Modelling of future changes in the water regime of the Upper Kama River

A S Kalugin
Water Problems Institute RAS, Gubkina 3, Moscow, 119333, Russia
andrey.kalugin@iwp.ru

Abstract. Calculations of future changes in the water regime for the Kama reservoir basin were carried out based on the ECOMAG regional semi-distributed runoff formation model and data from an ensemble of four atmosphere-ocean general circulation models using the RCP2.6 and RCP6.0 scenarios. Estimates of changes in the runoff of the Upper Kama River are presented for the middle and end of the 21st century relative to the historical period 1986–2005. The downward trend in both annual and summer water inflow into the Kama reservoir will continue in the future, despite an increase in winter runoff. Moreover, the decrease in runoff will be more significant under the RCP6.0 scenario. Despite the increase in precipitation up to 10%, the decrease in the annual runoff of the Upper Kama River will be from 4% to 17% due to intense warming in the catchment area by 2–5°C, depending on the season of the year, the period of the 21st century and the RCP scenario.

1. Introduction
Due to the change in the ratio of the input and output parts of the hydrological cycle of the land in the last 30–40 years, changes in the flow of Russian rivers are mainly expressed in the seasonal transformation of the water regime, namely in an increase in winter runoff and a decrease in melt runoff of rivers in the European Russia, and also an increase in the summer-autumn runoff of rivers with a flood regime, which is characterized by extremely high temporal and spatial variability [1]. An increase in winter low-flow runoff has been noted for the Kama River basin [2] with a weak trend of increased winter liquid precipitation since the early 1980s [3]. The share of spring melt runoff in the annual volume remained practically unchanged in the Kama reservoir basin, while in the rest of the Volga basin, this share decreased by 5–25% [4]. The increase in winter runoff over the period 1978–2010 relative to 1945–1977 was less than 20%, which is the smallest value in the Volga basin [5].

The catchment area of the Kama Reservoir is 168,000 km². The structure of landscapes is dominated by coniferous and mixed forests. The annual water inflow into the Kama reservoir is almost a quarter of the long-time mean annual flow of the Volga River. The daily water inflow into the reservoir for a long-term period was obtained based on the synthesis of the measured runoff at gauges of the reservoir tributaries, and the restored runoff from ungauged territory using analogous rivers. Compared to the 1980s and 1990s, the water inflow into the Kama reservoir at the beginning of the 21st century decreased by 8%. This is due to a decrease in river runoff during the warm period from May to October by 14% because of a decrease in precipitation by 5% and an increase in air humidity deficit by 10%. The largest decrease in water inflow into the Kama reservoir is typical for July-August by 23%, and precipitation in these months decreased by 16%.
The main objective of this study was to assess changes in the intra-annual flow regime of the Kama River up to the Kama hydroelectric power station for the 21st century based on a runoff formation model calibrated and verified on independent data series. The approach used, combining the regional hydrological model with general circulation models (GCMs), allows to take into account the diversity of physical mechanisms of the runoff response to future climatic forcing (reviews for rivers in different regions of the world in [6, 7]).

2. Materials and methods

At the first stage, a regional process-based runoff formation model was developed for the Upper Kama River basin (this is part of the universal model for the Volga basin [8]) based on the ECOMAG software [9], which describes the main processes of the hydrological cycle for each of the 91 subbasins. The initial model information was the global databases of land surface parameters and long-term observation series at hydrometeorological stations. The daily observation data at 39 meteorological stations were used. The model was calibrated using discharge data for the period 2000–2014, and the verification was carried out for the period 1986–1999. The Nash-Sutcliffe Efficiency (NSE) and percent bias (PBIAS) were selected as the criteria for evaluating the ratio of simulated and observed water inflow into the Kama Reservoir.

The GCMs output data prepared by downscaling the initial data to a 0.5° grid and bias correction procedure in monthly resolution using meteorological reanalysis [10, 11] within the framework of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), initiated by the Potsdam Institute for Climate Research were used for numerical experiments for the future calculation period. Thus, the daily meteorological output data (air temperature and humidity, precipitation) of four GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5) for the Kama River basin, required for the hydrological model, were prepared.

The period 1986–2005 was taken as the base historical period, for which the accuracy of the reproduction of the seasonal norms of the averaged-basin meteorological values by the GCMs ensemble was assessed in comparison with the station data. To assess the variability of seasonal hydrometeorological characteristics, the period from November to March was considered as winter, April-May as spring flood, from June to October as summer-autumn.

The GCMs output data for two Representative Concentration Pathways (RCPs) scenarios RCP2.6 and RCP6.0 were used to carry out numerical experiments for the period up to the end of the 21st century. According to the developed runoff formation model, calculations for the 21st century were carried out with the same parameters that were established for the historical period. Possible changes in climatic and hydrological characteristics in the Kama River basin during the 21st century were estimated by calculating the anomalies of these values, i.e. relative change compared to the values of the base period 1986–2005 for each GCM, followed by averaging over the GCMs ensemble and twenty-year periods of the middle (2040–2059) and the end (2080–2099) of the 21st century.

3. Results and discussion

The values of the NSE and BIAS criteria for the period of calibration and verification of the runoff formation model were 0.93 and −7%, 0.93 and −4%, respectively (figure 1). The hydrological model efficiently calculates the daily runoff over a long-term period from the observation data (NSE> 0.90 and |PBIAS|<10%) and can be used for numerical experiments with GCMs. The hydrological model calculates the Kama River runoff for the base period with NSE 0.94 and PBIAS −6%. According to the methodology in [12, 13] this model is robust for different calculation periods.
Figure 1. Simulated (1) and observed (2) daily water inflow into the Kama Reservoir for the period of verification (a) and calibration (b) of the hydrological model.

Estimation of the accuracy of reproduction of the long-time mean annual and seasonal averaged-basin meteorological values by the GCMs ensemble in comparison with the station data for the base period 1986–2005 showed that the error in calculating the mean annual air temperature in the Kama Reservoir basin was 0.3°C, in spring and summer up to 0.5°C, and in winter 0.1°C.

Figure 2. Observed and simulated long-time mean monthly water inflow into the Kama Reservoir during the base period 1986–2005 using the meteorological station data and GCMs output data.

GCMs overestimate winter precipitation by 11%, underestimate spring and summer precipitation by 7% and 6%, respectively, with an error in calculating the annual precipitation of −1%. The results of the long-time mean annual runoff of the Kama River simulated using the GCMs ensemble data for
the base period showed that the PBIAS was 1% relative to the observed runoff. At the same time, the winter and spring water inflow into the Kama Reservoir are underestimated by 8% and 4%, respectively, and the summer-autumn runoff is overestimated by 12% (figure 2). As a result, the GCMs ensemble reproduces the regional features of atmospheric circulation in the Kama River basin over the historical period and can be used to assess possible changes in the studied characteristics during the 21st century. The obtained results of anomalies in the long-time mean averaged-basin meteorological characteristics and river runoff are shown in figure 3.

![Figure 3](image)

**Figure 3.** Anomalies in the long-time mean annual and seasonal averaged-basin meteorological values and water inflow into the Kama Reservoir, calculated using the GCMs output data for the middle and end of the 21st century according to RCP2.6 and RCP6.0 relative to the base period.

The results of calculations using the GCMs ensemble for the future period showed that a possible increase in the average annual temperature will be 2–2.2°C under RCP2.6, and according to RCP6.0 2.3°C and 4.4°C by the middle and end of the 21st century. The highest rates of warming (by 2.5–5°C) are typical for the winter period. At the same time, the increase in annual precipitation according to
RCP2.6 will be about 4%, and according to RCP6.0 by the end of the 21st century by 10%. The largest increase in precipitation was noted for winter by 7–20%, depending on the period of the 21st century and the RCP scenario. Spring and summer-autumn precipitation will be almost unchanged by the middle of the 21st century and will increase by 2–7% by the end of the century. The results of calculations using the GCMs ensemble showed that the possible decrease in the Kama River runoff will amount to 4–7% according to RCP2.6, as well as 17% and 10% according to RCP6.0 by the middle and the end of the 21st century, respectively. An increase in runoff during the winter low-flow period by 7–62%, a decrease in summer–autumn runoff by 16–41%, and a change in runoff during the spring flood by up to 8%, depending on the period of the 21st century and the RCP-scenario, were determined.

4. Conclusion
The downward trend in both annual and summer water inflow into the Kama Reservoir will continue in the future, despite an increase in winter runoff. Moreover, the decrease in runoff will be more significant under the RCP6.0 scenario. The main reason for the decrease in water inflow into the Kama Reservoir will be an increase in evaporation due to increased warming in the catchment. Similar results of changes in the future water regime were obtained earlier for the Oka River basin [14]. The features for the Oka River are in a significant decrease in runoff during the spring flood, in contrast to the Kama River, due to the increased influence of winter thaws and the transformation of spring runoff into winter.

Acknowledgments
This research was funded by the Russian Science Foundation (grant 20-77-00077).

References
[1] Frolova N L, Kireeva M B, Kharlamov M A, Samsonov T E, Entin A L and Lurie I K 2020 Mapping the current state and transformation of the water regime of rivers in the European territory of Russia Geodesy and cartography 961(7) 14–26 (in Russian)
[2] Kireeva M, Frolova N, Winde F, Dzhamalov R, Rets E, Povalishnikova E and Pakhomova O 2016 GES J. 9(4) 33–47
[3] Kireeva M, Frolova N, Rets E, Samsonov T, Entin A, Kharlamov M, Telegina E and Povalishnikova E 2020 Evaluating climate and water regime transformation in the European part of Russia using observation and reanalysis data for the 1945–2015 period Int. J. of River Basin Management 18(4) 491–502
[4] Frolova N, Agaonova S, Kireeva M, Povalishnikova E and Pakhomova O 2017 Recent changes of annual flow distribution of the Volga basin rivers GES J. 10(2) 28–39
[5] Dzhamalov R G, Frolova N L and Telegina E A 2015 Winter runoff variations in European Russia Water Resources 42(6) 758–65
[6] Eisner S et al. 2017 An ensemble analysis of climate change impacts on streamflow seasonality across 11 large river basins Clim. Change 141 401–17
[7] Krysanova V et al. 2017 Intercomparison of regional-scale hydrological models and climate change impacts projected for 12 large river basins worldwide – a synthesis Environm. Res. Lett. 12 105002
[8] Kalugin A S Universal hydrological model of the Volga River basin 2019 Proc. Int. Conf. Scientific problems and solutions to the improvement of Russian rivers (Moscow: Studio F1) chapter 1 pp 155–60 (in Russian)
[9] Motovilov Y G, Gottschalk L, Engeland L and Rodhe A 1999 Validation of a distributed hydrological model against spatial observation Agricult. and For. Meteorol. 98–99 257–77
[10] Hempel S, Frieler K, Warszawski L, Schewe J and Piontek F 2013 A trend-preserving bias correction – the ISI-MIP approach Earth Syst. Dynamics 4 219–36
[11] Lange S 2019 Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0) *Geoscientific Model Development* **12** 3055–70
[12] Gel'fan A, Kalugin A, Krylenko I, Nasonova O, Gusev Ye and Kovalev E 2020 Does a successful comprehensive evaluation increase confidence in a hydrological model intended for climate impact assessment? *Clim. Change* **163** 1165–85
[13] Gel'fan A, Kalugin A, Krylenko I, Nasonova O, Gusev E and Kovalev E 2020 Testing a hydrological model to evaluate climate change impact on river runoff *Russian Meteorol. and Hydrol.* **45** 353–359
[14] Kalugin A S 2019 The impact of climate change on surface, subsurface and groundwater flow: a case study of the Oka River (European Russia) *Water Resources* **46**(S2) S31–S39