RESEARCH PAPER

ASSESSMENT OF THE KOLYMA RIVER HYDROLOGICAL REGIME DYNAMICS IN THE 21ST CENTURY BASED ON RUNOFF FORMATION MODEL

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ABSTRACT. Using the physically-based model of runoff formation ECOMAG (ECOlogical Model for Applied Geophysics), the response of the Kolyma River's water regime to ongoing and projected climate changes has been investigated. To operate the ECOMAG model, which calculates daily water discharges for control sections, information was gathered on the characteristics of the land surface and watershed relief, as well as archives of daily observations from meteorological stations within the basin. The calibration and validation of the model, performed for two sections on the Kolyma River and two sections on its tributaries – the Bolshoy Anyuy and Yasachnaya rivers – demonstrated strong agreement between the modelled and observed water discharges for the Kolyma River. Moreover, the analysis of observed water discharges and those calculated by the ECOMAG model reveals similar changes in the water regime that occurred from 1979 to 2020, such as an increase in annual and summer-autumn runoff, and a decrease in the duration of the winter low-flow period. To assess potential changes in the Kolyma River's runoff in the 21st century, numerical experiments were conducted using the ECOMAG hydrological model and an ensemble of four global climate models. Calculations were performed for the periods 2020–2039, 2040–2059, 2060–2079, and 2080–2099 for four different Representative Concentration Pathway (RCP) scenarios. Anomalies in annual runoff, peak water discharges, flood volumes, winter low-flow periods, and summer-autumn periods were considered. Under all scenarios, the calculations indicate an increase in the annual and summer-autumn runoff of the Kolyma River.

KEYWORDS: river runoff, model of runoff formation, Kolyma, ECOMAG, CMIP5, climate change

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INTRODUCTION

Global climate changes inevitably lead to responses in the hydrological system of river basins. According to the latest report by the Intergovernmental Panel on Climate Change (IPCC 2013), greenhouse gas emissions will cause further warming and changes in other climate characteristics, with particularly intense effects in polar regions. Changes in the key factors of runoff formation – air temperature and precipitation – are most pronounced in polar areas compared to other regions of the planet. According to the Third Assessment Report by Roshydromet, by the end of the 21st century, a temperature increase of 2–7°C is expected in Russia, depending on the scenario (Roshydromet 2022).

Future changes in river runoff can be assessed, firstly, by modeling hydrological processes using climate models, and secondly, by calculations based on hydrological models that use climate model outputs as inputs. The use of hydrological models allows for a more comprehensive consideration of the mechanisms of hydrological regime response to climate impacts. Authors such as Krysanova et al. (2018) and Kundzewicz et al. (2018) agree that the use of regional hydrological models provides more reliable estimates of water regime characteristics than using a climate model ensemble. Furthermore, calculations with climate models provide more accurate results on a global scale, while for practical tasks related to the organization of safe water use, the regional scale is often of particular interest.

In this study, the spatially distributed model ECOMAG (ECOlogical Model for Applied Geophysics) is used to assess possible changes in the hydrological regime. This model has proven effective in calculating daily runoff values in watersheds of various sizes and different climate zones. Additionally, the ECOMAG model has demonstrated correct operation in non-stationary climate conditions, making it suitable for calculations under different climatic conditions than those used for model calibration and verification (Moreido and Kalugin 2017; Gelfan et al. 2015).

Meteorological data for the period 2020–2100 were obtained from model results within the CMIP5 project (IPCC 2013) under four different RCP (Representative Concentration Pathways) scenarios: RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5. The numbers in the scenario names indicate the level of radiative forcing in 2100 compared to pre-industrial values (RCP 2.6 corresponds to +2.6 W/m^2, etc.). Scenario RCP 2.6 implies a constant reduction in greenhouse gas emissions until 2100, while scenario RCP 8.5 assumes that greenhouse gas emissions will continue to rise (IPCC 2013).

The study focuses on the Kolyma River, the largest river whose basin is entirely located in the zone of continuous permafrost. Using the ECOMAG model of runoff formation and an ensemble of four climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5), estimates of the possible dynamics of the Kolyma River runoff in the 21st century were obtained under four radiative forcing scenarios: RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5.

MATERIALS AND METHODS

Study area

The Kolyma River is one of the largest rivers in the Arctic zone of the Russian Federation. Its basin, covering an area of 647,000 km^2, is located in the subarctic and arctic climatic zones within the region of continuous permafrost. The river is 2,129 km long, originates in the Okhotsk-Kolyma highlands, and flows into the East Siberian Sea. The upper and middle reaches of the Kolyma are situated in mountainous terrain, while the lower reaches lie in the Kolyma Lowland, encompassing taiga and tundra zones (Water of Russia 2022). More than half of the Kolyma basin is forested, with lakes covering a total area of up to 10%, and swamps comprising around 8%.

The hydrological regime of the Kolyma River is typical for rivers in Eastern Siberia. The spring flood usually occurs from late May to June, followed by a summer-autumn period with rain floods continuing until October. Winter runoff is mainly sustained by riverbank taliks and decreases during the winter low-water period (Lebedeva et al. 2019). The Kolyma has a mixed water supply: snowmelt contributes 47%, rain 42%, and groundwater 11% (Water of Russia 2022).

The Kolyma River's flow is regulated by the Kolyma Hydroelectric Cascade, which is for seasonal regulation. The upper stage, the Kolymskaya hydroelectric power plant (Kolymskaya HPP) (1894 km from the river mouth), began regulation in the 1980s. The lower stage, the Ust-Srednekanskaya hydroelectric power plant (Ust-Srednekanskaya HPP) (1678 km from the river mouth), saw its first two of four units commissioned in 2013 (Rushydro.ru 2024). The hydrological impacts of flow regulation have been extensively studied (Magritsky et al. 2018). The authors found that the operation of the HPPs reduced the volume of the spring flood by 30–50%, while winter runoff almost doubled in the downstream sections of the river.

Anthropogenic changes in the Kolyma's flow are compounded by climatic changes (Magritsky et al. 2019; Ushakov 2013). An increase in air temperature by 2–4°C (AMAP 2017) and an increase in precipitation (Lebedeva et al. 2019) have led to an 8.7 mm rise in annual runoff at Srednekolymsk (Magritsky et al. 2018). Studies focusing on the unregulated part of the basin (Lebedeva et al. 2019; Ushakov 2013; Majhi, Yang 2008) have shown a 14% increase in annual inflow to the reservoir, particularly noting a more than 30% increase in inflow in May, August, and September (Ushakov, Lebedeva 2016). Nasonova et al. (2018) provided estimates of possible changes in the Kolyma's runoff using the SWAP land surface model and climate model outputs. They assessed potential anomalies in annual runoff as 16% and 28% for the periods 2026–2045 and 2081–2100, respectively, compared to 1978–1998.

Input Data for the Model of runoff formation

The information-modelling complex ECOMAG (Motovilov et al. 1999) is a spatially-distributed physically based model of runoff formation. The hydrological block describes the main processes in the watershed: infiltration, evaporation, freezing and thawing, snow cover formation and melting, and the formation of surface, subsurface, groundwater, and river runoff. To schematize the watershed in ECOMAG, elementary watersheds are created, forming an irregular grid of relatively homogeneous landscape units (Motovilov, Gelfan 2018).

For the development of the Kolyma River basin model, information on the characteristics of the underlying surface and relief was collected. Data on landscape, soil type, and vegetation cover were determined from the landscape map of the former USSR and the soil map of Russia, developed by the Soil Institute of the Russian Academy of Sciences. The source of the digital elevation model is the GLOBE (Global Land One-kilometer Base Elevation) project by the Defense Mapping Agency (DMA).

Currently, there are 35 hydrological posts operating in the Kolyma basin, with 14 of them measuring water discharge. Data on water discharge for the Kolyma River are published for two gauging stations: the town of Srednekolymsk (641 km from the mouth) and the village of Ust-Srednekan, the lower reaches of the Ust-Srednekanskaya HPP (1623 km from the mouth). A long-term series of daily water discharges is also available for the Kolymskoye-I gauging station, located 283 km from the mouth and a few kilometers downstream from the confluence of the largest tributary, the Omolon River. Water levels are measured at the gauging station in the village of Kolymskoye, located 10 km upstream from the Kolymskoye-I gauging station, and thus upstream from the confluence of the Omolon. Since 1998, at the Kolymskoye-I gauging station (downstream from the confluence of the Omolon), flow velocities have not been measured, water discharges have been reconstructed using the $Q = f(H)$ curves, depending on the water level at the Kolymskoye village station (upstream from the confluence of the Omolon), resulting in a decrease in the quality of discharge calculations published in the annual reports of the Federal Department of Hydrometeorological and Environmental Monitoring (FDHEM).

Calibration and verification of the ECOMAG model of runoff formation were carried out by comparing the model's calculated daily water discharges with observed data from 1979-2020 published in the FDHEM annual reports and on the AIS GMVO system website (AIS GMVO 2024). Observation archives were used from two gauging stations on the Kolyma River – Kolymskoye-I (283 km from the mouth) and Srednekolymsk (641 km from the mouth), as well as from major tributaries with long-term water discharge series – Bolshoy Anyuy River at Konstantinovskaya station and Yasachnaya River at Nelemnoye village. Since the Kolyma River's flow is regulated, data on the volumes of water discharge through the Kolymskaya HPP dam from 1979-2020 were also used (Fig. 1).

The necessary daily values of air temperature, precipitation, and humidity deficit for the model were taken from observation archives at 37 meteorological stations (Fig. 1).

After calibration and verification of the model, a version of the ECOMAG model was launched in which it is not necessary to specify the air humidity deficit as input information. The deficit is calculated using an approximate formula based on air temperature and precipitation in accordance with Motovilov et al. 2022:

$$d = 2 \cdot e^{(0.08t - 0.1p)}$$

where *d* is a daily air humidity deficit, hPa; *t* is a daily air temperature, °C; *p* is a daily precipitation, mm.

This version of the model was used for 2014-2020, for which there was no data on the air humidity deficit.

RESULTS AND DISCUSSION

Application of the Model of runoff formation for the Kolyma River Basin

Calibration of the ECOMAG model parameters was conducted using average daily water discharge data from 1979–1999 for two gauging stations on the Kolyma River (Srednekolymsk and Kolymskoye-I), as well as for the Bolshoy Anyuy River (Konstantinovskaya) and the Yasachnaya River (Nelemnoye). The calibration was performed simultaneously for all stations, ensuring the model contains a consistent set of parameters.

For verification, independent data – water discharges at the studied posts from 2000–2020 – were used. To evaluate the quality of the ECOMAG model calculations, the Nash and Sutcliffe criterion *NSE* (Nash, Sutcliffe 1970), a commonly used efficiency coefficient for assessing model performance, and the bias (*BIAS*) were applied. The formulas for these calculations are as follows:

$$NSE = 1 - \frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - \bar{Q}_{obs})^2}$$

$$BIAS = \frac{\bar{Q}_{sim} - \bar{Q}_{obs}}{\bar{Q}_{obs}} \cdot 100\,\%$$

where Q_{obs} and Q_{sim} are the observed and simulated daily water discharges, respectively.

In addition to the Nash and Sutcliffe criterion and bias, the coefficients of determination R^2 for the relationship between observed and simulated monthly runoff volumes were also calculated (Table 1, Fig. 2, Fig. 3).

The obtained criteria values were compared with those accepted in practice: thus, when the *NSE* values exceed the practical threshold of 0.75 and |*BIAS*|, the quality of model calculations is considered good. Values with *NSE* ranging from 0.5 to 0.75 and |*BIAS*| from 10% to 15% are deemed satisfactory (Motovilov, Gelfan, 2018). During the calibration of the model parameters, the above quality criteria were calculated for four cross-sections and averaged proportionally to the basin area for each cross-section.

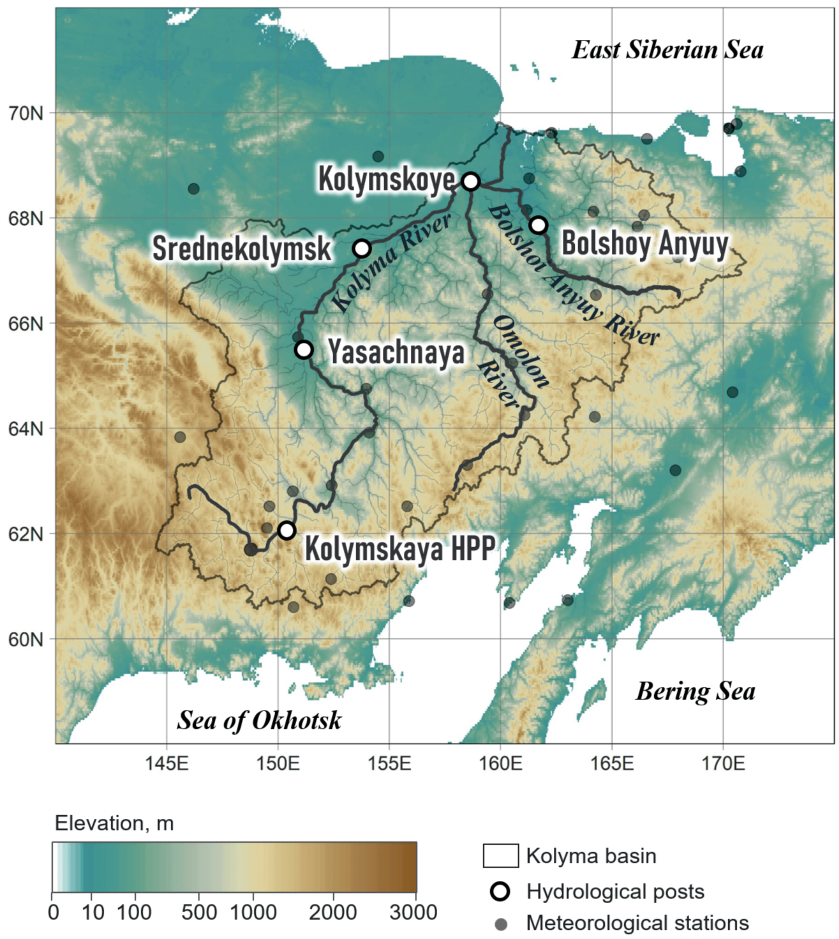

Fig. 1. The Kolyma River basin with the locations of hydrological (gauging) stations whose archives were used for the calibration and verification of the model of runoff formation

Table 1. Values of the performance criteria for daily and monthly runoff calculations in the Kolyma River basin for the calibration and verification periods

Hydrological Station	Basin area, ths. km²	Distance from Mouth/ Source, km	Calibration Period 1979–1999				Verification Period 2000–2020			
			daily		monthly		daily		monthly	
			NSE	*BIAS, %*	*NSE*	R^2	*NSE*	*BIAS, %*	*NSE*	R^2
Kolyma – Kolymskoye-I	526	283/1846	0.90	1.6	0.95	0.95	0.82	1.9	0.94	0.96
Kolyma – Srednekolymsk	361	641/1488	0.87	5.1	0.95	0.94	0.84	-1.3	0.95	0.96
Bolshoy Anyuy – Konstantinovskaya	49.6	67/626	0.51	5.2	0.87	0.87	0.51	7.3	0.75	0.79
Yasachnaya – Nelemnoye	32	80/410	0.57	4.1	0.63	0.91	0.53	6.8	0.58	0.89

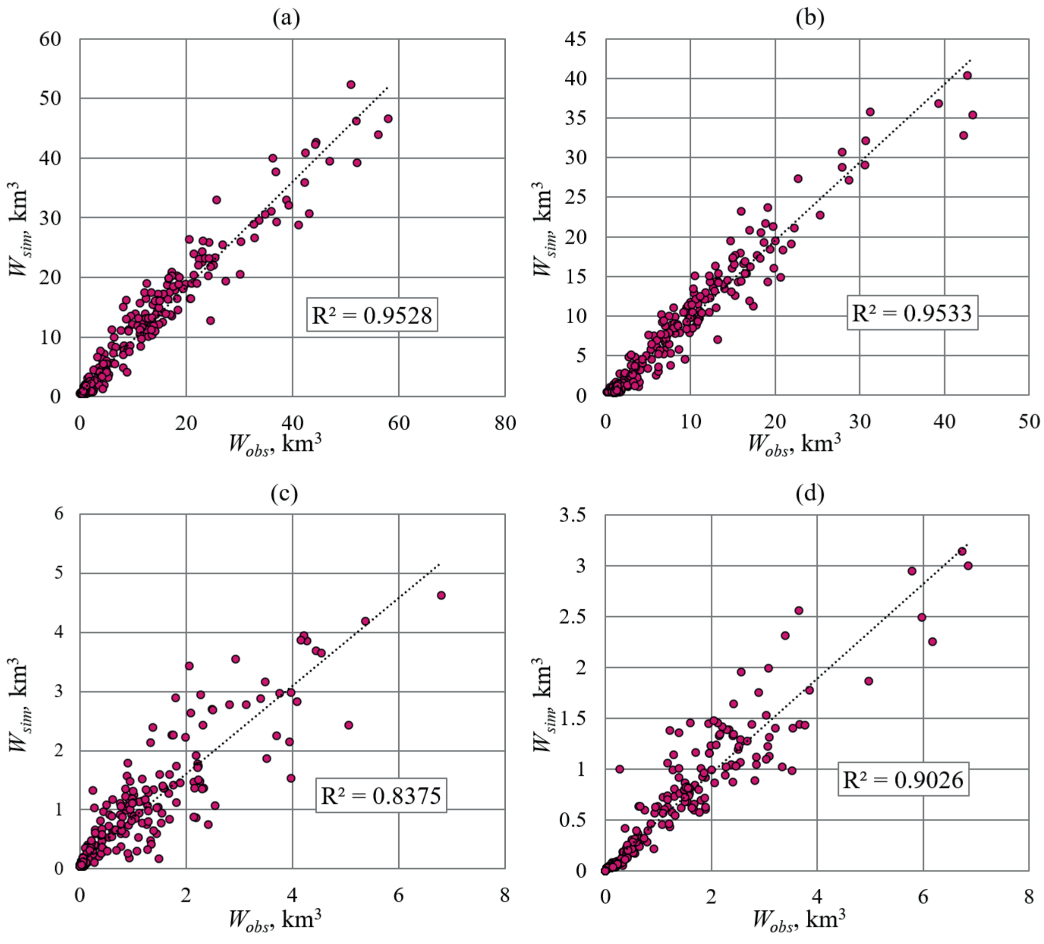

Fig. 2. The relationship between observed and simulated monthly runoff volumes for the calibration and verification period: (a) for the Kolyma River at the Kolymskoye-I; (b) for the Kolyma River at Srednekolymsk; (c) for the Bolshoy Anyuy River at Konstantinovskaya station; (d) for the Yasachnaya River at Nelemnoye village

The calculations demonstrated (Table 1) that the ECOMAG model shows good fit of observed water discharges for both cross-sections on the Kolyma River (at Srednekolymsk and the Kolymskoye-I hydrological post). For these cross-sections, the Nash-Sutcliffe efficiency during the verification period was 0.84 and 0.82, respectively, with bias of -1.3% and 1.9%, respectively. The quality of calculations for tributaries with smaller catchment areas (the Bolshoy Anyuy River at Konstantinovskaya station and the Yasachnaya River at Nelemnoye village) was worse, being satisfactory according to the accepted gradations.

In the figure below (Fig. 4), typical hydrographs are presented, the ordinates of which are obtained as the average water discharge for each date for the periods 1979–1999 and 2000–2020. The hydrographs illustrate the ECOMAG model's good reproduction of intra-annual runoff changes observed in recent decades: shifts in the flood wave to earlier dates, later onset of winter low flow, and increased flow in the second half of August to October. However, the calculated changes in maximum water discharges do not coincide with the observation data: for Srednekolymsk, maximum discharges according to observed data practically did not change, while the model shows an increase of 7%; for Kolymskoye-I, observed maximum discharges increased by 15%, while simulated ones increased by 10%.

The annual runoff volumes of the ECOMAG model are best reproduced for Srednekolymsk, which is explained by the large watershed area for this station, exceeding the watershed areas of the Bolshoy Anyuy and Yasachnaya rivers, as well as the fact that at the Srednekolymsk station, unlike the Kolymskoye-I hydro

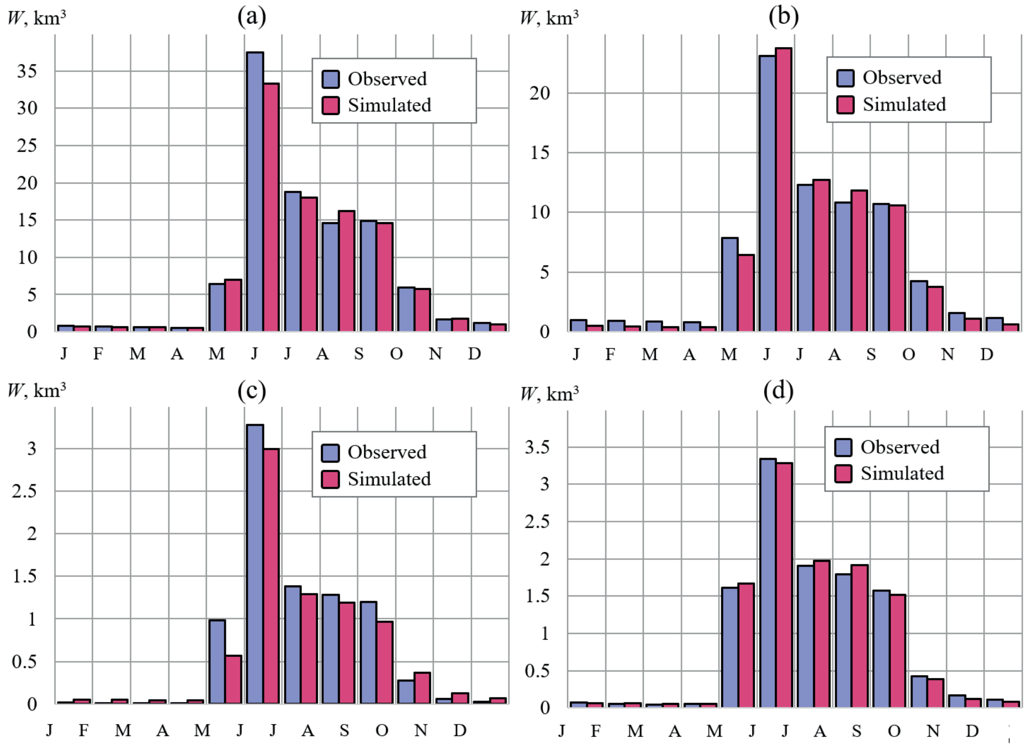

Fig. 3. Observed and simulated mean monthly runoff volumes for the verification period: (a) for the Kolyma River - Kolymskoye-I, (b) for the Kolyma River - Srednekolymsk, (c) for the Bolshoy Anyuy River – Konstantinovskaya station, (d) for the Yasachnaya River – Nelemnoye village

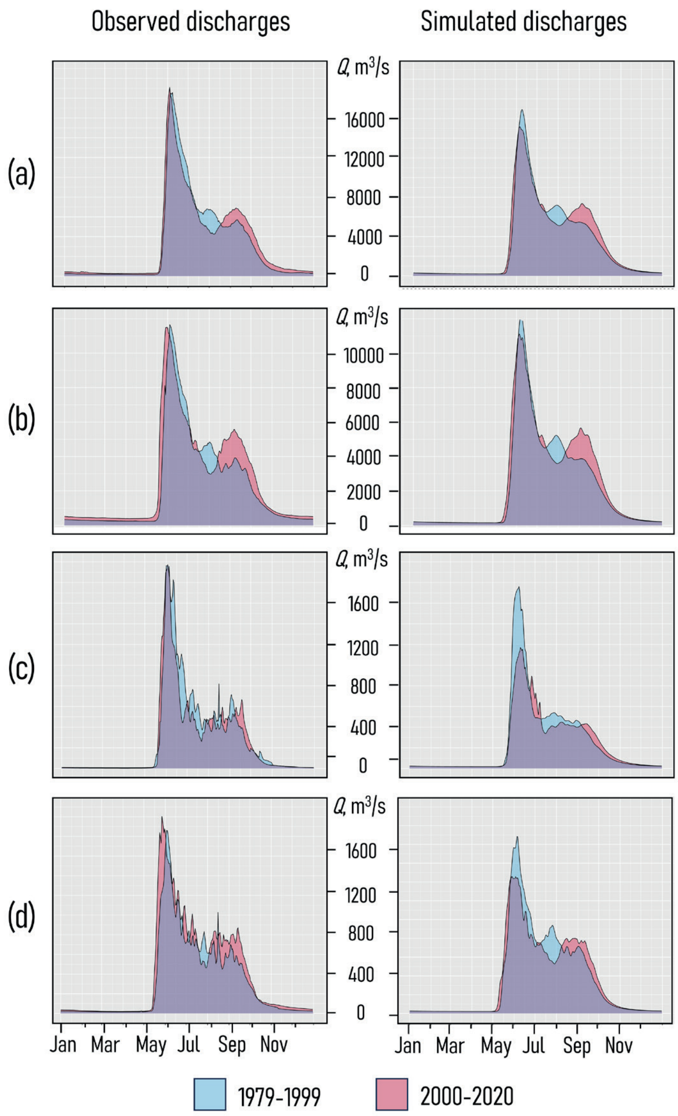

Fig. 4. Observed and simulated typical hydrographs for the periods 1979-1999 and 2000-2020 for studied stations

station, water discharges are calculated based on flow velocity measurements rather than being reconstructed based on the relationship *Q=f(H)*.

The results of the model calculation in the absence of data on air humidity deficit

When running the model with the calculation of the air humidity deficit, the quality of the calculations decreased but remained at a satisfactory level. For the Kolyma station – Kolymskoye, the Nash-Sutcliffe criterion decreased from 0.87 to 0.77, and the bias decreased from 1.9% to -16.3%. For the Kolyma River – Srednekolymsk station, the Nash-Sutcliffe criterion decreased more significantly, from 0.85 to 0.67, and the bias reached -17.9%. However, for the Bolshoy Anyuy River – Konstantinovskaya station, the calculation without using observed air humidity deficit did not decrease accuracy: the Nash and Sutcliffe criterion remained unchanged, and the BIAS changed from 5.5% to -2.7% (Table 2). The model with the calculation of the air humidity deficit was used for 2014-2020, as there was no data on the air humidity deficit.

Thus, despite the systematic underestimation of results, the application of the model version that calculates air humidity deficit allows obtaining satisfactory quality results. This indicates the feasibility of using this version of the ECOMAG model in the absence of observed data on humidity deficit.

Assessment of changes in the Kolyma River discharge based on global climate models

Historical simulations

To evaluate the hydrological consequences of climate change in the Kolyma River basin, the results of an ensemble of four global climate models (GCMs) were used: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, which are part of the CMIP5 project (Coupled Model Intercomparison Project Phase 5) (IPCC 2013).

To confirm the reliability of future climate scenario calculations by global models, a comparison was made between GCMs results for the historical period and observational data. Since the ensemble data for most climate models contain information up to 2006, the historical period considered was 1975-2004.

The GCMs data slightly smooth the annual temperature cycle. According to meteorological station data, the annual amplitude of monthly temperatures reaches 46.8°C (+14.1°C in July and -32.7°C in January), while according to climate models, the amplitude is 36.9°C (+10.2°C in July, -26.7°C in January). However, the annual mean values differ insignificantly. Climate models overestimate annual precipitation, most notably in November, October, and April (Table 3).

Table 2. Nash and Sutcliffe criterion and bias for daily streamflow calculation in the Kolyma River basin in various versions of the ECOMAG model from 1979-2013

Hydrological Stations	Air Humidity Deficit from Meteorological Stations Data		Calculated Air Humidity Deficit	
	NSE	*BIAS, %*	*NSE*	*BIAS, %*
The Kolyma River – Kolymskoye	0.87	1.9	0.77	-16.3
The Kolyma River – Srednekolymsk	0.85	-1.3	0.67	-17.9
The Bolshoy Anyuy River – Konstantinovskaya	0.51	5.5	0.51	-2.7
The Yasachnaya River – Nelemnoye	0.55	5.5	0.50	-4.8

Table 3. Monthly and annual air temperature and precipitation observed at meteorological stations and calculated from the ensemble of GCMs (average values for 1975-2004)

Month	Air temperature,°C		Precipitation, mm	
	Meteorological stations	Climate models	Meteorological stations	Climate models
January	-32.7	-26.7	17.3	19.2
February	-32.1	-25	15.3	17.2
March	-23.8	-19.0	14.9	17.8
April	-12.2	-9.9	13.3	24.3
May	1.7	-0.3	20.0	32.3
June	11.2	6.9	43.0	49.7
July	14.1	10.2	63.6	70.8
August	10.4	9.5	61.2	85.6
September	3.1	4.0	40.1	61.4
October	-10.4	-7.0	27.8	66.2
November	-24.7	-18.5	28.4	53.8
December	-32.8	-24.9	19.6	24.6
Annual	-10.7	-8.4	364	523

These differences result in a delayed onset of spring floods and a slightly higher maximum discharge according to GCMs compared to observed data. The table 4 presents the bias between observed water discharges (1) and those modelled by ECOMAG using two versions of forcing data: measured at meteorological stations (2) and simulated by GCMs (3). For data simulated by GCMs the most significant errors in May (see bias between (1) and (3)) are associated with inaccuracies in reproducing the timing of spring floods by ECOMAG model using forcing data from global climate models. When calculating from the observed meteorological data, the errors are less (see bias between (1) and (2)). Despite such differences in calendar terms, the flood volume is calculated with significantly smaller errors. The error in calculating the annual discharge volume is within 10% (Table 4). To avoid errors associated with inaccurate calculations of interannual discharge variability by GCMs, multi-year average values of hydrological characteristics were considered to assess the general trend in discharge changes in the 21st century.

Projections

For possible variations in meteorological characteristics in the 21st century, four greenhouse gas emission scenarios were considered – RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5. Daily air temperature and precipitation values for each model from the GCMs ensemble were used as input data for the runoff formation model for the Kolyma River. Then the series of runoff values calculated for each model were averaged. When analyzing anomalies in meteorological variables and hydrological characteristics, mean values were calculated for four twenty-year periods (2020–2039, 2040–2059, 2060–2079, 2080–2099) and compared with calculations for the historical period (1975–2004).

To illustrate possible climate changes, average air temperature and precipitation for the Kolyma River basin were calculated, and then the deviation of average meteorological values for twenty-year periods of the 21st century from the historical period (1975–2004) was determined. For example, with an average air temperature of -13.6°C in 1975–2004, by the end of the 21st century, models predict a temperature rise of 3.5–8.4°C depending on the scenario. According to GCMs, the amount of precipitation relative to 334 mm for the historical period will decrease slightly in 2020–2039 and increase by 0.4–28.9% by the end of the century (Table A1).

To assess the hydrological response to climate change, the ECOMAG model of runoff formation was launched using meteorological data series for the 21st century from GCMs. For the four studied stations (on the Kolyma River, as well as tributaries of the Bolshoy Anyuy and Yasachnaya rivers), anomalies of annual discharge (Fig. 5), maximum water discharge (Fig. 6), and volumes of discharge in the summer-autumn period, summer, and winter low-flow periods (Table A2) were calculated for twenty-year periods of the 21st century (2020–2039, 2040–2059, 2060–2079, 2080–2099).

Under any greenhouse gas emission scenarios, an increase in the annual discharge volumes of the studied rivers was obtained, more pronounced for the Kolyma and Yasachnaya, and less noticeable for the Bolshoy Anyuy (Fig. 6). For example, under the RCP 2.6 scenario during the 21st century (from 1975–2004 to 2080–2099), the Kolyma discharge at the Kolymskoe-I demonstrates an increase of 13.5%, and at the Srednekolymsk station – 15.0%. On the Yasachnaya River, the increase is 16.5%, and on the Bolshoy Anyuy River – 9.0%. Under the RCP 8.5 scenario, the annual discharge by the end of the century will increase by 47.2% for the Kolyma, 54.3% for Srednekolymsk, 26.0% for Bolshoy Anyuy, and 62.2% for Yasachnaya.

When considering mean values for twenty-year periods, a nonlinear trend in hydrological regime changes is observed. For example, under the RCP 4.5 and RCP 6.0 scenarios, the most rapid changes occur between 2040–2059 and 2060–2079.

Expected changes in summer-autumn discharge for the studied rivers correlate well with the dynamics of

Table 4. Monthly and annual water discharges observed at the Kolymskoye gauging station and calculated with forcing data from the ensemble of GCMs and meteorological stations (average values for 1975-2004)

Month	Observed water discharge (1), m^3/s	Calculated water discharge according to meteorological stations (2), m^3/s	Calculated water discharge according to climate models (3), m^3/s	Bias between (1) and (2), %	Bias between (1) and (3), %
January	269	266	298	-1.12	10.8
February	225	233	249	3.56	10.7
March	214	216	223	0.93	4.2
April	189	206	210	8.99	11.1
May	2040	2060	678	0.98	-66.7
June	15100	12800	17800	-15.2	17.7
July	7410	6760	8670	-8.77	17.0
August	5450	5770	6410	5.87	17.6
September	4940	4890	4890	-1.01	-1.01
October	1830	1920	1830	4.92	0.0
November	487	627	634	28.7	30.2
December	356	349	367	-1.97	3.1
Annual	3200	3090	3510	-3.44	9.7

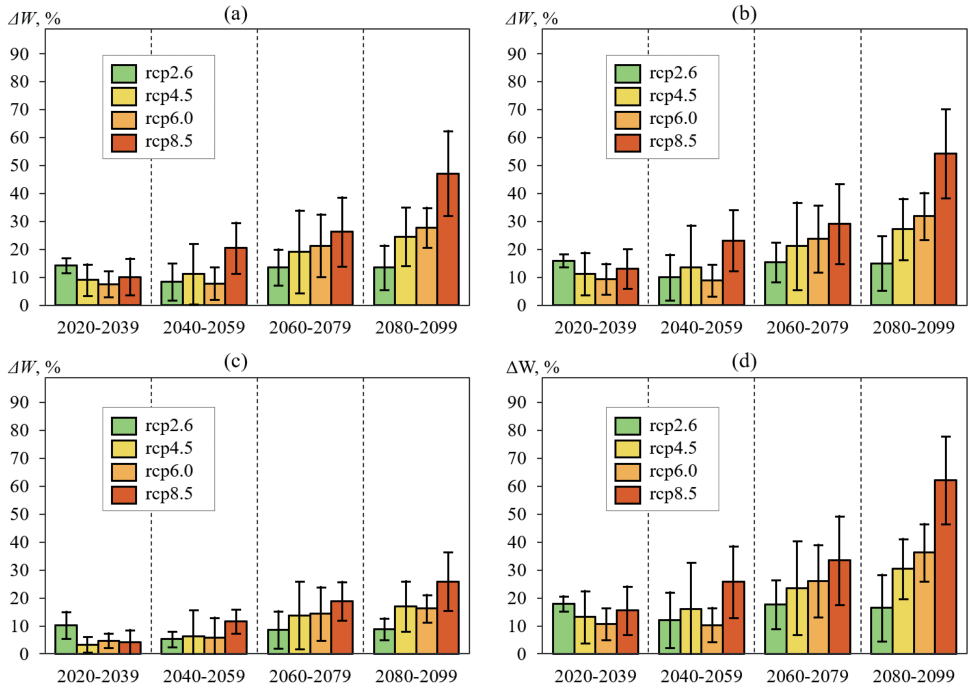

Fig. 5. Changes in the annual discharge volume for the 21st century periods under various greenhouse gas emission scenarios relative to the historical period: (a) for the Kolyma River – Kolymskoe-I; (b) for the Kolyma River – Srednekolymsk town; (c) for the Bolshoy Anyuy River – Konstantinovskaya station; (d) for the Yasachnaya River – Nelemnoye village

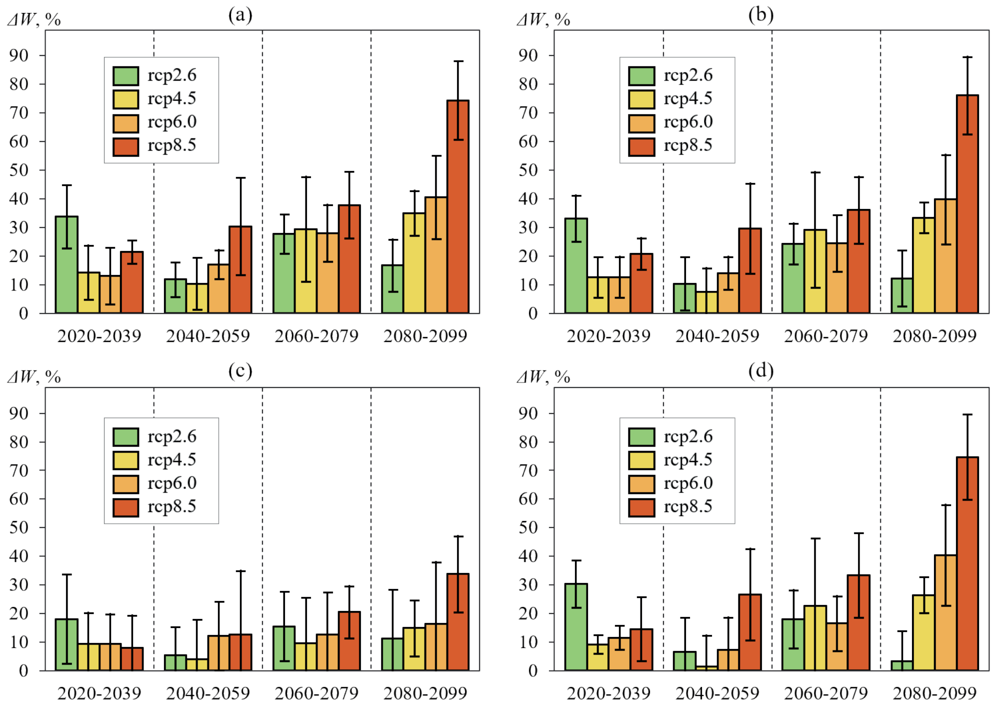

Fig. 6. Changes in maximum water discharge for the 21st century periods under various greenhouse gas emission scenarios relative to the historical period: (a) for the Kolyma River – Kolymskoe-I; (b) for the Kolyma River – Srednekolymsk town; (c) for the Bolshoy Anyuy River – Konstantinovskaya station; (d) for the Yasachnaya River – Nelemnoye village

annual discharge, although the summer-autumn discharge changes are less pronounced. Winter low-flow volumes are most affected by climate changes for the Bolshoy Anyuy River: by the end of the 21st century, calculations show an increase of 2.2% to 71.9% for the RCP 2.6 and RCP 8.5 scenarios, respectively. Maximum water discharges during the 21st century exceed values for the historical period. Under the RCP 2.6 scenario, the highest discharges are typical for 2020–2039, followed by a decrease.

Considering the RCP 4.5 scenario as the most likely (van Vuuren D.P. et al. 2011), the annual discharge of the studied rivers will steadily increase throughout the 21st century, and by 2080–2099, an increase of approximately a quarter can be expected for the Kolyma, 17% for the Bolshoy Anyuy, and 31% for Yasachnaya. Full results of the expected discharge changes calculation are presented in Table A1.

CONCLUSIONS

Physiclly based models of river runoff formation allow the study of river regime responses to ongoing and projected climate changes. The ECOMAG model was calibrated for the Kolyma River basin, the largest Russian river in the zone of continuous permafrost and the fourth largest by catchment area among the rivers of the Arctic Ocean basin.

Calibration and validation of the model demonstrated good fit of observed data for two sites on the Kolyma River and sites on its tributaries (Bolshoy Anyuy River and Yasachnaya River). In particular, the model accurately reproduces intra-annual runoff variations since 1979. This enabled the use of the model to assess possible changes in the runoff of the Kolyma River and its tributaries in the 21st century.

Air temperature and precipitation values for the 21st century were obtained for the Kolyma basin from an ensemble of four global climate models. By the end of the century, an increase in temperature of 3.5–8.4 ºC and an increase in precipitation of 0.4–28.9% can be expected, depending on the RCP radiation forcing scenario. Calculations were made for anomalies of annual runoff, maximum water discharge, and the volume of runoff during the winter low-water period and summer-autumn period under such changes in climatic characteristics in the Kolyma basin. It is shown that under any scenario, an increase in the annual runoff of the studied rivers can be expected: for the Kolyma River the increase is estimated at 13.5–47.2%, depending on the scenario, for the Bolshoy Anyuy – at 9.0–26.0% and for the the Yasachnaya River – at 16.5–62.2%. At the same time, an increase in summer-autumn flows, maximum discharges and winter low-flow volumes on the Kolyma River and its tributaries is expected in the 21st century, most noticeable under RCP 8.5 scenario.

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APPENDICES

Table A.1. Changes in hydrological regime characteristics of the Kolymskoe station for the 21st century periods under various greenhouse gas emission scenarios.

Period	RCP	Air temperature anomalies (ºC)	Precipitation Anomalies (%)	Annual discharge anomalies (%)	Maximum water flow anomalies (%)	Summer-autumn discharge volume anomalies (%)	Winter low-flow discharge volume anomalies (%)
Kolyma - Kolymskoe							
Relative to 1975-2004 Norm		-13.6 ºC	344 mm	109 km^3	23200 m^3/s	45.3 km^3	6.27 km^3
2020-2039	2.6	3.1	-0.2	14.2	19.8	15.7	2.3
	4.5	2.8	-4.3	9.0	11.8	11.8	-0.3
	6.0	2.9	-3.5	7.6	7.2	7.6	0.0
	8.5	3.3	-2.2	10.1	8.5	9.2	0.9
2040-2059	2.6	3.6	-0.7	8.3	6.1	9.7	9.9
	4.5	3.9	1.7	11.2	4.7	13.0	11.6
	6.0	3.3	-1.6	7.8	4.4	8.2	7.9
	8.5	4.8	8.0	20.4	16.1	19.8	15.7
2060-2079	2.6	3.3	0.6	13.6	14.5	11.2	0.5
	4.5	4.6	7.3	19.1	17.2	16.2	4.7
	6.0	4.6	7.8	21.3	17.8	21.9	8.4
	8.5	6.4	14.1	26.3	21.2	20.1	12.8
2080-2099	2.6	3.5	0.4	13.5	7.2	12.2	0.8
	4.5	4.7	9.0	24.6	20.1	25.1	6.9
	6.0	5.8	11.9	27.8	17.7	23.3	8.6
	8.5	8.4	28.9	47.2	35.7	34.2	31.4

Table A.2 (continued). Changes in hydrological regime characteristics of studied stations for the 21st century periods under various greenhouse gas emission scenarios

Period	RCP	Annual discharge anomalies (%)	Maximum water flow anomalies (%)	Summer-autumn discharge volume anomalies (%)	Winter low-flow discharge volume anomalies (%)
Kolyma - Srednekolymsk					
Relative to 1975-2004 norm		69.1 km^3	15500 m^3/s	26.0 km^3	4.07 km^3
2020-2039	2.6	16.0	16.5	19.0	1.7
	4.5	11.3	8.7	16.1	-0.4
	6.0	9.3	1.9	11.0	-0.2
	8.5	13.0	8.9	13.5	0.5
2040-2059	2.6	10.0	3.3	12.6	10.0
	4.5	13.6	0.9	17.7	11.7
	6.0	8.9	0.4	10.6	8.1
	8.5	23.2	13.2	23.0	15.0
2060-2079	2.6	15.4	10.3	13.8	0.2
	4.5	21.2	17.0	18.6	4.2
	6.0	23.7	17.2	25.2	7.1
	8.5	29.2	21.3	23.4	10.9
2080-2099	2.6	15.0	3.3	15.2	0.2
	4.5	27.3	19.5	28.7	5.9
	6.0	31.9	14.5	28.5	7.8
	8.5	54.3	39.1	41.0	30.5
Bolshoy Anyuy - Konstantinovskaya					
Relative to 1975-2004 norm		15.8 km^3	3140 m^3/s	6.51 km^3	0.647 km^3
2020-2039	2.6	10.4	8.7	9.7	3.7
	4.5	3.4	4.0	3.0	-0.3
	6.0	4.8	2.9	3.5	1.3
	8.5	4.3	-1.5	2.2	4.5
2040-2059	2.6	5.3	2.4	4.1	10.6
	4.5	6.3	-0.5	4.2	16.4
	6.0	5.9	0.8	2.4	12.0
	8.5	11.7	-0.1	12.5	23.8
2060-2079	2.6	8.7	5.1	6.2	1.5
	4.5	13.9	-2.2	12.7	9.2
	6.0	14.4	-1.5	15.9	12.2
	8.5	19.0	1.9	16.2	36.7
2080-2099	2.6	9.0	-2.8	8.3	2.2
	4.5	17.1	2.4	18.5	16.8
	6.0	16.4	4.9	12.7	27.6
	8.5	26.0	-0.5	21.5	71.9

Table A.2 (continued). Changes in hydrological regime characteristics of studied stations for the 21st century periods under various greenhouse gas emission scenarios.

Yasachnaya - Nelemnoye					
Relative to 1975-2004 norm		5.05 km^3	1190 m^3/s	1.74 km^3	0.272 km^3
2020-2039	2.6	18.0	14.0	23.7	-3.7
	4.5	13.2	7.2	20.8	-5.3
	6.0	10.7	-2.0	14.6	-5.4
	8.5	15.5	5.9	18.4	-4.7
2040-2059	2.6	12.2	-0.1	15.5	8.2
	4.5	16.1	-3.6	23.6	11.2
	6.0	10.4	-6.5	13.0	6.8
	8.5	25.8	9.9	25.7	11.4
2060-2079	2.6	17.7	1.9	17.2	-4.4
	4.5	23.6	16.2	22.4	0.5
	6.0	26.2	12.6	29.8	-0.2
	8.5	33.4	16.4	29.2	5.6
2080-2099	2.6	16.5	-5.4	20.4	-4.3
	4.5	30.5	13.0	33.8	0.3
	6.0	36.3	10.5	35.1	6.4
	8.5	62.2	41.8	51.5	26.5