Oceanologia, uncorrected, in press
Polish Academy of Sciences
Institute of Oceanology
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https://doi.org/10.5697/PORP9186

Lowland catchment runoff response to climate change under CMIP6 in the Baltic region

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Abstract

Record or near-record high or low river flows are more often observed in different regions of the world. A thriving society must understand the magnitude of these changes in the future, mitigate their negative impacts, and be prepared to live in a different world. That is why qualified, constantly updated scientific projections of future changes are essential. Neither Lithuania nor the other Baltic countries have yet assessed runoff changes according to the latest climate change projection tools outlined in the IPCC 6th AR on climate change. In this study, the HBV model was used to project potential changes in river runoff. The ranking procedure was developed and used to select the best-fit GCMs that most accurately reproduced the climate conditions of Lithuania. Due to the anticipated changes in climatic factors affecting the studied rivers, the average annual discharge is projected to decrease by 12 to 42%, depending on the hydrological region (i.e., the conditions of river runoff formation) and the selected future period. High flows (Q5) are likely to decline very similarly to the annual ones, while low flows (Q95) are expected to decrease by approximately two-thirds compared to the reference period. An uncertainty analysis of the projections revealed that GCMs contributed up to two-thirds of the total uncertainty in the final results.

Keywords

River runoff; Climate change; CMIP6; HBV

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Received: 10 April 2025; **revised:** 8 November 2025; **accepted**: 12 November 2025

1. Introduction

The sustainable development of human society and the prosperity of all living organisms are highly dependent on the availability of water resources. In achieving the Sustainable Development Goals, water is positioned at front-and-center in the water-energy-food nexus systems (Susnik et al., 2023). An overwhelming amount of scientific evidence indicates the detrimental impact of ongoing changes on irreversible processes in planet ecosystems (Bongaarts, 2019; Lennox et al., 2019; Dialogue Earth, 2022; IPCC, 2023a). Freshwater ecosystems are particularly vulnerable to human-induced climate change because (i) their species have limited dispersal potential as the environment changes, (ii) water temperature and availability depend on climate, and (iii) many of these systems are already exposed to multiple anthropogenic stressors (Woodward et al., 2010). Rivers are essential providers of ecosystem services; therefore, understanding how climate change affects river hydrological processes is crucial (Yeakley et al., 2016; Etukudoh et al., 2024).

According to the most comprehensive climate change analysis published in the IPCC Sixth Assessment Report (AR6) (Calvin et al., 2023), there are no clear trends in changing streamflow at the global level. However, regional trends do emerge, with a generally increasing trend in the northern high-latitude regions and mixed trends in the rest of the world. Researchers are constantly looking for a regularity or pattern that may help them understand the processes. The runoff formation process is very complex, and even well-established hypotheses such as the DDWW (dry regions get drier and wet regions wetter) paradigm (Held and Soden, 2006), which explains many tendencies, are challenged by both observational data and modeling studies (Yang et al., 2019; Xiong et al., 2022).

Strong deviations in river flow from long-term historical patterns manifest as floods and droughts, posing challenges to households, public health, agriculture, energy, transportation sectors, and many other vital sectors of human life. The most recent report on the European State of the Climate, released jointly by the Copernicus Climate Change Service and the World Meteorological Organization (C3S, 2024), states that since the 1980s, Europe has warmed at twice the global average rate, making it the

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fastest-warming continent on Earth. Key findings include that nearly a quarter of the river network experienced "exceptionally high" flows in December. Record or near-record discharges were observed in major river catchments, including the Loire, Rhine, and Danube, largely due to a series of storms from October to December. In contrast, drought conditions were reported in catchments such as the Ebro, which had near-record low discharges in May, and the Po, which experienced below-average flows throughout the year, with near-record lows from February to April (C3S, 2024). Facing such dramatic changes, it is crucial to understand how altered river flows and their extremes may evolve in the future as the potential costs of inaction may be enormous. According to the European Environmental Agency (EEA, 2023), between 1980 and 2022, weather- and climate-related extreme events caused economic losses of assets estimated at EUR 650 billion in the EU Member States, of which EUR 59.4 billion occurred in 2021 and EUR 52.3 billion in 2022. Estimates show that each additional 0.5°C of warming in China alone is projected to increase flood-related losses by $67 billion, on average (Jiang et al., 2020). Therefore, growing concerns worldwide compel us to take action to increase resilience and adaptability to future changes. To ensure a sustainable approach to water systems management, the impacts of projected climate change must be understood and incorporated into regional water management strategies (Döll et al., 2015). That is why, living in such a rapidly changing environment, decision-makers need reliable and up-to-date projections of changes in the hydrological regime, along with assessments of the associated uncertainties (Lane and Kay, 2021).

With increasing data and research experience, scientists are rushing to improve and update climate change projections and periodically undertake large-scale model comparisons with the latest and most sophisticated models to better understand the climate system's response to a range of potential emission or concentration scenarios (Meinshausen et al., 2020). The IPCC Sixth Assessment Report (IPCC, 2023b) that gives the most complete information available on the subject to date has been called the starkest warning yet about unprecedented global changes (The Guardian, 2021). Along with the latest IPCC report, new state-of-the-art global climate models, known as CMIP6 models (Coupled Model Intercomparison Projects), were released. In addition, scenarios from CMIP5, known as Representative Concentration Pathways, were replaced with a new range of scenarios based on Shared Socioeconomic Pathways (SSPs) (IPCC, 2023a).

Research on river runoff projections is evolving in parallel with growing knowledge of global climate change. Using hydrological models enhances climate change impact assessments by capturing the spatial and seasonal variability in hydrological responses (Piniewski et al., 2018). Each study typically relies on the most up-to-date generation of climate scenarios and hydrological models, which are selected according to individual criteria (Clark et al., 2017). In Lithuania, projections of river runoff were based on the Special Report on Emissions Scenarios (SRES) (Kriaučiūnienė et al., 2008; Kriaučiūnienė et al., 2013) and the Representative Concentration Pathways scenarios (Stonevičius et al., 2017; Šarauskienė et al., 2018; Kriaučiūnienė et al., 2019; Jakimavičius et al., 2020; Akstinas et al., 2020). To date, the studies mentioned above for runoff predictions have used regional climate models (RCMs). However, according to the IPCC AR6, only global climate models (GCMs) are currently available. The present study was designed to determine the effect of a changing climate on Lithuanian lowland river runoff according to CMIP6-based GCMs. Many studies have shown that GCMs are the most versatile and effective tools for creating possible future climate scenarios (Bian et al., 2021). Each release of a new suite of GCMs (Eyring et al., 2016), updated with the latest findings, provides an opportunity to reassess the impact of a changing climate on the environment and society. Because the performance of GCMs is site-specific, researchers in different countries employ different procedures to select those that work best for the country or region they are studying. Accomplished studies in different countries reveal different best-performing GCMs with respect to temperature or precipitation indices (Raju and Kumar, 2020; Iqbal et al., 2021; Kurniadi et al., 2023; Nguyen-Duy et al., 2023; Rivera, 2024; Anil et al., 2024; Bhanage et al., 2024; Tariq et al., 2024). However, a major limitation of global climate models is their coarse spatial resolution, typically exceeding $1° \times 1°$, which is insufficient to capture local climatic factors that govern river runoff formation. Therefore, the research team (Gebrechorkos et al., 2023) reduced the grid size to 0.25° using statistical downscaling. The global climate models modified in this way could be used to simulate runoff projections in lowland river catchments.

Neither Lithuania nor the other Baltic countries have evaluated runoff changes according to the newest climate change research tools presented in the IPCC AR6. Therefore, this study examines the impact of climate change on lowland river runoff for the first time by using SSPs and new GCMs. From a set of 18 models, three GCMs that best correspond to the natural conditions of Lithuania were selected based on a proposed ranking procedure. This work will generate fresh insight into potential changes in average and extreme river discharge values in the near and far future for lowland rivers. Uncertainties in river runoff projections arising from the selected climate scenarios and global climate models will be assessed. In the absence of regional climate models, the developed methodology for applying global climate models could be effectively used for other lowland catchments.

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2. Materials and methods

2.1 Study area and data

The objects of this study are the Nemunas River and its major tributaries: Merkys, Neris, Nevėžis, Dubysa, Šešupė, Jūra, and Minija (Figure 1). The main characteristics of the rivers included in the hydrological modeling are presented in Table 1. As the water gauging stations of these rivers are located at elevations of up to 78 meters above sea level, the rivers are classified as lowland rivers. The area of the Nemunas catchment at its mouth is 97,928 km^2, and an average discharge into the Curonian Lagoon is 605 m^3 s^{-1}. The areas of the Nemunas sub-catchments range from 1,220 to 24,500 km^2, with average discharges varying between 14 and 160 m^3 s^{-1}. Table 1 also presents the feeding sources of the studied rivers and the seasonal distribution of runoff (expressed as a percentage of the annual runoff). In the studied region, river runoff is formed by groundwater, snow, and rainfall (Akstinas et al., 2022). Groundwater supply is represented by G, snow by S, and rainfall by R. The dominant feeding source is indicated by a capital letter, while the following feeding sources are marked with lowercase letters. For example, if groundwater is the dominant source of river runoff, while snow and rainfall contribute a smaller portion, it is marked as G-sr. The distribution of runoff throughout the year was studied over three periods previously proposed by Gailiušis et al. (2001).

For the development of hydrological models, daily precipitation (P, mm) and air temperature (T, °C) data from 14 meteorological stations (MS) (1. Dotnuva, 2. Kaunas, 3. Klaipėda, 4. Laukuva, 5. Lazdijai, 6. Panevėžys, 7. Raseiniai, 8. Šilutė, 9. Šiauliai, 10. Telšiai, 11. Ukmergė, 12. Utena, 13. Varėna, and 14. Vilnius) as well as daily discharges (Q, m^3 s^{-1}) from 11 water gauging stations (WGS) (1. Nemunas-Druskininkai, 2. Merkys-Puvočiai, 3.

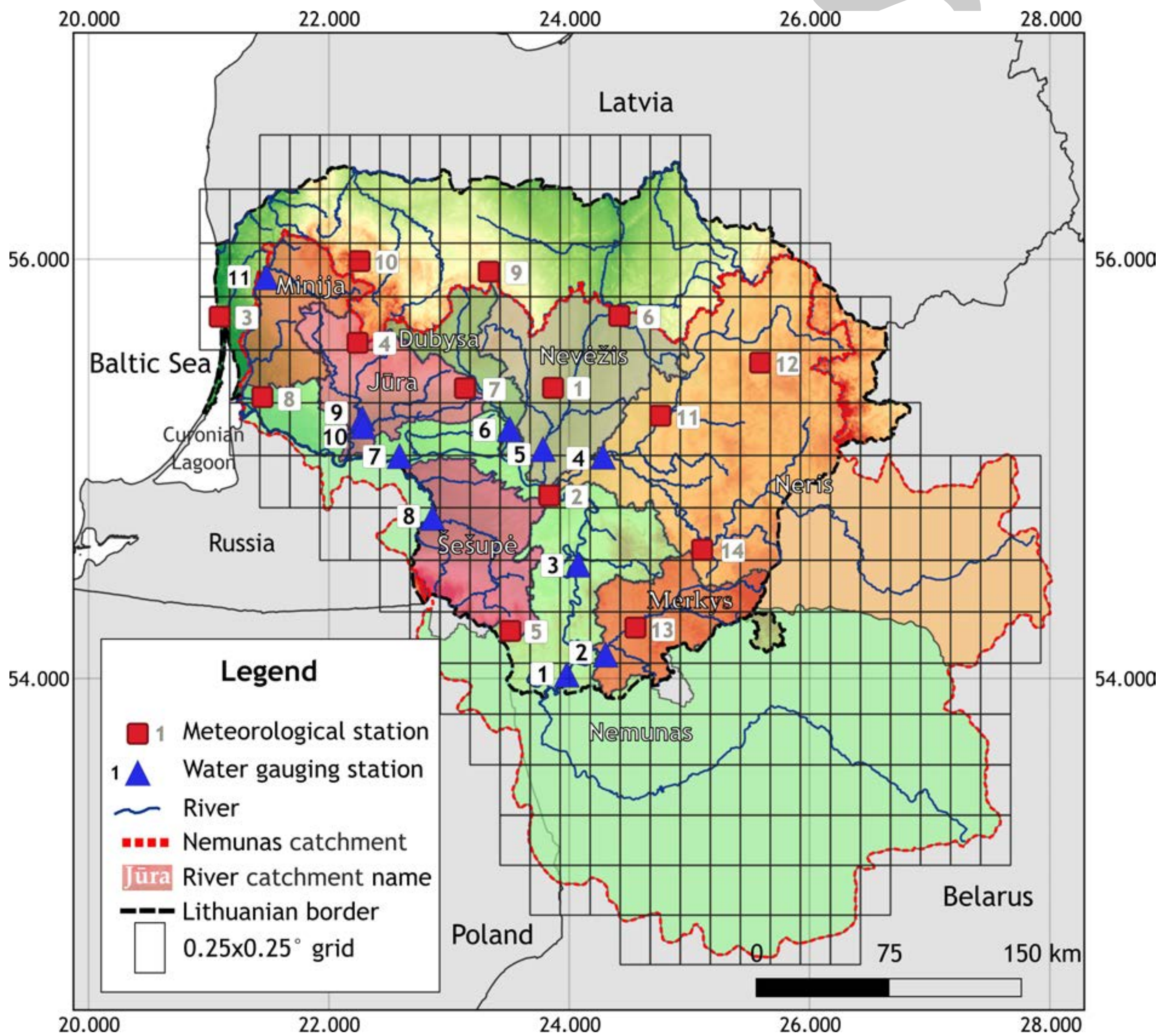

Figure 1. The Nemunas River catchment and subcatchments, meteorological and water gauging stations.

Table 1. Main characteristics of the selected rivers (according to the data in the reference period).

River-WGS	Catchment area, km²	Altitude of WGS, m.a.s.l.	Feeding source	Q, $m^3 s^{-1}$			Seasonal distribution of runoff, %		
				Annual	High flow (Q5)	Low flow (Q95)	Spring (March–April)	Summer (May–August)	Autumn (September–February)
Nemunas-Druskininkai	37400	77.49	G-sr	198	385	101	28.5	28.2	43.3
Merkys-Puvočiai	4300	78.05	G-rs	32.1	52.7	19.5	23.0	30.2	46.8
Nemunas-Nemajūnai	42900	50.65	G-sr	240	461	127	27.8	28.8	43.4
Neris-Jonava	24500	34.12	G-sr	160	318	79	28.2	27.2	44.6
Nevėžis-Babtai	5780	17.54	S-rg	31.5	115	3.54	37.1	15.2	47.7
Dubysa-Padubysys	1840	28.97	R-sg	14.2	43.6	2.99	29.0	18.0	53.0
Nemunas-Smalininkai	81200	7.33	G-sr	478	970	246	28.4	27.1	44.5
Šešupė-K.Naumiestis	3180	26.96	R-sg	34.0	102	6.12	34.0	19.7	46.3
Jūra at the mouth	3994	6.50	R-sg	42.6	162	6.13	24.1	13.6	62.3
Minija-Kartena	1220	18.01	R-sg	16.9	61.5	2.11	23.5	13.2	63.3
Nemunas at the mouth	97928	0.11	G-sr	605	1318	276	28.4	27.1	44.5

Nemunas-Nemajūnai, 4. Neris-Jonava, 5. Nevėžis-Babtai, 6. Dubysa-Padubysis, 7. Nemunas-Smalininkai, 8. Šešupė-K. Naumiestis, 9. Jūra-Tauragė, 10. Šešuvis-Skirgailai, and 11. Minija-Kartena) for the period 1995–2014 were used (Figure 1). This 20-year period was selected in accordance with the IPCC AR6 recommendations (Calvin et al., 2023). The data mentioned above were obtained from the hydrological and meteorological yearbooks of the Lithuanian Hydrometeorological Service under the Ministry of Environment. Discharge projections were based on data (P and T) from global climate models that had already been statistically downscaled applying the bias correction constructed analogues with quantile mapping reordering (BCCAQ) method (Gebrechorkos et al., 2023). These data are freely available for scientific purposes in the CEDA (Centre for Environmental Data Analysis) database. To identify climate models that adequately represent the climatic conditions of Lithuania, P and T data from all 18 models in the CEDA database for 1995–2014 were analyzed. Using a ranking method (section 2.2.1), three climate models were chosen. Their P and T data, under the SSP245 and SSP585 scenarios, were then applied to project river discharge for the near (2031–2050) and far future (2081–2100).

2.2 Methodology

The assessment of changes in the Lithuanian rivers' runoff according to SSP scenarios and global climate models was carried out in four stages. In the first stage, three out of 18 global climate models (already statistically downscaled) that most accurately represent the climatic conditions of Lithuania were selected. In the second stage, hydrological models of the rivers were developed, calibrated, and validated. In the third stage, river discharge was simulated for the near and far future using the selected climate models and the created hydrological models, under the two most commonly applied SSP scenarios (SSP245 and SSP585). In the fourth and final stage, the contributions of global climate models (GCM) and SSP scenarios to the uncertainties in runoff projections were quantified.

2.2.1 Climate model selection

Hydrological modeling based on the output data of GCMs is often used to assess future changes in river runoff. The most recent SSP scenarios and GCMs, proposed by the Sixth Assessment Report (IPCC, the Sixth Assessment Report (AR6)), are currently being applied. A large amount of data (P and T) from these climate models is available in open-source databases. However, in river hydrological modeling, it is important to choose models that accurately represent the climatic conditions of the study area. In practice, two approaches are commonly applied for this purpose: 1) based on the output data of all available GCMs, the median, lower and upper limit of the applied ensemble are derived, and 2) all available GCMs are used to simulate the past climate conditions and the best-performing GCM is then selected. The first approach provides a broad spectrum of future climate parameters, which will not always precisely capture the local climatic patterns. Meanwhile, the second approach is based on the assumption that climate models capable of reproducing the past climate with satisfactory accuracy are likely to provide more reliable projections of future conditions. Therefore, it was decided to apply the second approach, i.e., to select three climate models and use their average output data to project the discharge of rivers in the Nemunas catchment for the near (2031–2050) and far (2081–2100) future.

Five parameters were used for model selection: daily Q-Q plot, monthly standard deviation, and the minimal, average, and maximum values of precipitation and temperature. All five parameters were assigned equal weights because, in the absence of prior information favoring any

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Table 2. Calibration and validation results of hydrological models.

Subcatchments	Calibration			Validation		
	r	NSE	RE, %	r	NSE	RE, %
Nemunas at Druskininkai	0.85	0.69	-1.48	0.76	0.50	1.40
Merkys	0.81	0.54	0.23	0.82	0.59	-0.20
Nemunas at Nemajūnai	0.85	0.69	-2.28	0.76	0.51	2.18
Neris	0.84	0.61	4.16	0.85	0.59	-3.76
Nevėžis	0.84	0.70	-0.70	0.76	0.50	1.31
Dubysa	0.85	0.73	-0.41	0.78	0.60	0.43
Nemunas at Smalininkai	0.86	0.72	-0.69	0.79	0.52	0.71
Šešupė	0.89	0.79	2.61	0.76	0.51	-2.14
Jūra	0.87	0.74	4.14	0.86	0.73	-3.85
Minija	0.85	0.72	-1.88	0.84	0.70	1.83
Nemunas at the mouth	0.90	0.81	0.12	0.83	0.60	0.12

Table 3. Summary of global climate model ranking results.

	Precipitation, P					Air temperature, T						
Models	Q-Q plot	Avera-ge	STDEV	MIN	MAX	Q-Q plot	Average	STDEV	MIN	MAX	SUM	RANK
ACCESS-CM2	143	146	59	131	117	107	106	125	213	156	1303	10
BCC-CSM2-MR	99	98	141	120	124	113	113	129	73	173	1183	4
CESM2	98	99	217	118	210	184	181	129	76	161	1473	14
CMCC-CM2-SR5	101	98	112	124	108	147	147	107	83	89	1116	2
CMCC-ESM2	107	109	94	152	123	83	81	155	232	158	1294	8
GFDL-ESM4	147	145	142	103	128	122	122	156	126	160	1351	11
HadGEM3-GC31-LL	168	168	186	128	177	215	214	200	76	100	1632	18
IITM-ESM	205	212	92	149	127	128	126	111	172	97	1419	12
INM-CM4-8	161	160	142	83	131	177	178	114	121	154	1421	13
INM-CM5-0	139	137	202	105	151	96	98	124	91	152	1295	9
IPSL-CM6A-LR	96	94	165	190	115	139	139	121	59	135	1253	6
KACE-1-0-G	112	111	115	99	126	84	83	115	113	209	1167	3
MIROC-ES2L	97	97	67	161	107	113	113	112	100	61	1028	1
MIROC6	123	121	94	169	107	163	164	138	97	91	1267	7
MPI-ESM1-2-LR	163	160	123	135	140	138	138	120	250	117	1484	15
MRI-ESM2-0	170	167	90	163	117	192	195	187	102	105	1488	16
NorESM2-MM	167	170	229	166	155	96	97	107	192	192	1571	17
UKESM1-0-LL	98	102	124	98	131	97	99	144	218	84	1195	5

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specific parameter, equal weighting was considered a neutral and unbiased approach. Consequently, each parameter contributed equally to the overall ranking of the GCMs, with no single parameter regarded as more influential than the others. Following the recommendations of AR6, model performance was assessed against observations for the period 1995–2014. In the first step, the five parameters were calculated from observational data at 14 MSs. In the second step, the same parameters for the same 14 MSs were calculated based on the outputs of 18 GCMs. In the third step, the values obtained from the observational data were compared with those derived from the outputs of GCMs. The climate model, according to the data of which a specific parameter value calculated for a specific MS was the closest to the observational one, was assigned a rank of 1, the second most similar a rank of 2, the third a rank of 3, etc. In the fourth step, the ranks of the five precipitation indicators and the five air temperature indicators were summed up. The model with the lowest total rank over all 14 MSs was considered the most suitable for the studied area, followed by the second lowest, and so on.

2.2.2 Discharge projection of the Nemunas River catchment using the HBV hydrological model

The HBV (*Hydrologiska byråns vattenbalansavdelning*) model, developed at the Swedish Meteorological and Hydrological Institute (Bergstrom, 1992), was used to project the runoff of the Nemunas River catchment according to global climate models and Shared Socioeconomic Pathway scenarios. This hydrological model is widely used to address the impact of climate change on river hydrology (Pervin et al., 2021). Even though this software was originally developed in the early 1970s, it has undergone continuous improvements. This model requires relatively limited input data, including precipitation, air temperature, and geographical information of the river catchment for which runoff is modeled (catchment area, height above sea level, forest cover, lake cover, MS-defined catchment area). Due to its relative simplicity, various versions of the HBV model have been applied in more than 30 countries across diverse climatic conditions, e.g., Sweden, Zimbabwe, India, Colombia (Bergstrom, 1992). The HBV has also been successfully applied in our previous studies (Jakimavičius et al., 2018; Akstinas et al., 2020).

The model calculations were performed in three steps. In the first step, the amount of precipitation that reaches the ground was estimated. In the second, slope runoff was simulated; and in the third, river discharge and its transformation within the watercourse were evaluated.

The HBV model is based on the water balance equation (IHMS, 2005):

$$P - E - Q = \frac{d}{dt}\left[SP + SM + UZ + LZ + V\right] \qquad (1)$$

where P is precipitation, E is evaporation, Q is discharge, SM is soil moisture, SP is snowpack, UZ is upper groundwater zone, LZ is lower groundwater zone, and V is lake or dam volume.

For the development of the Nemunas River hydrological model, daily discharge data from 11 WGSs, as well as air temperature and precipitation data from 14 MSs, were used (Figure 1). The same information about the modeled catchment area, the presence of lakes and forests as well as mean elevation above sea level was used for both the reference period and the projections. The hydrological model consisted of 11 subcatchments: the Nemunas at Druskininkai, Nemajūnai, Smalininkai, and its mouth, together with its main tributaries in sequence – the Merkys, Neris, Nevėžis, Dubysa, Šešupė, Jūra, and Minija (Figure 1).

Following the recommendations of IPCC AR6 (Calvin et al., 2023), the period from 1995 to 2004 was selected for model calibration, whereas the period 2005–2014 was used for validation. The calibration procedure involved adjusting 16 model parameters and comparing calculated discharge values with the observed ones. Four groups of calibration parameters were used in the calibration process (IHMS, 2005): the model parameters that (i) control general runoff volume over the total calibration period, (ii) describe snow accumulation and melting intensity, (iii) characterize the moisture accumulated in soil, and (iv) define the extremes (river floods and droughts) in discharge hydrograms. During the spring flood, the most important calibration parameters for runoff modeling are related to snowmelt and soil moisture storage, while during the low water period - the parameter that determines river underground feeding (Kriaučiūnienė et al., 2013).

Ideally, the correlation coefficient (r) should approach 1; however, values above 0.7 are considered acceptable for proper calibration (IHMS, 2005). Similarly, the hydrological model can be regarded as calibrated when the Nash–Sutcliffe efficiency (NSE) exceeds 0.5 (Ritter and Muñoz-Carpena, 2013). Calibration and validation results for each subcatchment are presented in Table 2. Based on the obtained values of r, NSE, and RE (difference between observed and calculated discharge), it was decided that the hydrological model of the Nemunas River is ready to perform discharge projections for the near and far future using climate models data.

2.2.3 Estimation of uncertainty sources in projected runoff of the Nemunas River catchment

This study considered uncertainties in runoff projections arising from the selection of global climate models and SSP scenarios. All possible combinations (24 combinations for each of the eight rivers, i.e. (3 GCMs × 2 scenarios + 2 scenarios × 3 GCMs) × 2 periods (near and far future)) of uncertainty sources were analyzed to identify the two main sources of uncertainty. The assessment was conducted in four steps: 1) river discharge was calculated for each model and SSP scenario for the near and far future; 2) the differences between the lowest and highest water discharges under GCMs or SSP scenarios were estimated separately for each period; 3) the average of discharge differences was calculated for the scenarios and GCMs separately in the near (2031–2050) and far (2081–2100) future periods; 4) the relative contribution (%) of each model and scenario to the overall uncertainty was quantified based on these discharge differences.

For comparison, three models with the lowest ranking scores (Figure 2b–d) and three with the highest scores are presented (Figure 2e–g). A visual assessment revealed that the distributions of the lowest-ranking models differed only slightly from the distribution derived from observational data. Therefore, we assumed that if these models were able to reproduce past climate conditions with sufficient accuracy, then their future predictions should be suitable for the assessment of the climate conditions in the studied region.

3. Results

3.1 Climate model selections

Based on the methodology presented in section 2.2.1, daily Q-Q plots, monthly standard deviations (STDEV), minimal, average, and maximum values (of P and T) were calculated for 14 MSs using both observed data and output data from 18 GCMs. The results were arranged and summarized over all MSs (Table 3). The ranking results showed that the applied models received different scores depending on the evaluation criteria. If considering only the accuracy of P projections, the IPSL-CM6A-LR model exhibited the smallest deviations from the actual data according

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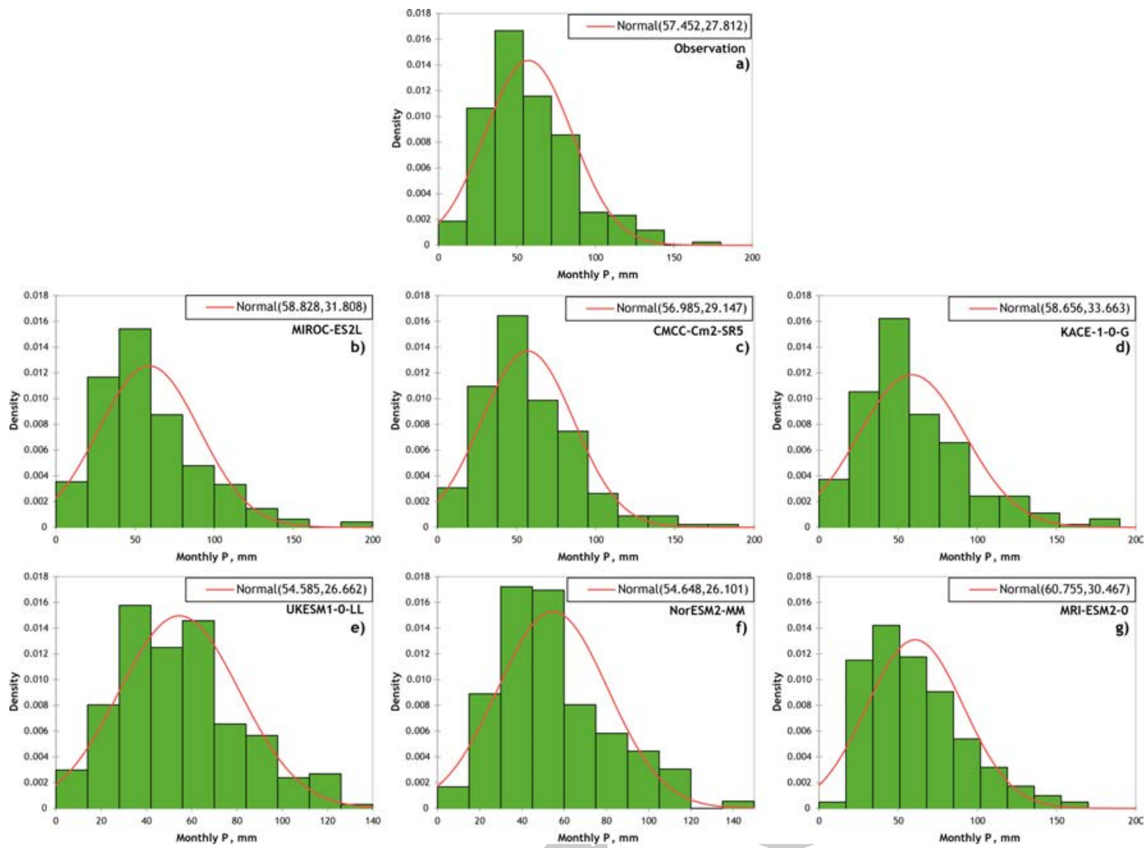

Figure 2. Comparison of observed (a) precipitation distributions with global climate models that scored the lowest (b–d) and highest (e–g) ranks.

to the Q-Q area and the average monthly P. The ACCESS-CM2 distinguished itself in terms of STDEV. Meanwhile, the INM-CM4-8, MIROC-ES2L, and MIROC6 models stood out when evaluating the monthly min and max P, respectively. The evaluation of T projections yielded somewhat different results. The CMCC-ESM2 model demonstrated the best performance in terms of the Q-Q area and average monthly T. Considering the average monthly T variability (STDEV), the CMCC-CM2-SR5 and NorESM2-MM got equal ranks. The minimum T was most accurately projected by the IPSL-CM6A-LR, and the maximum by the MIROC-ES2L model.

The river discharge was projected by applying P and T data according to various scenarios. Therefore, the selected GCMs (or their ensemble) must provide the most accurate possible estimates of both indicators. After summarizing all ranking criteria, we found that in the historical period, STDEV of P and T from actual observations were the smallest in the case of three models: MIROC-ES2L, CMCC-CM2-SR5, and KACE-1-0-G. Additionally, a visual comparison of the distributions of the selected models' outputs was performed. The distribution of average monthly P data was compiled based on the observation data from 14 MSs in the reference period (Figure 2a).

3.2 Changes in the conditions of runoff formation in the Nemunas River catchment according to global climate models and SSP scenarios

The runoff of Lithuanian rivers is shaped by physical-geographical and climatic conditions. Based on regional differences in these conditions, three hydrological regions are distinguished: western (W-LT), central (C-LT), and south-eastern (SE-LT) (Akstinas et al., 2022) (Figure 3). In W-LT, the greatest amount of precipitation falls. Combined with steep river slopes and favorable conditions for rapid water flow, this results in rivers being predominantly rain-fed, with rainfall accounting for 62% of their total runoff. In C-LT, river slopes are small, and impermeable soils are widespread, which creates more favorable conditions for evaporation. Summer precipitation is low, and the underground supply is scarce (17%), so rivers become even more depleted. In SE-LT, the relief is gradually rising, which increases river slopes. Runoff in this region is determined by a higher amount of precipitation compared to C-LT and abundant underground feeding (55%). Due to the reasons above, rivers here carry more water than in C-LT but are less watery than in W-LT.

Before analyzing future changes in river discharge, it should be helpful to find out how runoff formation conditions would change under the applied GCMs and SSPs

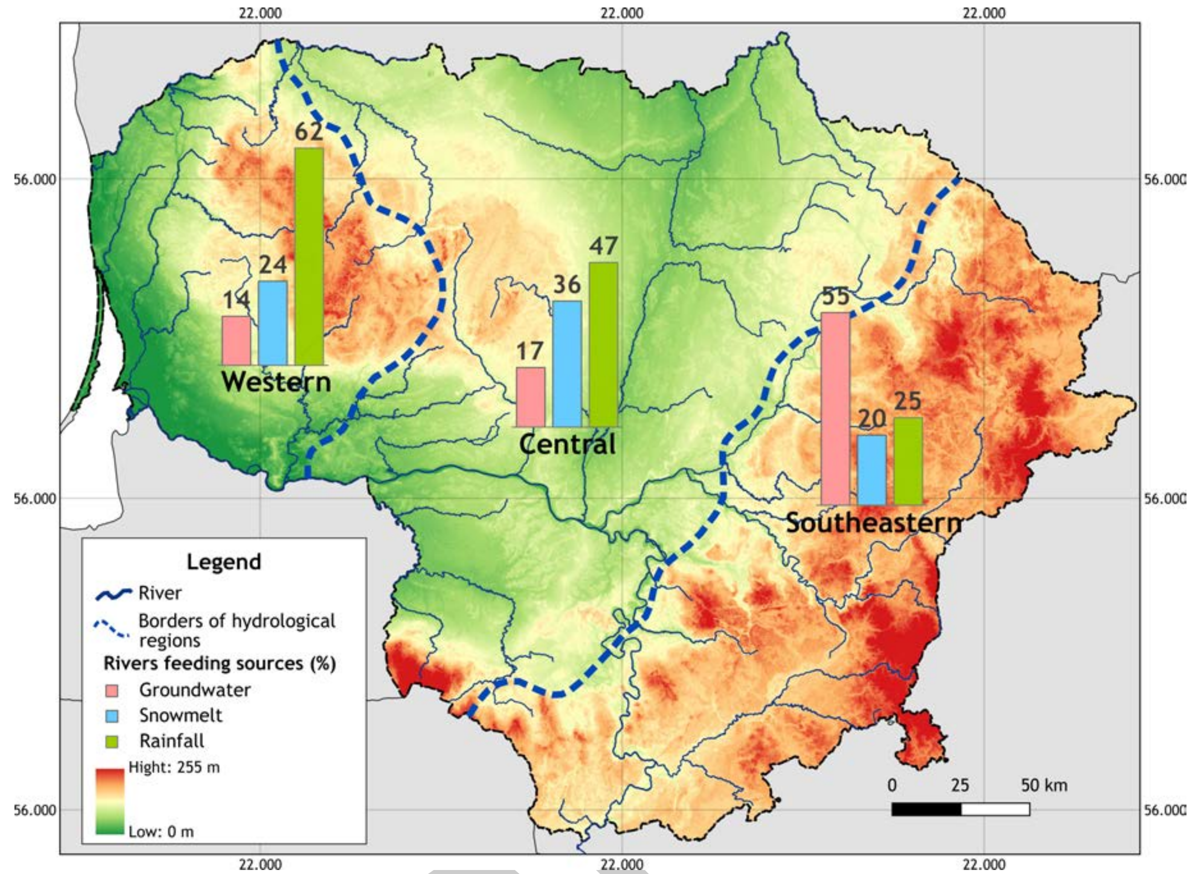

Figure 3. Hydrological regions of Lithuania (based on Akstinas et al., 2022).

across the different hydrological regions.

It was determined that P and T would change considerably in the future. As shown in Figure 4, across all hydrological regions, projected changes in T are going to be very similar. Based on the average of three models, the mean annual T during the reference period (1995–2014) was 7.4°C in W-LT, 7.2°C in C-LT, and 6.9°C in SE-LT. In the near future (2031–2050), no significant differences were identified between the applied scenarios. Under the most likely SSP245 scenario, T would rise by 2.2–2.3°C in the studied hydrological regions, and under the pessimistic SSP585 scenario by 2.5–2.8°C compared to the reference period. Considerably larger differences are possible in the far future (2081–2100): under SSP245 scenario, T would increase by 3.5–3.8°C, whereas, under the SSP585, from 5.8°C to 6.4°C depending on the hydrological region.

Analysis of seasonal air temperature changes does not indicate significant differences between the scenarios in the near future. The smallest increase is projected for autumn (1.8–2.4°C), a moderate rise for spring and summer (2.1–3.0°C), and the largest increase for winter (2.4–3.0°C). There would be no clear trends in seasonal temperature rise in the far future, but there will be apparent differences between scenarios. According to the SSP245 scenario, air temperature (depending on the region) is likely to rise by 3.2–3.4°C in autumn, 3.3–3.7°C in spring, 3.5–3.8°C in winter, and 3.8–4.2°C in summer. Meanwhile, under the SSP585 scenario, substantially greater warming is expected: up to 5.9°C in spring, 6.0°C in autumn, 6.5°C in winter, and 7.0°C in summer. Regional comparisons show that W-LT is likely to experience the smallest changes, whereas C-LT and SE-LT are projected to undergo the greatest increases relative to the reference period.

Based on the data from three GCMs, in the reference period, the highest amount of precipitation, 811 mm per year, was determined in the river subcatchments located in W-LT. In C-LT and SE-LT, P was 643 and 673 mm per year, respectively. Projections made using GCMs data under the SSP245 scenario revealed that in the near future, P should be from 2.2% (W-LT) to 3.8% (SE-LT) higher than in the reference period (Figure 4). In contrast, under the SSP585 scenario, P is expected to decline slightly, by 1.1% in W-LT and 1.8% in C-LT. In the far future, the most pronounced positive changes are projected for W-LT (5.0% under SSP245 and 3.0% under SSP585), followed by C-LT (3.3% and 2.1%, respectively), while the smallest increases would be in SE-LT (2.6% and 1.4%). Although the average annual precipitation may change slightly, significant positive and negative changes in the seasonal amount of precipitation are projected. The most significant positive

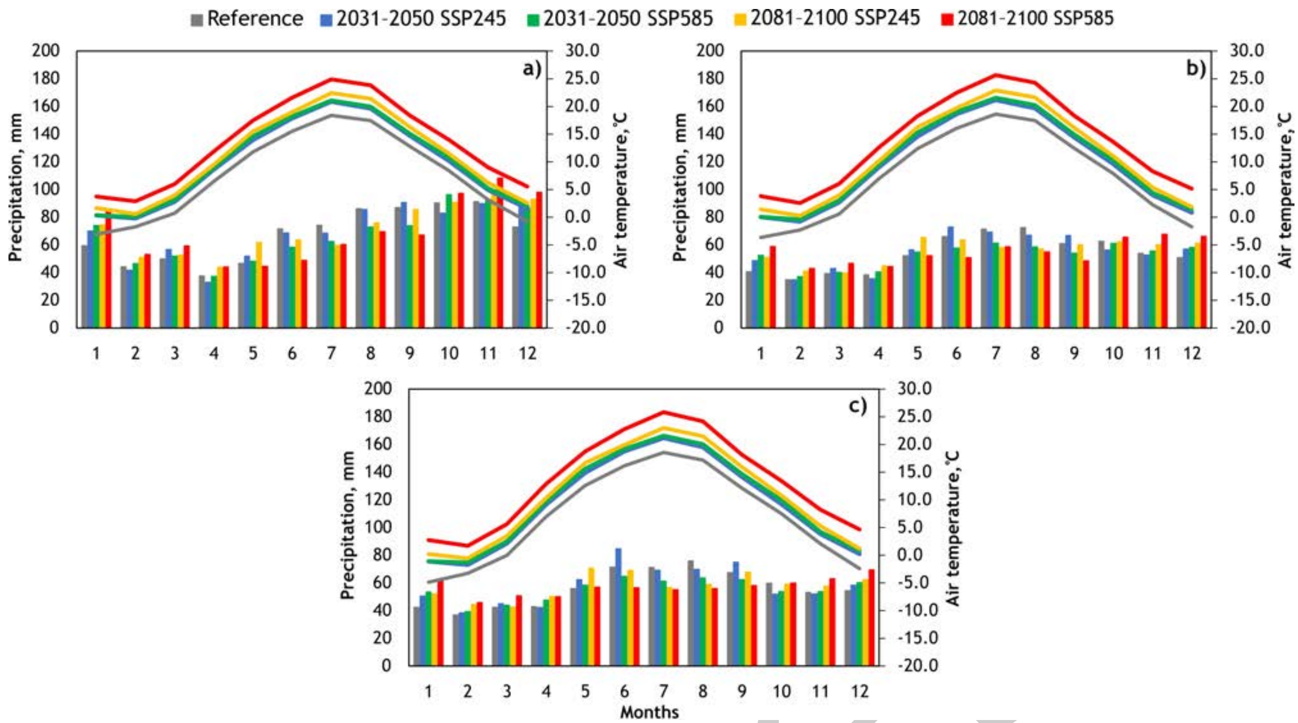

Figure 4. Projection of air temperature (°C) and precipitation (mm) in the western (a), central (b), and south-eastern (c) hydrological regions of Lithuania.

changes of P are expected in winter. In the near future, winter precipitation is expected to rise by 10.2–17.7%, and in the far future, by 18.9–33.7%, relative to the reference period. Spring is expected to experience smaller positive changes: precipitation is likely to increase by up to 6.3% in the near future, depending on the region and scenario, and by up to 18.0% in the far future. In contrast, significant negative changes in precipitation are projected for summer. In the near future under the SSP245 scenario, precipitation may decline by up to 3.9% in W-LT and C-LT, while SE-LT may experience an increase of up to 2.4%. However, according to the SSP585 scenario, summer precipitation would decrease from 13.2% to 16.4%, depending on the hydrological region. In the far future, the most substantial decreases are expected in summer, ranging from 14.2% to 23.2%. Meanwhile, in autumn, both negative and positive changes in precipitation are expected, depending on the projection period. In the near future, the slightest negative changes would be in W-LT (up to 2.0%), more significant in C-LT (up to 3.9%), and the largest in SE-LT (up to 5.9%). However, in the far future, the amount of precipitation is expected to increase by 0.6–2.9% relative to the reference period.

3.3 Projections of the Nemunas River catchment discharge in the near and far future

Discharge simulations for the near (2031–2050) and far (2081–2100) future were carried out using the outputs of three GCMs (MIROC-ES2L, CMCC-CM2-SR5, and KACE-1-0-G) under two SSPs (SSP245 and SSP585). The results were compared with the results of discharge simulations of the same models for the reference period (1995–2014). The estimated changes in Lithuanian river discharge had different regional patterns. Therefore, the analysis was performed at two spatial scales: the entire Nemunas catchment and individual hydrological regions, with one representative river selected from each region (Neris River for SE-LT, Nevėžis for C-LT, and Minija for W-LT). Based on the results, projected changes in average annual, high (Q5), and low (Q95) flows were assessed for the near and far future periods.

The projected changes in climate parameters are likely to significantly reduce the Nemunas discharge in both studied future periods (Figure 5a). In the near future, the average annual discharge is projected to decrease from 15.1% to 23.5%, while in the far future, from 24.2% to 41.7% compared to the reference period (Table 4).

The Nemunas River catchment covers 75% of Lithuania's territory and extends across all three hydrological regions, resulting in diverse river feeding conditions (Figure 3). In the far future, according to the most unfavorable scenario (SSP585), a considerable decrease in the discharge of the Nemunas River is expected, primarily driven by a pronounced temperature rise of 5.8–6.4°C across different hydrological regions. Although precipitation would increase slightly (1.4–3.0%) under the SSP585 scenario, this increase would not be sufficient to significantly reduce discharge in the long term. The Neris catchment is mainly

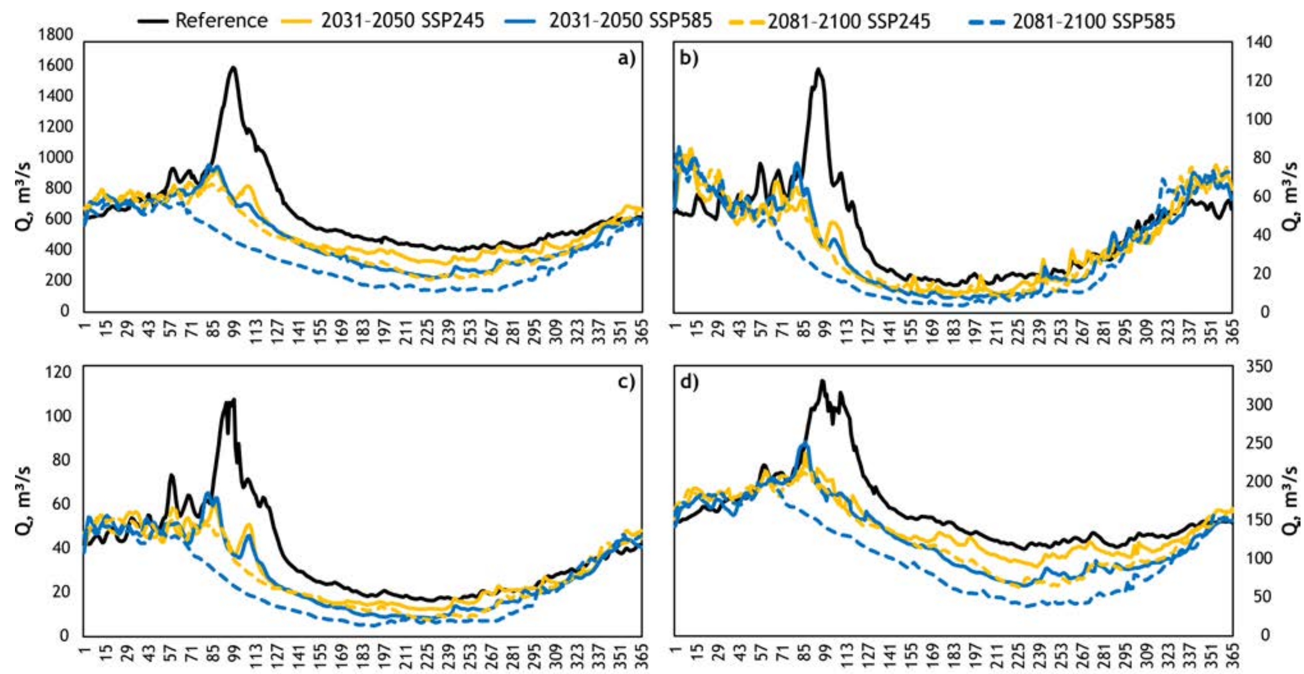

Figure 5. Nemunas (a), Minija (b), Nevėžis (c) and Neris (d) discharge projections in the near and far future compared to the reference period.

located in SE-LT, where groundwater feeding is predominant (Figure 3). As a result, the projected changes in the Neris are less notable than in the Nemunas catchment. Under both scenarios, the average annual discharge of the Neris would decline by 11.9–21.0% in the near future and by 19.9–34.7% in the far future, compared to the reference period (Figure 5d). In the Minija catchment, from W-LT, where precipitation is the primary source of river feeding (Figure 3), the discharge trend is different. Since W-LT is also projected to have more precipitation in the future, the Minija River is expected to experience the smallest reduction in discharge among the studied rivers: 14.3–15.9% in the near future and 15.3–26.7% in the far future, compared to the reference period (Figure 5b). The runoff formation of the Nevėžis River, located in C-LT, depends on both rainfall and snowmelt. However, in the far future, snowmelt floods are less likely, so its average annual discharge is projected to decrease more significantly, by 24.1–38.6% (Figure 5c).

The analysis revealed that the average annual discharges of all studied rivers are projected to change: the smallest changes are expected in the near future, while significantly larger changes are anticipated in the far future. Under the SSP245 scenario, the changes would be smaller, whereas under SSP585 they would be more pronounced. When comparing different hydrological regions, the results indicate that both in the near and far future, the smallest changes are possible in rivers from W-LT, moderate changes in rivers from SE-LT, and the largest changes in rivers from C-LT.

It was established that in all studied rivers, the high flows (Q5, typically associated with spring floods) and low flows (Q95, representing river water content during the dry season) would decrease considerably, though in different ways (Table 4). The most remarkable changes are expected in the far future when spring flood discharges (with a 5% probability) are projected to decline to a similar extent as the annual discharges. This means that floods would decline most significantly in the far future under the SSP585 scenario, as substantially higher air temperatures (especially during the winter season) are likely to prevent the formation of snowmelt-driven floods. The river discharge during the dry season (of a 95% probability) is also going to change drastically in the long term in the case of the SSP585 scenario, decreasing from 71.2% (in the Nemunas) to 81.5% (in the Minija) (Table 4). This may be due to the projected increase in summer temperatures (by up to 7.0°C) and the simultaneous reduction in precipitation compared to the reference period.

3.4 Estimation of uncertainties in the projections of the Nemunas River catchment discharge

The accuracy of river runoff projections depends on several factors, including the selected hydrological model parameters, the SSP scenario, and the global climate model (GCM). In this study, uncertainties in water flow projections were assessed only on the basis of climate models and SSP scenarios. The impact of hydrological model parameters and climate scenarios on runoff modeling results was estimated several years ago by the authors of this ar-

Table 4. Changes in discharge in the near and far future compared to the reference period.

River	Discharge	2031–2050		2081–2100	
		SSP245	SSP585	SSP245	SSP585
Nemunas	Q5	-22.3	-22.9	-28.7	-36.9
	Average	-15.1	-23.5	-24.2	-41.7
	Q95	-29.8	-47.6	-41.5	-71.2
Minija	Q5	-15.0	-12.4	-14.4	-19.9
	Average	-14.3	-15.9	-15.3	-27.6
	Q95	-44.6	-64.2	-61.3	-81.5
Nevėžis	Q5	-27.5	-27.2	-31.2	-37.2
	Average	-18.6	-23.8	-24.1	-38.6
	Q95	-36.9	-51.1	-55.1	-77.4
Neris	Q5	-16.1	-17.0	-22.1	-27.9
	Average	-11.9	-21.0	-19.9	-34.7
	Q95	-24.2	-45.7	-42.6	-73.3

ticle (Kriauciunienė et al., 2013). In both this study and the previous one, river runoff was modeled using the HBV software. For consistency, the same rivers – the Neris and the Merkys – were selected for the analysis. Therefore, the results reported by Kriauciunienė et al. (2013) provide valuable insights into the influence of hydrological model parameters on the uncertainties in water discharge projections. That assessment showed that, for the Merkys River, the accuracy of runoff projections was determined by model parameters (7.2%), SSP scenarios (60.9%), and GCM (32%). For the Neris River, the corresponding contributions were 5.6%, 64.4%, and 30%, respectively. A previous assessment of uncertainties confirmed that, in the studied rivers, hydrological model parameters represent the smallest source of uncertainty compared with climate models or SSP scenarios. Therefore, this study assessed only the uncertainties associated with the three selected global climate models and two SSP scenarios.

The uncertainty of river projections was analyzed separately for the entire Nemunas catchment and sub-catchments representing three hydrological regions: the Minija and the Jūra in W-LT, the Šešupė, the Dubysa, and the Nevėžis in C-LT, and the Neris and the Merkys in SE-LT. The analysis revealed that in the Nemunas discharge projections for the near future, SSP scenarios and climate models had an equal impact on the final result (50% each) (Figure 6). Meanwhile, in the case of the far future, the influence of scenarios decreased to 38%, while that of climate models increased by 62%. Somewhat different regularities were established in the studied sub-catchments. In the near future, climate models accounted for 61% and 60% of the uncertainty in W-LT and C-LT, respectively, compared to 50% in SE-LT. This could be explained by differences in hydrological regimes: groundwater contributes 14%, 17%, and 55% of the discharge in W-LT, C-LT, and SE-LT, respectively, and the rest consists of rainfall and snowmelt. Therefore, the response to climate change is more pronounced in W-LT and C-LT than in SE-LT. Even though in the near future, the influence of climate models on discharge projection results depending on hydrological regions has been clearly expressed, in the far future, these regional differences would disappear due to increasing climate extremes. Thus, in the far future, the influence of climate models should be very similar across all river sub-catchments from different hydrological regions, accounting for 63%, 64%, and 64%, respectively, with the remainder attributable to SSP scenarios.

4. Discussion

Scientific studies show that climate change strongly affects water resources, causing record high or low river flows worldwide. To adapt, society needs reliable, up-to-date scientific projections to mitigate risks and prepare for the future. To find the best-performing global climate models for projecting runoff in selected Lithuanian lowland rivers, five ranking parameters were applied: the daily Q-Q plot, monthly standard deviation, and minimal, average, and maximum values of precipitation and temperature. Eighteen GCMs from CMIP6 were ranked according to these selected parameters. Three GCMs, namely, MIROC-ES2L, CMCC-CM2-SR5, and KACE-1-0-G, received the highest scores. As the best representatives of Lithuanian climate conditions, the outputs of these models were subsequently used as inputs for hydrological simulations made for the near (2031–2050) and far (2081–2100) future periods. The general trends obtained in the recent runoff projections were quite similar to those reported in previous studies indicating a decline in spring floods and summer low flows, alongside an increase in winter discharge. However, in some cases, the scale of projected changes was greater if compared to the ones identified according to previous CMIP5 climate projections. Earlier assessments of future annual runoff revealed decreases of up to 24% (Šarauskienė et al., 2018), 31% (Jakimavičius et al., 2020), and 40% (Kriaučiūnienė et al., 2019) under the most extreme scenarios in the far future. These results are consistent with the present findings showing a possible decline in this hydrological parameter from 26.7% (in the Minija) to 41.7% (in the Nemunas) under the most unfavorable scenario. Regarding dry season discharge in the far future, the present study suggests decreasing to almost 70–80% in individual catchments. In contrast, the previous findings based on CMIP5 tools indicated summer low flow reductions of only 28–43% (Šarauskienė et al., 2018). Our findings indicate that the most significant changes are expected in the central hydrological region of Lithuania, where river catchments are considered particularly sensitive to climate change. This is consistent with the results reported by other authors (Nazarenko et al., 2023). The significant negative trends in low flows observed in this

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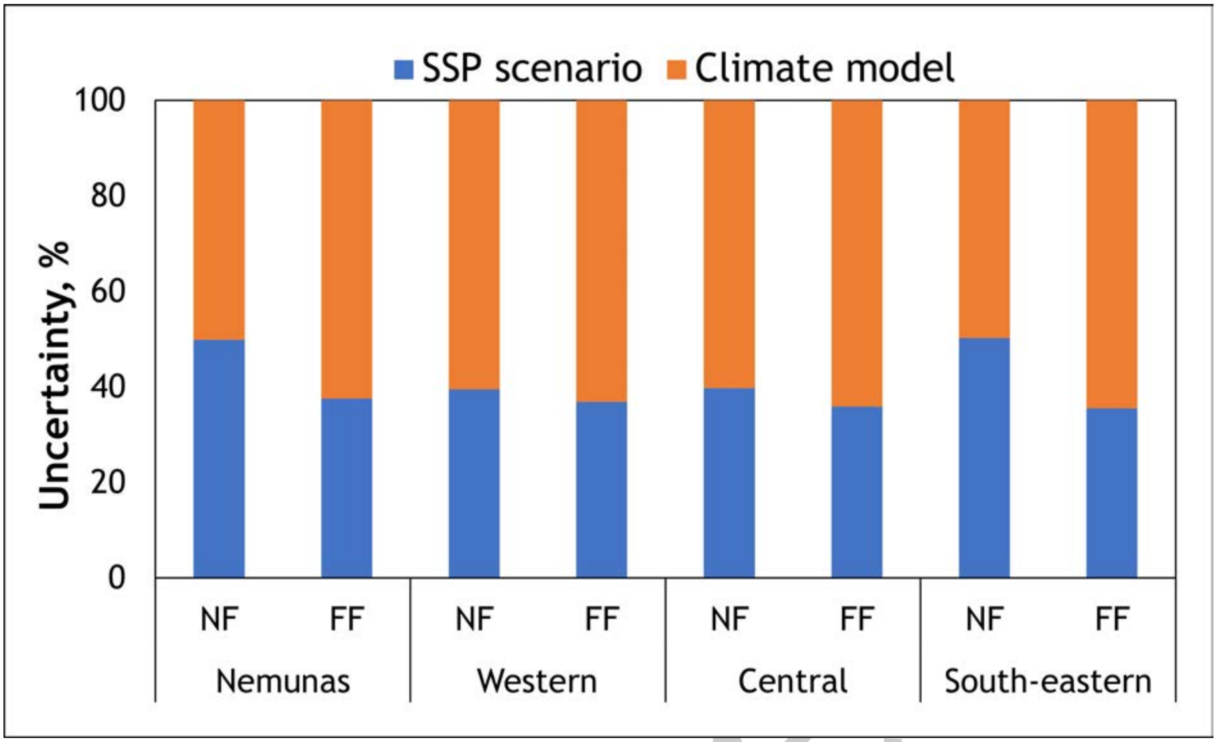

Figure 6. Uncertainties of the discharge projections in the near (NF) and far future (FF).

region in the past (Nazarenko et al., 2022), together with flow intermittency phenomena (Šarauskienė et al., 2020), indicate that this process is not new but has been ongoing for some time.

The magnitude of projected annual runoff reported in other studies exhibits considerable variation depending on the specific regions and geographical contexts examined. Such variability is observed not only in large-scale global and continental assessments (e.g., Donnelly et al., 2017; Duan et al., 2017; Yang et al., 2017; Brêda et al., 2020; Guan et al., 2021; Kis and Pongrácz, 2024) but also in more localized, national-scale investigations (e.g., Piniewski et al., 2018; Muelchi et al., 2021; Dallison et al., 2022; Murphy et al., 2023) that share methodological similarities with the present study. Interestingly, despite differences in catchment characteristics, some seasonal projections across these studies display notable similarities – for instance, increases in projected discharge during winter (Piniewski et al., 2018; Afzal et al., 2020; Muelchi et al., 2021; Sleziak et al., 2021; Dallison et al., 2022; Kis and Pongrácz, 2024), decrease in summer (Afzal et al., 2020; Sleziak et al., 2021; Dallison et al., 2022). One possible reason for the differences in future runoff simulation results may be the peculiarities of the CMIP6 models. Compared to the IPCC AR5, precipitation projections in the GCMs from AR6 indicate a stronger drying trend, which extends even to parts of northern Europe (Palmer et al., 2021). The higher global climate sensitivities of CMIP6 models determine higher summer temperatures in northern Europe as well. Another possible reason for the identified differences is the variation in grid resolutions among climate models. Using regional climate models (RCMs) with higher spatial resolution is recommended to obtain more accurate runoff projection results. Unfortunately, RCMs for AR6 have not yet been developed; therefore, this study used global climate models with output data already downscaled to a 0.25° × 0.25° grid, which may still be too coarse for catchment-scale modeling. In general, each new Phase of the Coupled Model Intercomparison Project is expected to improve model performance – just as CMIP6 GCMs are anticipated to deliver more reliable and comprehensive projections (Wei et al., 2023). Previous studies comparing the performance of CMIP6 GCMs with those from the earlier CMIP5 generation generally demonstrate an improved ability of the newest models to reproduce various temperature and precipitation patterns across different regions of the world (Chen et al., 2020; Grose et al., 2020; Gusain et al., 2020; Kim et al., 2020; Xin et al., 2020; Gebresellase et al., 2022; Martel et al., 2022; Wei et al., 2023). There is no doubt that the use of combined SSP-RCP pathways, rather than RCP emission scenarios, also influences the present results, as these pathways account for socio-economic indicators. The incorporation of Shared Socioeconomic Pathways provides a framework for accounting for potential socioeconomic developments at the global scale, thereby at least partially addressing uncertainties related to human-induced impacts on runoff conditions. Nevertheless, in this river runoff projection study, the limitations of model simulations concerning human influences are unavoidable, as future modifications in catchment management, land use, hydraulic infrastructure or other anthropogenic interventions cannot be reliably predicted.

Additionally, this study involved an uncertainty assessment, which is considered a very important part of the whole climate modeling process and may contribute to improving the applied modeling techniques (Tian et al., 2016; Vetter et al., 2017; Kundzewicz et al., 2018). Uncertainty ranges in the discharge projections made for the selected lowland rivers under the chosen GCMs and SSP scenarios for the near future diverged. For the rivers less dependent on precipitation, the influence of selected models and scenarios on runoff modeling results was very similar, whereas, in predominantly rain-fed and snow-fed rivers, the uncertainty attributable to GCMs accounted for 60–61% of the projection results. In contrast, for the far future, the influence of the used GCMs and SSPs on the runoff projections was found to be very similar for all rivers, with more than 60% of the uncertainty from GCMs and the remainder from SSPs. Even though the influence of river feeding characteristics on discharge projections is clearly expressed in the near future, these differences will disappear in the far future, likely due to increasing climate variability. Similar findings were also reported by Hattermann et al. (2018), who determined that uncertainty associated with GCMs is most pronounced during the seasons and in the regions where the river flow regime is dominated by precipitation. Many studies accomplished using CMIP6 climate forcing models and scenarios (Wen et al., 2021; Haider et al., 2023; Núñez Mejía et al., 2023) as well as those employing CMIP5 tools (Tian et al., 2016; Su et al., 2017; Vetter et al., 2017; Senatore et al., 2022; Jeantet et al., 2023) have demonstrated that the choice of representative GCMs has a significant impact on the outcomes of climate impact assessments. In many cases, the dominant source of uncertainty in modeling results stems from the choice of GCMs rather than from the selection of emission scenarios. Moreover, different techniques selected for the ranking procedure may produce different sets of suitable GCMs for the studied river catchments. Although there is no universally accepted method for ranking GCMs, and the process remains inherently subjective (Anil et al., 2021), it can still be an excellent way to reduce uncertainty in the final result (Rahman and Pekkat, 2024). The high GCM-related uncertainty poses significant challenges for decision-makers and water resource managers, making it difficult to develop robust adaptation strategies. Projected changes in runoff patterns affected by this uncertainty may have serious implications for water availability, ecosystem health, agriculture, and flood risk management in affected regions. Therefore, further research is needed to better understand the sources of GCM uncertainty (Hattermann et al., 2018) and to improve selection methodologies. This will ultimately enhance the robustness of climate change impact assessments and support more effective policymaking.

5. Conclusions

This study developed and applied a ranking procedure based on five criteria to identify the best-performing GCMs, thereby enhancing the reliability of runoff projections. Based on this approach, three climate models – MIROC-ES2L, CMCC-CM2-SR5, and KACE-1-0-G – were identified as best representing Lithuania's climatic conditions. According to the selected GCMs, significant future changes in air temperature and precipitation were estimated. Temperatures were projected to rise by up to 2.8°C in the near future and up to 6.4°C in the far future, with the most pronounced seasonal increases occurring in winter and summer. Changes in annual precipitation were relatively modest , with increases up to 5%. Seasonal variability was anticipated to be greater, with winter precipitation potentially increasing by as much as 33.7% and summer precipitation decreasing by up to 23.2%, depending on the region and scenario. Runoff projections revealed a substantial decline, with an average annual runoff decreasing by 12–24% in the near future and 15–42% in the far future, relative to the reference period. Notably, low flow conditions (Q95) were projected to diminish by approximately two-thirds in the far future, posing critical risks for hydrological regimes. The uncertainty assessment highlighted that selected GCMs contributed up to two-thirds of the total uncertainty, confirming the utility of the ranking method for model selection in the absence of regional climate models.

Despite limitations due to low climate model resolution, this study improves our understanding of future lowland river runoff changes. The use of newly developed regional climate models will likely enhance the accuracy of Lithuanian runoff projections.

Acknowledgements

The authors wish to thank the Lithuanian Hydrometeorological Service under the Ministry of Environment for providing the daily hydrometeorological data.

Funding

This research received no external funding.

Data availability statement

All raw data utilized in this study belong to the respective institutions listed in the "Study area and data" section. To gain access to these data, please direct a justified request to the relevant institutions.

Conflict of interest

None declared.

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