






Water resources of the Desna river basin under future climate

Valeriy Osypov , Oleh Speka , Anastasiia Chyhareva, Nataliia Osadcha , Svitlana Krakovska 
and Volodymyr Osadchyi 

Ukrainian Hydrometeorological Institute (UHMI), 03028, pr. Nauki 37, Kyiv, Ukraine

*Corresponding author. E-mail: valery_osipov@ukr.net

 VO, 0000-0003-4853-8021; OS, 0000-0002-2315-5959; NO, 0000-0001-6215-3246; SK, 0000-0001-9972-0937; VO, 0000-0002-0428-4827

ABSTRACT

Climate change impact on water resources has been observed in Ukraine since the end of the 20th century. For now, only large-scale climate impact studies cover Ukraine's territory, having low credibility for a specific catchment. This study aims to calculate future changes in river discharge, water flow components, and soil water within the Desna basin and evaluate vulnerability trends on this basis. The framework assembles the process-based SWAT (Soil and Water Assessment Tool) model and eight high-resolution regional climate models (RCMs) driven by RCP4.5 and RCP8.5 emission scenarios. The climate models are provided by the Euro-CORDEX initiative and based on three RCMs (RCA4, HIRHAM5, and RACMO22E) forced by five general circulation models (CNRM-CM5, EC-EARTH, IPSL-CM5A-MR, HadGEM2-ES, and MPI-ESM-LR). The results preferably show a moderate increase in the annual discharge until the end of the 21st century. The intra-annual changes of water balance components negatively affect the vegetation period because of higher dryness and temperature stress but reduce flood risk, diffuse pollution, and water erosion in the far future. In the river basin management plan, the highest attention should be paid to adaptive strategies in agriculture because of possible water deficit in the vegetation season under future climate scenarios.

Key words: climate change, Desna River Basin, Euro-CORDEX, soil water, SWAT model, water flow

HIGHLIGHTS

- The Desna river annual runoff as well as evapotranspiration will increase under an expected warmer and wetter climate.
- Winter warming will reduce flood risk and increase groundwater flow during the year.
- Soil water will significantly decrease in the vegetation period toward the end of the 21st century under RCP4.5 or RCP8.5.

INTRODUCTION

Water resources management must take into account climate change because global warming evidently accelerates (Allen *et al.* 2018). In Ukraine, the highest warming rate for the period 1981–2010 was observed for the northern and northeastern parts with the rates of annual mean temperature 0.58–0.66 °C/10 years (Balabukh & Malitskaya 2017). Annual precipitation has not significantly changed, but monthly values have smoothed out, and heavy rain frequency has risen (Grebin 2010; Balabukh *et al.* 2018; Palamarchuk & Shedemenko 2020). In the river runoff, the spring flood and flood peak have decreased, and the annual minimum discharge has increased along with the groundwater ratio in total runoff (Grebin 2010).

Ukraine belongs to the countries with insufficient water supply and uneven distribution of water flow over the territory (Stashuk *et al.* 2014). Water resources of the Dnipro, which is the main waterway of Ukraine, are mostly formed in the north-western part of the country, Belarus, and the Russian Federation by the transboundary rivers Prypiat (30% of the Dnipro discharge), Upper Dnipro (31%), and Desna (27%). Then, the water flow is accumulated by six reservoirs and redistributed by 15 artificial channels to households, heavy industry, and agriculture in water-scarce central and south Ukraine.

The Desna mean water runoff decreased by only 6% in 1991–2020 compared with 1961–1990. However, in the last decade (2011–2020), the mean annual discharge was the lowest since observation started in 1895. If the trend continues, it could be a risk for the Dnipro downstream water supply infrastructure. Secondly, a decrease in river discharge causes a higher concentration of water pollutants from municipal wastewater plants and agriculture practices (Osadcha *et al.* 2020). Water quality is critical because the Desna river outlets supplies the capital Kyiv with fresh water.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

For now, only continental- or country-scale studies cover the projected changes in water yield, discharge, and soil water within the Desna basin (Krakovska & Gnatiuk 2013; van Vliet *et al.* 2015; Rouholahnejad *et al.* 2017; Didovets *et al.* 2020; Loboda & Kozlov 2020; Mentaschi *et al.* 2020; Snizhko *et al.* 2020). The results show a wide spread of the annual discharge change even in the near future: from -35% (Loboda & Kozlov 2020) to $+55\%$ (Mentaschi *et al.* 2020). The studies omit the intra-annual changes in water balance components. Moreover, zooming in on specific catchment from large-scale maps is not recommended for climate impact assessment (Krysanova *et al.* 2018).

In the last decades, the ecohydrological process-based river basin models are used globally to support decision-making processes in a changing environment (Fatichi *et al.* 2016). These models provide complex insights into ecosystem-climate behavior and could be used to quantify the effectiveness of possible adaptive measures. In Ukraine, the SWIM (Soil and Water Integrated Model) was used to assess climate change impact on flood risk and water resources in several mesoscale catchments (Didovets *et al.* 2017, 2019), and the SWAT (Soil and Water Assessment Tool) model was used to estimate future water budgets in the Upper Western Bug catchment (Fischer *et al.* 2014).

This study aims to provide a quantitative background for the water resources management within the Desna basin, predict trends of environmental issues, and highlight risks of climate change. To achieve robust outcomes, the research calibrates the daily discharge of 12 gauges SWAT model and wide spread of possible future scenarios: eight high-resolution (~ 12 km) climate models from the Euro-CORDEX initiative (Jacob *et al.* 2014). The multi-model ensemble couples three regional climate models (RCMs) forced by five general circulation models (GCMs) from CMIP5 (Coupled Model Intercomparison Project 5) and includes two representative concentration pathways (RCPs), the RCP4.5 and RCP8.5 scenarios (Moss *et al.* 2010). The past-performance approach was used to verify the ability of climate models to represent long-term monthly variations of temperature and precipitation. The results summarize the annual and intra-annual spatial changes in temperatures, water balance components, and weather extremes for two future periods 2021–2050 and 2071–2100 over the baseline 1991–2020. In the discussion, the results are addressed to the vulnerabilities of the Desna basin over climate change.

STUDY AREA

The Desna river basin is located in the central part of the East European Plain: the upstream part – in the Russian Federation (62%) within Smolenskaya, Bryanskaya, Kurskaya, Kaluzhskaya, and Tulska Oblasts; and the downstream part – in Ukraine (38%) within Chernihiv's'ka, Sums'ka, and Kyivs'ka Oblasts (Figure 1). The Tulska mixed forest zone dominates across the basin, except for the forest-steppe zone in the southeast part of the basin. The landscape is plain, mainly cut by gullies and ravines.

Eutric podzoluvisols cover 42% of the basin territory; their gleyed species are formed in the depressed areas (4.5%) (Figure 1(b)). The rest of the territory is covered by greyzems (24%), chernozems (10%), phaeozems (10%), fluvisols over floodplains (10%), and histosols (4%).

For the Desna SWAT model, we used the merged land cover layer from GlobeLand30 (<http://www.globallandcover.com/>, 2010 land cover) and Global Forest Change (<https://earthenginepartners.appspot.com/science-2013-global-forest>, 2012 forest state) (Hlotka 2017). Agricultural lands cover 55% of the basin territory, mixed forests – 29%, meadows – 9%, residential areas – 3%, wetlands – 2%, and water – 2%. (Figure 1(c)). Crop production is the leading economic sector of the Chernihiv and Sumy regions.

The Desna basin has a moderate continental climate with both warm humid summer and winter. According to the E-OBS dataset (ver. 23.1) (Cornes *et al.* 2018), the mean annual temperature increased by 1.3 °C compared with the period of 1961–1990. The highest growth was in winter, by 2 °C, followed by summer by 1.3 °C, then spring by 1.2 °C, and autumn by 0.8 °C (Table 1). Summer precipitation decreased by 14%, while precipitation in spring and autumn increased by 7 and 8%, respectively, and did not change in winter.

Snowmelt drives a hydrological regime inducing spring flood. But the spring flood peak tremendously decreased in the last decades (Figure 2). Instead, the cold season discharge increased due to more frequent thaws and higher precipitation in October, January, and February (Grebin 2010) (Table 1).

METHODOLOGY

SWAT model

The SWAT is an open-source semi-distributed process-based ecohydrological model that is globally used to support the decision-making process in a complex environment (Arnold *et al.* 2012).

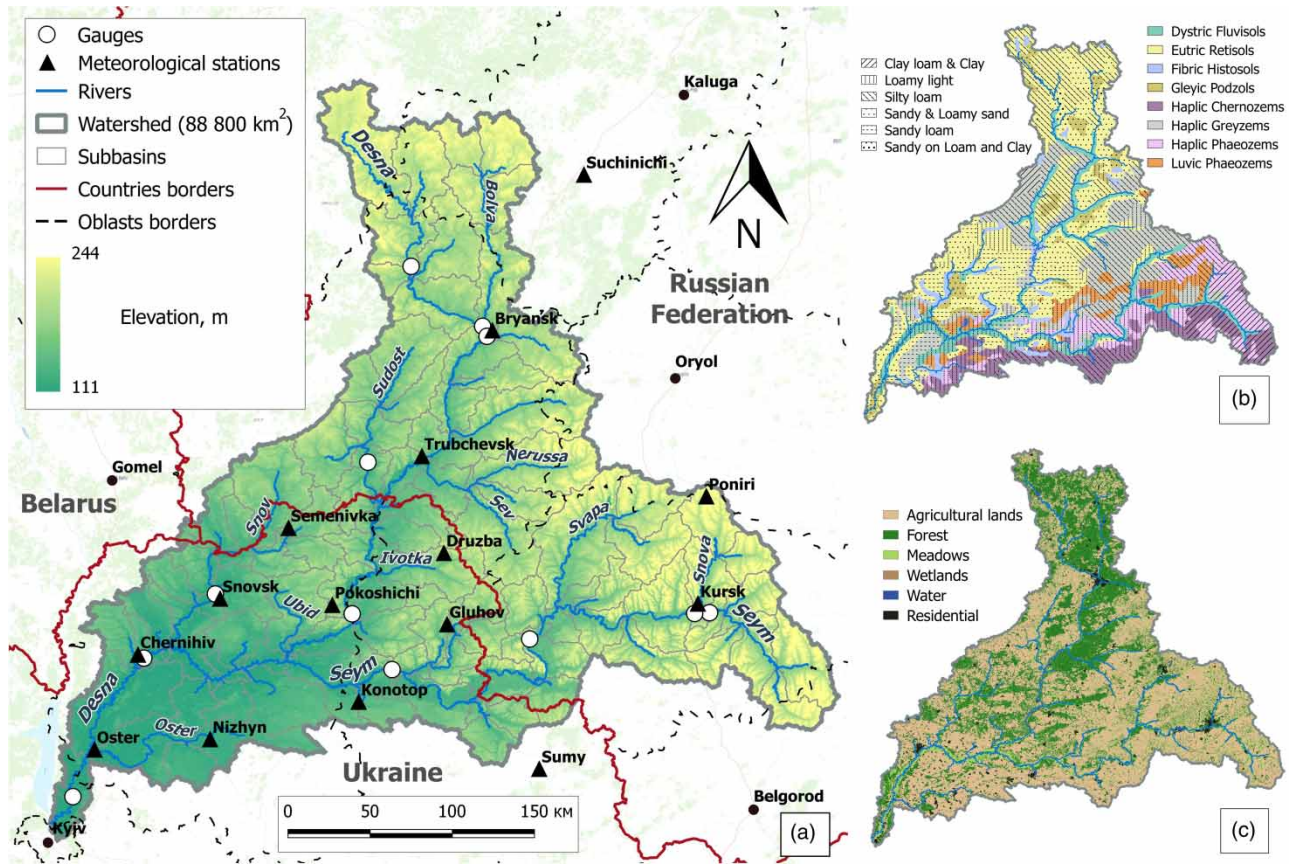


Figure 1 | The Desna river basin: (a) delineation into 116 subbasins, DEM, gauges used for the SWAT model calibration, and meteorological stations used for the past-performance assessment of RCMs; (b) soil type and texture; (c) land cover.

Table 1 | Mean temperature and total precipitation of the Desna river basin based on the E-OBS dataset

Month	Temperature (°C)			Precipitation (mm)		
	1961–1990	1991–2020	Δ (°C)	1961–1990	1991–2020	Δ (%)
1	−8.2	−5.2	3.0	38	40	5
2	−6.9	−4.6	2.2	31	37	18
3	−1.6	0.3	2.0	36	37	3
4	7.1	8.3	1.3	40	36	−11
5	14.1	14.6	0.4	46	58	25
6	17.2	18.1	0.9	71	61	−14
7	18.4	20.1	1.6	79	72	−8
8	17.4	18.8	1.4	60	48	−21
9	12.3	13.2	1.0	49	53	9
10	6.1	7.0	0.8	40	52	29
11	0.1	0.7	0.6	49	43	−11
12	−4.5	−3.6	0.8	49	43	−12
Year	6.0	7.3	1.3	589	581	−1

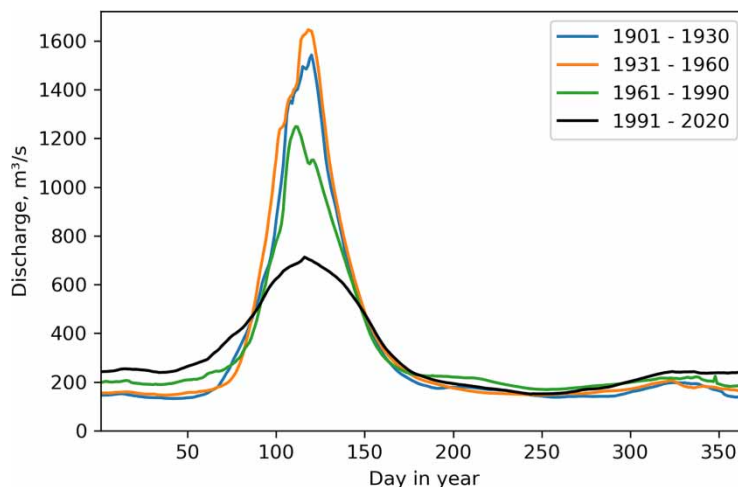


Figure 2 | Long-term annual daily discharge of the Desna river at gauge Desna-Chernihiv.

The SWAT assimilates weather and landscape information to calculate the hydrological cycle as well as sediment and nutrient transport. The input data include daily weather parameters (maximum and minimum air temperature, precipitation, relative humidity, wind speed, and solar radiation), DEM, soils, land cover, and agricultural operation schedule (e.g., planting of crops, fertilization, tillage, harvest). The watershed is delineated into subbasins where areas with similar land cover, soils, and slope are grouped into hydrological response units (HRUs). The water balance is simulated for each HRU calculating evapotranspiration, infiltration, capillary flow, shallow and deep aquifer recharge, surface, lateral, and groundwater flows. In comparison with previous versions, the SWAT2012 includes deep groundwater flow in total water yield (https://swat.tamu.edu/media/116557/rev681_source.zip, file subbasin.f, lines 411–412). Then, the water is routed through the river network calculating the discharge of the reach in each subbasin.

In a previous study, we calibrated and validated the SWAT model of the Desna basin for the period 2008–2014 (Osypov *et al.* 2018). For this research, we extended the modeling period to 2008–2019. The calibration was based on daily river discharge (12 gauges), snow cover depth (13 stations), and crop yield. The performance criteria were good ($NS > 0.7$, $R^2 > 0.75$, $PBIAS < 10\%$) for all five gauges located in Ukraine.

To assess the impact of climate change, the SWAT model is sequentially fed by the climate variables of each RCM. The results are aggregated for the subbasins of the Desna watershed, the main channel, and the tributaries more than 450 km². The geospatial data are presented using Python packages: geopandas (<https://geopandas.org/>), matplotlib (<https://matplotlib.org/>), and mapclassify (<https://pypi.org/project/mapclassify/>).

Evaluation of RCMs

For Europe, the Euro-CORDEX initiative provides high-resolution (~12 km) bias-adjusted temperature and precipitation data of RCMs (Jacob *et al.* 2014) that are based on the five CMIP5 global climate projections (Taylor *et al.* 2012) and the new RCPs (Moss *et al.* 2010). Bias correction is commonly performed for precipitation and temperature as the major hydrological drivers. It improves the reliability of simulated hydrological process and projected mean river discharge (Huang *et al.* 2014).

Regional climate impact studies usually reduce the number of climate models because of computational reasons trying to keep the range of possible future scenarios. We selected eight RCMs that have climate variables required for the SWAT simulation and have both RCP4.5 and RCP8.5 emission scenarios (Table 2).

A climate model should be able to reproduce the behavior of hydrology-relevant parameters (e.g., precipitation and temperature) in the past for the studied watershed (Yuan *et al.* 2020). On the other hand, the selection of only the ‘best’ performance model may omit possible future scenarios (Lutz *et al.* 2016). There is no evidence that the best performing models in the past are the most realistic with regard to a climate signal. Therefore, it seems reasonable that the model performance in the past should rather be used to detect and remove severely unrealistic models (Mendlik & Gobiet 2016).

We used a skill-score approach (Fu *et al.* 2013) to eliminate RCMs (if they exist) that substantially miss long-term annual and monthly values of precipitation and temperature. The criteria include systematic bias (B), quantile biases (QB_i),

Table 2 | List of RCMS forced by GCMs used in the study

GCM (initial conditions)	RCM	Institute
CNRM-CM5 (r1i1p1)	RCA4	Swedish Meteorological and Hydrological Institute (SMHI)
EC-EARTH (r3i1p1)	HIRHAM5	Danish Meteorological Institute (DMI)
EC-EARTH (r1i1p1)	RACMO22E	Royal Netherlands National Meteorological Institute (KNMI)
EC-EARTH (r12i1p1)	RCA4	Swedish Meteorological and Hydrological Institute (SMHI)
IPSL-CM5A-MR (r1i1p1)	RCA4	Swedish Meteorological and Hydrological Institute (SMHI)
HadGEM2-ES (r1i1p1)	RACMO22E	Royal Netherlands National Meteorological Institute (KNMI)
HadGEM2-ES (r1i1p1)	RCA4	Swedish Meteorological and Hydrological Institute (SMHI)
MPI-ESM-LR (r1i1p1)	RCA4	Swedish Meteorological and Hydrological Institute (SMHI)

coefficient of determination (R^2), normalized root mean square error (NRMSE):

$$B = \frac{\sum_{i=1}^n X_{m,i}}{\sum_{i=1}^n X_{o,i}} \quad (1)$$

$$QB_t = \frac{\sum_i^n (X_{m,i} | X_{m,i} \geq t)}{\sum_i^n (X_{o,i} | X_{o,i} \geq t)} \quad (2)$$

$$R^2 = \frac{\left[\sum_i^n (X_{o,i} - \bar{X}_o)(X_{m,i} - \bar{X}_m) \right]^2}{\sum_i^n (X_{o,i} - \bar{X}_o)^2 \sum_i^n (X_{m,i} - \bar{X}_m)^2} \quad (3)$$

$$NRMSE = \frac{\sqrt{\frac{1}{n} \sum_i^n (X_{m,i} - X_{o,i})^2}}{\sqrt{\frac{1}{n-1} \sum_i^n (X_{o,i} - \bar{X}_o)^2}} \quad (4)$$

where $X_{m,i}$ and $X_{o,i}$ are model and observed monthly values, respectively; for B and QB_t , n is the number of months in the reference period (1970–2005 for stations in the Russian Federation or 1976–2005 for stations in Ukraine) or, for R^2 and NRMSE, $n = 12$ – the number of months in a year; t is the threshold (25th, 50th, and 75th percentiles). Observed values (15 stations) are downloaded from the European Climate Assessment & Dataset project (ECAD) for Bryansk, Kursk, Poniri, Suchinichi, and Trubchevsk (<https://www.ecad.eu/dailydata/customquery.php>) and requested from the central geophysical observatory named after Boris Sreznevsky for Gluhov, Druzba, Konotop, Sumy, Nizhyn, Oster, Semenivka, Chernihiv, Shchors, and Pokoshichi. The model data are taken from the RCM's node nearest to the station.

The RCA4 model forced by HadGEM2-ES and MPI-ESM-LR showed the best past performance, but the criteria of other models were close to each other (Table 3). However, RCA4 forced by CNRM-CM5 and EC-EARTH showed the worst results and substantially missed the long-term monthly cycle of precipitation (Appendix A), therefore, it was excluded from the analysis of the SWAT output.

Communication of the degree of certainty

Climate impact studies should provide traceable findings to evaluate the relevance of possible adaptation measures. To communicate the degree of certainty of the results, the calibrated language developed in (Mastrandrea *et al.* 2010) is widely used in climate projection studies, including IPCC reports. The core vocabulary includes:

Table 3 | The performance skill score of RCMs against observed temperature and precipitation (15 stations across the Desna basin) for the historical period (1970–2005)

RCM	Temperature						Precipitation						Final score ^a
	B	B25	B50	B75	R ²	NRMSE	B	B25	B50	B75	R ²	NRMSE	
CNRM-CM5_RCA4	1.073	1.046	1.027	1.024	0.994	0.072	1.039	1.043	1.044	1.038	0.54	0.65	
EC-EARTH_HIRHAM5	1.057	1.03	1.03	1.034	0.995	0.065	1.019	1.027	1.031	1.02	0.70	0.52	
EC-EARTH_RACMO22E	1.083	1.041	1.038	1.039	0.992	0.084	0.957	0.965	0.979	1	0.68	0.53	
EC-EARTH_RCA4	1.094	1.058	1.046	1.051	0.991	0.088	0.94	0.957	0.972	0.989	0.49	0.68	
IPSL-CM5A-MR_RCA4	1.012	1.016	1.008	1.006	0.998	0.041	0.969	0.971	0.969	0.963	0.73	0.49	
HadGEM2-ES_RACMO22E	1.026	1.008	1.016	1.019	0.996	0.062	0.979	0.992	1.005	1.013	0.70	0.52	
HadGEM2-ES_RCA4	1.043	1.023	1.014	1.015	0.996	0.056	0.983	0.991	1	0.999	0.72	0.49	
MPI-ESM-LR_RCA4	1.071	1.025	1.008	1.009	0.993	0.080	1.017	1.02	1.02	1.008	0.80	0.42	
Ensemble_8RCMs	1.057	1.031	1.023	1.025	0.996	0.057	0.988	0.996	1.002	1.004	0.78	0.44	
Ensemble_6RCMs^b	1.049	1.024	1.019	1.020	0.997	0.053	0.987	0.994	1.001	1.000	0.81	0.41	
	Skill score (8 – best, 1 – worst)												
HadGEM2-ES_RCA4	6	6	6	6	7	7	7	7	8	7	6	6	6.7
MPI-ESM-LR_RCA4	4	5	7	7	3	3	8	6	6	6	8	8	6.3
HadGEM2-ES_RACMO22E	7	8	5	5	6	6	5	8	7	4	5	4	5.7
IPSL-CM5A-MR_RCA4	8	7	8	8	8	8	4	4	2	2	7	7	5.5
EC-EARTH_HIRHAM5	5	4	3	3	5	5	6	5	3	3	4	5	4.3
EC-EARTH_RACMO22E	2	3	2	2	2	2	2	3	5	8	3	3	3.4
CNRM-CM5_RCA4	3	2	4	4	4	4	3	2	1	1	2	2	2.4
EC-EARTH_RCA4	1	1	1	1	1	1	1	1	4	5	1	1	1.8

^aFinal score is defined as weighted mean (temperature weight – 0.5, precipitation weight – 1) because the Desna SWAT model is more sensitive to precipitation change.

^bEnsemble includes six from eight RCMs (without CNRM_CM5_RCA, and EC-EARTH_RCA4).

- Consistency of evidence (e.g., quality of models): ‘limited’, ‘medium’, ‘robust’.
- Degree of agreement (e.g., between modeling results): ‘low’, ‘medium’, ‘high’.
- Level of confidence in the validity of a finding: ‘very low’, ‘low’, ‘medium’, ‘high’, ‘very high’. Confidence increases along with more robust evidence and higher agreement.
- Likelihood: ‘very likely’ (>90%), ‘likely’ (66–100%), ‘about as likely as not’ (33–66%), ‘unlikely’ (0–33%), ‘very unlikely’ (0–10%). Likelihood can be assigned in case of high agreement and(or) robust evidence.

The evidence of this study could be expressed as robust because it is based on the well-calibrated SWAT model of the Desna basin and the high-resolution bias-adjusted RCMs that capture the wide spread of climate signals. The likelihood is assigned as ‘very likely’ when all six models agree on the direction of change or show no change ($\pm 5\%$), ‘likely’ – 4–5 of six models, ‘unlikely’ – 1 of 6 models and ‘very unlikely’ – any models.

RESULTS

Climate projections of temperature and precipitation

The comparison between climate model data and observations is given in Table 4. Additionally, the exceedance probability of mean annual temperature and precipitation is presented in Appendix D. All models were right predicting noticeable warming against 1961–1990. Considering temperature and precipitation trend together, we could say that RCA4 forced by HadGEM-ES and MPI-ESM-LR and RACMO22E forced by HadGEM-ES better agree with the observed trend.

Projections of annual temperature and precipitation by all eight RCMs are presented in the diagram of Figure 3 and their ensemble mean with standard deviation in Figures 4 and 5. Temperature and precipitation signals mostly fall in one area in the near future (2021–2050): warming around 1 °C and precipitation increase by 0–10%. In the far future (2071–2100),

Table 4 | Mean annual temperature and total precipitation for stations across the Desna basin (data are available only for nine stations for the period 1961–2019: Bryansk, Kursk, Poniri, Suchinichi, Trubchevsk, Pokoshichi, Sumy, Semenivka, and Shchors) and RCM nodes nearest to the stations in 1961–1990 and 1990–2019

RCP/ RCM	Temperature (°C)			Precipitation (mm)		
	1961(1970) – 1990	1990–2019	Δ (°C)	1961(1970) – 1990	1990–2019	Δ (%)
Observed	5.5 (5.6)	6.7	1.2 (1.1)	633 (661)	625	– 1% (–5%)
RCP4.5						
CNRM-CM5_RCA4 ^a	5.8	7.0	1.1	668	655	– 2
EC_EARTH_HIRHAM5	6.0	6.8	0.8	607	641	6
EC_EARTH_RACMO22E	5.9	6.6	0.7	596	649	9
EC_EARTH_RCA4 ^a	6.1	6.7	0.7	590	624	6
IPSL-CM5A-MR_RCA4 ^a	5.5	7.0	1.5	605	640	6
HadGEM2-ES_RACMO22E	5.6	6.9	1.3	600	652	9
HadGEM2-ES_RCA4 ^a	5.6	6.8	1.2	633	662	5
MPI-ESM-LR_RCA4 ^a	6.1	6.7	0.6	637	644	1
RCP8.5						
CNRM-CM5_RCA4 ^a	6.0	6.8	0.8	655	666	2
EC_EARTH_HIRHAM5	6.0	6.7	0.7	607	653	8
EC_EARTH_RACMO22E	6.0	6.8	0.8	579	635	10
EC_EARTH_RCA4 ^a	6.1	6.9	0.8	599	635	6
IPSL-CM5A-MR_RCA4 ^a	5.4	7.1	1.7	584	652	12
HadGEM2-ES_RACMO22E	5.5	7.0	1.4	630	645	2
HadGEM2-ES_RCA4 ^a	5.7	6.9	1.2	644	633	– 2
MPI-ESM-LR_RCA4 ^a	6.1	6.8	0.7	641	612	– 4

^aRCM starts in 1970.

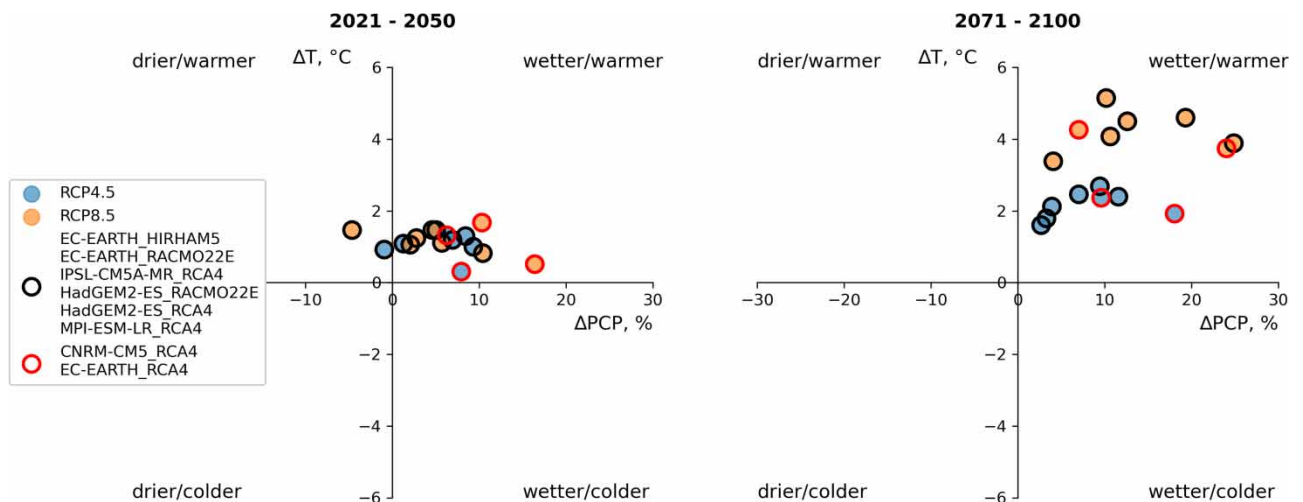


Figure 3 | Temperature and precipitation climate signals of the Desna river basin. RCA4 forced by CNRM-CM5 and EC-EARTH were excluded from the hydrological assessment because of unrealistic long-term monthly precipitation cycle during the historical period (Appendix A).

RCP4.5 scenarios also fall nearby – around 2 °C warming and 8% precipitation surplus. RCP8.5 scenario spreads wider – up to 3–5 °C warming and 5–25% precipitation surplus.

Across the Desna basin, projected temperature increases in the direction from west to east (Figure 4). Precipitation increases more strongly for the northern part of the basin; uncertainty is higher for the southern part (Figure 5).

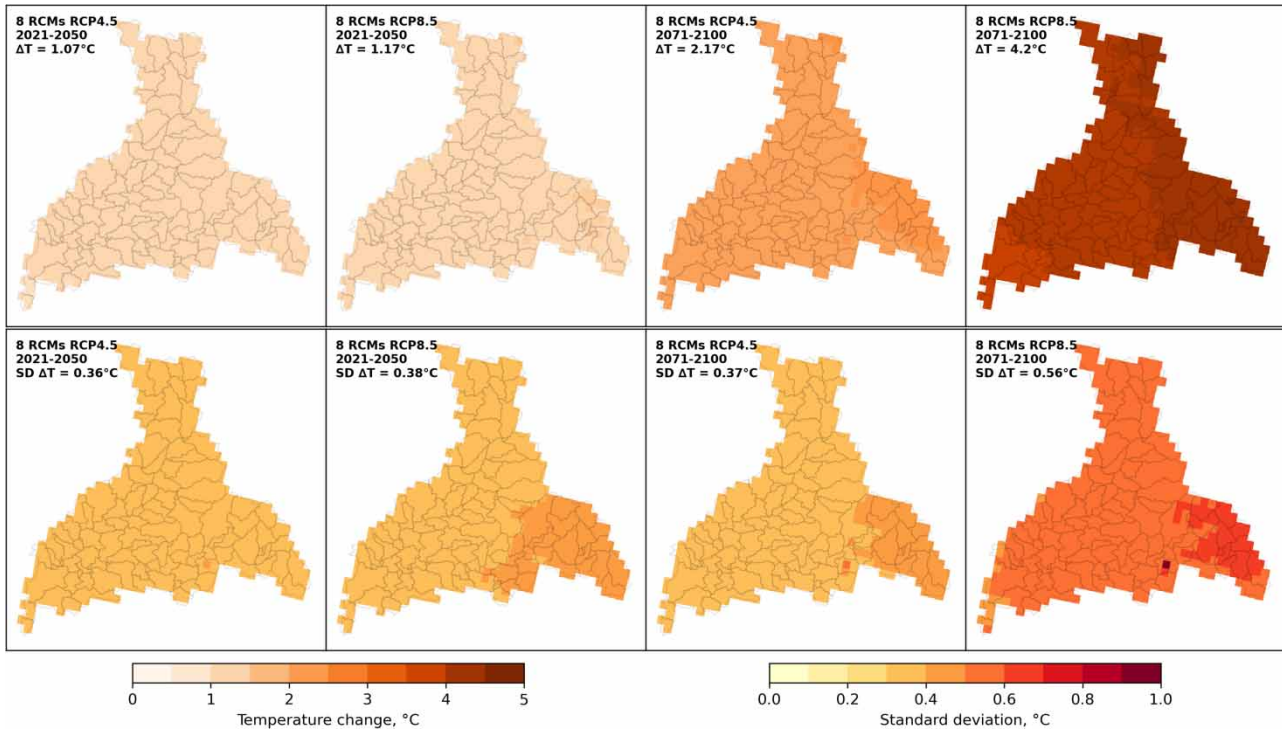


Figure 4 | Future changes of mean temperature (ΔT , $^{\circ}\text{C}$) with standard deviation (SD, $^{\circ}\text{C}$) of the RCMs ensemble across the Desna basin.

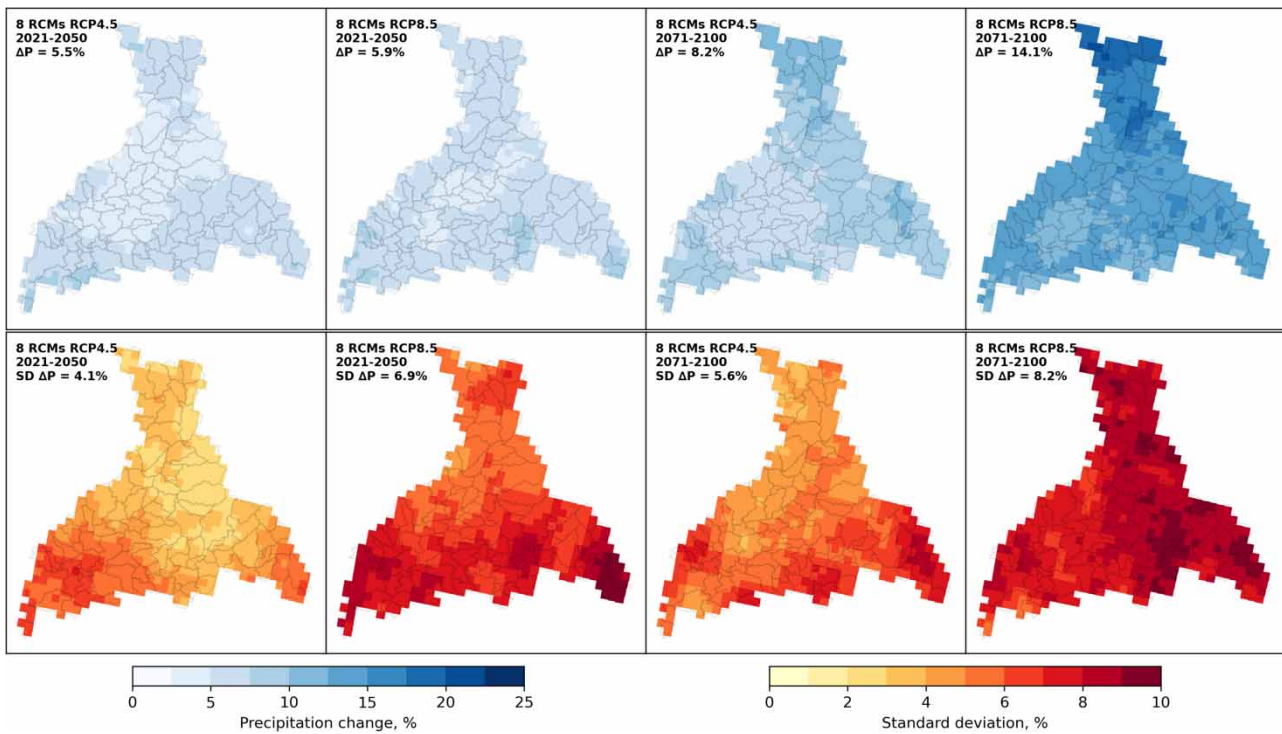


Figure 5 | Future changes of mean precipitation (ΔP , %) with standard deviation (SD, %) of the RCMs ensemble across the Desna basin.

The models predict the increase in the intensity of heavy precipitations by 12–20% and the number of the periods (three consecutive days) with extreme temperature by 0.3–1.7 per year in the far future (Appendix C).

Annual changes of water balance components

In the 21st century, annual water yield might stay almost constant ($\pm 10\%$) or prominently increase (16–53%) under both RCP4.5 and RCP8.5 (Table 5). The increase is explained by higher precipitation, especially during the cold period when the soil becomes highly saturated stimulating the formation of water runoff. Only HIRHAM5 forced by EC-EARTH projects water yield decrease by 24% in the near future because of precipitation loss by 6%.

Groundwater and lateral flows will likely increase, mostly due to higher water infiltration during the cold period rather than accumulation in the snow cover. In the near future, the surface flow could moderately decrease as likely as increase under RCP4.5 and likely decrease more than 15% under RCP8.5. In the far future, the surface flow will likely fall by more than 20% under RCP4.5 or 40% under RCP8.5. A decrease in surface runoff is caused by two main reasons: first, lower soil moisture in June–October due to higher evapotranspiration; second, soils in the catchment do not freeze because of higher winter temperatures, while frequent thaws contribute water infiltration into deeper horizons.

A soil water change will likely fluctuate near zero due to simultaneous effects of higher precipitation and higher evapotranspiration. However, intra-annual changes are significant.

The discharge of the Desna river will likely slightly increase in the near future and will continue to rise slowly during the 21st century, mostly as a result of the noticeable increase of the discharge in the northern part of the basin (Figure 6). The same is true for the tributaries. Note that the possible future range also includes the slight decrease of discharge.

Intra-annual future changes

Precipitation will likely be increasing in November–March and May in the near future, then all months between October and May (Figure 7). In June–September, models disagree about the direction of precipitation change, and the mean signal is close to zero.

Water yield mostly repeats the dynamics of precipitation, except for March and April because of lower snowmelt runoff (Figure 7). Furthermore, water yield might increase even under precipitation loss due to higher groundwater discharge during the year (Appendix B).

At the Desna outlet, the water discharge reflects the water yield across the whole basin with a delay of around 1.5 months (Figure 8). Like previous years, the discharge will very likely continue to increase during the cold period and likely decrease during the spring flood peak (April or May). For the low water period (late June–October), the trend is unclear, primarily because precipitation change in June–September is also unclear. There is a high agreement that the discharge will rise in July, but the surplus might be as small as significant ($>30\%$ in the near future and $>50\%$ in the far future). In the near future, the discharge will likely increase in August and slightly decrease in October. Therefore, September and October will be the months with the lowest water levels. In the far future, the models disagree on the direction of discharge change in August–October, but the possible surplus (70%) is higher than the possible loss (20%).

The predicted discharge trends are very similar under RCP4.5 and RCP8.5, but the most extreme decrease and increase are possible under RCP8.5. In particular, HIRHAM5 forced by EC-EARTH predicts discharge loss by 30–36% at the Desna outlet in August–October in the near future. RCA4 forced by MPI-ESM-LR predicts a rise by 30–48% in all months except February, May, and June in the near future and rise by near 50% in April and June, near 60% in October–December, and near 80% in January–March and July–September in the far future.

Soil water will likely slightly decrease during the vegetation period in the near future and very likely more seriously decrease in the far future (Figures 7 and 9).

DISCUSSION

We suggest that climate change may exacerbate temperature and water stresses for crops, fire risk, and eutrophication (Table 6). Soil water will be decreasing during the warm period because of higher evapotranspiration and likely lower precipitation in July and(or) August. This negative effect will be compensated partially by precipitation surplus in October–May.

On the positive side, the surface runoff will likely be decreasing in the 2050s preventing flood risk, soil erosion, and diffuse pollution. The lower snow accumulation will smooth peak discharge in spring. Moreover, the warming in winter intensifies infiltration that will increase groundwater inflow during the year.

Table 5 | Changes of annual water balance components for 2021–2050 and 2071–2100 over 1991–2020 (the Ukrainian part of the Desna river basin)

RCP/RCM	Changes in 2021–2050 over 1991–2020							Changes in 2071–2100 over 1991–2020								
	ΔPrecipitation (%)	ΔSnowmelt (%)	ΔEvapotranspiration (%)	ΔWater yield (%)	ΔSurface flow (%)	ΔLateral flow (%)	ΔGroundwater flow (%)	ΔSoil water (%)	ΔPrecipitation (%)	ΔSnowmelt (%)	ΔEvapotranspiration (%)	ΔWater yield (%)	ΔSurface flow (%)	ΔLateral flow (%)	ΔGroundwater flow (%)	ΔSoil water (%)
RCP4.5																
CNRM-CM5_RCA4	8	-18	6	25	117	8	15	8	17	-46	10	45	66	27	50	10
EC-EARTH_HIRHAM5	-3	-13	1	-10	-20	-2	-11	-9	2	-22	3	-6	-34	6	1	-4
EC-EARTH_RACMO22E	0	1	3	-4	-8	-1	-3	-6	3	-18	3	4	-26	9	14	-9
EC-EARTH_RCA4	6	-18	5	3	-23	11	7	2	9	-34	8	9	-25	17	16	1
IPSL-CM5A-MR_RCA4	8	-15	5	18	18	10	23	3	5	-38	6	-4	-32	9	0	-4
HadGEM2-ES_RACMO22E	4	-14	3	2	-7	4	2	-6	7	-27	2	16	-21	14	27	-6
HadGEM2-ES_RCA4	11	-27	4	23	3	17	33	4	13	-30	3	40	5	26	62	4
MPI-ESM-LR_RCA4	11	-14	3	33	8	23	52	7	2	-26	2	2	-36	7	16	-1
Average of six RCMs	5	-14	3	10	-1	9	16	-1	5	-27	3	9	-24	12	20	-3
RCP8.5																
CNRM-CM5_RCA4	16	-16	6	56	135	26	55	13	22	-69	13	49	9	41	63	8
EC-EARTH_HIRHAM5	-6	-24	2	-24	-51	-6	-19	-11	3	-44	6	-9	-58	11	5	-11
EC-EARTH_RACMO22E	8	-4	8	8	-26	14	17	1	13	-41	15	5	-67	24	18	-2
EC-EARTH_RCA4	13	-11	7	29	47	19	29	7	5	-70	7	-8	-70	13	-5	-5
IPSL-CM5A-MR_RCA4	2	-20	4	-3	3	1	-8	0	15	-75	11	20	-43	29	36	-3
HadGEM2-ES_RACMO22E	3	4	4	3	-22	5	7	-4	8	-62	9	-1	-75	17	5	-8
HadGEM2-ES_RCA4	1	-14	1	3	-15	2	9	-3	11	-64	7	22	-60	25	46	-2
MPI-ESM-LR_RCA4	10	0	2	38	69	18	40	8	23	-52	11	53	15	41	73	9
Average of six RCMs	3	-10	4	4	-7	6	8	-1	12	-56	10	15	-48	24	31	-3

The crossed-out models (RCA4 forced by CNRM-CM5 and EC-EARTH) were excluded from the hydrological assessment because of low confidence in the results (Appendix A).

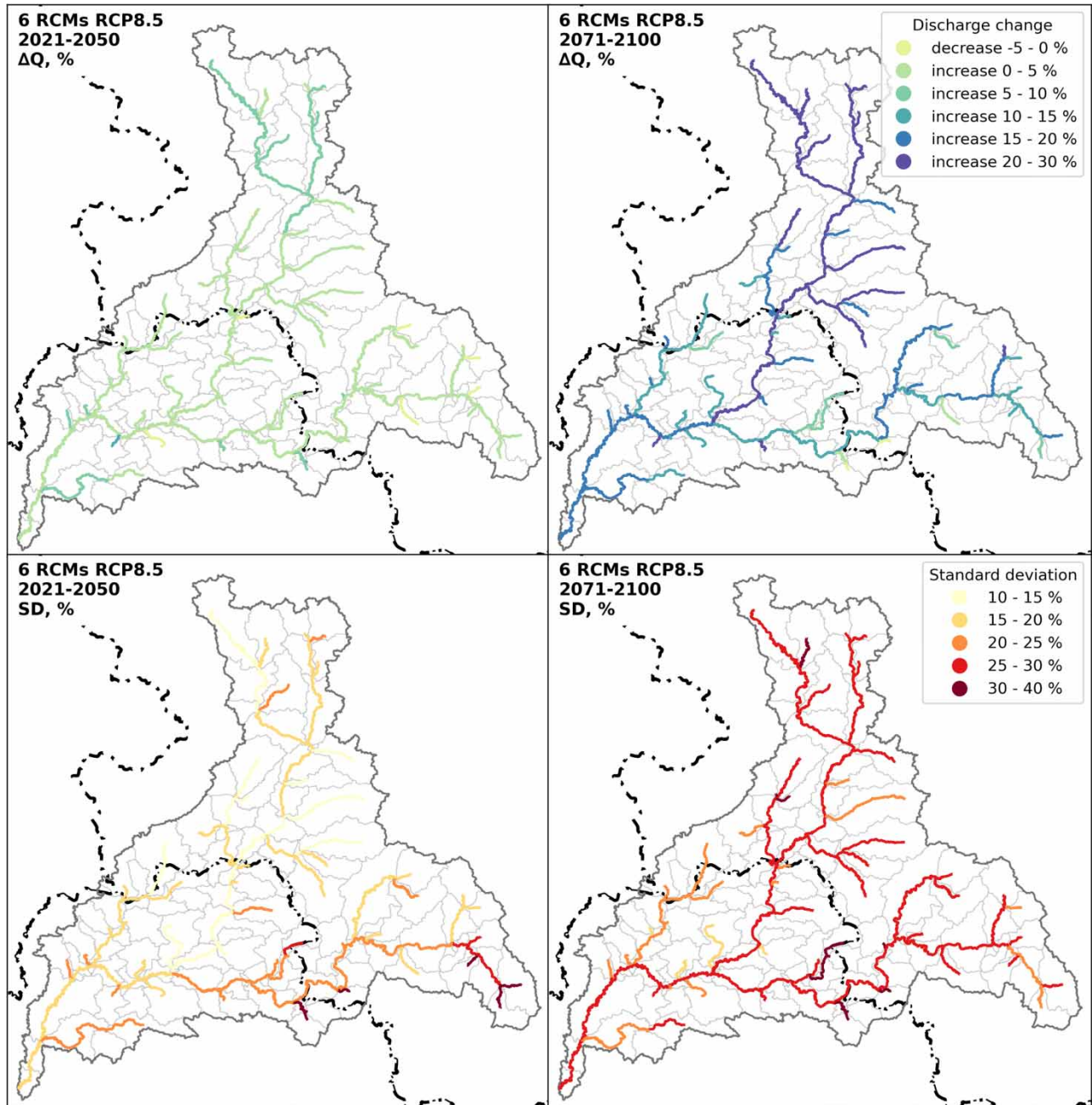


Figure 6 | Change in mean annual flow (ΔQ , %) with standard deviation (SD, %) of the RCMs ensemble under RCP8.5 for 2021–2050 and 2071–2100 over 1991–2020.

The uncertainty of climate models prevents achieving a confident conclusion in some cases. In particular, the disagreement on the direction of precipitation change in summer leads to three possible scenarios of the lowest water period (August–October): no change, medium-high surplus, or medium loss. If the negative trend of summer precipitation continues, it will be a signal of the higher risk of point source pollution.

Adaptive planning should also take into account ‘low likelihood’ scenarios with high risks. One of eight models, HIRHAM5 forced by EC-EARTH, predicts a slight precipitation loss that will lead to the soil water decrease by 20% in summer even in the near future and a prominent decrease in water discharge during the low water period in June–October (by 36% in October).

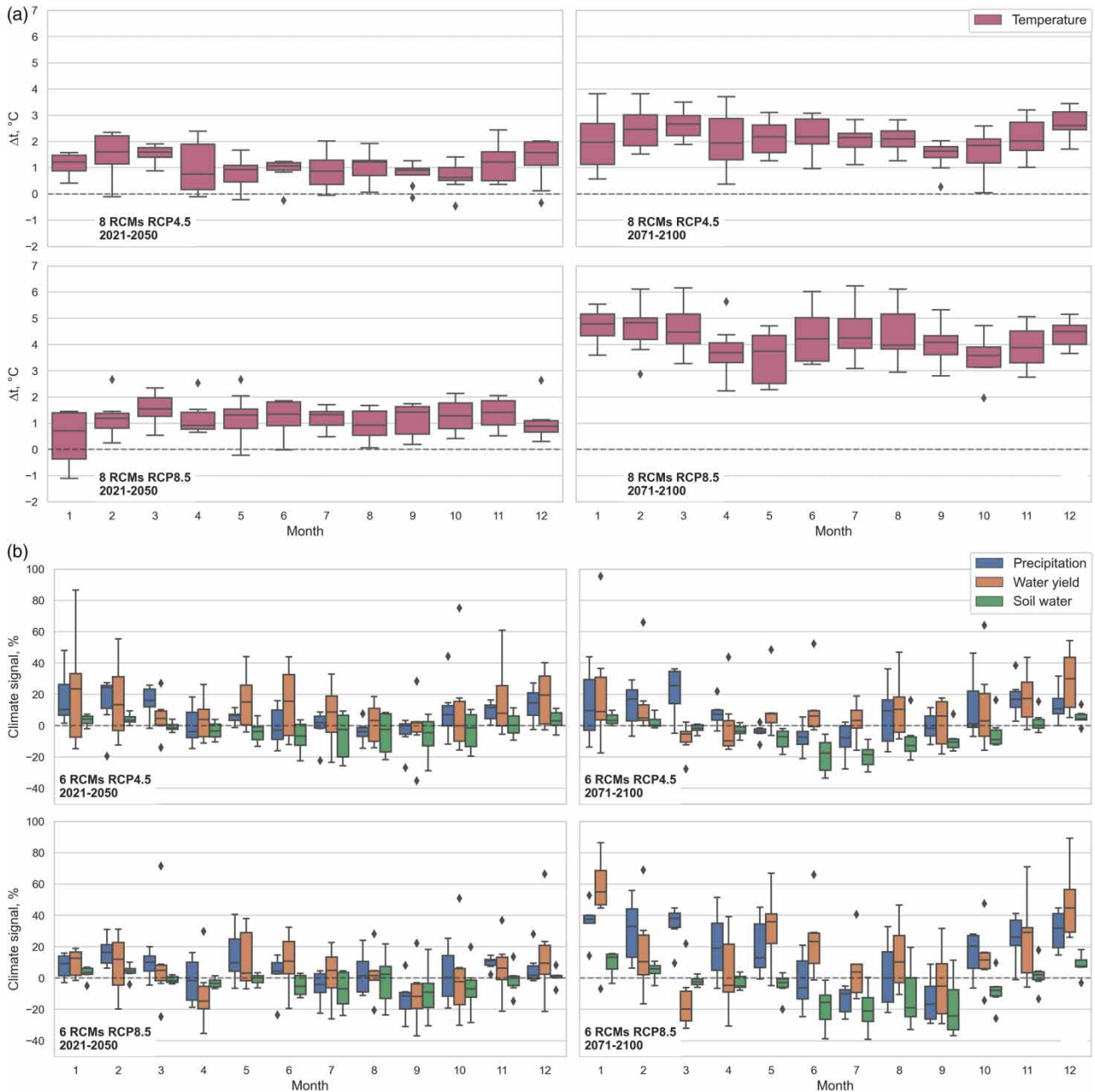


Figure 7 | Future changes of monthly temperature (a), precipitation, water yield, and soil water (b) for the Ukrainian part of the Desna river basin of the RCMs ensemble under RCP4.5 and RCP8.5 for 2021–2050 and 2071–2100 over 1991–2020. Plots represent the 1st(Q1)–3rd(Q3) quartiles as boxes, medians as lines within boxes, and ± 1.5 IQR (interquartile range) as whiskers over the ensembles of RCMs.

Among other studies, the results better agree with *Didovets et al. (2020)*, who have used the global hydrological model WaterGAP calibrated on long-term annual river discharge at 1319 basins all over the world, including the Desna river (*Hunger & Döll 2008*) (Table 7). Despite the lower calibration efficiency in comparison with the current study (*Didovets et al. 2020*), the results also have good agreement on monthly signals for the highest water discharge (April–May) and the lowest one (August–September). This supports the conclusion that annual discharge will rather increase, and only a slight fall (5–10%) is possible.

Large-scale studies commonly have low confidence for a specific basin because they lack comprehensive calibration since computational capabilities and limited access to the observations (*Krysanova et al. 2018*). As mentioned above, this research is based on the SWAT model calibrated on daily discharge at 12 gauges across the basin, snow observations at 13 stations, and

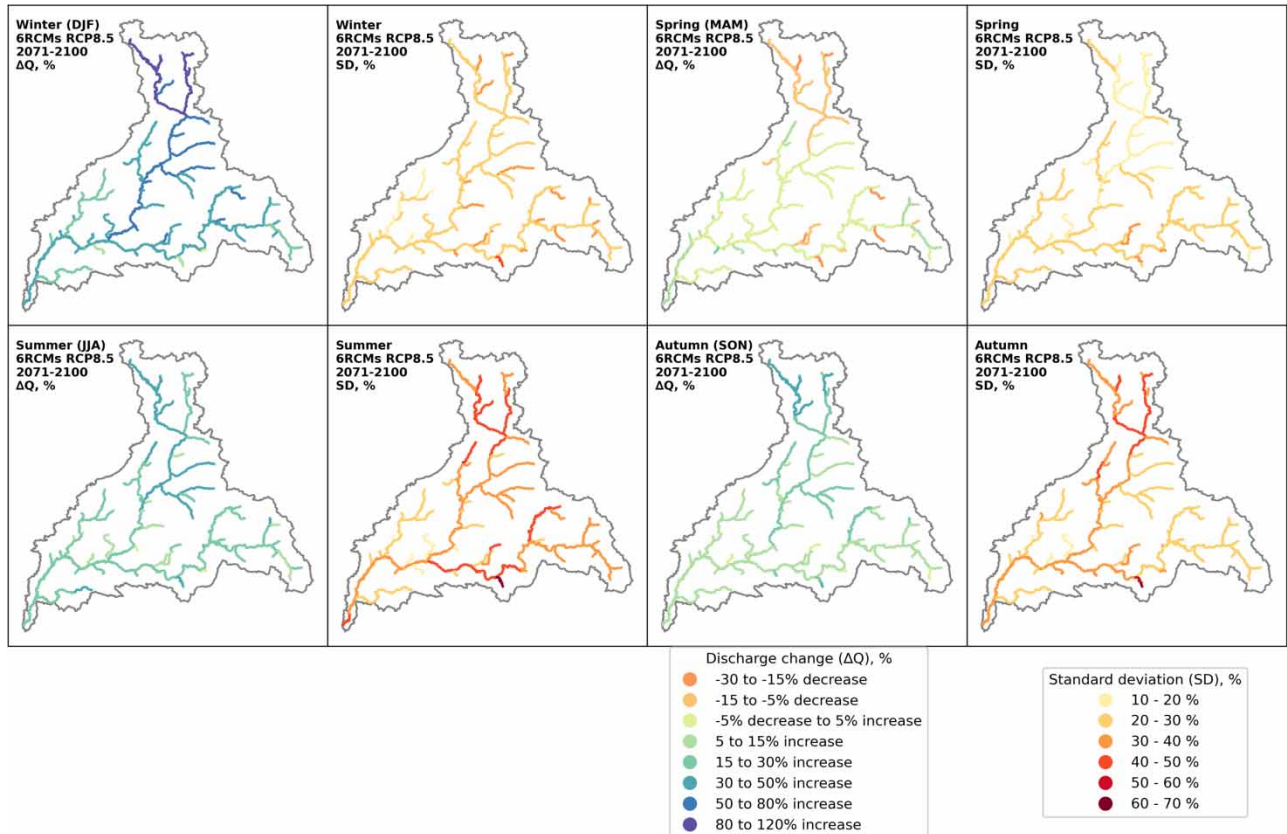


Figure 8 | Change in mean seasonal flow (ΔQ , %) with standard deviation (SD, %) of the RCMs ensemble under RCP8.5 for 2071–2100 over 1991–2020.

crop yield of the main crops (Osypov *et al.* 2018). Therefore, we believe that our results have higher credibility because of a better representation of the processes, especially for the tributaries.

However, the current Desna model omits comprehensive adjustment of nutrient transport, land-use change scenarios, and future agricultural practices. These factors obstruct the decisive prediction about the diffuse pollution trend. Nonetheless, we justify that climate will favor the reduction of nitrogen and phosphorus loads, especially in the far future (Table 6). Van Vliet *et al.* (2015) concluded the same for Ukraine based on the HYPE model for Europe.

Uncertainty in climate change projection comes from three different sources: internal variability, climate model response, and emission scenario. Lehner *et al.* (2020) estimated absolute and relative uncertainties for GCMs from the CMIP5 project. They showed that the emission scenario is the main source of uncertainty for temperature projection and climate model for precipitation. The ensemble used in this study includes a wide range of possible climate projections (e.g., from 6% decrease to 23% increase in precipitation) that ensure coverage of the major part of uncertainties.

The findings could help to reach environmental objectives established in the river basin management plan (RBMP), which Ukraine should launch in 2024. In the second and third cycles of RBMP, the experts should develop the monitoring program of climate change detection, indicate expected climate pressure and impacts, and propose an adaptation strategy (European Communities 2009). As a sign of climate change, here we demonstrate that winter discharge has been rising since the end of the 20th century and very likely will continue rising according to the model prediction. Another important finding of our study is the projected higher temperature and soil water deficit in the vegetation period that will definitely require adaptation measures for agriculture in the Desna basin.

CONCLUSIONS

We presented the novel projections for the water resources of the Desna river basin that are based on Euro-CORDEX high-resolution RCMs and the process-based SWAT model. In comparison with the period 1991–2020, the mean annual discharge

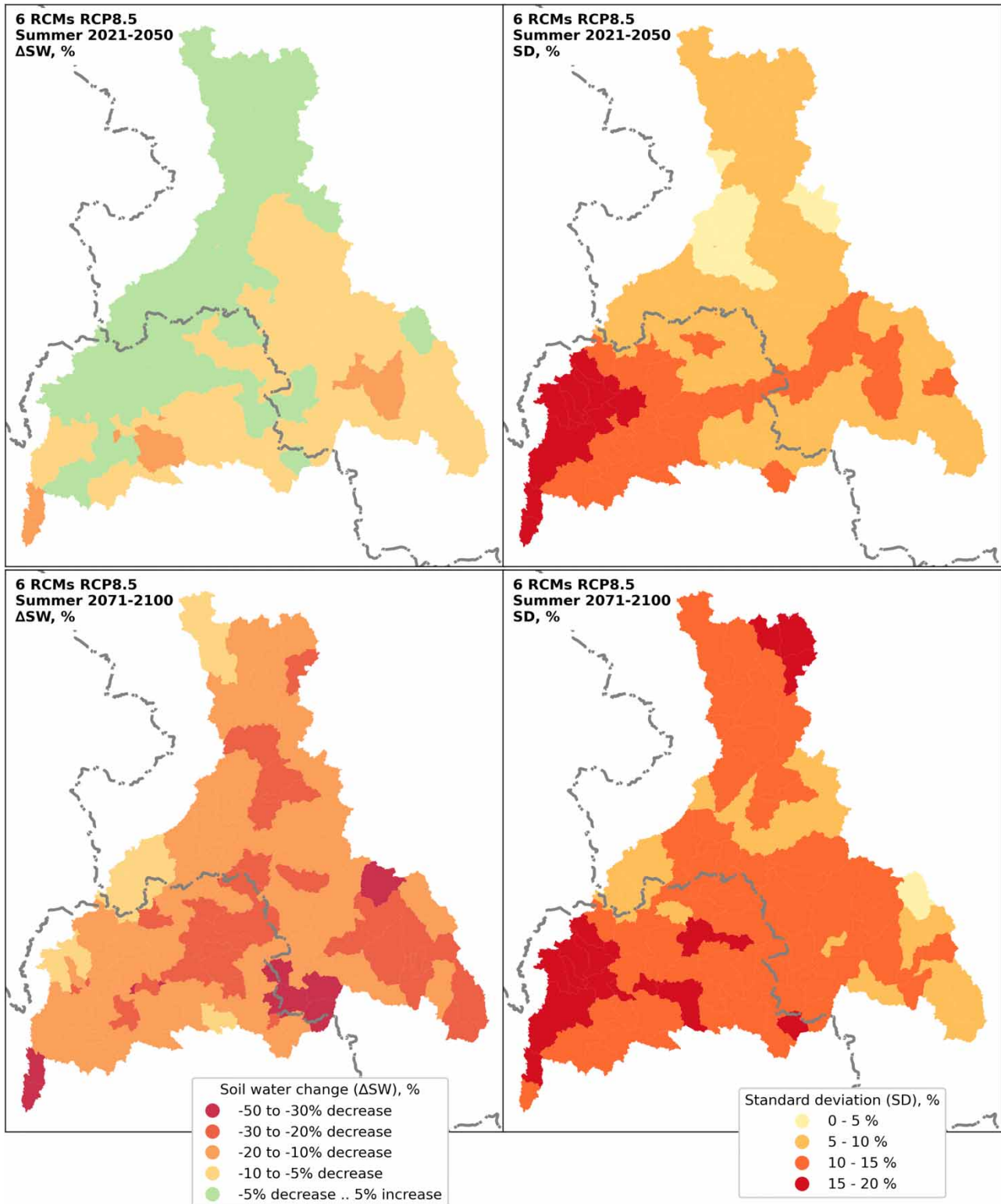


Figure 9 | Mean change in summer soil water (Δ SW, %) with standard deviation (SD, %) of the RCMs ensemble under RCP8.5 for 2021–2050 and 2071–2100 over 1991–2020.

will likely increase by 8% (possible range from -7 to 26%) under RCP4.5 and by 4% (from -23 to 33%) under RCP8.5 in the near future (2021–2050), and by 9% (from -1 to 30%) under RCP4.5 and by 17% (from -6 to 60%) under RCP8.5 in the far future (2071–2100) at the Desna outlet. The flood risk will stay at the same level or go down because of lower snow

Table 6 | Climate change impact on environmental issues of the Desna basin (the Ukrainian part of the basin territory)

Environmental issue / Negative (-) or positive (+) climate change impacts	Trend over 1991-2020 / Level of certainty			
	2021-2050		2071-2100	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Flood risk	→			
+ Lower spring flood peak	●		●	●
Wind erosion	↗			
- Drier soil in summer	●		●	●
Water erosion	→			
+ Lower snowmelt runoff	●	●	●	●
+ Lower surface runoff during the year	●		●	●
- Higher heavy rains (Appendix C)	●		●	●
Forest fires	↗			
- Drier forest soils in summer	●		●	●
Point source pollution	↗			
+ Higher water discharge during cold period	●		●	●
- Lower water discharge in August-October		●		
Diffuse source pollution^a	↗			
- Higher water yield during fertilization (Mar-Jun)	●		●	●
- Higher surface flow during fertilization (Mar-Jun)	●		○	●
+ Lower surface runoff during the year	●		●	●
- Higher soil temperature		●		
+ Drier soils during warm period	●		●	●
Eutrophication	↗			
- Higher water temperature in a stream		●		
Concentration of organic substances	↗			
- Higher lateral flow ratio in total flow	●	●		●
- Higher soil temperature		●		
+ Drier soils during warm period	●		●	●
Water stress for crops	↗			
- Drier soils in summer	●		●	●
- Longer dry spells (Appendix C)		no change		
Temperature stress for crops	↗			
- More frequent heat waves (Appendix C)	●		●	●

● - very likely, ● - likely, ● - about as likely as not, ● - unlikely, ○ - very unlikely
 ↘ - decreasing trend, ↗ - increasing trend, ↔ - zero or decreasing trend, ↗ - zero or increasing trend,
 ↔ - zero, increasing, or decreasing trend

^a The trend highly depends on the future adaptation measures in agriculture

accumulation before the spring thaw. Soil water will strongly decrease in summer from the middle of the 21st century – by 16% (possible range from –26 to –7%) under RCP4.5 and by 18% (from –35 to 5%) under RCP8.5 in the far future (2071–2100) for the Ukrainian part of the basin.

The model results disagree on the sign of the Desna river discharge change in the low water period (August–October). The surface runoff also might change both ways in the near future. However, in the far future for both RCPs, the surface runoff will likely decrease, minimizing diffuse pollution.

We consider that strong attention should be paid to the best management practices in agriculture (e.g., irrigation strategies, new crop rotations, etc.) because of possible higher water stress for crops and temperature impact under future climate.

Table 7 | Relative changes of water yield (WYLD, %), surface flow (SurQ, %), discharge at the outlet (Q, %), soil moisture deficit (SMD, days), and soil water (SW, %) in the Ukrainian part of the Desna basin: comparison with other studies

Study area (References)	Climate model	Hydrological model	Emission scenario	Period ^a	Parameter	Mean ^b (range)	Current study
Ukraine (Krakovska & Gnatiuk 2013)	REMO	'Surface runoff'	A1B ^c (between RCP4.5 and RCP8.5)	2021–2050	Δ SurQ, %	5 (–12–21)	–7 (–51–69)
					Δ SurQ _{MAM} , %	–15 (–34–4)	–3 (–42–97)
					Δ SurQ _{JJA} , %	38 (–26–151)	0 (–54–36)
Europe (van Vliet <i>et al.</i> 2015)	Five GCMs	E-HYPE, VIC	RCP8.5	2040–2070	Δ WYLD, %	0 (–30–30)	9 (–21–52)
				2040–2070	Δ SMD, days:	30 (5–60)	–
				2070–2100		55 (20–80)	–
Black Sea Catchment (Rouholahnejad <i>et al.</i> 2017)	One RCM	SWAT	Mean A2 and B2 ^c (closer to RCP8.5)	2020–2050	Δ WYLD, %	–5 (–20–5)	4 (–24–38)
					Δ SW, %	–5 (–15–0)	–1 (–11–8)
Europe (Mentaschi <i>et al.</i> 2020)	11 RCMs	LISFLOOD	RCP8.5 and RCP4.5	+ Δ 1.5 °C	Δ Q, %	35 (15–55)	–
				+ Δ 2 °C		30 (15–45)	–
Ukraine (Loboda & Kozlov 2020)	14 RCMs	'Climate-runoff'	RCP4.5	2021–2050	Δ WYLD, %	–5	10 (–10–33)
				2021–2050		–35	4 (–24–38)
Eight Ukraine basins (Didovets <i>et al.</i> 2020)	Four GCMs	WaterGAP	RCP8.5	2041–2070	Δ Q, %	12 (–5–18)	9 (–18–45)
				2071–2100	Δ Q _{APR} , %	11 (–6–21)	17 (–6–60)
				2071–2100	Δ Q _{MAY} , %	7 (–7–24)	7 (–20–50)
					Δ Q _{AUG} , %	–1 (–8–8)	–13 (–31–13)
					Δ Q _{SEP} , %	6 (–14–32)	17 (–26–88)
						2 (–23–20)	12 (–40–74)
Ukraine (Snizhko <i>et al.</i> 2020)	1 RCM	L. Turk's model	RCP4.5	2041–2070	Δ Q, %	7	8 (–14–36)

^a Δ WYLD and Δ Q are recalculated over 1991–2020, Δ SurQ is calculated over 1961–1990 in Krakovska & Gnatiuk (2013), and Δ SW – over 1973–2006 in Rouholahnejad *et al.* (2017). All parameters of the current study are presented over 1991–2020.

^bThe values correspond to the Ukrainian part of the Desna basin.

^cThe results are presented for RCP8.5 in the 'Current study' column.

ACKNOWLEDGMENT

The authors are grateful to Serhii Filipchuk for the text editing.

DATA AVAILABILITY STATEMENT

All relevant data are available from <https://drive.google.com/drive/folders/1NmXhC-dDQn0mDSzjZ1qsZfAt0bZ7Ng98?usp=sharing>.

REFERENCES

- Allen, M. R., Dube, O. P., Solecki, W., Aragon-Durand, F., Cramer, W., Humphreys, S., Kainuma, M., Kala, J., Mahowald, N., Muluetta, Y., Perez, R., Wairiu, M. & Zickfeld, K. 2018 Framing and context. In: *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-Industrial Levels and Related Global Greenhouse gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*. IPCC. Available from: <https://www.ipcc.ch/sr15/chapter/chapter-1/>.
- Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., van Griensven, A., Van Liew, M. W., Kannan, N. & Jha, M. K. 2012 **SWAT: model use, calibration, and validation**. *Transactions of the ASABE* **55** (4), 1491–1508. <https://doi.org/10.13031/2013.42256>.
- Balabukh, V. O. & Malitskaya, L. V. 2017 Assessment of the current changes in the thermal regime of Ukraine. *Geoinformatika* **64** (4), 34–49 (in Ukrainian).
- Balabukh, V., Lavrynenko, O., Bilaniuk, V., Mykhnovych, A. & Pylypovych, O. 2018 Extreme weather events in Ukraine: occurrence and changes. In: *Extreme Weather*. InTech. <https://doi.org/10.5772/intechopen.77306>.
- Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M. & Jones, P. D. 2018 An ensemble version of the E-OBS temperature and precipitation data sets. *Journal of Geophysical Research: Atmospheres* **123** (17), 9391–9409. <https://doi.org/10.1029/2017JD028200>.

- Didovets, I., Lobanova, A., Bronstert, A., Snizhko, S., Maule, C. & Krysanova, V. 2017 Assessment of climate change impacts on water resources in three representative Ukrainian catchments using eco-hydrological modelling. *Water* **9** (3), 204. <https://doi.org/10.3390/w9030204>.
- Didovets, I., Krysanova, V., Bürger, G., Snizhko, S., Balabukh, V. & Bronstert, A. 2019 Climate change impact on regional floods in the Carpathian region. *Journal of Hydrology: Regional Studies* **22**, 100590. <https://doi.org/10.1016/j.ejrh.2019.01.002>.
- Didovets, I., Krysanova, V., Hattermann, F. F., del Rocío Rivas López, M., Snizhko, S. & Müller Schmied, H. 2020 Climate change impact on water availability of main river basins in Ukraine. *Journal of Hydrology: Regional Studies* **32**, 100761. <https://doi.org/10.1016/j.ejrh.2020.100761>.
- European Communities 2009 *Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Guidance Document No. 24. River Basin Management in A Changing Climate*. Available from: https://ec.europa.eu/environment/water/water-framework/facts_figures/guidance_docs_en.htm.
- Fatichi, S., Vivoni, E. R., Ogden, F. L., Ivanov, V. Y., Mirus, B., Gochis, D., Downer, C. W., Camporese, M., Davison, J. H., Ebel, B., Jones, N., Kim, J., Mascaro, G., Niswonger, R., Restrepo, P., Rigon, R., Shen, C., Sulis, M. & Tarboton, D. 2016 An overview of current applications, challenges, and future trends in distributed process-based models in hydrology. *Journal of Hydrology* **537**, 45–60. <https://doi.org/10.1016/j.jhydrol.2016.03.026>.
- Fischer, S., Pluntke, T., Pavlik, D. & Bernhofer, C. 2014 Hydrologic effects of climate change in a sub-basin of the Western Bug River, Western Ukraine. *Environmental Earth Sciences* **72** (12), 4727–4744. <https://doi.org/10.1007/s12665-014-3256-z>.
- Fu, G., Liu, Z., Charles, S. P., Xu, Z. & Yao, Z. 2013 A score-based method for assessing the performance of GCMs: a case study of southeastern Australia. *Journal of Geophysical Research: Atmospheres* **118** (10), 4154–4167. <https://doi.org/10.1002/jgrd.50269>.
- Grebin, V. V. 2010 *Modern Streamflow Regime of Rivers in Ukraine (Landscape-Hydrology Analysis)*. Nika-Centr, Kyiv (in Ukrainian).
- Hlotka, D. 2017 Globeland30 LULC and Global Forest Change geodata merging for environmental modelling. *Geographical Journal* **69** (1), 61–73.
- Huang, S., Krysanova, V. & Hattermann, F. F. 2014 Does bias correction increase reliability of flood projections under climate change? A case study of large rivers in Germany. *International Journal of Climatology* **34** (14), 3780–3800. <https://doi.org/10.1002/joc.3945>.
- Hunger, M. & Döll, P. 2008 Value of river discharge data for global-scale hydrological modeling. *Hydrology and Earth System Sciences* **12** (3), 841–861. <https://doi.org/10.5194/hess-12-841-2008>.
- Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B. & Yiou, P. 2014 EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change* **14** (2), 563–578. <https://doi.org/10.1007/s10113-013-0499-2>.
- Krakovska, S. V. & Gnatiuk, N. V. 2013 Changes of surface river runoff in Ukraine till 2050 based on the projection of regional climate model REMO. *Geoinformatika* **47** (3), 76–81 (in Ukrainian).
- Krysanova, V., Donnelly, C., Gelfan, A., Gerten, D., Arheimer, B., Hattermann, F. & Kundzewicz, Z. W. 2018 How the performance of hydrological models relates to credibility of projections under climate change. *Hydrological Sciences Journal* **63** (5), 696–720. <https://doi.org/10.1080/02626667.2018.1446214>.
- Lehner, F., Deser, C., Maher, N., Marotzke, J., Fischer, E. M., Brunner, L., Knutti, R. & Hawkins, E. 2020 Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. *Earth System Dynamics* **11** (2), 491–508. <https://doi.org/10.5194/esd-11-491-2020>.
- Loboda, N. S. & Kozlov, M. O. 2020 Assessment of water resources of the Ukrainian rivers according to the average statistical models of climate change trajectories RCP4.5 and RCP8.5 over the period of 2021 to 2050. *Ukrainian Hydrometeorological Journal* **25**, 93–104 (in Ukrainian). <https://doi.org/10.31481/uhmj.25.2020.09>.
- Lutz, A. F., ter Maat, H. W., Biemans, H., Shrestha, A. B., Wester, P. & Immerzeel, W. W. 2016 Selecting representative climate models for climate change impact studies: an advanced envelope-based selection approach. *International Journal of Climatology* **36** (12), 3988–4005. <https://doi.org/10.1002/joc.4608>.
- Mastrandrea, M. D., Field, C. B., Stocker, T. F., Edenhofer, O., Ebi, K. L., Frame, D. J., Held, H., Kriegler, E., Mach, K. J., Matschoss, P. R., Plattner, G.-K., Yohe, G. W. & Zwiers, F. W. 2010 *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Available from: <http://www.ipcc.ch>.
- Mendlik, T. & Gobiet, A. 2016 Selecting climate simulations for impact studies based on multivariate patterns of climate change. *Climatic Change* **135** (3–4), 381–393. <https://doi.org/10.1007/s10584-015-1582-0>.
- Mentaschi, L., Alfieri, L., Dottori, F., Cammalleri, C., Bisselink, B., De, R. A. & Feyen, L. 2020 Independence of future changes of river runoff in Europe from the pathway to global warming. *Climate* **8** (2), 22. <https://doi.org/10.3390/cli8020022>.
- Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P. & Wilbanks, T. J. 2010 The next generation of scenarios for climate change research and assessment. *Nature* **463** (7282), 747–756. <https://doi.org/10.1038/nature08823>.
- Osadcha, N., Nabyvanets, Y., Grebin, V., Afanasev, S., Ukhan, O., Luzovitska, Y., Osypov, V., Klebanov, D., Iaroshevych, O., Vasylenko, E., Koshkina, O., Danko, K., Mudra, K., Biletska, S. & Rogozhyna, A. 2020 *Development of Draft River Basin Management Plan for Dnipro*

- River Basin in Ukraine: Phase 1, Step 2 – Analysis of Pressures & Impact, Risk Assessment, Environmental Objectives for Surface Water Bodies.* (in Ukrainian). Available from: <https://www.euwipluseast.eu/en/component/k2/item/979-ukraine-dnipro-rbmp-report-risk-surface-water-ukr?fromsearch=1>.
- Osyrov, V., Osadcha, N., Hlotka, D., Osadchyi, V. & Nabyvanets, J. 2018 The Desna River daily multi-site streamflow Modeling Using SWAT with detail snowmelt adjustment. *Journal of Geography and Geology* **10** (3), 92–110. <https://doi.org/10.5539/jgg.v10n3p92>.
- Palamarchuk, L. V. & Shedemenko, I. P. 2020 Statistical evaluation of temporal changes in annual precipitation in the plain territory of Ukraine. *Physical Geography and Geomorphology* **101–102** (3–4), 7–18 (in Ukrainian). <https://doi.org/10.17721/phgg.2020.3-4.0X>.
- Rouholahnejad, F. E., Abbaspour, K. & Lehmann, A. 2017 Water resources of the Black Sea catchment under future climate and landuse change projections. *Water* **9** (8), 598. <https://doi.org/10.3390/w9080598>.
- Snizhko, S., Shevchenko, O., Kuprikov, I., Lukianets, O. & Didovets, I. 2020 The long-term projection of water runoff in the XXI century. In: *River Runoff in Ukraine Under Climate Change Conditions* (Obodovskyi, O. G., ed.). LAP Lambert Academic Publishing, Chisinau.
- Stashuk, V., Mokin, V., Grebin, V. & Chunarov, O. 2014 *Scientific principles of rational management of water resources in Ukraine according to the basin principle*. Grin' D.S., Kherson (in Ukrainian).
- Taylor, K. E., Stouffer, R. J. & Meehl, G. A. 2012 An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society* **93** (4), 485–498. <https://doi.org/10.1175/BAMS-D-11-00094.1>.
- van Vliet, M. T. H., Donnelly, C., Strömbäck, L., Capell, R. & Ludwig, F. 2015 European scale climate information services for water use sectors. *Journal of Hydrology* **528**, 503–513. <https://doi.org/10.1016/j.jhydrol.2015.06.060>.
- Yuan, S., Quiring, S. M., Kalcic, M. M., Apostel, A. M., Evenson, G. R. & Kujawa, H. A. 2020 Optimizing climate model selection for hydrological modeling: a case study in the Maumee River basin using the SWAT. *Journal of Hydrology* **588**, 125064. <https://doi.org/10.1016/j.jhydrol.2020.125064>.

First received 4 February 2021; accepted in revised form 5 July 2021. Available online 19 July 2021