RESEARCH PAPER

CHANGES IN ANNUAL RIVER FLOW IN THE VOLGA–KAMA AND ANGARA–YENISEI RESERVOIR BASINS UNDER CONTEMPORARY AND SCENARIO GLOBAL WARMING

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ABSTRACT. The paper presents a study of annual runoff and water availability changes in the Volga–Kama and Angara–Yenisei reservoir basins under contemporary and mid-21st century scenario global anthropogenic warming. The estimates of changes are based on a comparison of runoff under global warming and for the reference period, calculated from observational data and averaged results of its calculation performed with an ensemble of global climate models. During the period of contemporary global warming, the average long-term annual runoff and water availability per unit area and per capita increased, especially in the Volga–Kama reservoir basins, with the exception of the Volgograd reservoir basin, where they decreased sharply. The observed and average model annual runoff in the considered reservoir basins is closely correlated for contemporary global warming as well as for baseline periods. However, for a fairly significant number of basins, the model runoff differs significantly from the observed value. The observed and model difference in the runoff of the two compared periods differs significantly in the Volga–Kama as well as in Angara–Yenisei reservoir basins. Nevertheless, the sign of the difference is the same in almost all basins. In 2040–2069 the annual runoff under varying intensity warming scenarios may increase relative to the model reference period runoff in all reservoir basins of the Angara–Yenisei cascade, whereas in the Volga–Kama reservoir basins the probable runoff changes are likely to have different signs relative to the runoff of the reference period. In most basins the per capita scenario water availability is likely to increase by varying degrees, partly owing to the probable population decline.

KEYWORDS: Volga–Kama and Angara–Yenisei reservoir basins, river runoff, specific water availability, contemporary and scenario global warming, global climate models

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INTRODUCTION

The problem of assessing changes in runoff in reservoir basins in Russia during the period of modern and scenario global warming have received significantly less attention than changes in river basins.

In recent years, results have been published relating to the assessment of changes in runoff formed in reservoir basins during the period of modern global warming and in the baseline period preceding it. Among them, we note the work carried out at the State Hydrological Institute of Roshydromet of the Russian Federation (Georgievskii 2017), in which, based on the summation of observed runoff data and the river analogue method, long-term series of annual and seasonal runoff were obtained for the catchment areas of the main reservoirs of Russia. For the basins of a number of reservoirs, for these purposes, the method of transforming annual hydrographs of daily water discharges was also used, based on a linear model describing the relationship between water discharges at the inlet and outlet of the calculated section of the river, based on the Kalinin–Milyukov method (Kalinin and Milyukov 1958; Georgievskii and Moiseenkov 1994; Shiklomanov et al. 2011; Milyukova et al. 2020; Yang and Kane 2021; Georgiadi et al. 2023, 2024). Runoff in the Irkutsk Reservoir basin has also been estimated using the regression relationship between the average monthly runoff of the Angara and the average monthly water levels of Lake Baikal, reconstructed using the water balance method, for the period after the commissioning of the Irkutsk Reservoir (Sinyukovich et al. 2024).

A number of studies are devoted to the problem of choosing the boundaries of the base period as a basis for obtaining comparable results of calculations of changes in runoff under both modern and scenario global warming conditions (Georgiadi and Kashutina 2014, 2016; Georgiadi and Milyukova 2023), as well as the issue of regional binding of the boundaries of the base period and the period of modern global warming (Georgiadi and Kashutina 2014, 2016; Frolova et al. 2022; Georgiadi and Milyukova 2023; Shpakova and Wang 2023). Studies were carried out on the relationship between the boundaries of these periods and the boundaries of long-term phases of increased/decreased runoff, which are among the main features of its long-term changes (Georgiadi and Milyukova 2023; Georgiadi et al. 2023).

Considerable attention is paid to the issue of assessing the quality of simulation of observed hydroclimatic characteristics in river basins using the data of calculation performed on an ensemble of global climate models (Mokhov et al. 2003; Katsov and Govorkova 2013; Georgievsky and Golovanov 2015, 2019; Hai Guo et al. 2022; Georgiadi et al. 2024).

The main objective of the study was to identify the features of changes in annual river runoff and specific water availability for the population and territory under conditions of modern and scenario global warming in the basins of the main Volga–Kama and Angara–Yenisei reservoirs. The study is based on data on annual river runoff formed in the reservoir basins (the so-called local runoff), calculated on the basis of observations and calculations performed on the ensemble of global climate models of the CMIP6 project. One of the important tasks was to assess the quality of simulation of the observed runoff by global climate models.

MATERIALS AND METHODS

Study objects

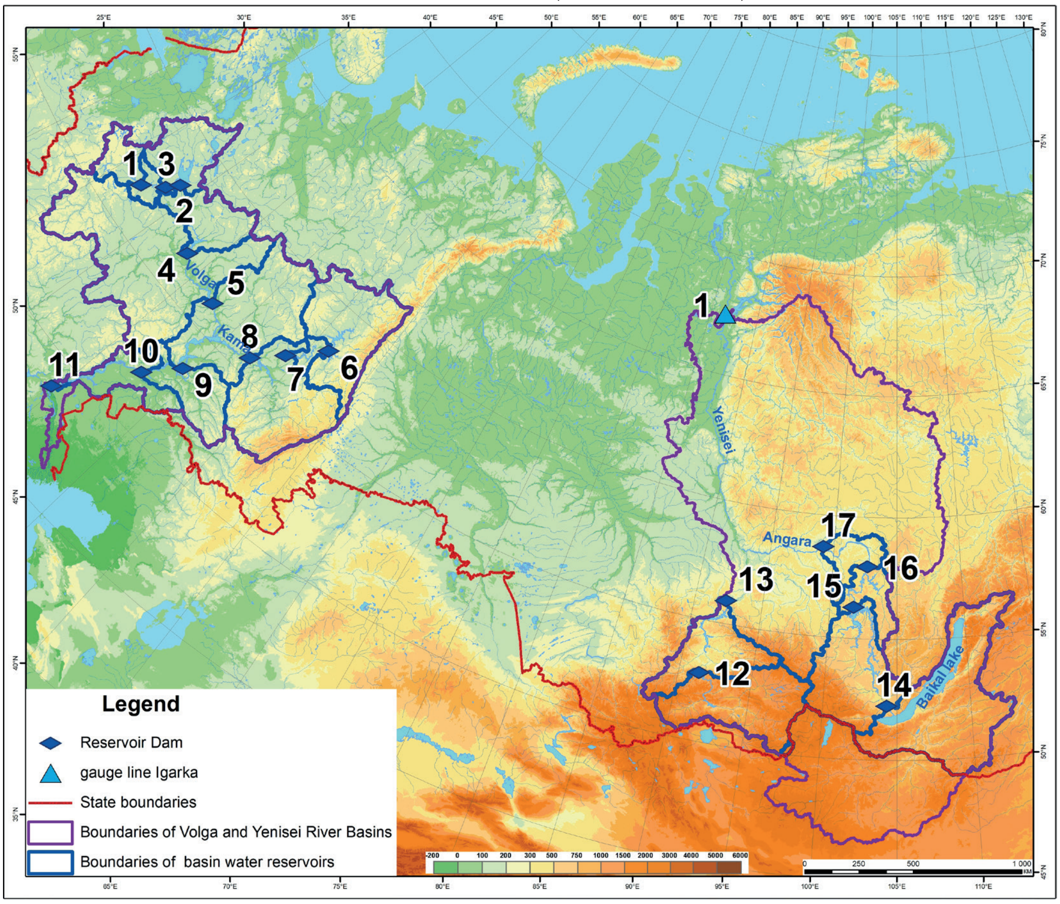
The objects of the study are the local reservoir basins of the Volga–Kama and Angara–Yenisei reservoir cascades, most of which were constructed between the 1950s and 1980s (Fig. 1) (Barabanova 2004). The local reservoir basins are considered, the boundaries of which are limited by the dams of neighboring reservoirs.

According to hydrological zoning (Kuzin 1960; Kuzin and Babkin 1979), in most of the Volga basin, rivers characterized by spring snowmelt floods, rain floods during the warm season, and low-water periods predominate. The ratio of runoff in the main hydrological seasons of the year changes in the sublatitudinal direction, as well as from the west to the east.

At the same time, in the Yenisei and Angara basins, the main source of runoff formation is rain floods, typical for the entire warm period, the volume of which exceeds the volume of snowmelt flood runoff, and in the winter season there is a low runoff, which is formed due to underground recharge. The Angara runoff, especially at its source, is regulated by Lake Baikal.

In recent decades, there have been significant changes in the annual flow of rivers in Northern Eurasia and their intra-annual distribution (Shiklomanov 2008; Georgiadi et al. 2014; Georgievskii 2017; Frolova et al. 2022; Georgiadi et al. 2024).

The flow of the Volga and Kama, Yenisei and Angara rivers, especially before their confluence, is regulated by large reservoirs. The total volume of the main Volga–Kama reservoirs is 168 km^3, and that of the Angara–Yenisei is 393 km^3 (Barabanova 2004).



Ivan'kovo (basin area 41×103 km^2), (2) Uglich (19×103 km^2), (3) Rybinsk (66×103 km^2), (4) Gor'ky (77×103 km^2), (5) Cheboksary (374×103 km^2), (6) Kama (165×103 km^2), (7) Votkinsk (16×103 km^2), (8) Nizhnekamsk (187×103 km^2), (9) Kuibyshev (234×103 km^2), (10) Saratov (78×103 km^2), (11) Volgograd (67×103 km^2), (12), Sayano-Shushenskoe (185×103 km^2), (13) Krasnoyarsk (106×103 km^2), (14) Irkutsk (542×103 km^2), (15) Ust'-Ilimsk (49×103 km^2), (16) Bratsk (158×103 km^2), (17) Boguchany (44×103 km^2)

Fig. 1. Map of catchment areas of the Volga–Kama and Angara–Yenisei reservoirs

DATA

Period of instrumental observations

Annual runoff calculated based on observation data

The study used data on annual runoff formed in reservoir catchment areas, averaged over the period of modern global warming and the baseline period, which are discussed in more detail in the Methods section.

The results of calculations for the period 1946–2013 were used as the source data on the annual flow (inflow to reservoirs), which is formed in their local catchment areas. They are based on the runoff summation method for rivers flowing into reservoirs and the river analogue method (Georgievskii 2017). In this approach, for a part of the territory of the reservoir basin, the available observed data are calculated by summing up the river discharges determined at the outlet gages. To calculate the inflow from the catchment area not covered by hydrometric observations, the method of hydrological analogy is used, the essence of which consists of transferring hydrometric data of the studied rivers (analog rivers) to an area where observations of river runoff are not carried out.

The average long-term annual runoff calculated in this way for the period 1978–2013 served as its estimate for the period of contemporary global warming (PCGW), and for the period 1946–1977 it was used as the reference period (RP) runoff. Since in our model runoff calculations we use the periods of the 1931–1980 and 1981–2010 as the RP and PCGW, respectively, it was necessary to assess how significantly the differences in the boundaries and duration of the above periods affect the average long-term runoff. Since the Georgievskii (2017) provides runoff only for 1946–1977 and 1978–2013, we carried out such a comparison for catchment areas of a number of reservoirs (Table 1), for which long-term series of reconstructed water flows were obtained based on the method of transforming annual hydrographs of daily water discharges (Milyukova et al. 2020; Georgiadi et al. 2024) and based on the regression relationship between the average monthly flow of the Angara and the levels of Lake Baikal, obtained from data for the period before the filling of the Irkutsk Reservoir. The water levels of Baikal were reconstructed using the lake water balance method (Sinyukovich et al. 2024). Comparison of the runoff of each period with different boundaries showed that the differences in the average annual runoff in these periods are insignificant (Table 1) (Georgievskii 2017; Milyukova et al. 2020; Georgiadi et al. 2024). At the same time, the average runoff for the periods 1946–1977 and 1978–2013 for the basins of the Krasnoyarsk and Irkutsk reservoirs, determined on the basis of the two considered methods, may differ from each other. The difference in this case is several percent, although for the Krasnoyarsk reservoir basin it reaches 9%.

Annual runoff calculated using an ensemble of global climate models

The annual runoff data from the IPCC CMIP6 project were obtained by its calculations in specially developed blocks of global climate models. The main calculation schemes of river flow performed on an ensemble of global climate models are analyzed in (Georgievsky and Golovanov 2015, 2019). The annual runoff data were calculated by using the daily water discharges obtained under the IPCC CMIP6 project[1] (Eyring et al. 2016; O'Neill et al. 2016) for each of the 19 global climate models (GCMs) for the so-called "historical" period (1850–2014). Data from a list of global climate models of relatively high spatial resolution, which are used for scenario forecasts in the Climate Center of Roshydromet of Russia[2]), were used. The initial daily runoff data were averaged for each year and interpolated using the bilinear interpolation method into the nodes of a uniform grid of 0.5 degrees in latitude and longitude. The data were averaged for the periods 1931–1980 (base period), 1981–2010 (the period of modern global warming), and for the territory of the reservoir basins considered.

The period of the mid-21st century global warming scenario

The initial data were the daily runoff calculated on the ensemble of global climate models (discussed above), obtained for the period 2015–2100 under three scenarios: the least intense warming (SSP 1-2.6), moderate warming (SSP 2-4.5), and the most intense warming (SSP 5-8.5). The study used data on annual runoff averaged for the period 2040–2069 and for the territory of the reservoir basins under consideration.

METHODS

Approach to assessing changes

The approach to assessing changes in runoff during both the modern and scenario (anthropogenic) global warming periods is based on the method of comparing

Table 1. Comparison of the average long-term annual runoff (km³), calculated by the method of summing up river runoff and the method of transforming the annual hydrograph

Reservoir basin	River flow summation method		Method of transformation of annual hydrograph			
	1946–1977	1978–2013	1946–1977	1978–2013	1936–1980	1981–2010
Kama	52.4	57.2	51	57.8	50.26	57.45
Sayano-Shushenskoe	47.5	48.5	47.5	48.7	47.6	48.8
Krasnoyarsk	42.1	42.8	45.9	45.8	46	47
Irkutsk	61.4	62.6	64*	65.6*	65.2*	68.3*

*Calculations were carried out based on regression relationships between the average monthly flow of the Angara and the average monthly levels of Lake Baikal (Sinyukovich et al. 2024).

[1]ESGF MetaGrid (2025). [online] Available at: https://esgf-metagrid.cloud.dkrz.de/search/cmip6-dkrz/ [Accessed 26 Aug. 2025].
[2] Roshydromet Climate Center (2025). Official Website. [online] Available at: https://cc.voeikovmgo.ru/ru/ [Accessed 26 Aug. 2025]

the runoff averaged over these periods with the runoff of the same base period. Such a comparison for the period of instrumental observations is carried out on the basis of runoff estimates for the above periods, calculated both on the basis of observational data and on the basis of data obtained on an ensemble of global climate models. In this case, for the period of instrumental observations, the results of runoff calculations for each of the periods and the difference in runoff between them, obtained both on the basis of observation data and results of calculations carried out on an ensemble of global climate models, are compared.

About the base period

Since the late 1970s–early 1980s, a period of global warming has begun, characterized for the territory of Russia by a significant increase in air temperature and less noticeable changes in atmospheric precipitation compared to the previous multiyear base period. They led to corresponding changes in the characteristics of river runoff. The boundary between these periods is somewhat different in different regions of Russia (Georgiadi et al. 2014, 2023, 2024; Georgiadi and Kashutina 2014, 2016; Frolova et al. 2022; Shpakova and Wang 2023). The period from the 1930s–1940s to the late 1970s–early 1980s is typically used as the base period for calculating climatological norms of river flow in Russia.. The period starting from the above years and continuing until recent years is considered to be the period of modern global warming. Other shorter periods are also used. In this study, the period 1946–1978 served as an estimate of the average long-term runoff of the base period, and for the period of modern global warming we use the period 1979–2013 (Georgievskii 2017). See the Data section for more information.

An important issue of the correct use of the results of calculations of changes in runoff under conditions of modern and scenario (anthropogenic) global warming, performed on an ensemble of global climate models, consists of assessing the quality of reproduction of runoff characteristics (in this case, annual runoff in reservoir catchment areas) based on a comparison of model and observed values.

To do this, the simulated and observed runoff of the base period and the period of modern global warming are compared, as well as the difference in the runoff of these periods, calculated using an ensemble of global climate models and based on observation data.

Assessment of specific water availability in reservoir basins

The availability of water resources of the annual river flow in reservoir catchment areas is assessed using their per capita volume (Koronkevich et al. 2014; Georgiadi et al. 2021). The calculations are based on the 1989 population data (by constituent entities of the Russian Federation)[3], which are attributed to the base period, and the 2021 population census data (by municipalities of the Russian Federation)[4], attributed to the period of modern global warming. It should be noted that both population and the character of its spatial distribution in the regions under consideration in the 1989 and 1979 differed slightly. While in 2021 the total population has changed slightly, it has decreased significantly over the most part of territory under consideration. Data on the constituent entities of the Russian Federation were used as the scenario population for 2045[5]. The above materials served as the basis for assessing the population by municipalities in the Volga–Kama and Angara–Yenisei reservoir basins. At the same time, the population in the basins for 2021 was calculated based on available data for municipalities. The population estimates for 1989 and the scenario population for 2045 in reservoir basins were based on the estimated population in municipalities. These calculations were based on data on the difference in population in the constituent entities of the Russian Federation relative to its population in 2021 and its use for municipalities of the corresponding constituent entity of the Russian Federation. The calculations of the actual and scenario population for reservoir catchment areas were carried out using GIS technologies.

Water availability per capita was compared with the availability of local river runoff resources per unit area of reservoir basins.

RESULTS

Contemporary global warming

Annual runoff in reservoir catchment areas and its changes during the period of contemporary global warming based on observational data Sub-section title

The largest volume of annual runoff, according to Georgievskii (2017), is formed in the basins of the Cheboksary, Kama, Kuibyshev, Sayano-Shushenskoe, Krasnoyarsk, Irkutsk, as well as Nizhnekamsk and Bratsk reservoirs. Their volume is the smallest in the basins of the Ivan'kovo, Uglich, Votkinsk, Saratov, Volgograd, Ust'-Ilimsk, and Boguchany reservoirs (Fig. 2).

During the period of modern global warming, the average long-term annual runoff (see Fig. 2) in the local basins of the considered reservoirs changed quite significantly (according to the calculations given in Georgievskii (2017) relative to the reference period. At the same time, in the basins of all reservoirs (except for the Volgograd Reservoir), the runoff increased, but to varying degrees. In the Volgograd Reservoir basin, there was a sharp (twofold) decrease. The most noticeable increase in runoff (from 10 to more than 20%) was observed in the Volga–Kama reservoir basins, while in the Angara–Yenisei reservoir basins, its growth was much less noticeable (except for the Irkutsk Reservoir, where it increased by about 9%); in the Boguchany Reservoir basin, the runoff even decreased, albeit by only 0.5%.

Specific water availability in reservoir catchment areas and its change in the period of modern global warming

The per capita water availability (Fig. 3a) in the Volga–Kama reservoir basins is considerably lower compared to the Angara–Yenisei reservoir basins, which is explained mainly by the significantly higher population density in the regions of the European part of Russia. At the same time, the specific water availability in the territory (Fig. 3b) in all the considered basins is quite high (with the exception of the Volgograd reservoir basin, located in the steppe zone with its characteristic low

[3]Population of the USSR: According to the All-Union Population Census 1989 (1990). Moscow: Fin. Stat. (in Russian)
[4]Federal State Statistics Service (2025). Population of the Russian Federation by municipalities as of January 1, 2021. [online] Available at: https://web.archive.org/web/20211029094621/https://rosstat.gov.ru/compendium/document/13282?print=1 [Accessed 26 Aug. 2025]
[5]Federal State Statistics Service (2025). Estimated Population of the Russian Federation up to 2045 [online] Available at: https://rosstat.gov.ru/compendium/document/13285 [Accessed 26 Aug. 2025]

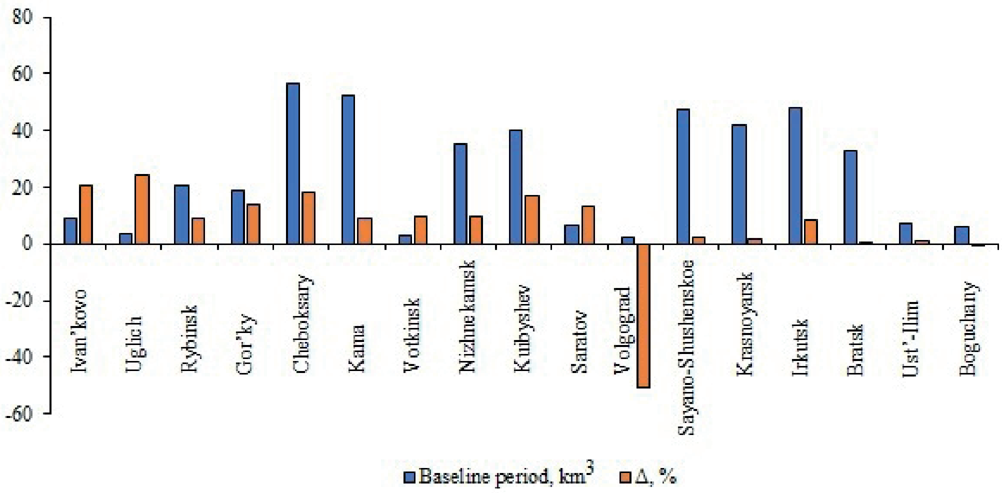


Fig. 2. Average long-term annual runoff in reservoir catchment areas in the base period and its changes during the period of modern global warming, calculated on the basis of observational data

precipitation). The same factors explain the relatively low specific water availability in the Saratov and Irkutsk reservoir basins. The distribution of the volumes of annual runoff and specific water availability per unit area (km2) by reservoir basins has very similar features (Figs. 2, 3b). However, the character of the distribution of water availability per capita over the basins is significantly influenced by the size of the population, which is more influenced by socioeconomic and historical factors (Figs. 2, 3a).

For most of the basins of the Volga–Kama and Angara–Yenisei reservoirs, a relatively close relationship is revealed between these two specific indicators (Fig. 4a, b), although in each of the regions, data for one of the basins (the basins of the Gor'ky and Sayano-Shushenskoe reservoirs) deviate significantly from the average line of relationship, which can be explained by the anomalous combination of these specific indicators of water availability.

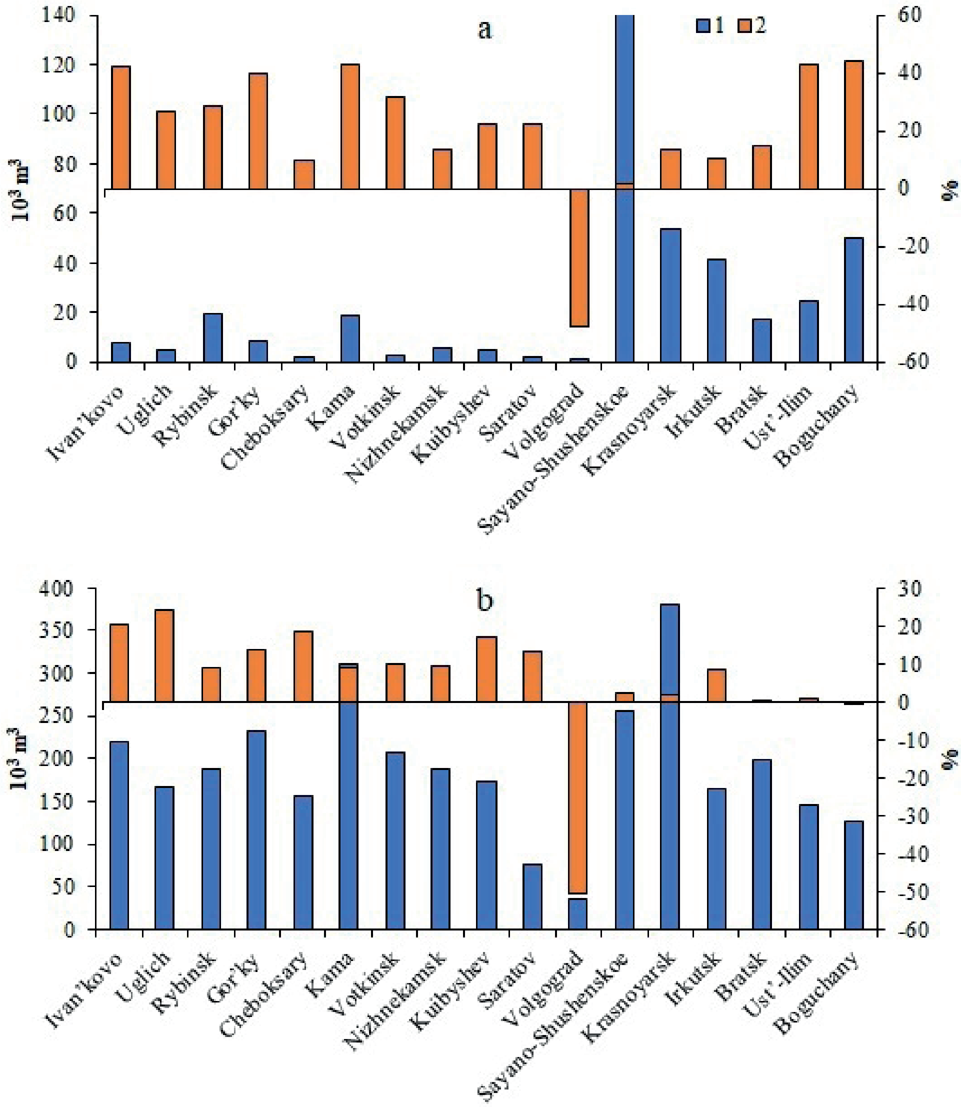


Fig. 3. Water availability due to annual runoff to (a) the population and (b) territory in reservoir catchment areas (1) in the base period and (2) its relative changes (in %) during the period of modern global warming

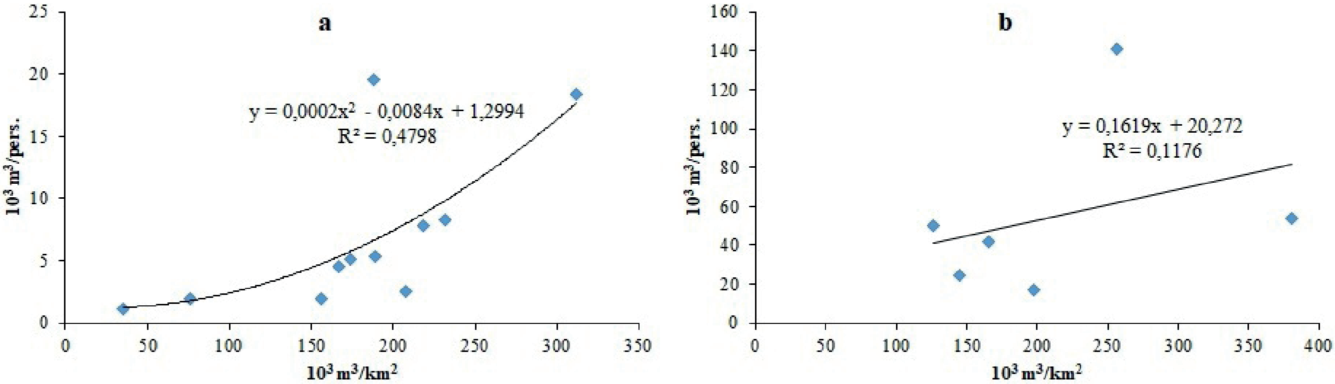


Fig. 4. Relationships between water availability, average long-term annual runoff per capita, and per unit area in (a) the Volga–Kama and (b) Angara–Yenisei reservoir basins, based on base period data

The above also applies to the peculiarities of changes in the specific water availability for the population and territory in the basins of the considered reservoirs during the period of modern global warming. The character of changes in the specific water supply of the territory of reservoir catchment areas is to a certain extent similar to changes in the annual runoff. On the other hand, the per capita water supply changes were greatly influenced by long-term population multidirectional trends in the period from 1989 to 2021. In the overwhelming majority of basins, it decreased and, in most of them, significantly (by 20–30% and more). Only in the Cheboksary Reservoir basin did the population increase (by 7.5%).

Quality of simulation of annual runoff and its changes during the period of modern global warming by ensemble-averaged data of global climate modeling

In this case, the model and observed runoff of the base period and the period of modern global warming are compared, as well as the difference in the runoff of these periods, calculated using an ensemble of global climate models and based on observation data.

It should be noted that the annual runoff for the considered basins of the Volga–Kama and Angara–Yenisei reservoirs, obtained by averaging the results of calculations carried out on an ensemble of global climate models and calculated from observation data, correlate very closely with each other (Fig. 5). At the same time, for a fairly significant number of the basins of the considered reservoirs (especially for Volga–Kama reservoir basins), the model runoff differs significantly from the observed one.

A comparison of the annual runoff calculated based on observational data and the model runoff calculated by averaging the results of calculations performed on an ensemble of global climate models (GCMs) under the CMIP6 program shows that for both the period of modern global warming and the baseline period, the model runoff overestimates the observed annual local runoff in most of the Volga–Kama reservoir basins and underestimates it in most of the Angara–Yenisei reservoir basins (Fig. 6). Only in two Volga–Kama reservoir basins was it lower for the baseline period (in the Kama and Nizhnekamsk reservoirs) and in one (Kama) for the period of modern global warming. Among the basins of the Angara–Yenisei reservoirs, only in the basin of the Irkutsk Reservoir and only during the period of modern global warming did the model runoff exceed the observed one.

The difference between the model and observed annual runoff varied in the Volga–Kama reservoir basins from almost zero values (Gor'ky Reservoir basin) to 3–6 times (Volgograd Reservoir basin). In the Angara–Yenisei reservoir basins, this difference changes in a narrower range: from values close to zero (Irkutsk, Bratsk and Boguchany (for BP) reservoir basins) to 32% (Krasnoyarsk Reservoir basin). In general, we note that, as a rule, the difference between the model and observed runoff in both the Volga–Kama and Angara–Yenisei reservoir basins during the period of modern global warming is less than in the baseline period (except for the Kama, Nizhnekamsk, and Boguchany reservoirs).

Now let us compare the changes in annual runoff in reservoir catchment areas during the period of modern global warming relative to the base period calculated using the CMIP6 GCM ensemble and their observation data.

The direction of relative changes in the model annual runoff, averaged over the CMIP6 GCM ensemble, during the period of modern global warming and the observed annual runoff relative to the baseline period (in percent of the annual runoff of the baseline period) coincide in most of the considered basins (Fig. 7). The exception is the Saratov Reservoir basin, in which, under the conditions of the PCGW, the model and observed changes occurred in different directions. Note that in the basins of all other

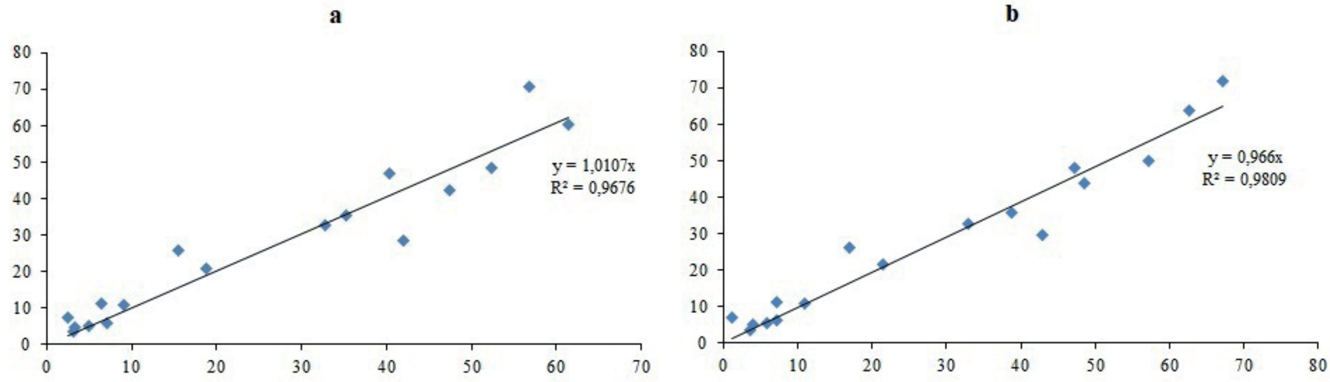


Fig. 5. Regression relationships of annual runoff (km3) in (a) RP and in (b) PCGW, calculated from observational data (ordinate axis) and from global climate models of the CMIP6 project (abscissa axis)

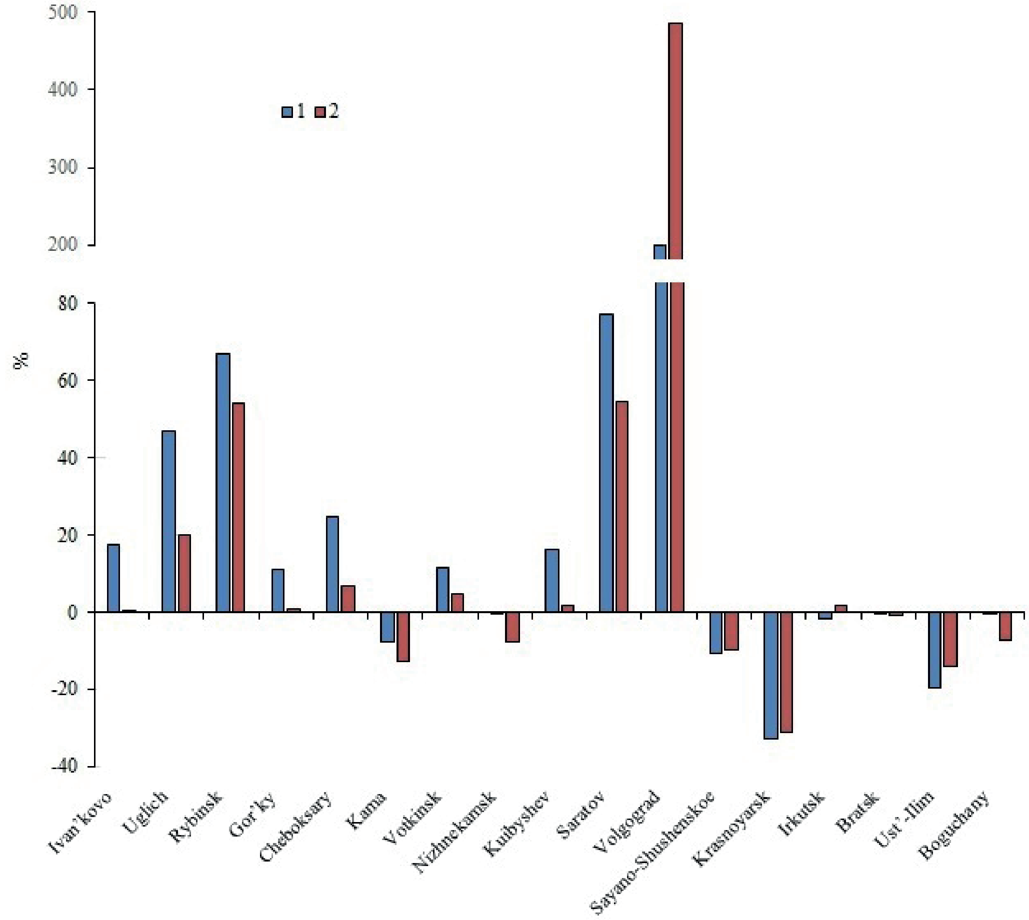


Fig. 6. Difference (in %) between the model (averaged over the ensemble of global climate models of the CMIP6 project) and the annual runoff calculated based on observational data in (1) the baseline period and (2) the period of modern global warming

reservoirs, the model and observed changes in the PCGW were directed toward a decrease in runoff, except for the Volgograd Reservoir basin, where the runoff decreased. The increase in observed runoff was more significant in the Volga–Kama reservoir basins, as well as in the Boguchany and Bratsk reservoirs (in which the changes were barely noticeable). In the basins of other Angara–Yenisei reservoirs, on the contrary, the model increase was greater than the observed one.

In a single basin (the Volgograd Reservoir), the model and observed runoff decreased. Note also that the difference between the model and observed changes was more significant in the Volga–Kama Reservoir basins.

Scenario global warming

Changes in annual runoff

Several groups of basins are identified by the character of changes in the average long-term annual runoff in 2040–2069 relative to the model runoff of the base period under scenario warming of varying intensity (Fig. 8). One of them includes the basins of Angara–Yenisei reservoirs, as well as the Kama and Votkinsk reservoirs. In them, the runoff will probably increase (to varying degrees) under all the considered scenarios of anthropogenic warming. In the basins of another large group of the Volga–Kama reservoirs (Ivan'kovo, Uglich, Rybinsk, Cheboksary, Nizhnekamsk, Kuibyshev, and Saratov), under conditions of the least intense warming, the runoff may increase very slightly (by no more than 5%), whereas under warming of medium and maximum intensity, the runoff will probably decrease. It is only in the Volgograd Reservoir basin that the runoff can decrease under different warming scenarios. In the Gor'ky Reservoir basin, the runoff will decrease at a low and high warming rate and increase at its medium rate. At the same time, the scale of changes varies within only a few percent.

If we evaluate the changes in runoff in the mid-21st century relative to the model runoff for the period of modern global warming, then the direction of its changes in the Angara–Yenisei reservoir basins and in the Kama reservoir basin will remain the same (Fig. 9), but their scale will decrease. The number of reservoir basins in the second group highlighted above will be reduced to four from among the Volga–Kama reservoirs. The third large group of basins (see Fig. 9) of the Volga–Kama reservoirs (which, when assessing scenario changes in runoff relative to the base period, included only the Volgograd Reservoir basin), in which runoff will probably decrease under scenarios of global warming of varying intensity, may already include six basins, including the Volgograd Reservoir basin.

We next compare the differences in runoff in the reservoir basins under the scenario of warming conditions in 2040–2069 of different intensity with each other. That is, let us compare the difference in runoff between the base period and the ssp 1-2.6 scenario for the following pairs of scenarios: ssp 1-2.6 and ssp 2-4.5, ssp 2-4.5 and ssp 5-8.5 (Fig. 10).

Under the conditions of low-intensity warming, the runoff may increase in the basins of all reservoirs except for the Gor'ky and Volgograd reservoirs (which was already mentioned above). Under conditions of medium-intensity global warming, the runoff in the basins of most reservoirs will probably decrease relative to the runoff under low-intensity warming (except for the Gor'ky and Kama reservoirs). Under the most intense warming (SSP 5-8.5), relative to the runoff during the period of medium-

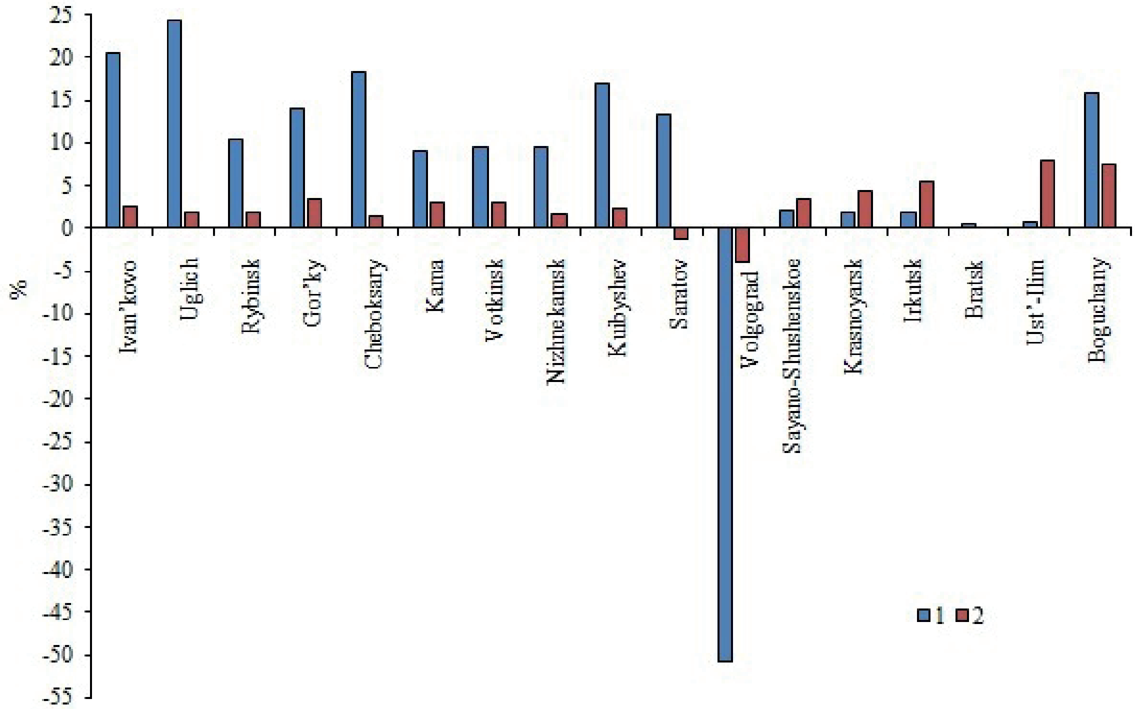


Fig. 7. Difference (in %) between annual runoff in catchment areas of the Volga–Kama and Angara–Yenisei reservoirs during the period of modern global warming and in the baseline period, calculated based on (1) observational data and (2) data averaged over the ensemble of global climate models of the CMIP6 project

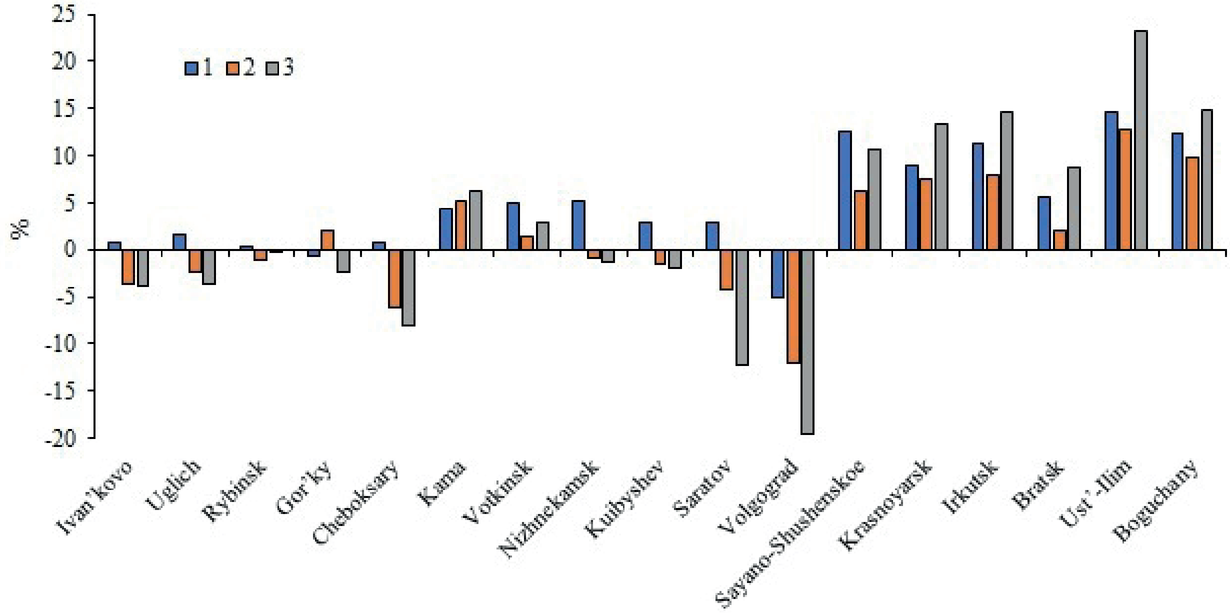


Fig. 8. Changes in annual runoff in 2040–2069 under scenarios (1) SSP 1-2.6, (2) ssp 2-4.5 and (3) ssp 5-8.5 relative to the base-period model runoff

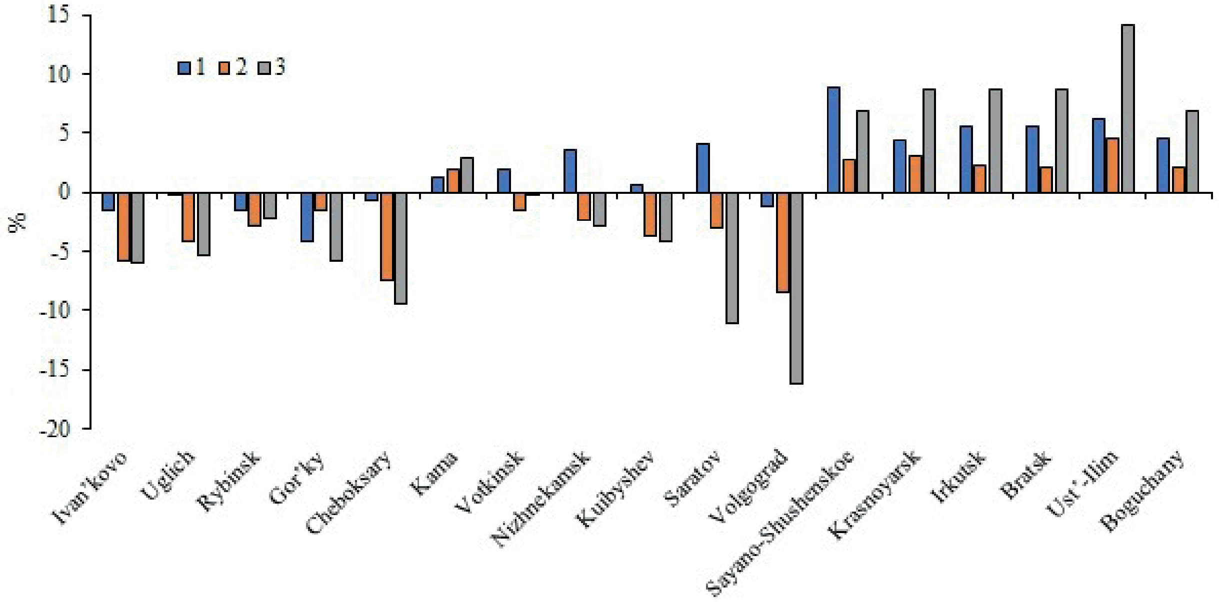


Fig. 9. Changes in annual runoff in 2040–2069 under scenarios (1) ssp 1-2.6, (2) ssp 2-4.5 and (3) ssp 5-8.5 relative to model runoff during modern global warming

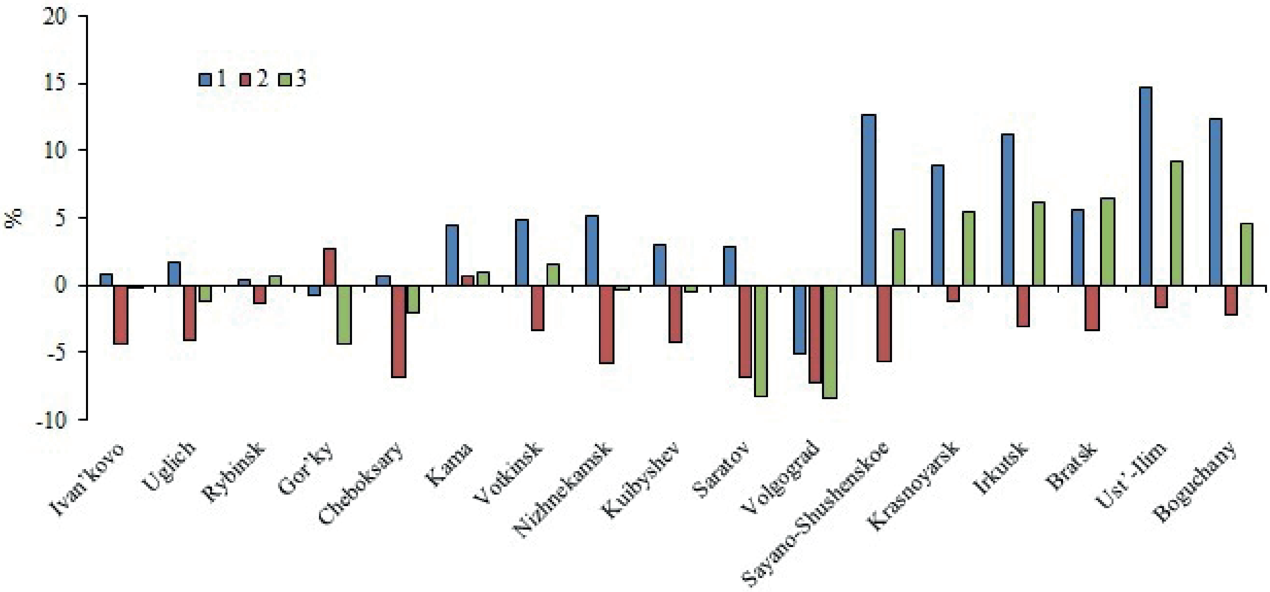


Fig. 10. Changes in the model annual runoff in 2040–2069 under the conditions of: (1) scenario ssp 1-2.6 relative to the runoff of the base period, (2) scenario ssp 2-4.5 relative to the runoff under the conditions of the scenario ssp 1-2.6, (3) scenario ssp 5-8.5 relative to runoff under conditions of scenario ssp 2-4.5

intensity warming, it may increase by 4–9% in the basins of all the Angara–Yenisei reservoirs. In the basins of most of the Volga–Kama reservoirs, it decreases to varying degrees, mostly very insignificantly. Only in the basins of the Gorky, Saratov, and Volgograd reservoirs, the decrease in runoff is comparable to the scale of the possible increase in runoff in the basins of the Angara–Yenisei reservoirs.

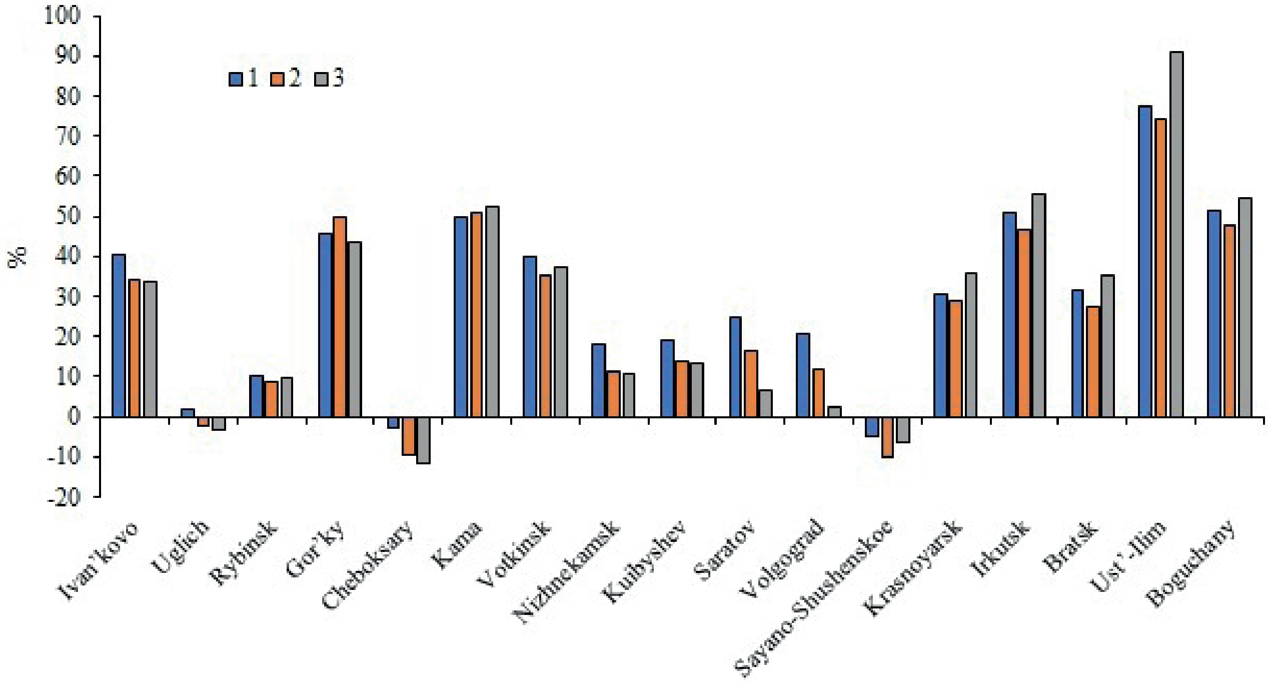
Scenario changes in water availability

The character of the scenario changes in water availability per unit area and the volumes of annual runoff in reservoir catchment areas are similar. The character of the scenario changes in per capita water availability in reservoir basins is significantly different, since they are determined not only by changes in annual river flow but also by the population size. Note that under the conditions of all three considered scenarios of varying warming intensity in the basins of most reservoirs, the per capita water availability increases (Fig. 11) and quite significantly (by 10–70%). It decreases only in three basins (from several to 10%). Note that in the Uglich Reservoir basin, this can occur only under scenarios ssp 2-4.5 and ssp 5-8.5.

DISCUSSION

The results obtained in this study make a certain contribution to improving the understanding of the features of changes in annual runoff under conditions of contemporary and probable future global warming based on observation data and estimates obtained using an ensemble of global climate models.

The obtained estimates of the quality of model calculations of the annual runoff formed in reservoir catchment areas in the period of modern global warming and the baseline period allow us to conclude that global climate models for a number of the considered basins of the Volga–Kama and Angara–Yenisei reservoirs reproduce the long-term averaged annual runoff in the specified periods with acceptable accuracy. At the same time, for the



(1) ssp 1-2.6, (2) ssp 2-4.5, (3) ssp 5-8.5

Fig. 11. Scenario changes in per capita water availability relative to the model baseline period

basins of a number of the considered reservoirs (especially for the Volga–Kama reservoirs), the model runoff differs significantly from the observed one, which also is true for model estimates of the difference in runoff during the period of modern global warming and in the baseline period. This is confirmed by other studies (Georgievsky and Golovanov 2015, 2019). All this suggests that estimates of the average long-term annual runoff for a number of regions, obtained by averaging the results of calculations carried out on an ensemble of global climate models, do not adequately estimate the average runoff during the period of modern global warming, the base period, and trends in modern long-term changes in average annual runoff.

To improve the results of runoff change calculations under modern and scenario global warming, it is apparently possible to develop two lines of research. One of them is to take into account regional features of runoff formation to improve the runoff calculation schemes used in global climate models, discussed in (Georgievsky and Golovanov 2015, 2019). Another line of research can be proposed, which involves selecting the best models from the entire available ensemble of global climate models based on a comparison of model results with observational data. It should be noted that such an approach is already being used (Menzhulin et al. 2005; Kislov et al. 2008; Anisimov and Kokorev 2013; Georgiadi et al. 2014; Babina and Georgiadi 2016), but river runoff is usually not used among the compared characteristics. Therefore, when selecting global climate models, it is reasonable to use not only climatic characteristics but also the observed (and most reliably determined) and calculated GCM river runoff for the period of modern global warming and the baseline period and the difference in runoff between these two periods. Also, extremely useful for these purposes is a comparison of observed and calculated long-term runoff series and their statistical characteristics (Motovilov and Gelfan 2019; Hai Guo et al. 2022; Kalugin 2023).

CONCLUSIONS

The study was focused on changes in the annual runoff in catchment areas of the Volga–Kama and Angara–Yenisei reservoirs in periods of modern and scenario global anthropogenic warming in the middle of the 21st century. The assessments of changes are based on a comparison of runoff under conditions of global warming and the base period, calculated on the basis of observational data and on an ensemble of global climate models.

The obtained results are as follows.

1. Comparison of the annual runoff for the period of modern global warming and the base period for the basins of the Kama, Krasnoyarsk, Sayano-Shushenskoe, and Irkutsk reservoirs, calculated by summation and analogy methods (Georgievskii 2017) and the method of calculating daily water discharges for the entire year based on the method of transforming annual hydrographs (Kalinin and Milyukov 1958; Milyukova et al. 2020; Georgiadi et al. 2023, 2024) showed that they give close results.

2. During the period of modern global warming, the average long-term annual runoff (according to calculations based on the methods of runoff summation and analogy given in (Georgievskii 2017)) and the specific water supply for the territory have increased most noticeably in the Volga–Kama reservoir basins, while in the Angara–Yenisei reservoir basins their growth was significantly less noticeable (except for the Irkutsk reservoir).

3. In most basins, the per capita water availability increased not only due to increased runoff but also due to a significant decrease in population (by 20–30% or more) in the period from 1989 to 2021. Only in the Cheboksary Reservoir basin was there a noticeable (7.5%) reverse trend in population change, which affected the corresponding change in the per capita water availability. For most basins of the Volga–Kama and Angara–Yenisei reservoirs, a relatively close relationship is revealed between the specific water availability for the population and the territory.

4. Comparison of the observed annual runoff in reservoir basins, its changes during the period of modern global warming, and its estimates obtained on the basis of averaging the results of calculations carried out on an ensemble of global climate models of relatively high spatial resolution, which are used for scenario forecasts in the Climate Center of Roshydromet of Russia showed that:

–the observed and average model annual runoff in the considered reservoir basins are closely correlated (R^2 >0.9). However, for a fairly significant number of basins, the model runoff differs significantly from the observed value;

–for both the period of modern global warming and the baseline period, the model runoff overestimates the observed annual runoff in most basins of Volga–Kama reservoirs and underestimates it for most of the Angara–Yenisei reservoir basins. At the same time, the difference between them is significantly greater in the Volga–Kama reservoir basins;

–in the basins of all reservoirs, both the observed (except for the Volgograd Reservoir) and model (except for the Saratov and Volgograd reservoirs) runoff during the period of modern global warming increased compared to the baseline period. The increase in the observed runoff was more significant in the basins of the Volga–Kama reservoirs, as well as in the basins of the Boguchany and Bratsk reservoirs (in which the changes were barely noticeable). In the basins of other Angara–Yenisei reservoirs, on the contrary, the model increase in runoff was greater than the observed one. In only one basin (Volgograd Reservoir), both the model and observed runoff decreased quite noticeably.

5. According to the character of changes in annual runoff in 2040–2069 relative to the model runoff of the base period under conditions of scenario warming of varying intensity, two main groups of basins are distinguished. In one of them (which consists of the basins of the Angara–Yenisei, as well as the Kama and Votkinsk reservoirs), the scenario runoff will probably increase to varying degrees under all the considered anthropogenic warming scenarios. In the basins of another group (which includes the Volga–Kama reservoir basins), under the conditions of the least intense warming, the runoff may increase very slightly (by no more than 5%), whereas under warming of medium and maximum intensity, the runoff may decrease. Only in the Volgograd Reservoir basin, under the implementation of different warming scenarios, the runoff will probably decrease quite significantly.

6. The character of scenario changes in the water supply of the territory of reservoir catchment areas both in the base period and in the conditions of modern global warming is in many ways similar to changes in the volumes of annual runoff in these basins. Scenario changes in water availability per capita are characterized by regional features of population change (both in the base period and in the conditions of modern global warming). Under the conditions of all three considered scenarios of different warming intensity in the basins of most reservoirs, water availability per capita may increase and quite significantly (by 10–70%), including in connection with the predicted change in the population. Only in three basins (Uglich, Cheboksary, and Sayano-Shushenskoe) it will probably decrease (from a few to 10%).

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