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Spatiotemporal Changes in Extreme Runoff Characteristics for the Volga Basin Rivers

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Abstract—Long-term changes in peak spring runoff and daily minimum winter and summer-autumn runoff in the Volga River basin are analyzed based on observational data from 94 gaging stations. It is revealed that climate changes in the basin during the period from the late 1970s till the middle of the 1980s led to the significant increase in minimum discharge, but maximum runoff changed ambiguously. The regions with the disturbed uniformity of the series of extreme values of river runoff are identified. Changes in the values of high runoff, above the 10% probability, and low runoff, below the 90% probability, are analyzed for current climate conditions. Under nonstationary conditions, it is recommended to assess the probability characteristics of extreme runoff with compound distribution curves or based on the Bayesian approach.

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INTRODUCTION

Informational support is of great importance for the use and protection of water bodies. Its main task is to provide objective quantification of probability characteristics of river runoff. These data are needed to assess a water body state, to substantiate the plan of activities that guarantee water supply to population and economic branches, to provide the construction and safe operation of hydraulic structures and the optimum use of coastal areas. The problem of calculation of major runoff characteristics cannot be solved without studying long-term changes in river water content. The modern methods for runoff computation are based on investigation of its temporal variability using the data of hydrometric observations in the Russian Federation from their beginning till the 1980s. These methods are based on the concept of stationarity of time series of runoff characteristics. According to this concept, their statistical parameters (the mean, coefficients of variation, asymmetry, and autocorrelation) remain invariable over the observation periods and next decades.

The climate warming has been observed in the Russian Federation since the second half of the 1970s. As a result, runoff formation conditions considerably changed in its most part; this change led to the transformation of its intraannual distribution and to oppositely directed variations in its components. Changes in the water regime of rivers caused by climatic factors became a reason for the nonstationarity of long-term series of runoff characteristics in some regions of the country.

The results of the studies carried out in the recent years [1, 5–7, 11] corroborated the presence of statistically significant changes in seasonal runoff for the Volga basin rivers characterized by the considerable increase in winter and summer-autumn runoff on its entire territory and by runoff reduction during the period of spring flood in the southern and southwestern parts of the basin. According to [9–11], this phenomenon is caused by the surface air temperature rise during the cold season that leads to the considerable transformation of the water cycle.

The changes in extreme runoff characteristics under current conditions and their account for the determination of design values remain insufficiently explored. The results of studies of long-term changes in

30-day minimum discharges for winter presented in [2, 3] are noteworthy. It was found that the dramatic climate-related increase in minimum river runoff occurred within the whole basin from the second half of the 1970s to the middle of the 1980s. This led to the disturbed uniformity of their long-term series. In view of this, the method was proposed for the assessment of characteristics of minimum runoff under nonstationary conditions based on the Bayesian approach. Using the results of the earlier studies of high river runoff [2, 6, 9], the fact of differently directed changes in this hydrological characteristic was proved for the Volga basin rivers.

The main objective of the present paper is to investigate the long-term dynamics of extreme runoff values, namely, of peak discharge during the period of spring flood and of daily minimum discharge during the period of winter and summer-autumn low water as well as of the peculiarities of their changes under climate warming.

INITIAL DATA AND METHODS

Data of hydrometric observations of peak discharge during the spring flood and daily minimum discharge during the period of winter and summer-autumn low water were used to study spatiotemporal changes in extreme runoff characteristics for the Volga basin rivers. Data from 94 gaging stations were used where observation period is not less than 65 years (till 2015 inclusive). The stations were located on the medium-size rivers not controlled by reservoirs whose water regimes are minimally influenced by economic activity. Data obtained for rivers in the adjoining regions were also utilized.

The studies of spatiotemporal changes in extreme runoff characteristics included: the analysis of chronological graphs and residual mass curves for the considered characteristics; the determination of the date of change in long-term phases of water content; the quantification of correlation between extreme runoff characteristics for each gaging station; the assessment of phase coincidence (noncoincidence) for long-term changes in the analyzed characteristics, the uniformity of the series of runoff and its current changes, and the changes in the values of maximum runoff above the 10% probability and below the 90% probability; the zoning of the territory based on the value of climate-related changes in high and low runoff.

RESULTS

The long low-water phase in long-term variations in minimum winter and summer-autumn runoff observed for all analyzed rivers was observed since the beginning of instrumental hydrometric observations. It changed to the high-water phase in 1979–1987. The phase changed in 1979–1981 in most of the basin and in 1985–1987 in its southeastern part and on the Lower Volga tributaries.

The analysis of long-term dynamics of maximum river runoff revealed some specific features. For example, two regions can be distinguished according to the type of long phases of water content. The first region includes the Upper and Lower Volga basins and the right-bank tributaries of the Middle Volga. For this region, the main phase in long-term variations in maximum runoff is the long high-water phase that started at the beginning of hydrometric observations and changed to the low-water phase observed till now; variations in minimum runoff are accompanied by the change of the long low-water phase to the high-water one (Figs. 1a and 1b). Asynchronous variations are clearly observed in long-term changes in high and low runoff that is corroborated by the negative coefficients of correlation between the maximum and minimum values of water discharge. Significant correlations of minimum discharges in summer and winter were revealed for the region rivers. The second region includes most of the Kama River basin and the basins of rivers located in the northern part of the analyzed area (the Vetluga and Unzha rivers). For this region, the phase of peak discharge growth has been registered in the recent decades. The phase coincidence is observed in long-term changes in high and low runoff (Figs. 1c and 1d). The coefficients of correlation between them are positive for all rivers in this region. Based on the results of studying the effects of climatic factors on the runoff formation in the winter-spring period [8, 9], it may be concluded with high confidence that the main reason for the peak discharge growth in the rivers in this region is increase in precipitation during the cold season and, consequently, in the snow water equivalent.

It should be noted that the trend towards the stabilization or even reduction of maximum and minimum runoff has been observed in the recent years for the rivers in the eastern and northeastern parts of the Volga basin. Currently, it is hardly possible to speculate on the beginning of the next long low-water phase due to the uncertainty of future climate estimates. At the same time, such scenario cannot be ruled out considering the natural variability of runoff and factors defining it. This is of fundamental importance for the assessment of probability characteristics of runoff.

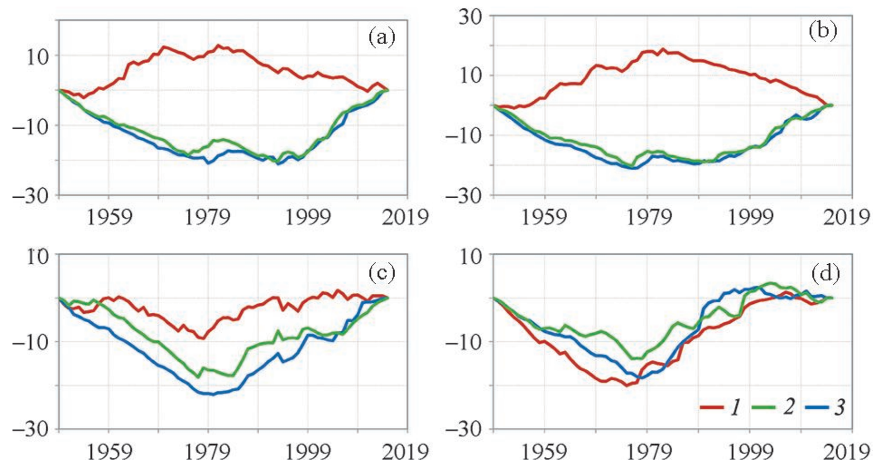

Fig. 1. Residual mass curves $(k \quad 1)/C_v$) for (*1*) maximum spring, daily minimum (*2*) summer and (*3*) winter runoff. (a) The Moksha River–Shevelevskii Maidan; (b) the Tsivil' River–Tusvi; (c) the Unzha River–Makar'ev; (d) the Chusovaya River–Kosoi Brod.

The current regulatory documents make strict demands for initial hydrological information, especially for the uniformity of runoff series [15]. In view of this, the statistical uniformity of initial observation series was checked based on the *t*- and *F*-tests using observational data for 1950–2015. Two periods with different water content were separated within the above period using the data of analysis of residual mass curves. For the Volga basin as a whole, 86% of all analyzed series of minimum winter runoff were nonuniform according to the *t*-test and 58%, according to the *F*-test; the respective values for minimum summer-autumn runoff are 71 and 50%. The nonuniformity assessed with the *F*-test is caused by the considerable increase in minimum runoff variability in the recent decades. The nonuniformity in the series of maximum runoff was revealed for 35% of their total number based on the *t*-test and for 26% of the series, based on the *F*-test. The vast majority of rivers with nonuniform series of high runoff are located in the southern part of the Volga basin, where maximum runoff and its variability decreased. The climate-related changes in extreme runoff characteristics for the Volga basin rivers were assessed by comparing mean runoff values for two periods, current and preceding.

Minimum winter and summer-autumn runoff increased on the whole territory of the Volga basin. The most significant growth (by 100–250%) was registered on the tributaries of the rivers flowing into the Lower Volga reservoirs and on the rivers in the southern part of the Oka River basin; the smallest growth (by 30–60%) was observed in the northern part of the Volga basin.

The type of relative changes in maximum runoff for the Volga basin rivers during the current period as compared to the preceding one can be judged by Fig. 2. The region with positive runoff anomalies and the region with negative ones are distinguished. It should be noted that the relative change in maximum runoff is much smaller than for the minimum one. The most significant reduction of peak discharge (40–60%) is observed on the rivers in the Lower Volga basin and in the southern part of the Oka River basin. The increase in high runoff is registered in the northern and northeastern parts of the Volga basin and reaches the maximum values (20–40%) in the basins of the Unzha, Vetluga, Chusovaya, and Belaya rivers (Fig. 2). Besides, the two- and more-fold increase in the frequency of occurrence of peak discharge with low probability ($P < 10\%$) is observed. The number of cases when peak discharge exceeds the values with the 10% probability, declines in most of the Volga basin. The occurrence frequency of minimum discharges with the probability below 90% was reduced by four times for the whole basin. No minimum discharges below this threshold have been observed since the 1980s for the Oka and Lower Volga basins.

Thus, the occurrence frequency of extremely low and high discharges has decreased in most of the Volga basin in the recent decades that indicates the positive climate impact.

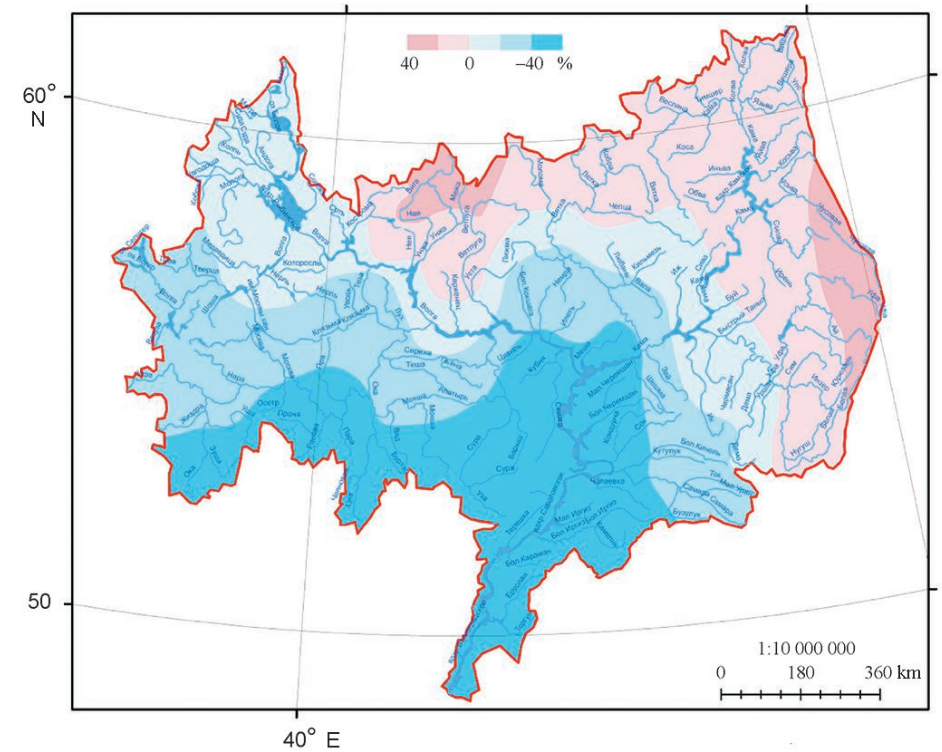

Fig. 2. The schematic map of changes (%) in the maximum spring runoff for the Volga basin rivers during the current period as compared to the preceding one.

CALCULATION OF PROBABILITY CHARACTERISTICS OF EXTREME RIVER RUNOFF UNDER NONSTATIONARITY OF THEIR SERIES

Based on the above results, it may be stated that the disturbed uniformity of long-term series of minimum winter runoff is observed almost in the entire Volga basin, and the disturbed uniformity of minimum summer runoff series is registered in its most part. This is caused by the significant growth of minimum runoff in the recent decades due to observed climate change. The nonuniformity in the series of high runoff is typical of the rivers located in the southern part of the basin, where its decline is maximum as compared to the previous long-term period.

The assessment of probability characteristics of river runoff from nonuniform series of observational data is one of the key problems of engineering hydrological calculations. This issue is investigated in papers [2, 4, 6, 12, 13, 16]. Their authors concluded that not the gradual (monotonous) increase or decrease in different runoff characteristics but their dramatic (uneven) changes during a relatively short period have been observed in most of the European part of Russia in the recent 30–40 years. Obviously, this was a reason for the disturbed uniformity of long-term series of hydrological characteristics. As a result, two stationary (quasistationary) periods with considerably differing characteristics of river water regime were separated. Since future climate scenarios are quite uncertain and the regularities of formation of long phases with various water contents are not sufficiently studied, the methods were proposed for the determination of design hydrological characteristics under conditions of nonstationarity of their time series. The compound distribution curves or the Bayesian approach are used (the results are very close).

For example, let us consider the computation of peak discharge over the period of spring flood on the Tsivil' River in the area of Tusvi village with the 1% probability. It should be noted that the determination of the maximum discharges in a year with the probability of exceeding once in 100 years is a quite responsible and topical problem, in particular, in view of the implementation of the decree of the Government of the Russian Federation "On Identification of Zones of Flooding" [14]. The mentioned probability of high runoff is reference: based on it, the water level corresponding to this discharge and, hence, the zone of flooding is determined. Data characterizing long-term variations in maximum runoff during the period of spring flood for the Tsivil' River are presented in Fig. 3a. It is clear that their pattern fundamentally

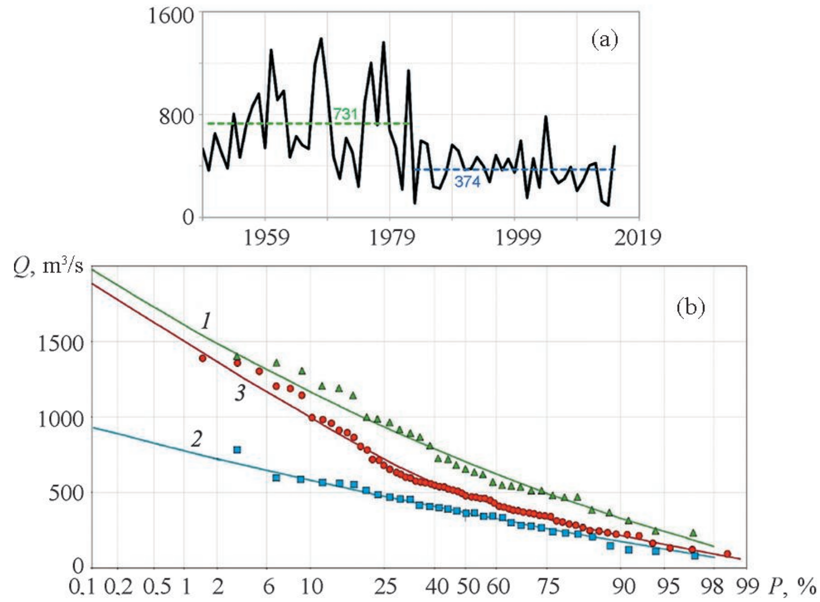

Fig. 3. (a) The long-term variations in peak discharge (m^3/s) for the Tsivil' River–Tusvi and (b) empirical (symbols) and analytic (curves) distributions of peak discharge for (*1*) 1950–1982 and (*2*) 1983–2015; (*3*) compound distribution curve. The dash horizontal sections in figure a show mean values for 1950–1982 and 1983–2015.

changed after 1982: the mean water discharge for 1983–2015 is by almost two times smaller as compared with the preceding period, while runoff variability significantly decreased. This is a typical example of the disturbed uniformity (stationarity) of maximum runoff for the rivers in the southern part of the Volga basin. If data for the second period alone are used for calculations, errors might arise, because not only the low-water phase might change to the high-water one but also high water discharge observed during the period before the beginning of climate change might take place. So, data for the whole observation period should be used for calculations. Such opportunity is provided in case of applying compound distribution curves. Empirical and analytic distribution curves for two stationary (quasistationary) periods as well as the compound distribution curve are presented in Fig. 3b. If only data for the last period are utilized, the calculated peak discharge with the 1% probability is equal to 777 m^3/s. In our opinion, it would be incorrect to use this value for the assessment, for example, of flooding zones, because peak discharges observed during the preceding period are not taken into account in this case. Therefore, the most optimum solution is the use of the design discharge of 1490 m^3/s estimated from the compound distribution curve.

CONCLUSIONS

Changes in the regime of maximum and minimum runoff which have occurred in the recent decades on the Volga basin rivers are caused by the impact of climatic factors, are of regional nature, and differ in the moment of their beginning, in direction, and intensity. The most significant changes in the pattern of long-term variations in extreme runoff characteristics are registered in the southern part of the analyzed territory, where increase in daily minimum winter and summer-autumn runoff reached 100–250% and peak water discharge during the period of spring flood was reduced by 40–60%. In general, the risk of extreme hydrological events was reduced for the Volga basin except for the basins of the Unzha, Vetluga, Chusovaya, and Belaya rivers, where the occurrence frequency of low-probability peak discharges increased. The observed changes should be considered as positive ones for the water utilization system taking into account the significant reduction of the frequency of extremely low and high discharges in the most part of the basin.

When planning activities in the Volga basin which are aimed at the guaranteed provision of population and industrial facilities with water as well as at their protection against the negative impact of water, it is necessary to take into account changes in river water regime characteristics. It is done using hydrological data obtained during all years of observations. If time series of high and low runoff are nonstationary, it is reasonable to assess their probability characteristics with compound distribution curves or using the Bayesian approach.

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