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**MATHEMATICAL MODELS  
IN SOLVING PROBLEMS OF LAND HYDROLOGY**

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## **River Runoff in European Russia under Global Warming by 1.5 and 2 Degrees**

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**Abstract**—The ECOMAG hydrological model was used to evaluate runoff characteristics in the basins of the major rivers in European Russia: the Volga, Don, Northern Dvina, Pechora, and Kuban. The models of runoff formation for various hydrometric gauging stations in these basins were calibrated using data of weather station observations. Next, the input data were represented by the data of an ensemble of global climate models for assessing the regional hydrometeorological regime at the realization of a scenario of global warming by 1.5 and 2°C in the XXI century relative to the preindustrial values. The reproduction of the annual and seasonal runoff by data of climatic models was evaluated by comparison with observation data. According to the results of numerical experiments at global warming by 1.5 and 2°C, the values of the relative changes in river runoff in European Russia increase from N to S and from E to W, i.e., the hydrological systems under milder climate were found to be more sensitive to changes in the meteorological characteristics. The estimation of runoff anomalies in the European Russia showed the following common features: an increase in the winter runoff in the northern rivers and in the Volga basin, a decrease in the spring snowmelt runoff in the Northern Dvina, Volga, and Don, a decrease in the summer–autumn runoff of all studied rivers with various intensity. In this case, the annual runoff of the Pechora will show a positive trend, and that of the Northern Dvina, Volga, Don, and Kuban, a negative trend.

**Keywords:** runoff formation, global warming, hydrological models, European Russia, Volga, Don, Northern Dvina, Pechora and Kuban

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### INTRODUCTION

The climate changes in the European Russia (ER) in the recent decades, have a considerable effect, primarily, on the intra-annual runoff distribution. The results of analysis of such changes are widely presented in the studies of the Department of Land Hydrology, Moscow State University [17, 21, 31]; Water Problems Institute, Russian Academy of Sciences [1, 9]; Institute of Geography, Russian Academy of Sciences [4, 5]; State Hydrological Institute [6, 10], and other institutions. Some generalizations of these and other studies are given in [8] and [16], published under the editorship of the IG RAS and SHI, respectively.

Summarizing the main conclusions of the above studies, it should be noted that, in the period since the 1980s the winter runoff in the rivers in the Volga and Don basins increased by 30–120% [4, 9, 32]. The water storage of the snow cover is shown to decrease by the early spring, which creates conditions for a decrease in the spring flood runoff. Thus, the spring runoff in the rivers of the central ER decreased by 10–30% [17]. Over the period since the 1980s, the maximal spring flood discharges decreased by 20–50% in the major portion of the Volga basin, except for the

upper reaches of the mountain forested tributaries of the Kama River [6]. An increase in the summer–autumn runoff was recorded in the forest-steppe and steppe zones of ER, which demonstrates a high spatial variability [31]. Overall, the seasonal variability of runoff is due to the earlier and flattened spring flood, an increase in winter runoff because of long winter thaws caused by the intrusion of moist and warm air and the earlier passage of air temperature to positive values. Over the recent 40 years, the level of natural river flow regulation in the Volga and Don basins has increased, on the average, by 30% [21]. At the same time, the rivers of the northern ER showed a weak positive trend in the annual runoff without statistically significant changes in the intra-annual of flow and maximal water discharges [18]. In rivers with the major portion of rain flow in the Kuban basin, an increase was recorded in the recurrence of hazardous hydrometeorological phenomena, caused by storm rainfall. However, a decrease in the flow in July–August was observed in the recent decades in the Kuban R. basin due to a decrease in the glacial component [41].

Given below are the existing estimates of the future changes in the runoff of the rivers under study, determined with the use of various hydrological models and the data on the ensemble of global climate models (GCMs). Groups of researchers from SHI and IG RAS estimated the changes in water regime using water-balance hydrological models with a ten-day and monthly calculation step [4, 5, 7]. Thus, in the early XXI century, the possible increase in the annual Volga runoff is 3–10% and that of the Don will not exceed 5%, depending on the scenario. According to calculations by the conceptual STREAM model, an increase in the Volga flow in the XXI century will be ~7% [40]. Calculations in [24] with the use of model TOP-MODEL under scenario RCP8.5 show that the runoff in the Kama basin will increase by 14% by the mid-XXI century compared with the late XX century, while in the other part of the Volga basin, the changes in runoff in the nearest 40 years will not exceed 5%. Calculations by a regional climate model and the simplified model CaMa-Flood under scenario RCP8.5 show that the maximal runoff in the rivers of the Volga basin in the period of snow melting can decrease by 10–30% [42]. According to calculations by SWIM model, the runoff of the Northern Dvina in the XXI century can increase by 5–15% under various RCP scenarios [37]. Similar results were obtained by SWAP model—an increase in the Northern Dvina runoff by 5–10%, while according to ECOMAG model with the use of Russian databases of land surface parameters, the changes in the annual runoff in the XXI century are nearly zero at a considerable transformation within the year [12]. The analysis of publications showed that no estimates of the possible changes of Pechora and Kuban runoff are available for the XXI century.

In the recent years, methods for evaluating changes in the water regime of large rivers with the use of physicomathematical models have gained in popularity; in these models, the boundary conditions are specified in the form of scenarios of hydrometeorological impacts on the river watershed, calculated with the use of GCMs [2, 3, 35]. The use of hydrological models of this class, operating in a daily time interval, enables detail estimation of the physical mechanisms of the response of river basins to the climatic impacts, taking into account regional features, and to reduce the uncertainty in the estimates of changes in river runoff when solving problems of super-long-term forecasting of water regime variations.

A special report [38] was published in 2018 focused on determining the adverse effect of global warming (GW)—1.5 and 2°C (the objectives formulated in the Paris Agreement on Climate Change) above than the preindustrial values—on the natural and social systems at the world scale. The European Russia practically is not covered by such studies, thus making especially significant and urgent the acquisition of new physically based estimates of the hydrological effects of GW by 1.5 and 2°C in the XXI century based on the

synthesis of detail physically based models of runoff formation, along with an ensemble of GCMs within large river basins of the ER: the Volga, Don, Northern Dvina, Pechora, and Kuban.

## THE PROCEDURE AND SOURCE DATA

### *The Developing and Testing of Runoff Formation Models*

The physically based changes in the water regime were studied with the use of runoff formation models for the basins of the Volga, Don, Northern Dvina, Pechora, and Kuban on the platform of the ECOMAG information-simulation system [15], which was used before for large rivers of the European and Asian parts of Russia [23, 25–27, 29, 30, 34], as well as mountain rivers [19, 28, 33]. Earlier, ECOMAG system was used to construct and, for the first time, successfully test a joint model of the Volga basin for calculating the formation of daily runoff in the outlet gauges of the major tributaries of the Volga and Kama over a long period, because of flow regulation by the Volga–Kama reservoir cascade [22]. The analysis of publications has shown that hydrological spatially distributed models on a daily average time interval for the Don and Kuban basin were constructed and verified for the first time. Analogues of the runoff formation models for the Northern Dvina and Pechora are known [11, 37, 39] as well as detail runoff formation models for a small part of the Kuban and Don basins, based on the finite-element method [13, 14]. Models for all five river basins mentioned above were constructed based on common sources of data on the land surface and variations of the meteorological characteristics. Such an approach enables carrying out the comparative analysis of the estimates of changes in river water regime.

The construction of a model river network and the schematization of river basins by their division into unit catchments was based on a digital elevation model with a spatial resolution of 1 km. The number of constructed elementary river catchments was 775 for the Volga basin, 129 for the Don, 198 for the Northern Dvina, 174 for the Pechora, and 31 for the Kuban. The spatially distributed model parameters were determined with the use of global databases on soils (Harmonized World Soil Database), and landscapes (Global Land Cover Characterization). The boundary conditions for the models were taken from long-term series of daily air temperature and humidity and precipitation measured at weather station network. The observation data from 306 weather stations were used for the Volga basin, 75 for the Don, 50 for the Northern Dvina, 30 for the Pechora, and 21 for the Kuban.

The models were calibrated using long-term series of daily water discharges at various hydrometric gauging stations in the basins of the Volga, Don, Northern Dvina, Pechora, and Kuban. In the Volga basin, the calculations were made for the section in the Upper

Volga (Staritsa) and the outlet sections of the major tributaries of the Volga and Kama: the Oka, Belaya, Vyatka, Vetluga, Sura, and Unzha, as well as for the Kama Reservoir basin. The model for the Don basin was calibrated based on the gauging stations on the Don that control the upper (Zadonsk) and middle (Kazanskaya) parts of the drainage basin; the Belyaevskii gauge, which determines ~95% of water inflow into the Tsimlyansk Reservoir and which was regarded as an outlet section; as well as on the major tributaries: the Khoper, Sosna, Voronezh, and Medveditsa. In the basin of the Northern Dvina, three gauging stations were chosen in the main channel—the Abramkovo and Zvoz, and the outlet section at Ust-Pinega; as well as gauging stations on the rivers in the upper part of the drainage basin and the major tributaries: the Sukhona, Yug, Luza, Vychedga, and Pinega. The calibration gauging stations for the Pechora basin were taken in the main channel in the upper (Ust-Shchugor) and middle (Ust-Tsilma) parts and the outlet section Oksino, as well as on the main Pechora tributary—the Usa R. The runoff formation model for the Kuban basin was calibrated using gauging stations Armavir and Ladozhskaya, located upstream of the Krasnodar Reservoir and determining water inflow into it via the Kuban, as well as at the outlet section on the Laba R., the main tributary of the Kuban. In addition, at the stage of Kuban model calibration, the boundary conditions were specified in the form of daily water discharges at the hydropower system at Ust-Dzheguta, located at the beginning of the Bol'shoi Stavropol'skii channel, the supply of which takes almost 80% of the Upper Kuban runoff.

While the outlet sections in the Northern Dvina, Pechora, and Don are determined, the choice of such sections in the Volga basin is hampered by the presence of the Volga–Kama cascade of reservoirs, and in the Kuban basin, by the location of gauging stations. Because of this, the reproduction accuracy of the natural flow of the Volga over the long period was evaluated relative to the estimate with specification in model boundary conditions at eight river sections considered above (the runoff in which equaled to  $\frac{3}{4}$  of the Volga runoff) of observed daily discharges. The calculation accuracy of the natural runoff of the Upper Volga upstream of the inflow of the Oka, the Kama before its emptying into the Volga, and the Kuban based on the daily discharges at the Ladozhskaya gauging station on the Kuban and Doguzhiev gauging station on the Laba, the total drainage area of which amounts to 93% of the Kuban drainage area before emptying into the Krasnodar Reservoir. The outlet section for the Oka is Gorbatov.

The modeling was carried out with the use of the method of spatial calibration of models by Nash–Sutcliffe NSE, Kling–Gupta KGE, and the relative systematic calculation error BIAS. The calculation quality is the better, the closer the values of NSE and KGE to unit, and the value of BIAS to zero. The robustness

of the models was evaluated by their verification with the use of independent data of runoff measurement for the same sections in the river network.

#### *Hydrological Modeling by GCMs Data*

With the aim to reduce the existing uncertainties and to improve the accuracy and the space and time detail of the climatic projections for the ER, a daily meteorological database was prepared, as required for hydrological models, with the use of grid data of ensemble GCMs CMIP5 (Coupled Model Intercomparison Project 5) from the project ISIMIP (Inter-Sectoral Impact Model Intercomparison Project). These data represent surface fields of meteorological characteristics, interpolated onto a regular  $0.5^\circ$  grid over the latitude and longitude (downscaling), and a procedure for removing systematic model errors in the annual variations of meteorological characteristics (bias-correction) was applied with the incorporation of reanalysis data of the ERA family [36]. GFDL-ESM2M and MIROC5 were chosen as the most accurately reproducing the observed dynamics of global air temperature over 1861–2005 [20].

These runoff formation models were used to study the potential of the reproduction of the annual and seasonal runoff in ER rivers over the historic period with the use of grid GCM data as boundary conditions in the hydrological models of for calculating the appropriate ensemble of long-term daily hydrographs. These calculations did not take into account runoff regulation by hydraulic power systems, because the focus of the study was the response of natural hydrological systems to the regional climate changes in ER at GW by 1.5 and  $2^\circ\text{C}$ . The chosen basic historic period was 1970–1999. The characteristics of water regime calculated based on GCMs data and compared with those obtained earlier by simulation based on observation data of weather stations included: the normal annual and seasonal runoff, the high ( $Q_{10}$ —the exceedance probability of 10% of days in a year) and low ( $Q_{90}$ —the exceedance probability of 90% of days in a year) runoff (by the curves of the duration of the mean daily flow) the runoff coefficient. The calculations were carried out for the outlet sections: Ust-Pinega in the Northern Dvina basin, Oksino in the Pechora basin; Belyaevskii in the Don basin; a section before the inflow into the Krasnodar Reservoir downstream of the Laba R. mouth in the Kuban basin; the section of the Zhigulevskaya HPP with the drainage area of almost 90% of the Volga R. basin; a section before the inflow of the Oka R. in the Upper Volga; a section before the inflow into the Volga R. in the Kama R., and a section at Gorbatov in the Oka R. The distribution of runoff over a season was as follows: the winter season in the Northern Dvina, Don, Kuban, and in the Volga basin—from November to March; in the Pechora—from November to April; the spring flood in the Northern Dvina, Kama, and in the outlet

**Table 1.** Years of reaching threshold values of GW by 1.5 and 2°C relative to the preindustrial values for various GCMs and RCPs

GCM	RCP	1.5°C	2°C
GFDL-ESM2M	RCP2.6	—	—
GFDL-ESM2M	RCP4.5	2049	—
GFDL-ESM2M	RCP6.0	2056	2076
GFDL-ESM2M	RCP8.5	2036	2053
MIROC5	RCP2.6	2048	—
MIROC5	RCP4.5	2039	2069
MIROC5	RCP6.0	2052	2071
MIROC5	RCP8.5	2033	2048

section of the Volga—from April to June; in the Oka, Upper Volga, Don, and Kuban—since June to October. In addition, the results of modeling were used to compare the calculations by the data of weather stations and GCMs for the runoff-forming factors, such as water storage of the snow cover and the depth of seasonal freezing of soils on the average over the basins. To assess the spatial verification of runoff modeling, the fields of the annual runoff depths for elementary catchments in the basins under consideration calculated based on GCM data were compared with those observed at weather stations.

The calculations for the future period up to the late XXI century were carried out using projections of the global climate changes according to four RCP-scenarios (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5). First, the periods of reaching threshold values of GW by 1.5 and 2°C relative to the preindustrial values were determined for each GCM and each RCP. This was made by anomalies of the global air temperature over 30-year moving average, i.e., for example, the year of 2050 corresponds to the mean value over period 2036–2065. Next, each of the seven possible realizations of GW by 1.5°C and each of the five possible realizations of GW by 2°C relative to the preindustrial values were specified as boundary values in the model of runoff formation of the examined rivers, after which, the results of calculations (with a daily time step and a spatial resolution equal to the size of elementary watersheds) were averaged for the threshold values of 1.5 and 2°C over seven and five sets, respectively. The calculations by the hydrological model for the XXI century were carried out with the same parameters that were established for the historical period. According to the data used, on the average, GW by 1.5°C will be achieved by 2045 and that by 2°C, by 2064 (Table 1). Anomalies of climatic and hydrological characteristics of the studied rivers were calculated as the ratio of the calculated value for the conditions of GW by 1.5 and 2°C to the appropriate value determined by GCM data for the basic period of 1970–1999.

To evaluate the space and time variations of climatic and hydrological characteristics, maps of the normal annual fields of air temperature and precipitation, as well as runoff depth were constructed based on the calculations using models of its formation with GCMs data for periods of the XXI century corresponding to GW by 1.5 and 2°C. Next, these fields were compared with those constructed using GCMs data over the base period of 1970–1999, and the changes in the normal annual air temperature, the total annual precipitation, and the runoff depth were evaluated. The statistical significance of the climate-induced changes in the annual and seasonal river runoff was identified with the use of the Mann–Whitney test at a 5% significance level.

## CALCULATION RESULTS

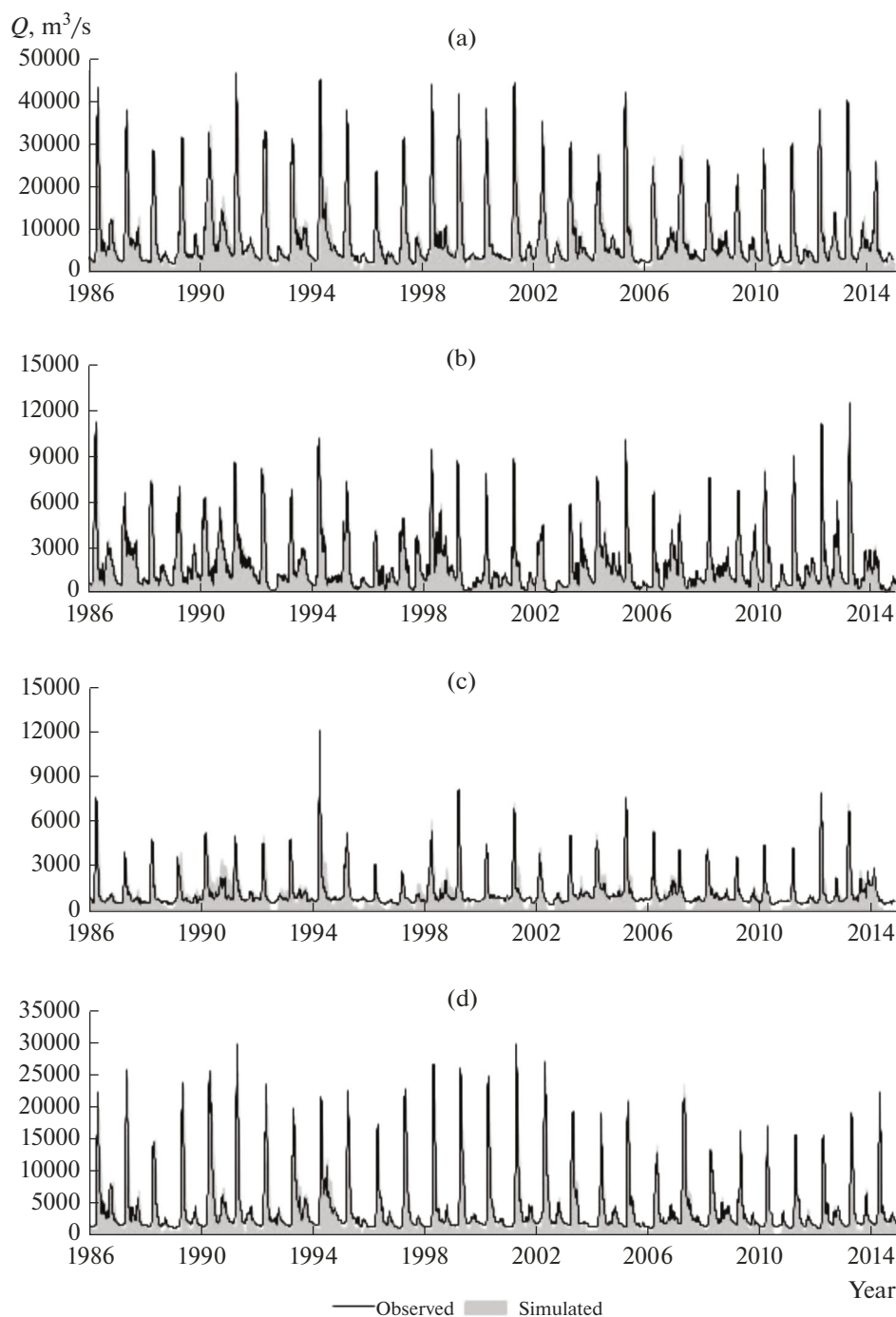
### *Testing Runoff Formation Models*

The model parameters were calibrated over the period 1986–1999 at eight gauging stations for the Volga basin; over the period 1985–1999 at eight gauging stations for the Don; over period 1985–1999 at eight gauging stations for the Northern Dvina; over period 1985–1999 at four gaging stations for the Pechora; and over period 1989–1995 (the duration is determined by the availability of data on water discharges at Ust-Dzheguta gauging station) at three gauging stations for the Kuban (Table 2). The models were tested on independent measurement data at the same gauging stations over period 2000–2014, and that for the Kuban, over 1996–2002, including the gauging station at the Zhigulevskaya HPP, the Upper Volga upstream of the Oka inflow, the Kama upstream its inflow into the Volga, and Kuban upstream of its inflow into the Krasnodar Reservoir.

According to criteria NSE, KGE, and BIAS, the results over the periods of calibration and verification were good ( $0.70 \leq NSE \leq 1$ ,  $0.70 \leq KGE \leq 1$ ,  $|BIAS| \leq 15\%$ ) or satisfactory ( $0.50 \leq NSE < 0.70$ ,  $0.50 \leq KGE < 0.70$ ,  $15\% < |BIAS| \leq 25\%$ ) for water discharges at all eleven gauging stations in the Volga basin, five gauging stations in the Don basin, all eight gauging stations in the Northern Dvina basin, all four gauging stations in the Pechora basin, and all four gauging stations in the Kuban basin. The calculation results were unsatisfactory in terms of NSE for the Don–Kazanskaya gauging station for the verification period, Voronezh–Lipetsk in terms of BIAS over the verification period, and the Medveditsa–Archedinskaya in terms of NSE over the calibration period. The errors in rivers with relatively low water abundance, such as the Voronezh and Medveditsa at the gauging stations Lipetsk and Archedinskaya, may be due to the neglect of the local features of river flow formation, typical of these rivers and having both natural and anthropogenic origin, and that for the Kazanskaya gauging station is most likely due to the

**Table 2.** The values of statistical criteria of the calculated mean daily runoff in the basins of the Volga, Don, Northern Dvina, Pechora, and Kuban over the period of model calibration and verification

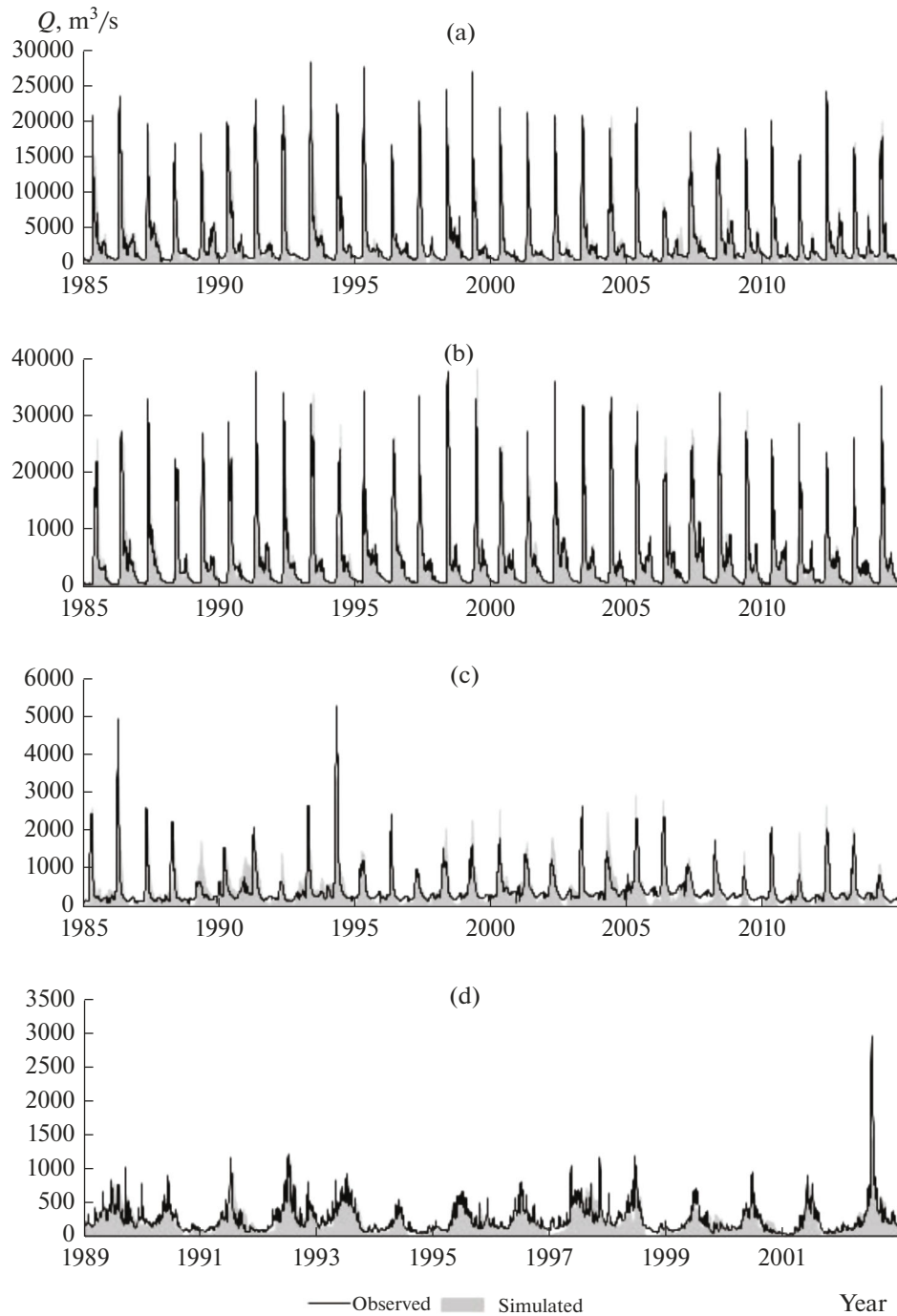
River—gauging station	<i>F</i> , thous. km <sup>2</sup>	NSE	KGE	BIAS, %	NSE	KGE	BIAS, %
Volga basin		1986–1999			2000–2014		
Oka—Gorbatov	244	0.73	0.83	6.4	0.75	0.80	−6.6
Vyatka—Vyatskie Polyany	124	0.84	0.85	−3.1	0.89	0.93	−1.6
Belaya—Birsk	121	0.87	0.82	−13	0.86	0.70	−12
Catchment area of the Kamskoe Reservoir	168	0.94	0.92	−7.1	0.93	0.91	−3.8
Sura—Poretskoe	50.1	0.51	0.77	9.8	0.59	0.70	−15
Vetluga—Vetluzhskii	27.5	0.86	0.81	1	0.87	0.83	5.7
Volga—Staritsa	21.1	0.66	0.72	12	0.67	0.77	3.7
Unzna—Makar’ev	18.5	0.74	0.74	−0.5	0.72	0.78	1
Upper Volga	239	0.99	0.98	1	0.99	0.99	0.5
Kama	516	0.95	0.93	−6.4	0.96	0.90	−4.5
Volga as a whole	1210	0.96	0.96	−1.7	0.97	0.93	−3.4
Don basin		1985–1999			2000–2014		
Don—Belyaevskii	204	0.66	0.75	2.1	0.62	0.68	−12
Don—Kazanskaya	102	0.59	0.65	−8.5	0.43	0.56	−23
Don—Zadonsk	31.1	0.55	0.52	4.4	0.52	0.67	−19.2
Khoper—Povorino	19.1	0.51	0.57	−5.3	0.64	0.68	−11.5
Khoper—Barminskii	57.3	0.62	0.76	−3.7	0.58	0.66	−18
Sosna—Elets	16.3	0.52	0.48	3.2	0.61	0.73	−13
Voronezh—Lipetsk	15.3	0.54	0.61	−1.4	0.56	0.64	−29
Medveditsa—Archedinskaya	33.7	0.43	0.55	−0.9	0.51	0.63	−7.3
Northern Dvina basin		1985–1999			2000–2014		
Northern Dvina—Ust-Pinega	348	0.91	0.94	−3.3	0.89	0.94	0.1
Northern Dvina—Zvoz	285	0.91	0.94	0.7	0.90	0.95	1.6
Northern Dvina—Abramkovo	220	0.90	0.94	0.7	0.90	0.94	3.5
Sukhona—Kalikino	49.2	0.78	0.75	−14	0.77	0.79	−13
Yug—Podosinovets	15.2	0.70	0.72	8.9	0.71	0.78	3.9
Vychegda—Fedyzkovo	112	0.80	0.87	8.7	0.87	0.89	9.5
Luza—Krasavino	16.3	0.77	0.85	3.5	0.78	0.85	−8.6
Pinega—Kulogory	36.7	0.74	0.84	−1.6	0.68	0.84	1.3
Pechora basin		1985–1999			2000–2014		
Pechora—Oksino	312	0.84	0.87	−6.1	0.88	0.92	−2.6
Pechora—Ust-Tsil’ma	248	0.89	0.88	2.7	0.88	0.89	5.8
Pechora—Ust-Shchugor	67.5	0.80	0.88	1.7	0.80	0.90	−1.9
Usa—Petrun	27.5	0.76	0.70	−25	0.82	0.78	−21
Kuban basin		1989–1995			1996–2002		
Kuban—Armavir	16.9	0.64	0.81	−4.1	0.62	0.78	−4
Kuban—Ladozhskaya	19.8	0.67	0.83	4.4	0.63	0.72	0.6
Laba—Doguzhiev	12	0.59	0.66	−9.8	0.58	0.72	−16
Kuban upstream of the Krasnodar Reservoir	34.1	0.73	0.83	−2.7	0.70	0.81	−7.3



**Fig. 1.** Hydrographs of the simulated and observed daily water discharges in the outlet sections of the rivers of (a) Volga, (b) Upper Volga, (c) Oka, and (d) Kama.

natural regulating effect of the floodplain at the passage of high discharges during spring flood. Moreover, in the assessment of the simulation accuracy for the mean daily flow for the Don and Kuban basins, which feature a high interannual and annual runoff variations, the KGE criterion has an advantage over NSE, because the former lacks the drawback of the NSE cri-

terion, consisting in the underestimation of the variance of the calculated water discharges. Figures 1–2 show the hydrographs of the simulated and observed water discharges in the outlet sections of the studied rivers. In addition, the models showed robustness at the passage from the calibration to verification period.

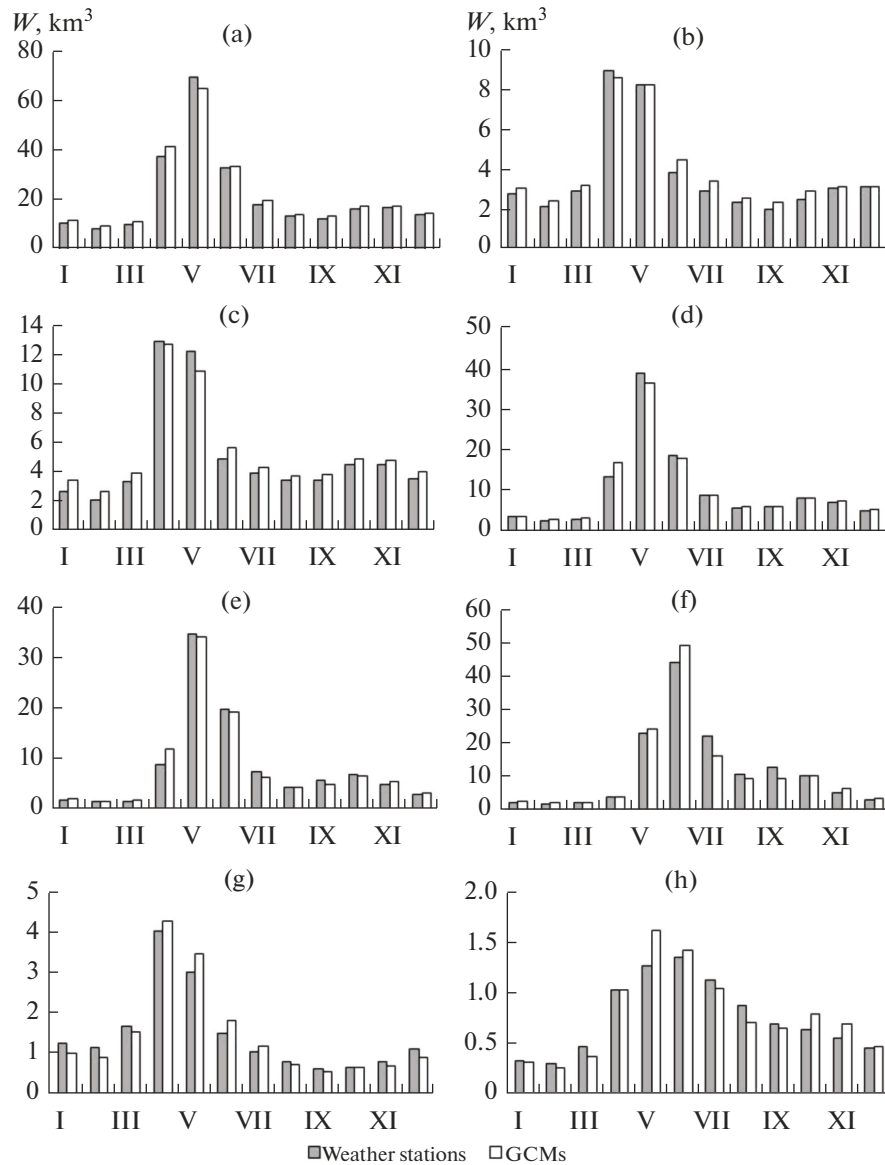


**Fig. 2.** Hydrographs of the simulated and observed daily water discharges in the outlet sections of the rivers of (a) Northern Dvina (b) Pechora, (c) Don, and (d) Kuban.

#### *Assessment of the Changes in the Hydrological Regime Using GCMs Data*

Figure 3 gives the long-term mean values of the mean monthly runoff of the Volga, Oka, Upper Volga, Kama, Northern Dvina, Pechora, Don, and Kuban, calculated by the runoff-formation model based on data of an ensemble of GCMs and observations at

weather stations over 1970–1999. Hydrological models with GCM data reproduce the annual runoff in those gauging stations with an error of 0.2–6% relative to the estimation by the data of weather stations. The relative errors in the estimation of winter runoff vary from 1% (the Kuban) to 17% (the Upper Volga), those for the spring flood runoff vary from 3% (the Northern Dvina) to 15% (the Kuban), those for the sum-



**Fig. 3.** Mean monthly runoff of the rivers of (a) Volga, (b) Oka, (c) Upper Volga, (d) Kama, (e) Northern Dvina, (f) Pechora, (g) Don, and (h) Kuban, calculated by runoff formation models based on data of GCMs and observations at weather stations over period 1970–1999.

mer–autumn runoff vary from 1% (the Kuban) to 19% (the Pechora). In the assessment of the calculation accuracy of the high ( $Q_{10}$ ) and low ( $Q_{90}$ ) runoff by GCMs data, it should be mentioned that the error for high flow was 1–10%, and that for low flow was 2–16% with largest values for the Don and Kuban, which is explained by the small absolute values of flow compared with northern rivers. The coefficient of river flow is reproduced with sufficient accuracy: the error was 0.01 for the Upper Volga, Oka, Kama, Don, and Pechora; 0.02 for the Northern Dvina, and 0.04 for the Kuban. The spatial coefficient of correlation between the values of the annual runoff depth calculated by the model based on the GCMs data and the

results of observations at weather stations for elementary catchments was 0.96 for the Volga basin, 0.75 for the Northern Dvina, 0.68 for the Pechora, 0.98 for the Don, and 0.87 for the Kuban.

According to calculations, the rate of air temperature increase generally grows from S to N in the ER under GW. At GW by 1.5°C, the increase in the mean annual air temperature will be 2.7–2.8 in the basins of the Northern Dvina, Pechora, Oka, and Upper Volga, 2.5 in the Don basin and the remaining part of the Volga basin, and 1.9°C in the Kuban basin, relative to the base period of 1970–1999. At GW by 2°C, an increase in the mean annual temperature will be 4.1 in the Pechora basin, 3.7 in that of the Northern Dvina,



Oka, and Upper Volga, 3.4 in that of the Don and the remaining part of the Volga basin, and 2.7°C in the Kuban basin. Under both these scenarios, the largest warming rate in the basins of the Northern Dvina and Pechora was recorded by 3.1–4.3 and 3.8–5.5°C in winter, respectively; in the Don and Oka, by 3–4 and 3.6–4.8°C, respectively, in spring; and in the Kuban, by 2.3–3.2°C, in summer and autumn. An increase in the global air temperature from 1.5 to 2°C leads to an effect of additional warming in the studied river basins by 0.8–1.3 over a year and by 0.6–1.7°C over a season.

At GW by 1.5 and 2°C, the increase in the annual precipitation was largest in the Pechora—by 11 and 15%, respectively; those for the Don, Northern Dvina, and the Volga basin were 4–8%, while the changes in the Kuban are nearly zero. The largest increase in moistening is typical of winter in each river basin, where it varies from 6–9% in the Don to 15–19% in the Pechora at GW by 1.5 and 2°C. The relative increase in the summer–autumn precipitation in the Pechora basin was 9 and 13% at GW by 1.5 and 2°C, 5–8% in the Volga basin, up to 4% in the basins of the Northern Dvina and Don, while the precipitation in the Kuban basin decreased by 8 and 16%, respectively. The rise of the global temperature from 1.5 to 2°C leads to an effect of additional moistening of the drainage basins of the Northern Dvina, Kama, and Upper Volga by 3–4.5 and the Oka by 1.5% and to a decrease in the moistening of the Kuban drainage basin by 4% due to the warm season of the year at almost invariable total annual precipitation in the Don basin.

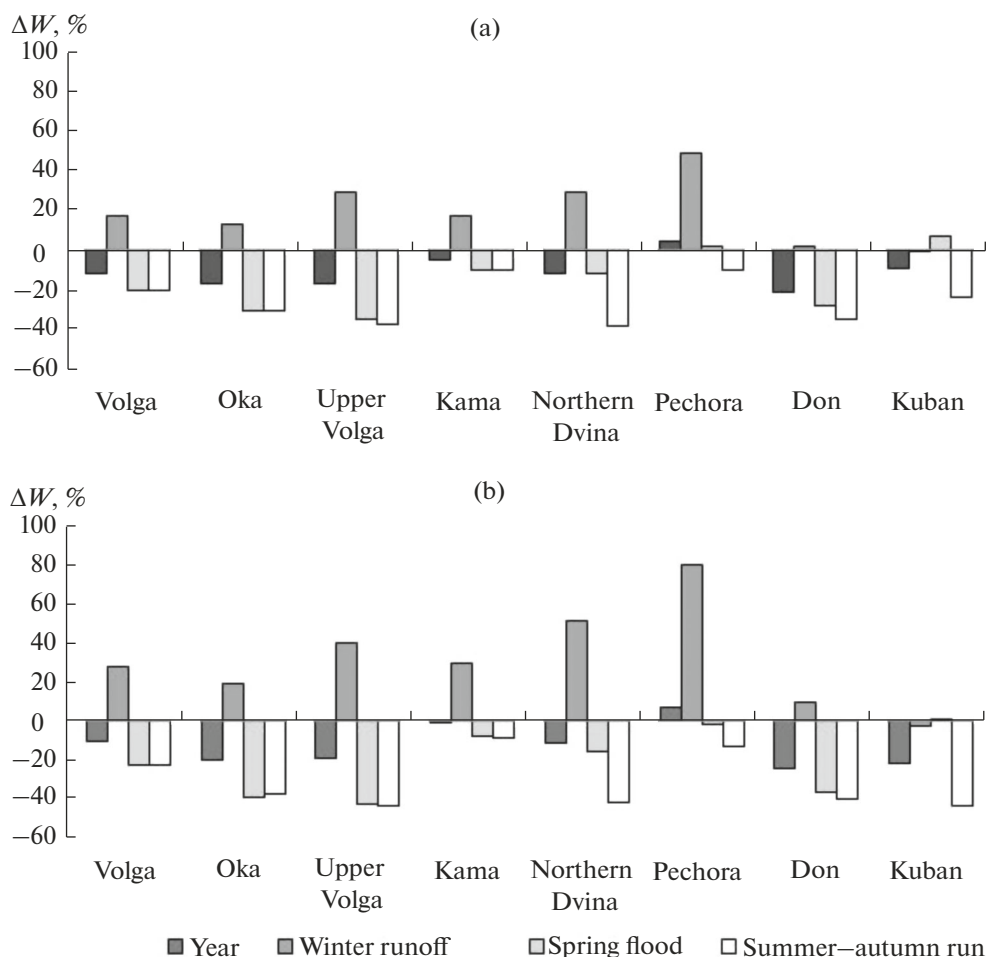
The duration of the period of the year with air temperature below zero will decrease by 2.5 and 4 weeks in the basins of the Northern Dvina and Pechora, 2 and 3 weeks in the Kama basin, by 3 and 4.5 weeks in the Oka and Upper Volga basins, and by 3 and 5 weeks in the basins of the Don and Kuban at GW by 1.5 and 2°C, respectively. At the same time, the amount of solid precipitation on the average over the basins of the Northern Dvina, Pechora, and Volga almost does not change, though in the Upper Volga and Oka, it decreased by 4 and 7% at GW by 2°C, while in the Kama, it on the contrary, increased by 3%, in the Don it decreased by 7 and 14%, in the Kuban, by 17 and 29%, at GW by 1.5 and 2°C, respectively. The increase in the amount of liquid precipitation was <5% in the Kuban basin, ~10% in the Don basin, 8 and 15% in the Northern Dvina, 11 and 16% in the Volga, 18 and 29% in the Pechora at GW by 1.5 and 2°C, respectively.

At GW by 1.5 and 2°C, the annual runoff will decrease by 11% in the Northern Dvina, by 10–11% in the Volga (a decrease by 17–20% is observed in the Oka and Upper Volga, while in the Kama, it will be only 1–5%), by 21 and 24% in the Don, by 9 and 22% in the Kuban, while this characteristic will, conversely, increase by 5 and 7%, respectively (Fig. 4). However, in the case of variations of the seasonal flow, the pic-

ture is quite variegated: a considerable increase in the winter runoff of the Northern Dvina (30–50%), Pechora (50–80%), Upper Volga (30–40%), at a lesser increase in the Oka (12–19%) and Kama (17–29%) at a low variability for the Don and Kuban, a decrease in runoff over the spring flood period in the Northern Dvina (10–15%), Upper Volga, Oka, and Don (30–40%), Kama (8–10%) at a low variability for the Pechora and Kuban, a decrease in the summer–autumn runoff in the Northern Dvina, Upper Volga, Oka, and Don (35–40%), Pechora and Kama (8–13%), and Kuban (25–45%). GW from 1.5 to 2°C has the strongest effect on the rate of decrease of the Kuban runoff due to the summer–autumn period (which is due to the considerable decrease in precipitation and the share of the glacial river recharge) and the runoff of the Oka, Don, and Upper Volga over the spring flood period; as well as in the rate of increase in the winter runoff of the Northern Dvina, Pechora and in the Volga basin due to an increase in the thaw period. At GW by 1.5 and 2°C, the mean maximal snow water equivalent decrease by 24–32% in the Don basin and by 14–20% in the basins of the Volga and Kuban, and by 7–14 and 2–7% in the basins of the northern rivers of the Northern Dvina and Pechora, respectively. Because of warming, the decrease in the mean depth of seasonal soil freezing was within 10 cm in the basins of the Northern Dvina, Volga, and Kuban and within the range of 10–20 cm in the basins of the Pechora and Don.

The anomalies of the seasonal redistribution of runoff cause a decrease in the high runoff  $Q_{10}$ , %: by 7–9 for the Kama, by 11–13 for the Northern Dvina, by 10–20 for the Kuban, by 23–27 for the Don, and by 30 for the Oka and Upper Volga, at a constant value for the Pechora in the implementation of both GW scenarios (Fig. 5). The difference between GW scenarios was largest for the Kuban. In this case, the low runoff  $Q_{90}$  of the Northern Dvina will increase by 15–20; the Pechora, by 10–30; and the Volga, by 14–15%, mostly due to an increase in the Kama runoff by 38–42%; and, conversely, it will decrease by 15–25% in the Don with an increase at the intensification of warming (Fig. 5). The effect for the low runoff of the Kuban is opposite: an increase by 12% at GW by 1.5°C and a decrease by 12% at GW by 2°C. At GW by 1.5 and 2°C, the runoff coefficient will decrease by 0.09–0.1 for the Northern Dvina, 0.05–0.06 for the Pechora, 0.03–0.04 for the Don, 0.03–0.06 for the Kuban, and 0.07 for the Volga, with a decrease by 0.1 in the Upper Volga and by 0.05 in the Kama (Fig. 6). This shows that, despite an increase in precipitation, the role of evaporation in the water balance of the river basins under consideration will only increase.

Calculations with the use of Mann–Whitney test revealed statistically significant (at a 5% level) changes in the annual runoff of the Northern Dvina, Don, Volga as a whole, Oka, and Upper Volga at GW by 1.5

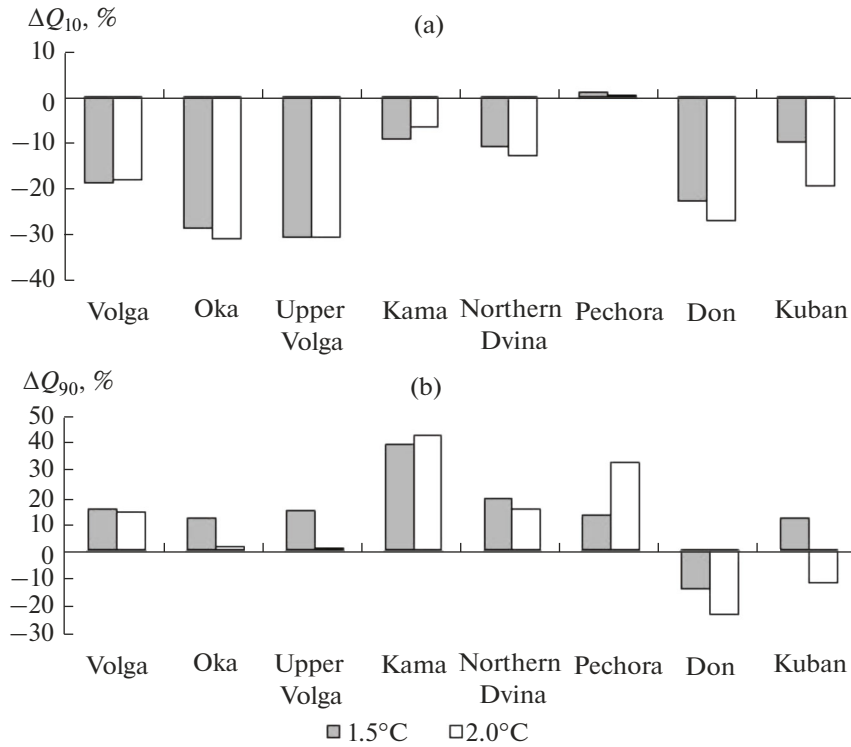


**Fig. 4.** Anomalies of the annual and seasonal runoff of the Volga, Oka, Upper Volga, Kama, Northern Dvina, Pechora, Don, and Kuban at GW by (a) 1.5°C and (b) 2°C in the XXI century relative to the period of 1970–1999.

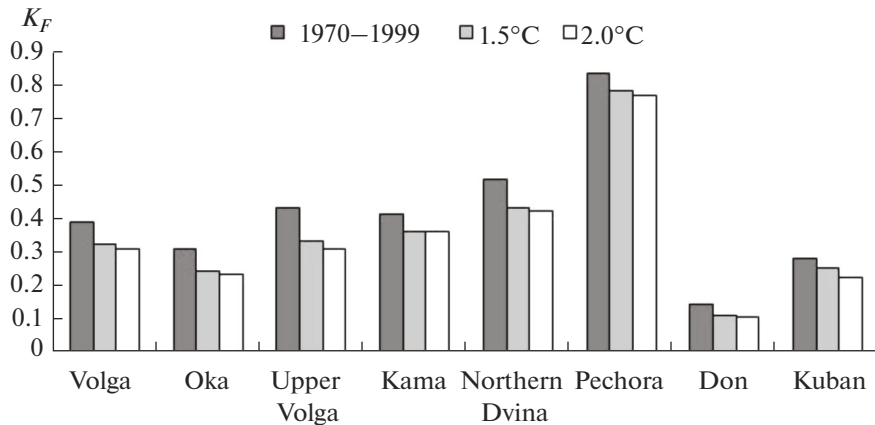
and 2°C, as well as the Pechora and Kuban at GW by 2°C. The anomalies of the winter runoff of the Don and Oka under the scenario of warming by 1.5°C, the winter runoff of the Kuban, and the summer–autumn runoff of the Kama under both scenarios, as well as the runoff over the period of spring flood in the Kuban and Kama at GW by 1.5 and 2°C, respectively.

In the assessment of the space and time variations of the annual runoff depth by scenarios of GW by 1.5 and 2°C in the Northern Dvina basin, the largest decrease in the runoff was recorded in the upper reaches of the Sukhona and Vaga (by 25 and 30%, respectively), while almost no changes were recorded in the upper reaches of the Vychegda. In the major portion of the Pechora basin, a positive anomaly of runoff, mostly, by 5–10%, was recorded with largest values for the Usa R. and the upper reaches of the Pechora and the lowest values, for the Tsil'ma and Izhma rivers. The changes in the runoff depth in the Don basin are very contrast: the largest (30–60%) decrease in runoff was recorded in the Bityug R., the middle reaches of the Khoper R., and the left tributaries

of the Tsimlyansk Reservoir, while the least values (up to 10–20%), to the Chir R. and the Don R. from the Kazanskaya gauging station to the Tsimlyansk Reservoir. The rate of the relative decrease in the runoff depth in the Kuban basin increases from the mountain to lowland territory with the largest values in the middle and lower reaches of the Laba R. and the middle reaches of the Kuban R. At GW by 1.5°C, negative anomalies by 10–20% were recorded in the major portion of the Volga basin down to the Kama mouth, in the Kama basin, mostly up to 10%, and the largest values—up to 40%—in the middle and lower reaches of the Oka. An increase in the runoff depth by up to 10% is typical of the upper reaches of the Samara R. and mountain drainage basins: the Vishera, Chusovaya, and the upper reaches of the Ufa and Belaya rivers. Under a scenario of GW by 2°C, compared with that by 1.5°C in the Volga basin, a similar distribution of changes in the runoff depth and an increase in the contrast of anomalies are observed. Thus, an increase is observed in the area with positive runoff anomalies, including the entire basin of the Samara, almost entire



**Fig. 5.** Anomalies of the (a) high and (b) low runoff of the Volga, Oka, Upper Volga, Kama, Northern Dvina, Pechora, Don, and Kuban at GW by 1.5 and 2°C in the XXI century relative to the period of 1970–1999.



**Fig. 6.** The runoff coefficient of the Volga, Oka, Upper Volga, Kama, Northern Dvina, Pechora, Don, and Kuban over the base period of 1970–1999 and at GW by 1.5 and 2°C in the XXI century.

drainage area of the Kama Reservoir, and a major portion of the Belaya R. basin.

**CONCLUSIONS**

The runoff formation models were calibrated for each of the five basins as a whole with a single set of parameters; however, it is shown that they adequately

describe the spatial heterogeneity of the climatic conditions and the diversity of the physical mechanisms of runoff formation in the vast territory of ER. Overall, at GW by 1.5 and 2°C, the values of the relative change of the annual runoff of ER rivers increase from N to S and from E to W, i.e., the hydrological systems under milder climate were more sensitive to changes in the meteorological characteristics. The largest negative

anomalies of runoff depth were recorded in the southwestern part of the Northern Dvina basin, the middle part of the Don basin, the relatively lowland part of the Kuban basin, and on the Moksha R. in the Volga basin, while the northern and eastern parts of the Pechora basin and rivers of the Volga basin, flowing from the Ural mountains show a positive runoff anomaly.

At GW by 1.5 and 2°C, the assessment of runoff anomalies in ER showed the following common features: an increase in the winter runoff of northern rivers and in the Volga basin, a decrease in the spring snowmelt runoff in the Northern Dvina, Volga, and Don, and a decrease in the summer–autumn runoff in all studied rivers with different rates. The annual runoff of the Pechora will have a positive trend, while that of the Northern Dvina, Volga, Don, and Kuban, a negative trend. Taking into account the current process of natural regulation of river flow in the Volga basin [21] and its forecasted increase in the future for all studied rivers, except for the Pechora, clearly, an additional need appears for adapting the current runoff regulation rules for the Volga–Kama cascade of HPP, as well as the Tsimlyansk and Krasnodar hydro-power stations.

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