strengthening of cyclonic activity. *Meteorol. Hydrol.* **1995**, *1*, 94–100. (In Russian)
39. Peterson, B.J.; Holmes, R.M.; McClelland, J.W.; Vorosmarty, C.J.; Lammers, R.B.; Shiklomanov, A.I.; Shiklomanov, I.A.; Rahmstorf, S. Increasing river discharge to the Arctic Ocean. *Science* **2002**, *298*, 2171–2173. [CrossRef] [PubMed]
40. Georgiadi, A.G.; Kashutina, E.A. Long-term changes in the flow of the largest Siberian rivers. *Proc. Russ. Acad. Sci. Geogr. Ser.* **2016**, *5*, 70–81. (In Russian) [CrossRef]
41. Popova, V.V.; Georgiadi, A.G. Spectral estimates of the relationship between the variability of the Volga runoff and the North Atlantic oscillation in 1882–2007. *Proc. Russ. Acad. Sci. Geogr. Ser.* **2017**, *2*, 47–59. (In Russian)

42. Kryjov, V.N.; Gorelits, O.V. Wintertime Arctic oscillation and formation of river spring floods in the Barents Sea Basin. *Russ. Meteorol. Hydrol.* **2019**, *44*, 187–195. [CrossRef]
43. Popova, V.V. Current Trends of the Regime of Precipitation and Atmospheric Circulation over the River Basins in European Russia. *Proc. Russ. Acad. Sci. Geogr. Ser.* **2023**, *1*, 1–17. (In Russian)
44. Kundzewicz, Z.W.; Robson, A. Change detection in hydrological records—A review of the methodology. *Hydrol. Sci. J.* **2004**, *49*, 7–19. [CrossRef]
45. Rodionov, S.N. A sequential algorithm for testing climate regime shifts. *Geophys. Res. Lett.* **2004**, *31*, 1–4. [CrossRef]
46. Rodionov, S.N. A sequential method of detecting abrupt changes in the correlation coefficient and its application to Bering Sea. *Climate* **2015**, *3*, 474–491. [CrossRef]
47. Xie, H.; Li, D.; Xiong, L. Exploring the ability of the Pettitt method for detecting change point by Monte Carlo simulation. *Stoch. Environ. Res. Risk. Assess.* **2014**, *28*, 1643–1655. [CrossRef]
48. Killick, R.; Eckley, I.A.; Jonathan, P.; Ewans, K. Detection of changes in the characteristics of oceanographic time-series using statistical change point analysis. *Ocean. Eng.* **2010**, *37*, 1120–1126. [CrossRef]
49. Jaiswal, R.K.; Lohani, A.K.; Tiwari, H.L. Statistical Analysis for Change Detection and Trend Assessment in Clima tological Parameters. *Environ. Process.* **2015**, *2*, 729–749. [CrossRef]
50. Temnerud1, J.; Weyhenmeyer, G.A. Abrupt changes in air temperature and precipitation: Do they matter for water chemistry? *Glob. Biogeochem. Cycles* **2008**, *22*, 1–8. [CrossRef]
51. Georgiadi, A.G.; Borodin, O.O. Extreme Low Flows in Rivers of the East European Plain in the 19th–21st Centuries. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2022; Volume 1023, pp. 1–6. [CrossRef]