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Hydrological and Meteorological Variability in the Volga River Basin under Global Warming by 1.5 and 2 Degrees

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Abstract: The idea of the research to assess the impact of 1.5 °C and 2 °C global warming in the 21st century on the runoff formation in the Volga basin corresponds to the Paris agreement on climate change 2016 with the main goal to keep the global air temperature rise to below 2 °C relative to the pre-industrial level and to take measures to limit warming to 1.5 °C by the end of the 21st century. The purpose of this study was to obtain physically based results of changes in the water regime of the Volga basin rivers under global warming by 1.5 °C and 2 °C relative to pre-industrial values. The physical and mathematical model of runoff generation ECOMAG (ECOlogical Model for Applied Geophysics) was applied in calculations using data from global climate models (GCMs). The estimation of flow anomalies of the Volga River and its major tributaries showed a decrease in annual runoff by 10–11% relative to the period from 1970 to 1999. The largest relative decrease in runoff by 17–20% was noted for the Oka and Upper Volga rivers, while the Kama River had only a 1–5% decrease. The Volga winter runoff increased by 17% and 28% under global warming by 1.5 °C and 2 °C, respectively, and negative runoff anomalies during the spring flood and the summer–autumn period turned out to be in the range of 21 to 23%. Despite the increase in precipitation, the role of evaporation in the water balance of the Volga basin will only increase.

Keywords: runoff generation; global warming; process-based hydrological modeling; Volga River; ISIMIP

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1. Introduction

In recent decades, there has been a significant change in the global climate, as measured by increases in surface air temperature, extremes, variability and changes in precipitation, etc. During the period of instrumental observations since the middle of the 19th century, the average annual global temperature has increased by 0.8–0.9 °C (link https://library.wmo.int/doc_num.php?explnum_id=3414 accessed on 3 July 2022). According to Roshydromet estimates, the Russian territory is warming about 2.5 times more intense than the average for the globe, and it amounted to 0.45 °C per 10 years for the period from 1976 to 2016 [1]. In spring and autumn, maximum warming is observed on the coast of the East Siberian Sea, and in winter, in the northwest of European Russia [2]. In summer, the fastest warming occurs in the south of European Russia against the background of a decrease in precipitation [3]. In most parts of European Russia, a tendency for a decrease in the duration of snow cover associated with thaws in winter was found [4,5]. Such current and predicted changes in meteorological conditions cannot but affect the river runoff generation.

In 2018, the IPCC (Intergovernmental Panel on Climate Change) released a Special report [6] on the impact of global warming of 1.5 °C above pre-industrial levels (1850–1900) on natural and social systems in the context of a global response to climate change threats and sustainable development. According to this report, it is possible to limit global the increase in air temperature to 1.5 °C if global carbon dioxide emissions are reduced by 45% by 2030 relative to 2010. At current emissions levels, global warming would reach 1.5 °C between 2030 and 2052, and 3–4 °C by 2100, depending on the scenario.

Most of the results of scientific publications dedicated to the analysis of changes in the conditions of river flow formation in European Russia have been obtained based on the analysis of observational data. The possibility of forecasting future changes in river runoff is limited by the lack of hydrological models required for this purpose, both in terms of spatial and temporal calculation steps. In the last 30–40 years, changes in river runoff are manifested in the seasonal transformation of the water regime, namely, an increase in winter river runoff and a decrease in snowmelt runoff. The increase in summer–autumn runoff is observed in the forest-steppe and steppe zones, which is characterized by high spatial variability [7]. In the Volga basin, the increase in winter runoff for the period 1978–2010 relative to 1945–1977 was 30–100% [8–10], and the share of snowmelt runoff in the annual volume decreased by 5 to 25% [11]. Since the 1980s, the maximum spring flood discharge has decreased by 20–50% in most of the Volga basin, except for the upper mountain forested tributaries of the Kama River [12].

Summarizing the main conclusions of the above papers, it should be noted that climatic changes have a very significant impact, primarily, on the intra-annual flow distribution. Over the past 40 years, the natural flow regulation of the rivers of European Russia has increased on average by 30% [11]. This indicates that flow formation conditions have changed significantly under the influence of climate. This conclusion is confirmed by the results of the analysis of the observation data at water-balance stations, as well as by the physical and mathematical modeling of moisture infiltration processes in freezing and thawing soils [13]. It was found that the snow water equivalent decreased by the beginning of spring, creating conditions for a decrease in the spring flood flow. In general, the seasonal variability of runoff is associated with earlier and lower floods, an increase in winter runoff due to prolonged winter thaws as a result of the invasion of moist and warm air and the early transition of air temperature to positive values. According to the ensemble data of global climate models (GCMs) [14], the decrease in Volga's runoff in the second half of the 21st century will be by about 5%. According to CMIP5 (Coupled Model Intercomparison Project 5) ensemble data and the hydrological model TOPMODEL, runoff will increase by 14% in the Kama basin under the RCP8.5 (Representative Concentration Pathway 8.5) scenario by the mid-21st century, and in the rest of the Volga basin, the runoff change will not exceed 5% in the nearest 40 years [15].

The purpose of this study was to obtain physically based results of changes in the water regimes of the Volga basin rivers under global warming by 1.5 °C and 2 °C relative to pre-industrial values. This kind of hydrometeorological research in the transition from global to regional scale is now extremely relevant. According to a number of highly ranked publications [16–22], differences in global warming by 1.5 °C and 2 °C are expected to be significant when assessing increases and decreases in water resources and extreme hydrological events (floods, droughts) by region around the world.

2. Data and Methods

2.1. Study Area

The Volga River is the largest river in Europe in terms of basin area (1,360,000 km^2), length (3530 km) and water content (250 km^3 per year). The Volga River basin is located between 48° and 62° N and 32° and 60° E. The natural water regime is characterized by spring floods, summer and winter low-water periods, and autumn rain floods. The highest water month is May. The main tributaries of the Volga River are the Kama, Oka, Vetluga, Unzha and Sura rivers (Table 1, Figure 1). The source of the Volga is 228 m above sea level, and the mouth of the river in the Caspian Sea is 28 m below sea level. The average annual air temperature in the Volga basin is 4 °C, and the amount of precipitation is 585 mm. The hydrometeorological values presented below are based on the author's calculations for current climatic conditions (since the late 1980s). Mean annual air temperature in the Volga basin is 4 °C, mean winter air temperature is –8 °C, mean spring air temperature is 8 °C and mean summer–autumn air temperature is 13 °C. The duration of the period with negative air temperature is five months. Annual precipitation in the Volga basin is 585 mm, of which the amounts of solid and liquid precipitation are 30% and 70%, respectively. The annual runoff of the Volga River is 262 km^3. The winter, spring flood and summer–autumn Volga runoffs are 23, 53 and 24%, respectively. The runoff coefficient of the Volga River is 0.38.

Table 1. Main hydrometeorological characteristics of the eight studied catchments of the Volga basin for the period 1986–2014.

River—Gauge	Catchment Area, km^2	Annual Runoff, km^3	High Water Months	Annual Precipitation, mm	Mean Annual Air Temperature, °C
Oka—Gorbatov	244,000	42.1	April–May	605	5.4
Vyatka—Vyatskie polyany	124,000	31.6	April–June	615	2.9
Belaya—Birsk	121,000	27.7	April–May	530	2.1
Kama reservoir	168,000	57.3	April–June	660	1.4
Sura—Poretskoe	50,100	6.9	April	500	6.5
Vetluga—Vetluzhsky	27,500	7.2	April–May	625	3.5
Volga—Staritsa	21,100	5.7	April	610	3.7
Unzha—Makariev	18,500	6.5	April–May	615	3.3

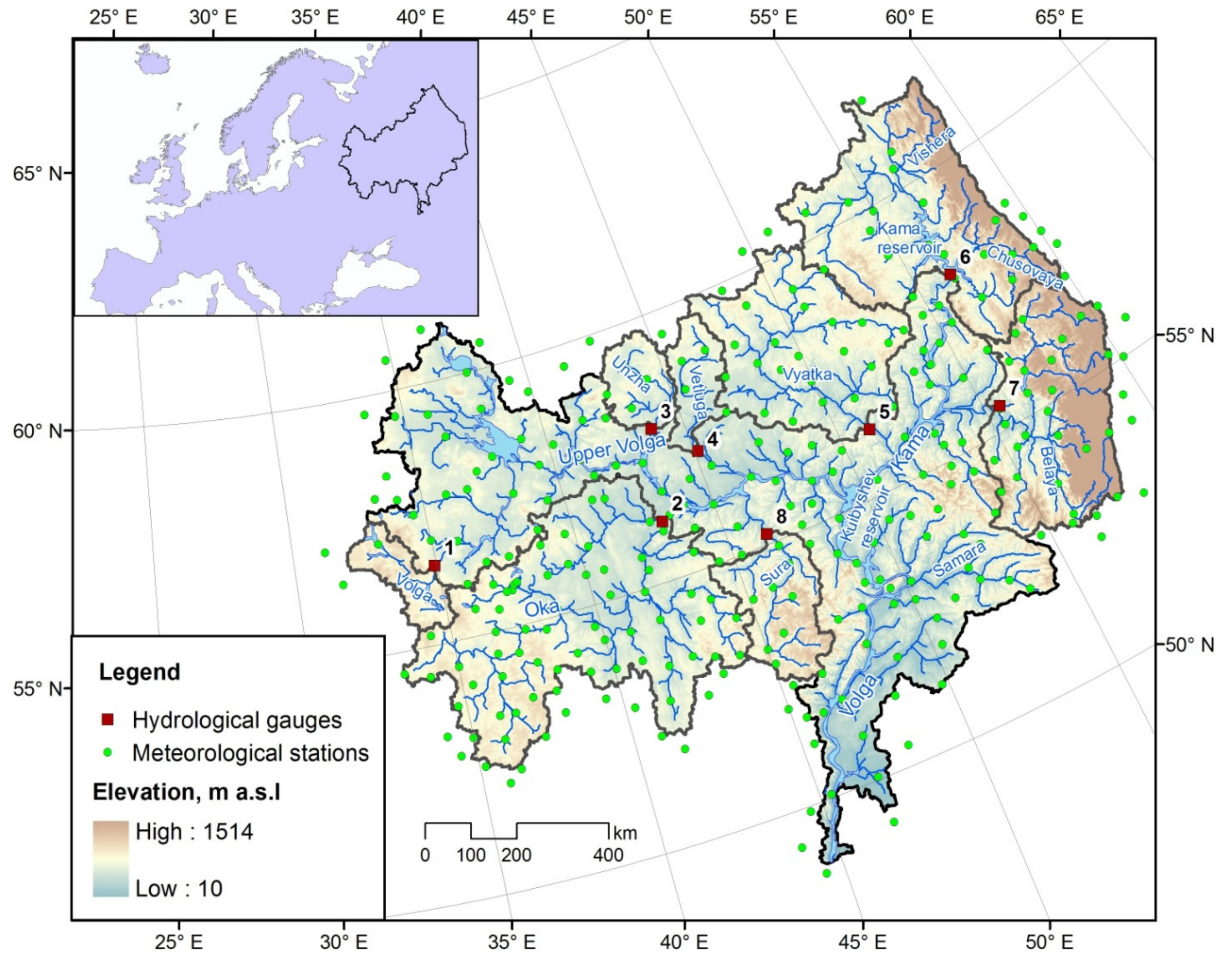

Figure 1. The Volga basin and main rivers whose flow data were used to test the hydrological model: 1—Upper Volga; 2—Oka; 3—Unzha; 4—Vetluga; 5—Vyatka; 6—Kama Reservoir; 7—Belaya; 8—Sura.

The structure of the landscapes, by area of distribution, is dominated by grass crops, cool mixed forest, evergreen forest and fields and narrow conifers. The most widespread soil types in the basin are eutric podzoluvisols, haplic greyzems and luvic chernozems. The Volga flow is regulated by the Volga–Kama cascade of hydroelectric power plants (HPPs) (the largest transport–water–energy system in Europe), which includes 11 HPPs located in the Volga and Kama channels.

2.2. Hydrological Model, Calibration and Validation

A process-based hydrological model [23] developed on the ECOMAG (ECOlogical Model for Applied Geophysics) software [24] was used to study physically based regional water regime changes in the Volga basin. This model makes it possible to calculate the spatial distribution of the processes of snow cover and snowmelt formation; soil freezing and thawing; vertical heat and moisture transport in frozen and unfrozen soil; evapotranspiration; surface, subsurface and groundwater flow; and streamflow transformation in the channel system. Modeling of hydrological processes at each hydrological response units (HRUs) is performed for four levels: the topsoil layer, horizon of caliche, groundwater and prechannel flow. During the cold season, snow cover is added. In the model, the subsurface and groundwater flow is described according to the Darcy equation, and the prechannel and stream flow is described by the kinematic wave equation. The total porosity in the soil aeration zone is divided into capillary and non-capillary zones. Potential evaporation is estimated according to the Dalton method. The snowmelt rate is calculated using the degree-day method. The phase transformation of precipitation depends on the air temperature. The evaporation of solid and liquid phases of snow is estimated using data on the air humidity deficit. Infiltration of rain and melt water into frozen soil is calculated taking into account the effect of ice content in frozen soil on the hydraulic conductivity of the soil. A more detailed mathematical description of the flow generation processes in the ECOMAG model is presented in [24,25].

Basin schematization requires digital elevation model (any detail depending on catchment size and study objectives) and raster data on soil types and landuse/landcover (LULC) types. Each HRU has its own set of soil and LULC types which define the parameters of the model. The input data for the model are average daily air temperature and humidity deficit and precipitation, which can be set either on a regular grid (reanalysis, climate models) or on an irregular grid (meteorological stations).

For more than 10 years, the ECOMAG model has been successfully used to describe hydrological processes and river water regimes in watersheds ranging from several thousands to millions of square kilometers across North America and Eurasia [26–36].

Catchment-scale hydrological models allow one to take into account to a greater extent the diversity of river flow formation mechanisms, the spatial distribution of land surface characteristics (relief, soil, vegetation) and other features of the river basin, which significantly reduces the uncertainty of future water regime calculations [37,38]. When solving extrapolation problems related to future climatic changes, it became necessary to build a detailed physical and mathematical model of runoff generation in the Volga basin both spatially and temporally. In this approach, an important step is to determine the correspondence between the observed annual and seasonal river runoff and those calculated by verified and robust hydrological models, as well as the flow duration curves in different gauges for long periods of averaging meteorological values (20–30 years). If the hydrological model is successfully tested on the basis of historical data, it can be used to study physically based regional changes in the water regime under various physiographic and climatic conditions within the river basin [39].

The development of a hydrological model of the Volga basin is a complex task due to both the high natural variability of flow formation conditions in different parts of the basin and anthropogenic activities in the watershed, especially considering the Volga–Kama cascade of reservoirs. There are several water-balance models for the Volga basin with decadal [40] and monthly [41] computational time steps. However, such models use a simplified description of many hydrological cycle processes. In this regard, the emphasis was placed on building a detailed process-based runoff generation model both in space and in time step, which will allow the efficient calculation of river runoff in different parts of the Volga basin with a single run for the entire catchment.

Schematization of the river basin by dividing it into subbasins (model grid cells) was carried out based on digital elevation model HYDRO1k (data are available online https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-hydro1k (accessed on 3 July 2022)) with spatial resolution of 1 km. A total of 775 subbasins with an average area of 1760 km^2 were constructed. The spatial model parameters depend on the distribution of soil types (filtration characteristics, wilting point, field capacity) and landscapes (snowmelt, soil moisture evaporation and soil freezing coefficients) [29]. Harmonized World Soil Database (HWSD—available online http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12 (accessed on 3 July 2022)) and Global Land Cover Characterization (GLCC—available online https://www.usgs.gov/centers/eros/science/usgs-eros-archive-land-cover-products-global-land-cover-characterization-glcc (accessed on 3 July 2022)) were used for their determination. According to the data, 31 soil types and 38 LULC types correspond to the Volga basin. Each subbasin has its own set of soil types, LULC and elevation. As boundary conditions in the runoff generation model, long-term series of daily air temperature and humidity deficit and precipitation, measured at 306 meteorological stations by the RIHMI-WDC, were used (http://meteo.ru/english/climate/cl_data.php accessed on 3 July 2022).

Due to the flow regulation by the Volga–Kama cascade of reservoirs, long-term data of daily discharge at different gauges were prepared for model calibration and verification: the Upper Volga (gauge Staritsa) and outlet gauges of main tributaries of the Volga and Kama rivers, including the Oka, Belaya, Vyatka, Vetluga, Sura and Unzha rivers, as well as the Kama reservoir catchment (Figure 1). The catchment area of these rivers ranges from 18,500 to 244,000 km^2. The runoff formation model was calibrated using various parameters, among which the main ones were soil moisture evaporation and snowmelt coefficients, horizontal and vertical hydraulic conductivity of soil, critical temperature of precipitation phase definition and snowmelt. At the same time, the method of spatial calibration according to the Nash–Sutcliffe efficiency NSE, Kling–Gupta KGE and systematic error PBIAS, in contrast to calibration for each gauge, allows one to take into account the features of flow formation in different parts of the basin in a single model run. The quality of calculations is better the closer the values of the NSE and KGE are to unity and the closer PBIAS is to zero. Based on the estimates of calculation quality proposed in [42], depending on the combination of NSE, KGE and PBIAS values, it was assumed that the results at $0.70 \leq \text{NSE} \leq 1$, $0.70 \leq \text{KGE} \leq 1$ and $|\text{PBIAS}| \leq 15\%$ can be considered good for calculations of hydrographs and satisfactory at $0.50 \leq \text{NSE} < 0.70$, $0.50 \leq \text{KGE} < 0.70$ and $15\% < |\text{PBIAS}| \leq 25\%$. The model parameters were calibrated for the period from 2000 to 2014. To assess the robustness of the model, its verification was carried out for the period from 1986 to 1999 for the same gauges.

Additional testing of the hydrological model was conducted on climatically contrasting periods according to the procedure proposed in the mid-1980s [43]. For this purpose, an annual precipitation of 585 mm was estimated for the period 1986–2014, with a range for individual years from 450 mm (1996) to 725 mm (1990). The 29 years were then divided into two categories depending on the excess of the above value: a wet period of 14 years (1989, 1990, 1993, 1994, 1997, 1998, 2001, 2004, 2006, 2007, 2008, 2011, 2012, 2013) with an average value of 630 mm and a dry period of 15 years (1986, 1987, 1988, 1991, 1992, 1995, 1996, 1999, 2000, 2002, 2003, 2005, 2009, 2010, 2014) with an average value of 540 mm. This difference is due to the fact that the main part of the Volga basin is a forest zone and a moderate continental climate, which is not characterized by multi-year dry periods.

Taking into account application of flow formation model for hydrological consequences of climate change, additional statistical assessment of effectiveness of river flow calculations at outlet gauges of the Volga, Upper Volga, Oka and Kama rivers was carried out, focused on the reproduction of flow duration curves, average annual and seasonal flow volumes. Due to the availability of the Volga–Kama cascade of reservoirs, difficulties arise with the determination of an outlet gauge for the Volga basin in the modeling of runoff formation. The following numerical experiment was conducted. As model boundary conditions, the eight gauges considered above (river runoff which is equal to 75% of the Volga basin's runoff) observed daily discharges were set, and from the rest of the area of the basin, runoff was calculated according to meteorological data with the same model parameters that were determined for the period of its calibration. Thus, the calculated average daily runoff of the Volga basin in natural conditions for a multi-year period was obtained. Then, this series was compared with the Volga basin's runoff calculated earlier by meteorological data for the entire basin at the Zhiguli HPP with a total catchment area of 1,210,000 km^2, or almost 90% of the Volga basin. Long-term daily observed inflow to the Kuibyshev reservoir for the period of 1986–2014 was about 8000 m^3 s^{-1}, which corresponds to the mean annual flow of the Volga at the Volgograd about 250 km^3 per year. This fact confirms the validity of the above-mentioned approach to the assessment of the Volga basin's runoff. In the same way, the calculation accuracies of the natural runoff of the Upper Volga before the inflow of the Oka (239,000 km^2) and of the Kama before the inflow of the Volga (516,000 km^2) were determined. The outlet gauge for the Oka is Gorbatov (244,000 km^2).

2.3. Hydrological Modeling Using the GCM Output Data for the Historical Period

Using a regional runoff generation model in the Volga basin, the possibilities of reproducing the characteristics of the river water regime over a historical period were investigated when GCMs ensemble data were set as boundary conditions in the hydrological model. Flow regulation by reservoirs located in the Volga basin was not considered in numerical experiments because the response of the natural hydrological system to regional climate changes under global warming by 1.5 °C and 2 °C was investigated. The period 1970–1999 was considered as the baseline historical period. The level of global warming is estimated relative to pre-industrial values. However, due to the lack of observational data for the 19th century and in order to have a modern understanding of water regime change, anomalies of climatic and hydrological characteristics in the Volga basin during the 21st century were estimated relative to the baseline period from 1970 to 1999.

In order to reduce existing uncertainties and increase accuracy and spatial and temporal detailing of climate projections for the Volga basin area, a database of daily meteorological information required for the hydrological model was prepared using GCMs ensemble data of the CMIP5 from the ISIMIP (Inter-Sectoral Impact Model Intercomparison Project). The downscaling to a regular 0.5° grid and bias-correction procedure was performed for the climate model output data using the ERA family reanalysis data [44,45]. The paper [46] presents the results of refining estimates of the hydrological consequences of climate change using different downscaling methods for GCMs data at the scale of large river basins. Two GCMs, GFDL-ESM2M and MIROC5, were chosen as reproducing the global air temperature dynamics over the historical period 1861–2005 most accurately relative to the observational data [47].

First, a comparison was made between the GCMs ensemble calculations and observations at meteorological stations both in the Volga basin as a whole and in its large parts: the Upper Volga, Oka and Kama catchments. The averaged basin climatic norms of the following meteorological variables for the historical period were compared: mean annual and seasonal air temperature, duration of the period with negative air temperature, annual and seasonal precipitation and solid and liquid precipitation. Division by seasons was as follows: winter from November to March, spring from April to May, summer-autumn from June to October.

The spatial accuracy of precipitation and air temperature calculations for subbasins in the Volga basin, calculated from GCMs data for the period 1970–1999, was assessed using the spatial correlation coefficient in comparison with meteorological stations. Then, the series of mean daily meteorological values calculated using GCMs for the period 1970–1999 were set as input data for the runoff formation model in the Volga basin, which was used to calculate river runoff under current climate conditions. The calculated characteristics of the water regime were compared with those obtained earlier as a result of modeling from meteorological station data for the Upper Volga, Oka, Kama and Volga basins as a whole. The following hydrological characteristics were compared for the baseline historical period: annual and seasonal runoff volume, high (Q10—probability of exceeding 10% days per year) and low (Q90—probability of exceeding 90% days per year) flow (according to flow duration curves) and runoff coefficient.

Division of runoff by seasons was as follows: winter low flow from November to March; spring flood in April to May for the Oka and Upper Volga and April to June for the Kama and Volga as a whole; summer–autumn period from June to October for the Oka and Upper Volga and from July to October for the Kama and Volga as a whole. To assess the spatial accuracy of runoff modeling, we compared the distribution of annual runoff depth for subbasins in the Volga basin calculated from GCMs and meteorological station data.

2.4. Hydrological Modeling Using the GCM Output Data for the Future Period

At the next stage, the runoff formation model was applied to study hydrological consequences of global warming in the 21st century by 1.5 °C and 2 °C relative to pre-industrial values in the Volga basin. Projections of global climatic changes according to four RCP scenarios (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5) were used in calculations for the future period until the end of the 21st century. First, the periods for reaching the global warming thresholds of 1.5 °C and 2 °C relative to pre-industrial values were determined for each GCM and RCP. This was performed using global air temperature anomalies on a thirty-year moving average, i.e., 2050 corresponds to an average for the period 2036–2065, for example (Table 2).

Table 2. Years of reaching global warming thresholds of 1.5 °C and 2 °C relative to pre-industrial values for different 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

Then, each of the seven possible trajectories of global warming by 1.5 °C and each of five possible trajectories of global warming by 2 °C relative to the pre-industrial level were set as the boundary conditions in the runoff formation model in the Volga basin. Calculation results were averaged for 1.5 °C and 2 °C thresholds over seven and five sets, respectively. Then, these seven hydrographs were averaged for the global warming by 1.5 °C scenario, and five hydrographs were averaged for the global warming by 2 °C scenario.

The hydrological model calculations for the 21st century were performed with the same parameters that were determined for the historical period. Global warming by 1.5 °C will be achieved by 2045 and 2 °C by 2064. Anomalies of climatic and hydrological characteristics are calculated as the ratio of the value corresponding to the increase in global air temperature by 1.5 °C and 2 °C to the corresponding value determined from GCMs data for the baseline period from 1970 to 1999.

To assess spatial and temporal variability of climatic and hydrological characteristics, maps of mean annual distribution of air temperature and precipitation, as well as runoff depth, were constructed based on the calculations of hydrological model for subbasins in the Volga basin according to GCMs for periods of the 21st century corresponding to global warming by 1.5 °C and 2 °C compared to pre-industrial level. These maps were compared with the average values of hydro-climatic elements from the baseline period of 1970–1999, and the deviations in mean annual air temperature (in degrees), annual precipitation and runoff depth (in percent) were estimated.

3. Results

3.1. Hydrological Modeling

Table 3 shows the results of checking the accuracy of the runoff calculation in different gauges in the Volga basin for the period of model calibration and verification, as well as climatically contrasting conditionally wet and dry periods. The values of the statistical criteria showed the robustness of the hydrological model when transitioning from one calculation period to another [48]. NSE values were equal for wet and dry periods for the four rivers, Vyatka, Upper Kama, Vetluga and Unzha. The NSE values were higher for the dry period by 0.02–0.1 for the Oka, Sura and Upper Volga and lower by 0.02 for the Belaya River. It should be noted that the wet period is generally characterized by overestimation of the mean annual runoff from the model, while the dry period by contrast is characterized by underestimation. However, values of both criteria of correspondence of the observed and calculated daily runoff are good or satisfactory for all gauges in the Volga basin.

Table 3. Model performance of daily runoff in the Volga River basin for the period of model calibration and verification.

№	River—Gauge	NSE	PBIAS, %	NSE	PBIAS, %	NSE	PBIAS, %	NSE	PBIAS, %
		1986–1999		2000–2014		Wet Period		Dry Period	
1	Oka—Gorbatov	0.73	6.4	0.75	−6.6	0.70	8.7	0.78	−9.9
2	Vyatka—Vyatskie polyany	0.84	−3.1	0.89	−1.6	0.86	5.6	0.86	−10.2
3	Belaya—Birsk	0.87	−13	0.86	−12	0.87	−9.1	0.85	−15.8
4	Kama reservoir	0.94	−7.1	0.93	−3.8	0.93	−2.5	0.93	−8.5
5	Sura—Poretskoe	0.51	9.8	0.59	−15	0.53	2.4	0.63	−11.8
6	Vetluga—Vetluzhsky	0.86	1	0.87	5.7	0.86	8.5	0.86	−2.6
7	Volga—Staritsa	0.66	12	0.67	3.7	0.65	9.9	0.67	5.1
8	Unzha—Makariev	0.74	−0.5	0.72	1	0.73	5.6	0.73	−5.3

The correlation coefficient between the observed and simulated annual water inflow into the Kuibyshev reservoir for the period of 1986–2014 was 0.89 with a PBIAS about 2%. At the same time, the error in calculating the total long-term runoff for the period of 1986–2014 at the eight gauges of the Volga basin was less than 4%. The results of the experiment to calculate the natural flow of the Upper Volga, Kama and Volga as a whole for the period 1986–2014 showed the following results: for the Upper Volga, the NSE was 0.99 and the PBIAS was 1%; for Kama, the NSE was 0.96 and the PBIAS was −5%; and for Volga, the NSE was 0.97 and the PBIAS was −3% (Figure 2).

3.2. Hydrological Modeling Using the GCM Output Data for the Historical Period

In the Volga basin, the GCMs reproduced averaged-basin mean monthly air temperature and precipitation with high accuracy relative to observations from 1970 to 1999 (Figure 3). The error in the determination of the mean annual air temperature was 0.3–0.5 °C (Table 4), with the smallest error values noted for winter (up to 0.1 °C) and the largest error noted for summer–autumn (up to 1 °C). The error of calculation of the duration of the period with negative air temperature does not exceed seven days. The error in the determination of the annual precipitation was up to 2%; for seasonal precipitation up to 5%; for solid precipitation 2–9%, with the highest value for the Oka basin; and for liquid precipitation up to 2%. The spatial correlation coefficient of the mean annual air temperature between calculations from GCMs and observational data in the Volga basin was 0.97, and for annual precipitation it was 0.90.

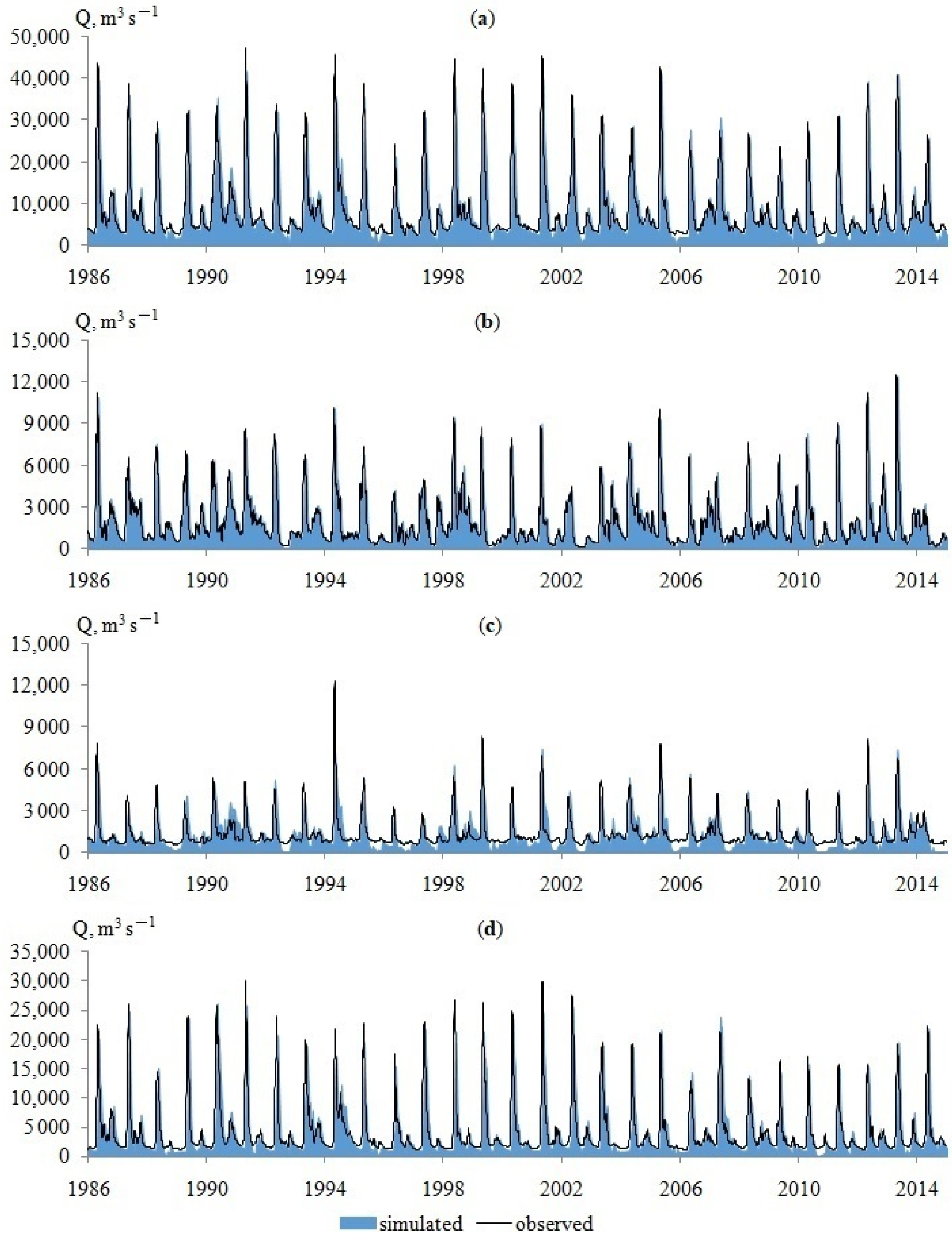

Figure 2. Hydrographs of calculated and observed daily discharges at outlet gauges of the Volga (**a**), Upper Volga (**b**), Oka (**c**) and Kama (**d**) rivers.

The hydrological model based on GCMs data reproduces the annual runoff of the Volga, Oka, Upper Volga and Kama rivers with an error of 1.5–6% relative to calculations based on meteorological station data for the period from 1970 to1999 (Table 5). The greatest relative calculation errors are typical for the winter flow (up to 17% in the Upper Volga), and the least ones are typical for the spring flood (up to 6%) (Figure 4). The assessment of the calculation of the high (Q_{10}) and low (Q_{90}) daily flows according to GCMs data noted an error for high flow of 1–5% and for low flow of 5–28%, which is explained by the small absolute values of the winter flow. The runoff coefficient of the rivers is reproduced quite effectively, and the error does not exceed 0.01.

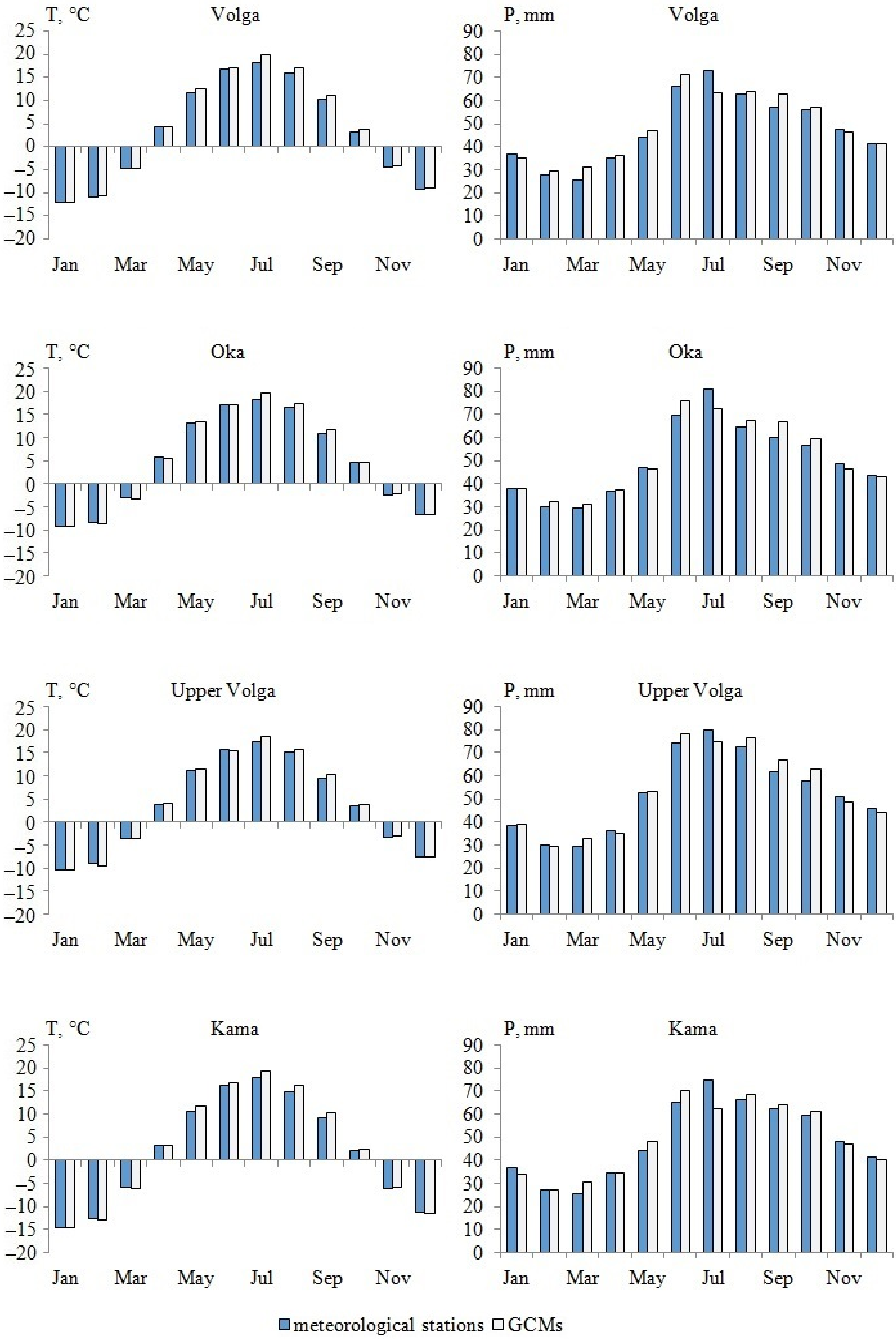

Figure 3. Averaged basin mean monthly air temperature and precipitation calculated from observational data and GCMs ensemble for the Volga, Oka, Upper Volga and Kama basins for the period 1970–1999.

Table 4. Averaged basin mean monthly air temperature and precipitation calculated from observational data for the Volga, Oka, Upper Volga and Kama basins and errors according to the GCMs ensemble data (in parentheses) for the period 1970–1999.

Parameter	Volga	Oka	Upper Volga	Kama
Mean annual air temperature, °C	3.4 (0.5)	4.7 (0.3)	3.6 (0.3)	2 (0.4)
Mean winter air temperature, °C	−8.2 (0.1)	−6 (−0.1)	−6.7 (−0.1)	−10.1 (−0.1)
Mean spring air temperature, °C	8.1 (0.4)	9.4 (0.1)	7.5 (0.2)	6.9 (0.5)
Mean summer-autumn air temperature, °C	12.8 (0.9)	13.4 (0.7)	12.2 (0.6)	12 (1)
Duration of the period with negative air temperature, day	151 (−1)	131 (7)	138 (5)	162 (−2)
Annual precipitation, mm	573 (2%)	605 (2%)	629 (2%)	586 (1%)
Winter precipitation, mm	179 (3%)	190 (1%)	195 (−1%)	179 (1%)
Spring precipitation, mm	79 (6%)	84 (−1%)	89 (−1%)	79 (5%)
Summer-autumn precipitation, mm	315 (1%)	331 (3%)	345 (4%)	328 (−1%)
Solid precipitation, mm	172 (2%)	149 (9%)	163 (4%)	190 (−3%)
Liquid precipitation, mm	401 (2%)	456 (1%)	466 (1%)	396 (2%)

Table 5. Water regime characteristics of the Upper Volga, Oka, Kama and Volga rivers, calculated from meteorological stations data and errors according to the GCMs ensemble data (in parentheses) for the period 1970–1999.

Parameter	Volga	Oka	Upper Volga	Kama
Annual runoff, km^3	262 (4%)	44.9 (5.9%)	62.3 (5.3%)	123 (1.5%)
Winter runoff, km^3	60.4 (9.5%)	14 (6.9%)	16.4 (17%)	22.1 (6.9%)
Spring flood runoff, km^3	140.2 (0.4%)	17.3 (−2.1%)	25.4 (−6.5%)	71.4 (−0.2%)
Summer–autumn runoff, km^3	61.4 (7.2%)	13.6 (15%)	20.5 (11%)	29.5 (1.5%)
Q_{10}, $m^3\ s^{-1}$	20500 (−0.8%)	4600 (−4.7%)	3090 (1.4%)	10500 (−1.2%)
Q_{90}, $m^3\ s^{-1}$	2590 (27%)	540 (28%)	450 (20%)	960 (5.1%)
Runoff coefficient	0.38 (0.01)	0.30 (0.01)	0.41 (0.01)	0.41 (0)

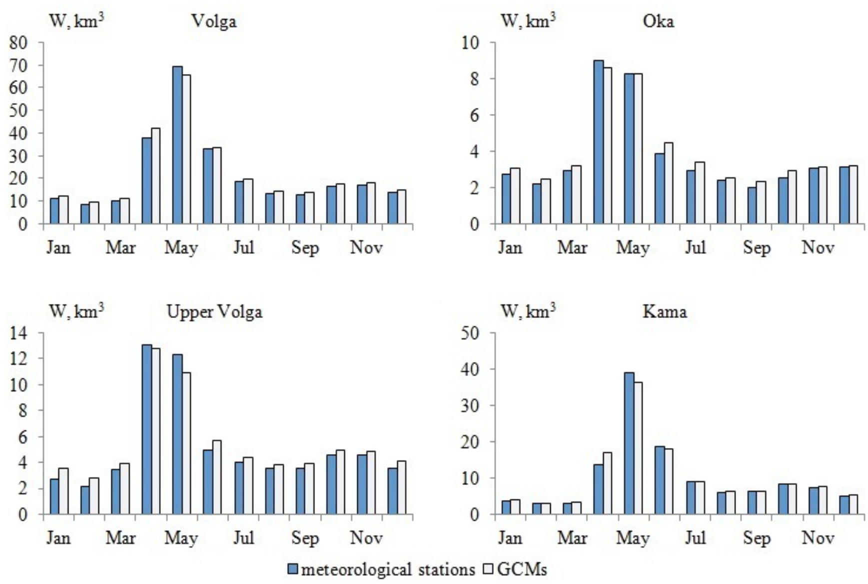

Figure 4. Mean monthly runoff of the Volga, Oka, Upper Volga and Kama rivers calculated using a hydrological model based on GCMs ensemble and meteorological stations data for the period 1970–1999.

Spatial correlation coefficient of annual runoff depth between modeling based on GCMs ensemble and meteorological stations data for the Volga basin was 0.96. Thus, in general, the GCMs ensemble reproduces the regional features of the atmospheric circulation in the Volga basin and the water regime of rivers calculated by the runoff generation model.

3.3. Hydrological Modeling Using the GCM Output Data for the Future Period

Furthermore, according to the results of climate-driven changes in hydrological characteristics in the Volga basin, the increase in the mean annual air temperature in the Volga basin will be 2.5 °C under global warming by 1.5 °C. The highest warming rate was noted for the Upper Volga by 2.8 °C relative to the baseline period of 1970 to 1999 (Figure 5). Global warming by 2 °C leads to a 3.4 °C increase in the mean annual air temperature in the Volga basin, 3.7 °C in the Oka and Upper Volga basins and 3.3 °C in the Kama basin. The highest warming values correspond to the spring period, the lowest to the summer-autumn period.

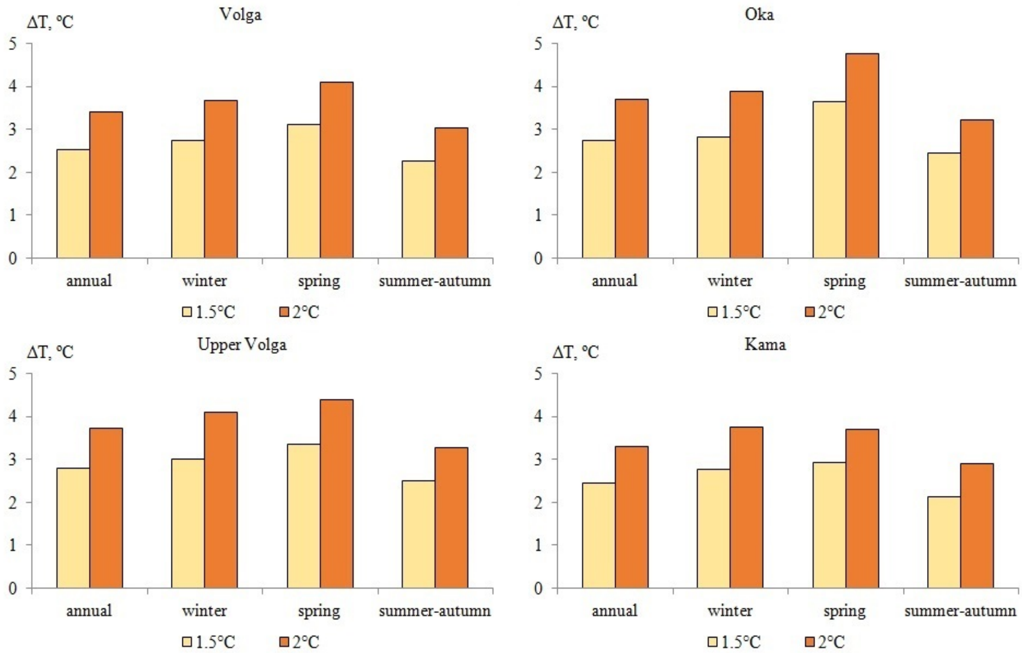

Figure 5. Anomalies of mean annual and seasonal air temperature in the Volga basin under global warming by 1.5 °C and 2 °C degrees in the 21st century relative to the baseline period 1970–1999.

The increase in annual precipitation in the Volga basin was 8% under global warming by 1.5 °C, and the increase in precipitation varies from 10% in the Oka basin to 13% in the Kama basin under global warming by 2 °C, with the average value of 11% in the Volga basin (Figure 6). The relative increase in winter precipitation in the Volga basin was 13% and 18% under global warming by 1.5 °C and 2 °C, respectively; spring precipitation increased by 4% and 11%, respectively; and summer and autumn precipitation increased by 6% to 7%. Winter precipitation in the Upper Volga will increase by 2% more and in the Oka by 2% less relative to the average value in the Volga basin. The most intense increase in precipitation is characteristic of the Kama basin by 9% and 18%, depending on the warming scenario.

The duration of the period with negative air temperature will decrease by 15–20 days in the Kama basin, by 20–30 days in the Upper Volga and Oka basins and by 18 and 24 days on average in the Volga basin under global warming by 1.5 °C and 2 °C, respectively (Figure 7). At the same time, solid precipitation in the Volga basin will not change, though it will decrease by 4% and 7% in the Upper Volga and Oka, respectively, under global warming by 2 °C, and increases by 3% in the Kama basin. Liquid precipitation in the Volga basin increases relatively uniformly by 11% and 16% under global warming by 1.5 °C and 2 °C, respectively.

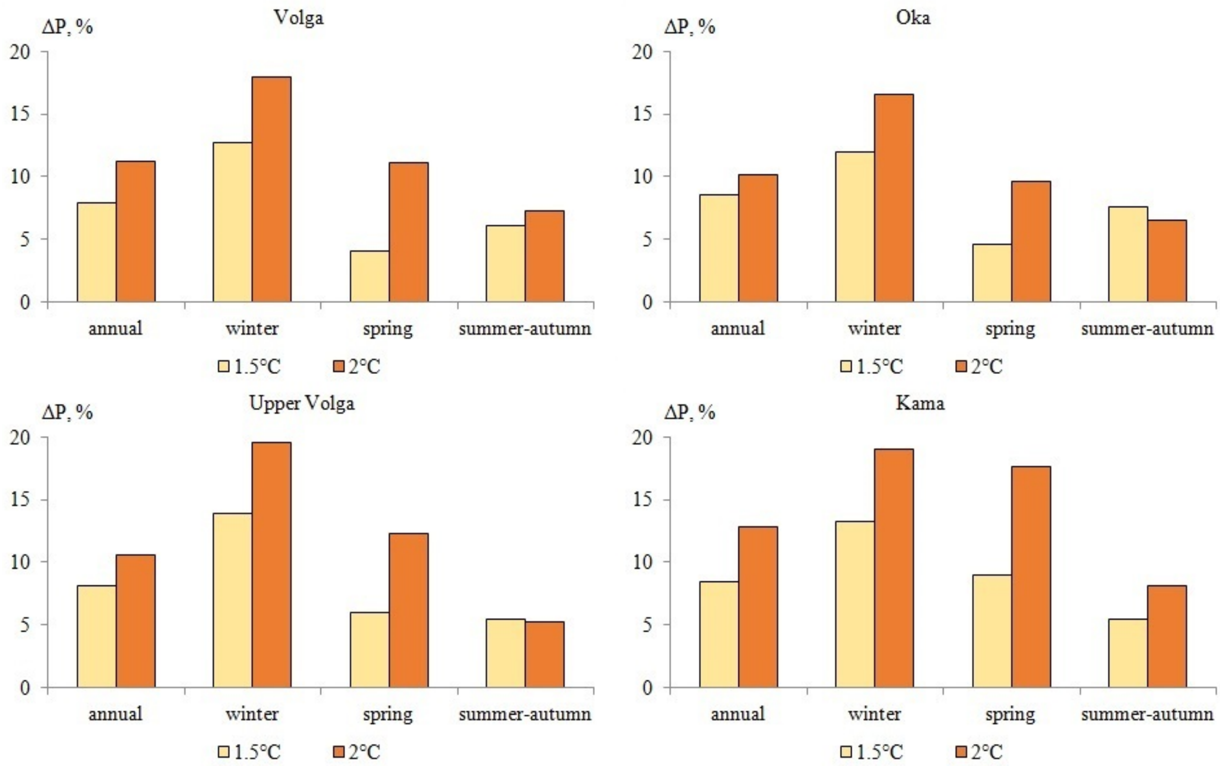

Figure 6. Anomalies of mean annual and seasonal precipitation in the Volga basin under global warming by 1.5 °C and 2 °C in the 21st century relative to the baseline period 1970–1999.

According to the 1.5 °C global warming scenario, the most intensive increase in mean annual air temperature up to 3 °C corresponds to the Upper Volga, and the lowest increase by 2.2–2.4 °C corresponds to the Kama reservoir watershed, upstream of the Ufa and Belaya rivers (Figure 8). The 2 °C global warming scenario in the Volga basin shows a similar distribution of air temperature increase anomalies, with uniformly higher warming rates relative to the 1.5 °C scenario. Only the Oka basin will be added to the territory of the Upper Volga with the largest increase in air temperature.

According to the 1.5 °C global warming scenario, an increase in annual precipitation by 5–10% is observed for most parts of the Volga basin, and an excess of up to 12% is observed for the Vishera, Chusovaya, Upper Oka, Ufa and Belaya rivers (Figure 9). According to the 2 °C global warming scenario, and increase in precipitation by 10–15% is typical for the Kama, Samara, Oka and Upper Volga basins, and the values above 15% correspond to the Vishera, Chusovaya and upstream of the Ufa and Belaya rivers. For the rest of the Volga basin, the increase in precipitation is mainly 5 to 10%.

Assessment of flow anomalies of the Volga River and its main tributaries under global warming of 1.5 °C and 2 °C showed the following general features: increase in winter flow, decrease in spring flood and summer–autumn flow and, as a result, a decrease in the annual flow. The decrease in the annual runoff of the Volga amounted to 10–11% under both warming scenarios relative to the period 1970 to 1999 (Figure 10). The greatest relative decrease in runoff by 17–20% was observed for the Oka and Upper Volga, while for the Kama, only by 1–5%. The Volga winter runoff increased by 17% and 28% under global warming by 1.5 °C and 2 °C respectively, and negative anomalies of spring flood and summer–autumn runoff were in the range of 21 to 23%. The most intensive increase in winter runoff by 30–40% was typical for the Upper Volga and the least intensive by 12–20% for the Oka, depending on the rate of global warming. The largest relative decrease in runoff during spring flood and summer–autumn was observed in the Upper Volga (about 40%), and the smallest decrease was in the Kama by 10% and 8% under global warming by 1.5 °C and 2 °C, respectively.

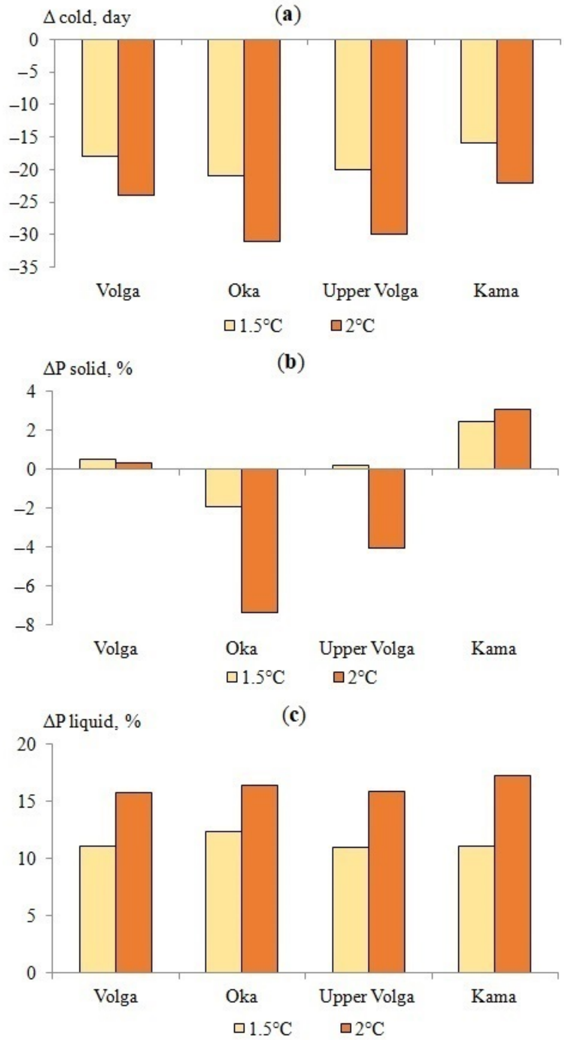

Figure 7. Anomalies of duration of the period with negative air temperature (**a**), solid (**b**) and liquid (**c**) precipitation in the Volga basin under global warming by 1.5 °C and 2 °C in the 21st century relative to the baseline period 1970–1999.

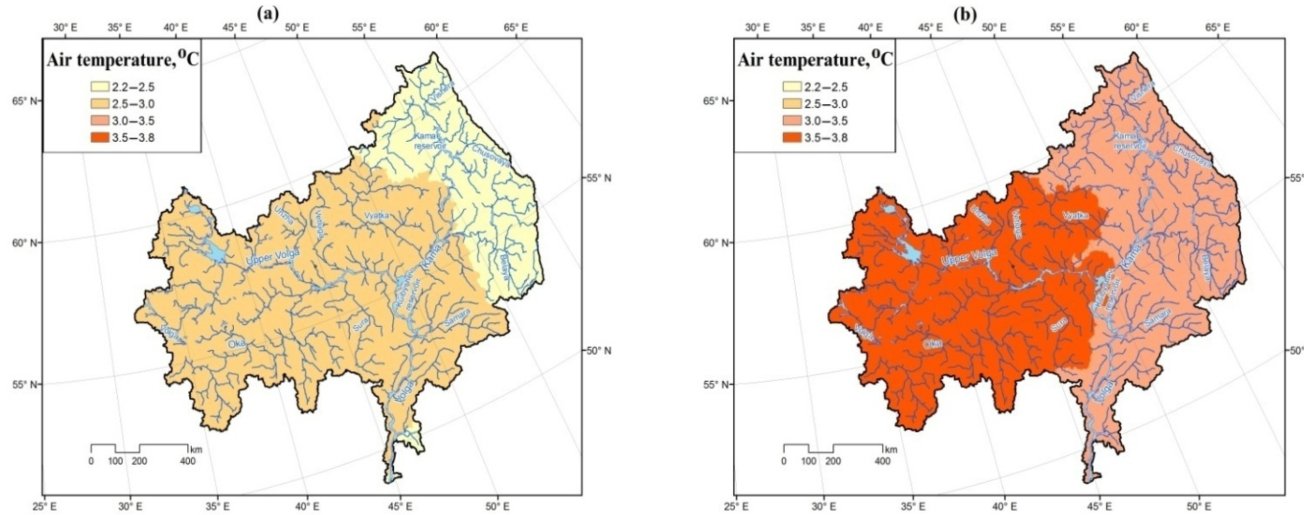

Figure 8. Anomalies of mean annual air temperature in the Volga basin under global warming of 1.5 °C (**a**) and 2 °C (**b**) in the 21st century relative to the average values of the baseline period 1970–1999.

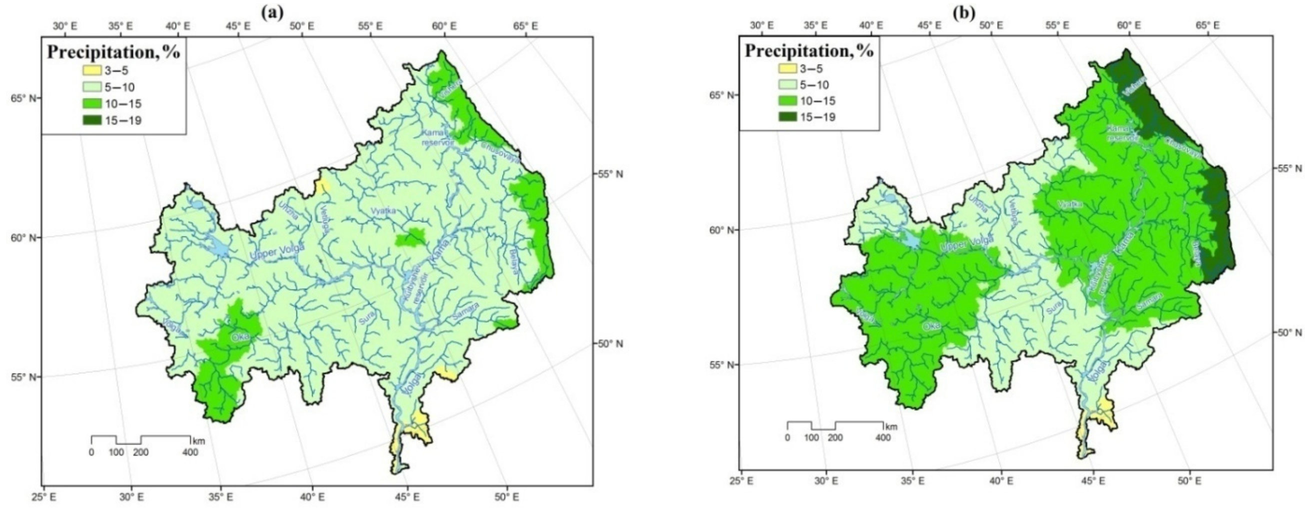

Figure 9. Anomalies of annual precipitation in the Volga basin under global warming by 1.5 °C (**a**) and 2 °C (**b**) in the 21st century relative to the average values of the baseline period 1970–1999.

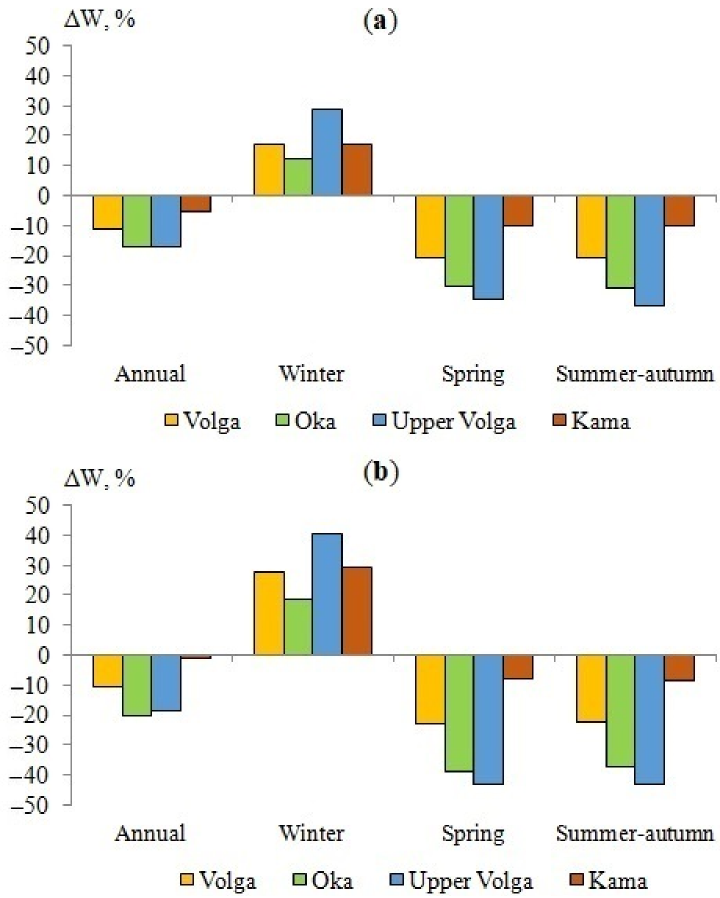

Figure 10. Anomalies of annual and seasonal runoff of the Volga, Oka, Upper Volga and Kama under global warming by 1.5 °C (**a**) and 2 °C (**b**) in the 21st century relative to the baseline period 1970–1999.

The preservation of the tendency of intra-annual runoff equalization in the Volga basin will contribute to a more effective use of water resources when regulating runoff by HPPs in the interests of water users and power generation. Global warming by 1.5 °C and 2 °C will lead to a decrease in the runoff coefficient of the Volga by 0.07–0.08, of the Upper Volga by 0.1–0.12, of the Kama by 0.05 and of the Oka by 0.07 to 0.08. This indicates that despite the increase in precipitation, the role of evaporation in the water balance of the Volga basin will only increase.

The described anomalies of seasonal runoff redistribution will lead to decreases in the high flow (Q_{10}) of the Volga by 18%, the Oka and Upper Volga by 30% and the Kama by 7–9% under both global warming scenarios (Figure 11). At the same time, the low flow (Q_{90}) of the Volga will increase by 14–15%, mainly due to the growth of the Kama's flow by 38 to 42%.

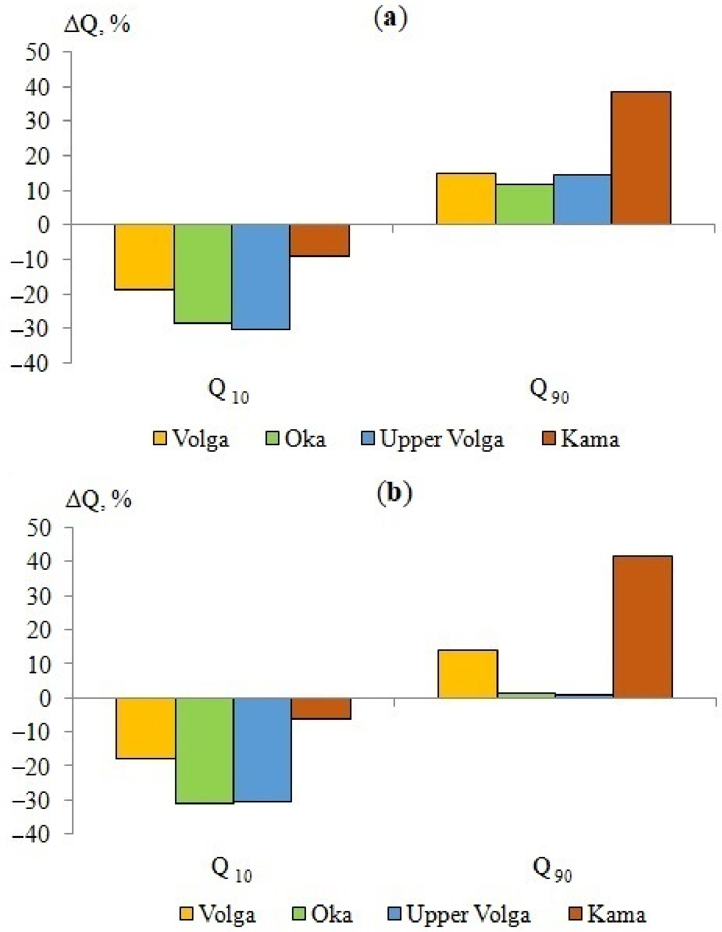

Figure 11. Anomalies of high (Q_{10}) and low (Q_{90}) flow of the Volga, Oka, Upper Volga and Kama rivers under global warming by 1.5 °C (**a**) and 2 °C (**b**) in the 21st century relative to the baseline period 1970–1999.

According to the scenario of global warming by 1.5 °C, negative anomalies of 10–20% in the annual runoff depth are observed for most of the Volga basin up to the Kama river mouth; in the Kama basin, these anomalies are mainly up to 10%. The highest values (up to 40%) are attributed to the Middle and Lower Oka (Figure 12). The increase in the runoff depth by up to 10% is characteristic of the Samara River and the mountainous parts of the Vishera, Chusovaya, Ufa and Belaya catchments. According to the scenario of global warming by 2 °C compared to 1.5 °C in the Volga basin, a similar distribution of runoff depth changes with increasing contrast of anomalies is observed. Thus, the area with positive flow anomalies increases, including almost the entire catchment area of the Kama reservoir and most of the Belaya River basin.

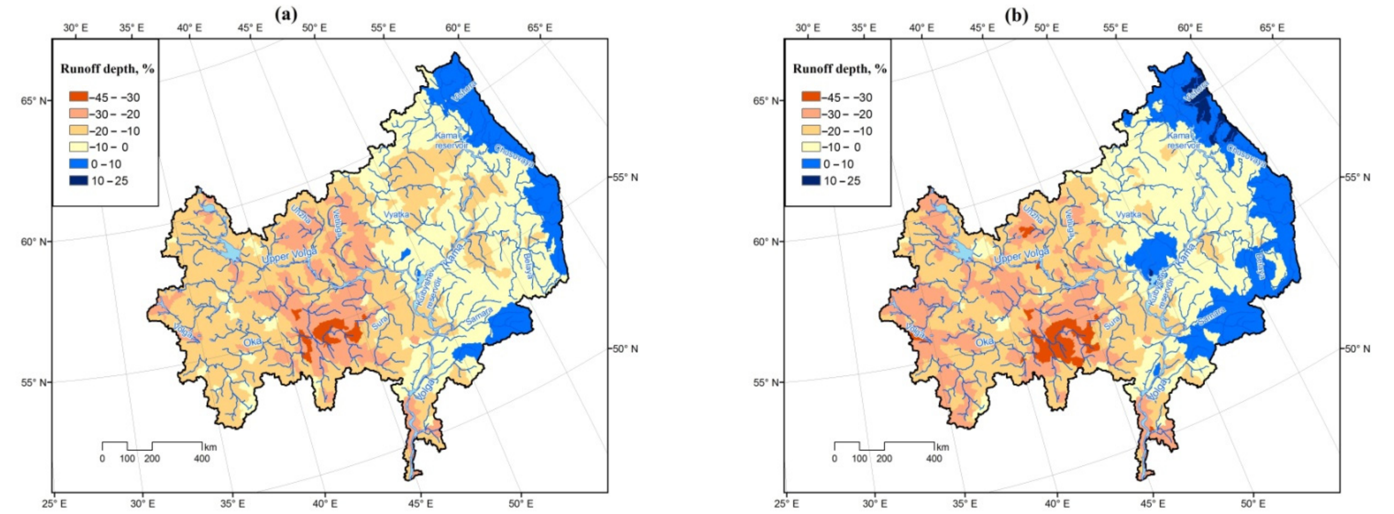

Figure 12. Anomalies of the annual runoff depth in the Volga basin under global warming by 1.5 °C (**a**) and 2 °C (**b**) in the 21st century relative to the average values of the baseline period 1970–1999.

4. Discussion

The obtained results of changes in water regime of rivers in the Volga basin under global warming by 1.5 °C and 2 °C can be compared with the results of runoff calculations only according to GCMs and using hydrological models. GCMs acceptably reproduce the Volga annual runoff [14,15,49] but reproduce its intra-annual variations with large errors. This is due to the fact that global hydrological models are characterized by simplified parameterization of land hydrological cycle processes and do not take into account regional peculiarities of river flow formation. Under such an approach, the seasonal runoff associated with snow accumulation and snowmelt processes in the watershed and the flow travel time is reproduced with significant errors. In addition, the spatial resolution of climate models creates problems for assessing the hydrological consequences of climate change in different parts of the river basin. Given the huge size of the Volga basin and high runoff from spring meltwater, it is not possible to effectively calculate changes in future seasonal runoff using only data from GCMs [50]. According to [15], possible changes in the Volga annual runoff vary from −5% to 10%, depending on the 21st century period and RCPs, or equal to −5% [14] and 5% [49] by the end of the 21st century. One of the arguments explaining the inaccuracies in the calculation of annual runoff from precipitation and evaporation data is that the correlation coefficient of the Volga annual runoff and annual precipitation does not exceed 0.3 to 0.4 [51].

The water-balance hydrological model was applied to estimate possible changes in river runoff in the Volga basin [52] in the first third of the 21st century. It was shown that there will be a possible increase in annual runoff by 5–10% depending on the RCPs. According to [52], based on STREAM conceptual model calculations and GCMs data, the Volga runoff will increase in the 21st century by about 7%. According to CMIP5 ensemble data and hydrological model TOPMODEL, the runoff will increase by 14% in the Kama basin under RCP8.5 by the mid-21st century, and in the rest of the Volga basin, the change in runoff will not exceed 5% in the nearest 40 years [15]. Research [53] using a regional climate model [54] and a simplified CaMa-Flood hydrodynamic model [55] presents estimates of possible changes in the maximum flow of the Volga basin rivers in the 21st century. According to the RCP8.5 scenario, a 10–30% decrease in maximum flow during snowmelt is possible by the mid-21st century. Thus, the results of our study are generally similar and turned out to be in the range of 10–30% decrease in high flow (Q_{10}) in different parts of the Volga basin.

Assessments of climate change impact on the water regime of large rivers were based on regional, spatially distributed, process-based runoff generation models, whose inputs are given by GCMs ensemble (e.g., [56,57]). The results of the international project ISIMIP for river basins located in different continents and physiographic conditions show that regional hydrological models successfully tested with observational data [39,48] can significantly reduce the uncertainty of estimates of current and future changes in the water regime of rivers compared to runoff calculations from global hydrological models or GCMs [58,59]. Thus, the results of calculations of annual runoff changes based on the ECOMAG model allowed for refining the estimates obtained from GCMs or conceptual and water-balance hydrological models, showing a greater decrease in the Volga basin's runoff by 10 to 11%. The main advantage of this spatially distributed, process-based hydrological model is the possibility of physical calculations of future changes in seasonal river runoff, which, under current climatic conditions, is significantly transformed in different parts of the Volga basin.

According to [60], the decrease in the Volga basin's runoff by 12% for the period after the construction of the Volga–Kama cascade of HPPs until the late 1980s relative to the period of natural flow is two-thirds explained by climatic changes and by one-third by anthropogenic factors (evaporation from reservoirs). Despite significant changes in the intra-annual runoff of the Volga basin rivers [61], the last 40 years can be characterized as a period of relatively stable annual runoff in the Volga basin, with alternating periods of high or low flow for several years.

According to our results, an increase in the mean annual air temperature in the Volga basin will exceed the global rate by 1 °C in case of global warming by 1.5 °C and by 1.4 °C in case of global warming by 2 °C. The increase in global air temperature from 1.5 °C to 2 °C leads to the effect of additional warming in the Volga basin by 0.8–1.1 °C, depending on season and part of catchment, and an additional increase in annual precipitation by 3%. The largest additional increase was noted for spring precipitation by 7%, for winter precipitation by 5% and was close to zero for the summer–autumn period. This increase in winter and spring precipitation was due to an increase in liquid precipitation. Thus, the current trend of increasing liquid precipitation in the Volga basin [11] will continue in the 21st century. The growth of global air temperature from 1.5 °C to 2 °C leads to the effect of reducing the duration of the period of year with negative air temperature will decrease by a week.

The assessment of flow anomalies of the Volga and its main tributaries under global warming by 1.5 °C and 2 °C showed the following general features: an increase in winter flow and a decrease in the flow during the spring flood and summer–autumn periods, i.e., continuation of changes in the water regime typical since 1980s [8]. The Oka and Upper Volga runoff decreases by 17–20%, while the Kama runoff remains almost unchanged. Note that, in general, the Volga basin's annual runoff is almost unaffected by global warming from 1.5 °C to 2 °C due to the compensation of precipitation increase by evaporation. At the same time, the additional increase in the Volga basin's winter runoff was 11% and was close to zero for the runoff during the spring flood and summer–autumn periods. These estimates of future changes in the water regime of the Volga basin have lower uncertainty compared to runoff calculations based on GCMs or simplified hydrological models. This is explained by the successful testing of the developed runoff generation model based on the ECOMAG for robustness in transition from one calculation period to another using observational data [62].

The Volga runoff under global warming by 1.5 °C and 2 °C will return approximately to the value of natural runoff before the construction of the Volga–Kama cascade of HPPs considering the predicted 10–11% decrease in runoff, but there will be a significant intra-annual transformation of the water regime. Previously, mechanisms have been analyzed for an 18–22% decrease in the Oka River runoff by the end of the 21st century due to a decrease in surface flow during the warm season and in the groundwater flow during the spring snowmelt [63]. Such processes will be likely for the main part of the Volga basin. In general, the seasonal variability in river runoff in the Volga basin will be associated with an increase in winter runoff due to thaws, earlier and lower spring floods, the transformation of spring runoff into winter runoff and a decrease in runoff during the summer–autumn period. Given the current process of natural flow regulation of the Volga basin rivers [11] and its predicted intensification in the future, there is already a need to adapt the current rules of flow regulation of the Volga–Kama cascade of HPPs [64].

Such significant changes in the annual and seasonal river flow of the Volga basin, of course, will generally have a negative impact on the generation of electricity by the Volga–Kama cascade of HPPs under the current rules for the use of water resources. Against the background of the downward trend in the annual runoff, a decrease in the average annual electricity generation can also be expected. On the one hand, a positive moment will be an increase in electricity generation in winter, when the economy and the population need large capacities, and a decrease in the likelihood of flooding of residential areas under melt water from spring floods. On the other hand, when implementing the simulated flow change scenarios, the solution to possible negative problems with flow regulation and low water levels of reservoirs in the summer–autumn period, causing difficulties in navigation and the self-cleaning capacity of rivers, should be the adaptation of existing reservoir operation curves to predicted climate changes.

5. Conclusions

The results of the spatial (for different gauges) testing of the hydrological model, both for different multi-year calendar and climatic contrast periods, as well as calculation of the total Volga flow, allow us to conclude that the developed model satisfactorily reproduces the daily, seasonal and annual runoff of the main rivers of the basin.

The increase in the mean annual air temperature in the Volga basin will be 2.5 °C under global warming by 1.5 °C. Global warming by 2 °C leads to a 3.4 °C increase in mean annual air temperature in the Volga basin. The highest warming values correspond to the spring period, the lowest to the summer–autumn period. The increase in annual precipitation in the Volga basin was 8% under global warming by 1.5 °C, and the increase in precipitation varies from 10% in the Oka basin to 13% in the Kama basin under global warming by 2 °C, with the average value of 11% in the Volga basin. The increase in winter precipitation in the Volga basin was 13% and 18% under global warming by 1.5 and 2 °C, respectively; spring precipitation increased by 4% and 11%; and summer and autumn precipitation increased by 6–7%.

Decrease in the annual runoff of the Volga amounted to 10–11% under both warming scenarios relative to the period from 1970 to 1999. The greatest relative decrease in runoff by 17–20% was observed for the Oka and Upper Volga rivers, while for the Kama, the decrease is only by 1 to 5%. The Volga winter runoff increased by 17% and 28% under global warming by 1.5 °C and 2 °C, respectively, and negative anomalies of spring flood and summer–autumn runoff were in the range of 21 to 23%. The most intensive increase in winter runoff by 30–40% was typical for the Upper Volga and the least intensive by 12–20% was typical for the Oka, depending on the rate of global warming. The largest relative decrease in runoff during spring flood and summer–autumn was observed in the Upper Volga (about 40%), and the smallest decrease was in the Kama by 10% and 8% under global warming by 1.5 °C and 2 °C, respectively. Global warming by 1.5 °C and 2 °C will lead to a decrease in the runoff coefficient of the Volga by 0.07 to 0.08. This indicates that despite the increase in precipitation, the role of evaporation in the water balance of the Volga basin will increase.

One of the directions of further development of studies of climate-driven changes in river runoff should be the analysis of the factors of its formation. The application of spatially distributed physical and mathematical models of runoff generation allows researchers to determine the contribution of processes of the hydrological cycle such as snow cover and snowmelt formation, soil freezing and thawing, evaporation, infiltration influencing the dynamics of soil moisture, subsurface runoff, etc. In particular, summer soil moisture in the Volga basin is expected to decrease by 20–40 mm [65] in the 21st century, and the spring snow water equivalent is expected to decrease by 20–30% under global warming by 1.5 °C [66]. These estimates indirectly confirm the results of calculating the change in future intra-annual flow of the Volga River presented in our study.

Another direction of refinement of the obtained results of the global warming impact on water regime changes in the Volga basin could be the use of meteorological data from the CMIP6 project and projections of vegetation and land use dynamics during the 21st century [67], which include changes of the area by different agricultural crops or urban landscapes [68].

A third direction to better understand climate change processes could be to separately account for the effects of natural and anthropogenic climate variability on streamflow (e.g., [69]). It is important to clarify the attribution of climatic causes of current and future changes in river runoff using hydrological models, which can have both natural and anthropogenic origins.

Based on the results of future flow changes presented in our study, it is recommended to adapt existing reservoir operation curves of large HPPs in the Volga basin to projected climate changes. At the same time, it is important to assess possible changes in river flow at the regional scale of decision making on the management of water systems, mitigation of flood risk and water scarcity [70].

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