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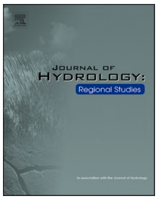

# Climate change impact on water availability of main river basins in Ukraine

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ABSTRACT

*Study region:* Eight main river basins covering the major part of Ukraine.
*Study focus:* The main aim of this study was to provide an assessment of climate change impacts on water availability across Ukraine using global hydrological models. Six global hydrological models were evaluated for their performance in the historical period in the basins under study. Future river discharge was simulated by using the best performing model and all available models driven by bias-corrected GCM projections from the ISIMIP project under the RCP 2.6 and RCP 8.5 scenarios.
*New hydrological insights for the region:* The results show precipitation increase up to 10 % under RCP 2.6, and variable changes from -14 % to +10 % under RCP 8.5 by the end of the century. The projections show the decreasing mean annual river discharge in the majority of basins for the middle (2040–2070) and far future (2071–2100) periods under both RCPs, and the decrease is stronger under RCP 8.5. The seasonal changes are characterised by a decrease in summer and a small to moderate increase in winter months in most of the basins. The highest reduction of mean annual discharge was projected for the Pripyat, Southern Bug and Dniester basins, reaching up to -30 % to the end of the century under RCP 8.5.

## 1. Introduction

During the last decades, an alteration of climate in Europe has been observed, and it is expected that changes will be stronger in the future (Kovats et al., 2014). Global warming would lead to changes in the water cycle, which are likely to affect water availability at different scales and sectors, e.g. energy, agriculture, forest and more. That kind of changes can bring society to the state where climate change is a prime political issue (Donnelly et al., 2017; IPCC, 2018; Schleussner et al., 2016).

However, even with a strong support of the scientific community on climate change and climate impact issues in Europe, the uncertainties in projected hydrological impacts for future are large. Many studies show large spreads in projections provoking a discussion about the robustness of the simulated signals of change and impact results (Frieler et al., 2017; Haddeland et al., 2014; Hattermann et al., 2018, 2017).

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Focusing on the European studies which also cover Ukraine and the +1.5 °C and +2.0 °C increments, the study of Jacob et al. (2018) displays possible changes in temperature and precipitation across Europe based on different GCMs-RCMs driven by RCP 2.6, 4.5 and 8.5 scenarios. Changes in total precipitation within Ukraine show an increase from 5 % to 15 % under +1.5 °C and +2.0 °C warming scenarios.

The results of Vliet et al. (2015) based on the bias-corrected GCMs from CMIP5 showed that changes in precipitation would vary from -5 % to 5 % for the major part of Ukraine in the 2050s under RCP 2.6. Precipitation would increase in the 2080s in the range from +5 % to +20 % under RCP 2.6, except for Crimean peninsula, where changes would be from -5 % to +5 %. Under RCP 8.5, precipitation changes would stay in the same ranges as under RCP 2.6 for the 2050s, but for the 2080s a decrease up to 20 % is projected for the southern and western parts of Ukraine.

The climate change impacts on water resources in Europe are presented in studies that used continental and global-scale hydrological models (Donnelly et al., 2017; Mentaschi et al., 2019; van Vliet et al., 2015). Two of them considered Ukrainian territory only partly, and only the last one covered the whole country. Also, there is a study focused on evaluation of performance of an ensemble of global hydrological models in 57 large river basins worldwide, with their further application for climate impact assessment with weighting coefficients (Krysanova et al., 2020), where small parts of Ukraine were covered. In the study of van Vliet et al. (2015), the authors assessed changes in river discharge simulated by the VIC and E-HYPE models driven by the bias-corrected GCMs. The results for RCP 8.5 show predominantly decreasing change signal varying from +5 to -40 % for the 2050s in the major part of Ukraine.

Besides, there is a number of regional-scale studies based on catchment-scale hydrological models (Fischer et al., 2014; Hesse et al., 2015; Didovets et al., 2017; Piniewski et al., 2018; Didovets et al., 2019) and statistical models and tools (Loboda and Bozhok, 2016; Snizhko et al., 2014). They all focus on specific catchments or parts of the country and not consider changes in water resources at the national level. The similar decreasing trends as in van Vilet et al. (2015) have been found also in the regional-scale studies by Loboda and Kozlov (2020) and Snizhko et al. (2014).). The results of study by Snizhko et al. (2014), which considered 19 river basins across Ukraine, showed mostly no changes in runoff (except a small increase) until 2040, but a moderate decrease was projected in the central and southern parts of the country at the end of the century.

As we see, there is practically only one study by van Vilet et al. (2015) dedicated to studying, climate change impacts on water availability in Ukraine based on hydrological models and covering the whole country. Therefore, there is a strong need in updating climate impact assessment at the country scale in order to improve understanding of expected changes and adaptation options at the national level.

The main goal of this study is to assess the impact of climate change on water availability for the main Ukrainian river basins by using global hydrological models (GHMs) driven by up-to-date climate projections under the “low-end” (RCP 2.6) and “high-end” (RCP 8.5) pathways. Besides, this study also aims to investigate the suitability of the GHMs for simulation of climate change impacts in the study area based on their performance in the historical period. The intention is to apply only well performing models for the assessment of climate change impacts.

The structure of the paper is the following: i) main information about the Ukrainian case study river basins; ii) overview of methods; iii) evaluation of GHMs and their suitability for simulation of impacts; iv) analysis of expected changes in precipitation and temperature based on GCMs; v) projections of river discharge across study areas using selected tools; and vi) discussion of the main outcomes.

## 2. Study area

Ukraine is characterised by notable climate differences across the country. The major part of the country is situated within the temperate climate zone, and only the southern coast of Crimea has a subtropical Mediterranean climate. The average temperature of the coldest month (January) has negative values on the major part of the territory (-2 °C - -7.5 °C), except the southern part of the Crimean peninsula. The average temperature in July varies from +17.5 °C to +22 °C (FAO, 2015).

Air humidity is much higher in the western part of the country in comparison to the eastern part. Also, differences in temperature regime in the east-west direction are prominent, and the vegetation period is longer in the western part due to the softer and wetter climate. Regular alteration of the Atlantic circulation and dry air from the east provoke cyclone and anticyclone movements on the plain part of the country. In winter, temperate warm air masses are replaced by cold air coming from the North Syberia. In summer, warm air is changed by Atlantic wet and temperate warm masses. Anticyclones that dominate in the southern and central parts of the country usually come from Central Asia. Cyclones, which are more intensive in the western part, come from the Atlantic Ocean and Mediterranean Sea (Zastavniy, 1994).

Precipitation is characterised by high values in the Carpathian mountainous region (up to 1600 mm $a^{-1}$) and Crimea (up to 1150 mm $a^{-1}$). The mean annual precipitation in other parts of the country varies from 700−750 mm in the north-west to 300−350 mm in the south-east, which can be explained by the dominance of cyclones and anticyclones (National Communication of Ukraine on Climate Change, 2013; Zastavniy, 1994).

In this study we focus on the main river basins of Ukraine: Dnieper and catchments of its two main tributaries (Desna, Pripyat), Siverskyi Donets, Sothern Bug, Dniester, Tisza (a tributary of the Danube River) and Western Bug (Bug). The selection of the river basins and their gauging stations was based on the following criteria: i) the drainage area should be larger than 30 000 $km^2$; and ii) observed discharge time series should be available for longer than 10 years. Majority of considered rivers are transboundary, so some parts of other countries were also included in the modelling.

The modelled areas of the river basins are shown in Fig. 1, and the main characteristics of the basins are presented in Table 1. The drainage areas of the basins vary from 39 000 $km^2$ to 482 000 $km^2$ and observed discharge time series are available for 14–32 years.

The Dnieper River is the 4th longest river in Europe, it originates in Russia and flows through Belarus and Ukraine to the Black Sea. It is a lowland river, its drainage basin covers about 65 % of Ukraine and divides the country from north to south into the left and right banks parts. The major tributaries are the Desna (left) and the Pripyat (right). The Dnieper is characterised by high water regulation in terms of a cascade of reservoirs and dams constructed in the twentieth century ("AQUASTAT - FAO's Information System on Water and Agriculture," 2020).

The Dniester River is the second largest river in Ukraine, and its basin covers about 12 % of the country area. The river originates in Ukraine, then flows to Moldova and returns to Ukraine 50 km before entering the Black Sea. Further to the northwest, the Western Bug River is flowing. It is a tributary of the Narew river, which belongs to the Vistula river basin, and it begins in Ukraine and flows to Poland.

The Danube River originates in Germany and flows southeast until entering the Black Sea on the border between Romania and Ukraine. The Prut and Tisza, originating in the Carpathian mountains, are the largest tributaries of the Danube located partly in Ukraine ("Water Report 15 - FAO," 2020).

The Southern Bug is an internal river basin of Ukraine, it originates on the northwest of the country and flows to the southeast. The Siverskyi Donets River is the left tributary of the Done River, and large part of its basin is situated in the eastern part of the country. The river length is 1 053 km, from which around 455 km lie within Ukraine, and the rest in Russia (Маринич, 1993).

## 3. Methods

For assessment of climate change impacts on water resources of the main Ukrainian river basins, our study was conducted in three steps:

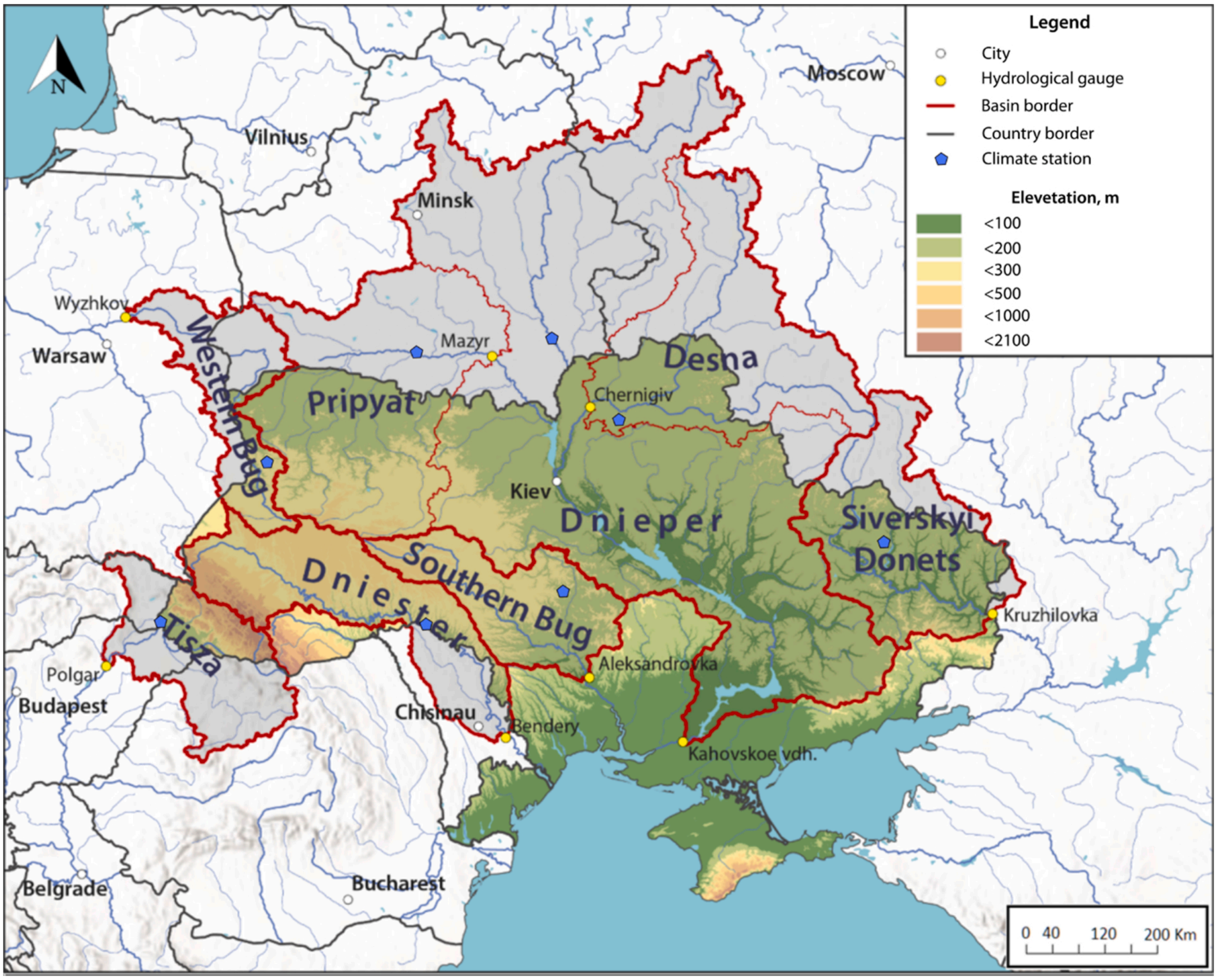


**Fig. 1.** The main river basins of Ukraine. Grey areas indicate parts of river basins that are located in neighbouring countries.

**Table 1**
The main characteristics of the river basins.

| | River under study | Country | River length, km | Total drainage area, km$^2$ | Main river | Gauging station | Modelled area under consideration**, km$^2$ | Observation period | Source of data |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Dnieper | Ukraine, Russia, Belarus | 2201 | 505000 | Dnieper | Kahovske vdh.* | 482000 | 1971-1988 | GRDC |
| 2 | Prypyat | Ukraine, Belarus | 2201 | 121000 | Dnieper | Mazyr* | 101000 | 1971-2002 | GRDC |
| 3 | Desna | Ukraine, Russia | 1130 | 88900 | Dnieper | Chernigiv* | 81400 | 1971-1986 | GRDC |
| 4 | Siverskyi Donets | Ukraine, Russia | 1053 | 98900 | Don | Kruzhilovka | 73200 | – | – |
| 5 | Dnister | Ukraine, Moldova | 1362 | 68627 | Dnister | Bendery* | 66100 | 1971-1988 | GRDC |
| 6 | Tisza | Ukraine, Hungary, Romania | 966 | 156087 | Danube | Polgar | 62723 | 1974-1986,1992-1996 | GRDC |
| 7 | Southern Bug | Ukraine | 806 | 63700 | Southern Bug | Aleksandrovka* | 46200 | 1971-1984 | GRDC |
| 8 | Western Bug | Ukraine, Poland | 774 | 38712 | Visla | Wyzhkov* | 39119 | 1971-1987 | GRDC |

* Gauges used for the WaterGAP calibration.

** Information was taken from the Global Runoff Data Centre, GRDC (http://grdc.bafg.de).

a Evaluation of performance of the global hydrological models and selection of the most representative ones with better performance for the study area.
b Analysis of climate projections and projected changes in temperature and precipitation for Ukraine.
c Analysis of changes in the river discharge in eight Ukrainian river basins until the end of the century under RCP 2.6 and RCP 8.5.

### 3.1. *Climate projections*

To analyse changes in mean temperature and precipitation until the end of the century, four climate projections were taken from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, 2020), phase 2b, they are from HadGEM2-ES, MIROC5, IPSL-CM5A-LR and GFDL-ESM2M models (Frieler et al., 2017). The climate data have been bias-corrected to the reanalysis climate dataset EWEMBI (Lange, 2018, 2019). The spatial resolution of the data is 0.5 × 0.5 °, and time series can be divided into two parts: historical simulations (1861–2005) and projections considering greenhouse gas emissions covering the period 2006-2099.

Two RCP scenarios were selected for this study: RCP 2.6 in line with the Paris Agreement, assuming a reduction of greenhouse gas emissions and returning to 2.6 W/m2 by 2100, and RCP 8.5: the “worst-case” scenario that does not include any specific climate mitigation goals (Riahi et al., 2011). So in total there were eight climate scenarios considered including four GCMS driven by two RCPs.

In order to analyse changes in precipitation and temperature until the end of the century, we considered the historical (1971–2000) and two future periods (2041–2070 and 2071–2100). Temperature, precipitation and river discharge in both future periods under both RCPs were compared with those in the historical one.

### 3.2. *Global hydrological models and climate data*

Simulations of six global hydrological models were performed previously and uploaded at the ISIMIP server, and then downloaded for our case study area, evaluated and applied for the assessment of changes in river discharge under climate change. The ensemble of models includes: LPJmL (Rost et al., 2008), MATSIRO (Pokhrel et al., 2015), H08 (Hanasaki et al., 2008), WaterGAP2 (Müller Schmied et al., 2016), DBH (Tang et al., 2007) and PCR-GLOBWB (Wada et al., 2014).

All models simulate evapotranspiration, snow cover, surface flow, subsurface flow, river discharge, etc. (see details in Hattermann et al., 2017), but only one of them, the WaterGAP2 model, was calibrated using discharge data from the GRDC database (Müller Schmied, 2017; Müller Schmied et al., 2014). More detailed information about the models’ characteristics and components can be found in the references above and in Krysanova et al. (2020).

Climate reanalysis data WATCH (Weedon et al., 2010) were used as a forcing for the model evaluation in historical period. Further, the models were driven by GCM projections listed above for the historical period (1861–2005) and future period (2006–2099). The spatial resolution of the model outputs is 0.5 × 0.5 °. Human water management influence was considered in all simulations. The “histsoc” (historically varying land use and other human influences) and the “2005soc” (fixed at the 2005 year land use and other human influences) simulations driven by GCMs were chosen for the historical and future periods, respectively (Frieler et al., 2017).

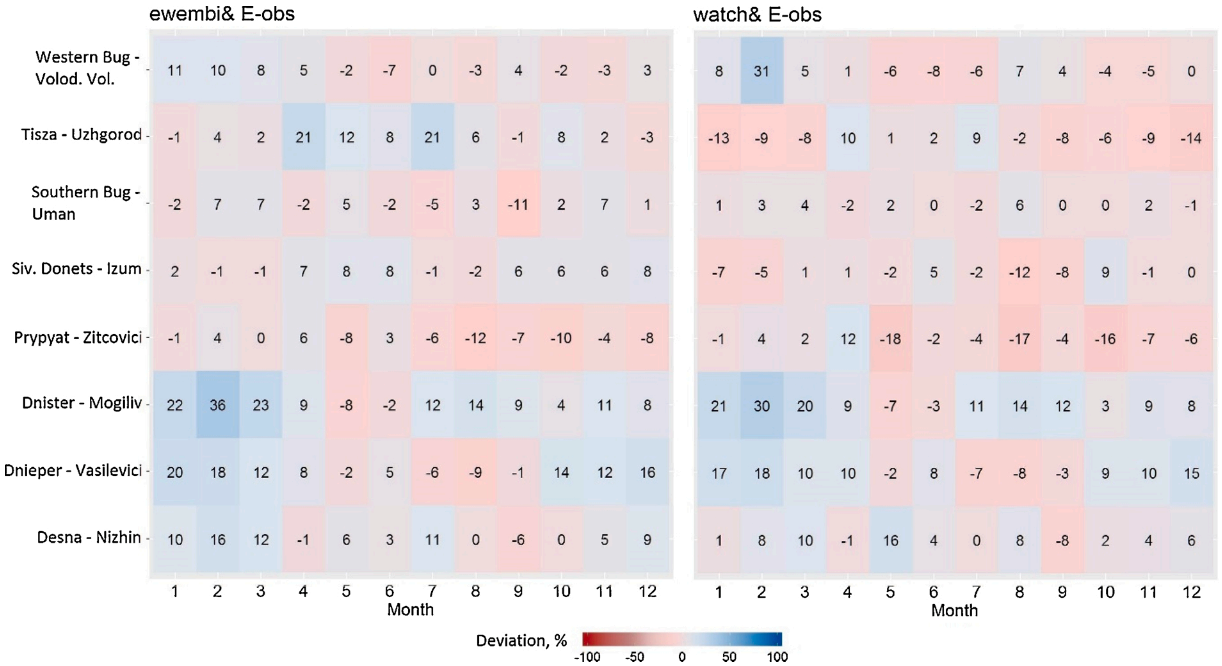
As stated above, WATCH and EWEMBI were used as forcing in the historical period for model evaluation and for bias correction of GCMs, correspondingly. To confirm the ability of both WATCH and EWEMBI data to reproduce climate in the case study areas and to assess possible uncertainty in the modelling, the both reanalysis datasets were additionally analysed in comparison to observations. To cover the whole case study region, it was decided to choose one climate station per river basin (Fig. 1) with a time span of at least 10 years of daily data. The stationary observations were taken from the European Assessment & Datasets (E-obs - www.ecad.eu). The analysis was focused on one of the major components – precipitation. Our results show a high correlation between both reanalysis data and observed precipitation data and low deviations in the long-term mean annual precipitation (see Annex 1 and Fig. 2). The average r2 and r values for all stations for the annual precipitation are r2 = 0.83, r = 0.91 (EWEMBI & E-obs) and $r^2 = 0.81$, r = 0.90 (WATCH & E-obs). The deviations in the long-term mean annual precipitation vary from 1.8 % to 4.2 % on average over the case study areas and can reach up to 30–36 % in some months in some basins.

### *3.3. The global water availability and water use model WaterGAP2 and datasets used for the Ukraine*

As WaterGAP2 was found to be the best performing model for the case study area, and the impact assessment was performed mainly with this model (Sect. 4.3), it is briefly described here. WaterGAP2 is a global water availability and water use model that is in development since 1996. WaterGAP includes of five water use models (irrigation, domestic, manufacturing, livestock, cooling of thermal power plants), the linking module GWSWUSE that calculates, based on the output of the water use models, net water abstractions from groundwater and surface water resources. Furthermore, the WaterGAP Global Hydrology Model calculates the water fluxes and storages for all continents (except Antarctica) at 0.5 × 0.5 ° spatial and daily temporal resolution, considering the water uses and other processes as such as alterations due to man-made dams and reservoirs. The main objectives of WaterGAP development is to assess water resources for human and environment and its impact due to anthropogenic alterations as such as water use, man-made reservoirs and climate change. Model descriptions can be found in Alcamo et al., 2003; Muller Schmied et al., 2014, 2016; 2017. The model versions being used here are WaterGAP 2.2 (ISIMIP2a) for the evaluation (within ISIMIP2a) and WaterGAP 2.2c for the impact assessment (within ISIMIP2b).

One particular feature of WaterGAP is its basin-specific calibration with the objective to reproduce long-term annual observed river discharge at 1319 basins (covering ~54 % of the global drainage area except for Antarctica and Greenland) by modifying one to three model parameters (details in Hunger and Döll, 2008; Muller Schmied, 2017). The majority of discharge stations used for evaluation in this study (Table 1) has been used as well for calibration but for different time spans according to the data availability: Dnieper: 1959–1988, Prypyat: 1973–2002, Desna: 1956–1985, Dnister: 1965–1984, Southern Bug: 1965–1984, Western Bug: 1957-1986. Please note that for evaluation, other than for calibration on the long-term annual mean, monthly time series have been used. Hence, the evaluation can be seen as somehow independent.

The reservoirs along the Dniepr are included in WaterGAP and handled for electricity purposes (for details to the reservoir scheme, the reader is referred to Döll et al., 2009).



| ewembi& E-obs | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Western Bug - Volod. Vol. | 11 | 10 | 8 | 5 | -2 | -7 | 0 | -3 | 4 | -2 | -3 | 3 |
| Tisza - Uzhgorod | -1 | 4 | 2 | 21 | 12 | 8 | 21 | 6 | -1 | 8 | 2 | -3 |
| Southern Bug - Uman | -2 | 7 | 7 | -2 | 5 | -2 | -5 | 3 | -11 | 2 | 7 | 1 |
| Siv. Donets - Izum | 2 | -1 | -1 | 7 | 8 | 8 | -1 | -2 | 6 | 6 | 6 | 8 |
| Prypyat - Zitcovici | -1 | 4 | 0 | 6 | -8 | 3 | -6 | -12 | -7 | -10 | -4 | -8 |
| Dnister - Mogiliv | 22 | 36 | 23 | 9 | -8 | -2 | 12 | 14 | 9 | 4 | 11 | 8 |
| Dnieper - Vasilevici | 20 | 18 | 12 | 8 | -2 | 5 | -6 | -9 | -1 | 14 | 12 | 16 |
| Desna - Nizhin | 10 | 16 | 12 | -1 | 6 | 3 | 11 | 0 | -6 | 0 | 5 | 9 |

| watch& E-obs | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Western Bug - Volod. Vol. | 8 | 31 | 5 | 1 | -6 | -8 | -6 | 7 | 4 | -4 | -5 | 0 |
| Tisza - Uzhgorod | -13 | -9 | -8 | 10 | 1 | 2 | 9 | -2 | -8 | -6 | -9 | -14 |
| Southern Bug - Uman | 1 | 3 | 4 | -2 | 2 | 0 | -2 | 6 | 0 | 0 | 2 | -1 |
| Siv. Donets - Izum | -7 | -5 | 1 | 1 | -2 | 5 | -2 | -12 | -8 | 9 | -1 | 0 |
| Prypyat - Zitcovici | -1 | 4 | 2 | 12 | -18 | -2 | -4 | -17 | -4 | -16 | -7 | -6 |
| Dnister - Mogiliv | 21 | 30 | 20 | 9 | -7 | -3 | 11 | 14 | 12 | 3 | 9 | 8 |
| Dnieper - Vasilevici | 17 | 18 | 10 | 10 | -2 | 8 | -7 | -8 | -3 | 9 | 10 | 15 |
| Desna - Nizhin | 1 | 8 | 10 | -1 | 16 | 4 | 0 | 8 | -8 | 2 | 4 | 6 |

**Fig. 2.** Deviation in long-term mean annual precipitation of EWMBI (left) and WATCH (right) in comparison to E-obs dataset for all study areas.

### 3.4. Evaluation of the global hydrological models

It was decided to use the model evaluation approach from Krysanova et al. (2020) to analyse the reliability of the global hydrological models for Ukrainian basins, comparing the simulations for the historical period driven by WATCH climate forcing data (see more in Muller Schmied et al., 2016; Weedon et al., 2010) with the observed river discharge for each basin. The monthly observed river discharge was taken from the GRDC database. The selected gauges for each basin, together with the time periods for model evaluation are presented in Table 1. The calculation of metrics was not possible for the Siverskyi Donets basin due to absence of the observation data. Some of the basins are highly regulated by dams and reservoirs (e.g. Dnieper), and this can affect the evaluation results. Though, hydrological models considered reservoirs which are included in different databases as such as Global Reservoirs and Dams Database (Lehner et al., 2011) following the modelling protocol ("ISIMIP - The Inter-Sectoral Impact Model Intercomparison Project," 2019; WWF, 2020).

For model evaluation, the next metrics were used: Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), percent bias (PBIAS) (Moriasi et al., 2015) and bias in standard deviation (BSD) - Δσ (eq. 3) (Gudmundsson et al., 2012). y

(1) NSE

$$\frac{\sum_{t=1}^{N}\left(Q_{s,t}-Q_{o,t}\right)^2}{\sum_{t=1}^{N}\left(Q_{o,t}-\overline{Q}_o\right)^2}$$

Where Qs,t and Qo,t are the tth simulations and observations for the constituent being evaluated;

(2) PBIAS

$$\frac{\sum\limits_{t=1}^{N}(Q_{s,t-}Q_{o,t})}{\sum_{t=1}^{N}Q_{o,t}}*100$$

Where *Qs,t* and *Qo,t* are the *t*th simulations and observations for the constituent being evaluated;

(3) (Δσ)

$$\frac{\sigma_s-\sigma_o}{\sigma_o}*100$$

Where $\sigma_s$ and $\sigma_o$ represent the standard deviation of simulated and observed mean annual cycle.

We evaluated the monthly and long-term mean monthly dynamics for each model simulation. Krysanova et al., 2020 suggested the next thresholds for the global model evaluation based on monthly river discharge:

Monthly dynamics:

NSE good: $NSE \geq 0.5$; satisfactory/weak: $0.3 \leq NSE < 0.5$; poor: $NSE < 0.3$

PBIAS (%) good: $|PBIAS| \leq 25$; satisfactory/weak: $25 < |PBIAS| \leq 35$; poor: $|PBIAS| > 35$

Long-term mean monthly dynamics:

NSE good: $NSE \geq 0.7$; satisfactory/weak: $0.5 \leq NSE < 0.7$, poor: $NSE < 0.5$

Δσ (%) good: $-25 \leq \Delta\sigma \leq 25$; satisfactory/weak: $25 < |\Delta\sigma| \leq 35$; poor: $|\Delta\sigma| > 35$

After estimation of the metrics for all basins and models, the scores were assigned. The score is 1 for good model performance, the score is 0.5 for satisfactory to weak performance, and the score is 0 for the poor performance. Based on the total scores for each model and basin, the well performing models could be selected for the case study area based on their performance in the historical period.

After model evaluation and selection, the changes in mean annual and long term mean seasonal river discharge for future periods in comparison with the reference period driven by four bias-corrected GCMs under RCP 2.6 and RCP 8.5 were analysed. The same time periods were used as for the climate projections analysis: the reference period (1971–2000) and two future periods (2041–2070 and 2071–2099).

## 4. Results

### 4.1. Model evaluation

The resulting metrics of model evaluation for the monthly and seasonal dynamics in all basins are presented in Annex 2 in Supplementary, and the sums of assigned scores are shown in Table 2. As one can see, the highest sum of scores among all models has the WaterGAP2 model with 16 of maximum 28 (four metrics in seven basins), and MATSIRO and PCR-GLOBWB show rather weak performance with 8 and 7.5, correspondingly. And the other three models: H08, LPJmL and DBH demonstrated quite poor performance according to our assessment. The comparison of the observed and simulated long-term mean monthly discharge in all seven basins simulated by six GHMs in the historical period are presented in Annex 3.

Only one model, the WaterGAP2, got more than a half of possible scores, and other models showed weak or poor results. Moreover, the DBH and PCR-GLOBWB models have no simulation runs for some GCMs/RCPs, and it is not possible to use them for the climate

**Table 2**
The scores assigned based on evaluation of six hydrological models with four metrics based on the monthly and mean monthly dynamics in the river basins under study.

| Rivers | Global hydrological models | | | | | |
|---|---|---|---|---|---|---|
| | DBH | H08 | LPJmL | MATSIRO | PCR-GLOBWB | WaterGAP2 |
| Dnieper | 0.0 | 0.0 | 0.0 | 1.0 | 1.0 | 2.5 |
| Prypyat | 0.0 | 0.0 | 0.0 | 2.0 | 0.5 | 3.0 |
| Desna | 0.0 | 0.0 | 0.0 | 0.5 | 2.0 | 1.5 |
| Dnister | 0.0 | 1.0 | 1.0 | 1.0 | 0.0 | 2.0 |
| Tisza | 0.0 | 1.0 | 0.5 | 2.5 | 1.5 | 2.0 |
| Southern Bug | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.0 |
| Western Bug | 0.0 | 0.0 | 0.0 | 1.0 | 2.0 | 1.0 |
| Sum | 0 | 2 | 1.5 | 8 | 7.5 | 16 |

impact assessment. The differences in the model evaluation results can be explained by calibration of the WaterGAP2 model to the long term mean annual streamflow observations for the historical period. Based on the evaluation results, it was decided to use mainly the WaterGAP2 model for further assessment of climate change impacts in all eight river basins. To compare results, ensemble-mean approach, including all GHMs, was also used for all basins under considerations. Similarly, good performance of the WaterGAP2 model and weak or poor performance of other GHMs for 40–57 large river basins worldwide was shown in the studies of Krysanova et al., 2020 and Zaherpour et al., 2018.

### 4.2. *Analysis of climate scenarios*

Fig. 3 presents projected changes in mean annual temperature based averaged over four bias-corrected GCMs until the end of the century under RCP 2.6 and RCP 8.5. The changes show an increase in both time periods under both RCPs across the whole study area, rising from the south to the northeast of the study domain.

Under RCP 2.6 the increase varies from 2.1 °C on the south of Ukraine (Crimea) to 2.8 °C on the north of the study area (Russia) for both time periods. The temperature is projected to rise up to 2.4 °C within southern and southeastern parts of Ukraine, up to 2.5–2.6 °C in the centre, north of Ukraine and east of Belarus, and up to 2.7–2.8 °C in western Belarus and Russia.

Under RCP 8.5, the differences in temperature increase between two time periods are much more notable. In the period 2041–2070 temperature is projected to rise from 3.1 °C to 4.5 °C in the study region: in Ukraine up to 4.2 °C, in Belarus up to 4.4 °C, and in Russia

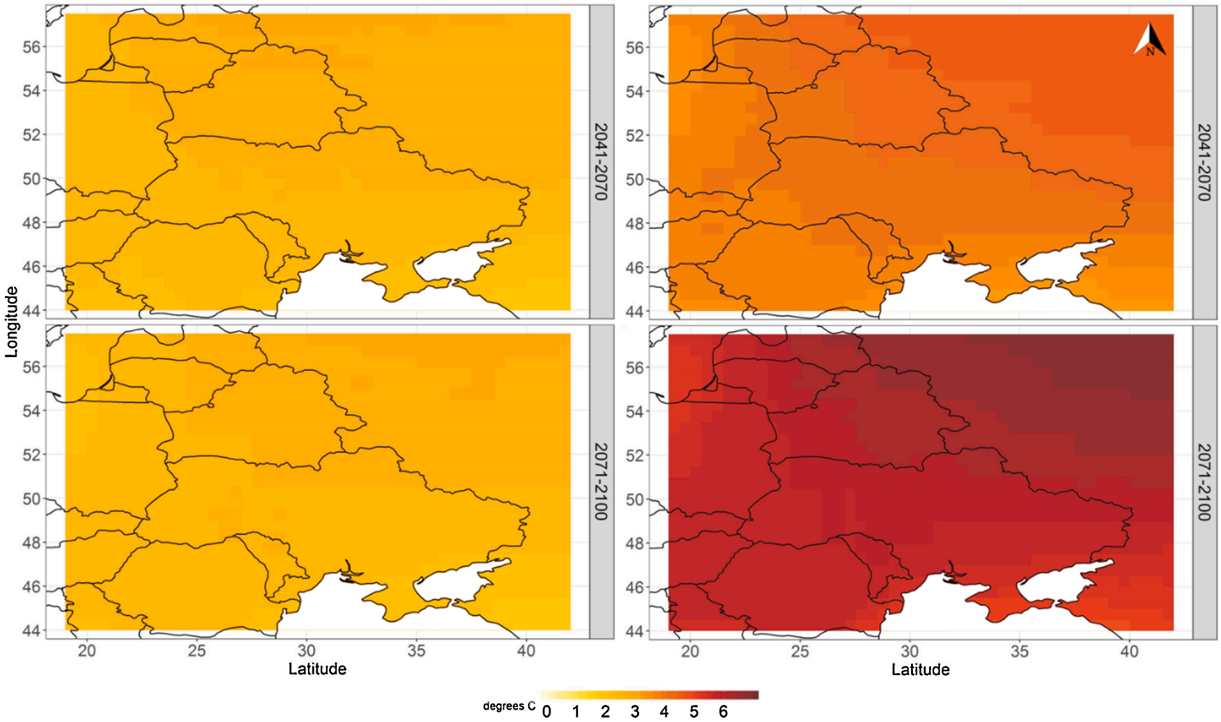


**Fig. 3.** Projected changes of average annual temperature for two future periods (2041–2070 and 2070–2100) in comparison to the reference period (1971–2000) under RCP 2.6 (left) and RCP 8.5 (right). Black lines indicate the countries borders.

(within the study area) up to 4.5 °C. In the period 2071–2100 changes are higher and vary from 4.8 °C to 6.6 °C: in Ukraine up to 6 °C, in Belarus up to 6.3 °C and in Russia (within the study area) up to 6.6 °C. It is noteworthy that there is a tendency of temperature increase under RCP 8.5 in the northeastern direction, starting from the central part of Ukraine.

The simulated future changes in precipitation are not so pronounced in comparison to changes in temperature. Precipitation under RCP 2.6 shows small to moderate (up to 10 %) increase across the whole study area for both future periods (Fig. 4). Changes under RCP 8.5 vary from a small decrease to a moderate increase (-5 to +10 %) in the period 2041–2070. At the end of the century (2071–2100), annual precipitation is projected to decrease up to 12–14 % in the southern and western parts of Ukraine, especially in Crimea, Carpathians and Odeska oblast, and to increase up to 15 % in Belarus and Russia.

### 4.3. Changes in river discharge

The projections of climate change impacts on water availability have similar patterns across basins under study as precipitation. Figs. 5 and 6 resent simulated changes in the mean annual and long-term mean monthly river discharge in the eight river basins for two future periods (2041–2070 and 2071–2100) under RCP 2.6 and RCP 8.5 as simulated by the WaterGAP2 model driven by four bias-corrected GCMs from ISIMIP2b.

Changes in the mean annual river discharge under RCP 2.6 for two future periods are small to moderate and vary from -10 % to +6 % in five basins (Tisza, Southern Bug, Siverskyi Donets, Desna, Western Bug). In the other three basins (Dnieper, Dniester and Pripyat) river discharge decreases up to 20 % on average in both future periods.

Changes under RCP 8.5 are generally much stronger in comparison to RCP 2.6. In the majority of basins, river discharge strongly decreases to the end of the century. The highest decreases are projected for the Pripyat, Southern Bug and Dniester and can reach up to -30 % to the end of the century. On the other hand, projections for the Siverskyi Donets and Desna basins show very small positive changes or zero changes.

In general, the results show decreasing trends in river discharge in the majority of the basins for the middle century (2040–2070) and far future (2070–2100) periods under both RCPs, which are more significant under RCP 8.5.

The projections of the long-term mean monthly river discharge show a general decrease during practically the whole year in the Dnieper, Western Bug, Dniester and Pripyat rivers basins in both future periods under both RCPs (except small increases in February or February-March in some cases) (Fig. 6).

A notable tendency of increasing discharge during winter months have the Desna, Tisza, Southern Bug and Siverskyi Donets in both time periods under both RCPs. All projections show a general decrease during summer months in all catchments in both periods and for both RCPs, except the Siverskyi Donets basin, where an increase in summer months is projected. In most cases, both decreases and increases are stronger under RCP 8.5 compared to RCP 2.6. The far future period under RCP 8.5 is characterised by more significant

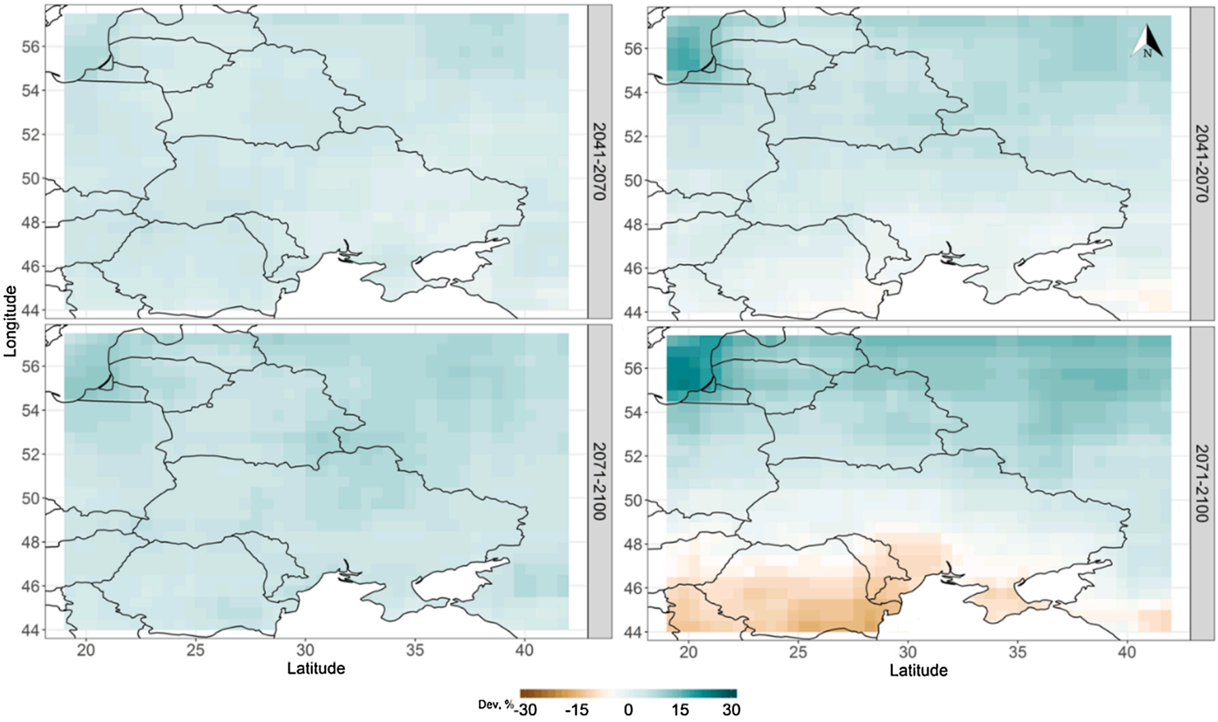


**Fig. 4.** Projected changes of annual precipitation for two future periods (2041–2070 and 2070–2100) in comparison to the reference period (1971–2000) under RCP 2.6 (left) and RCP 8.5 (right). Black lines indicate the countries borders.

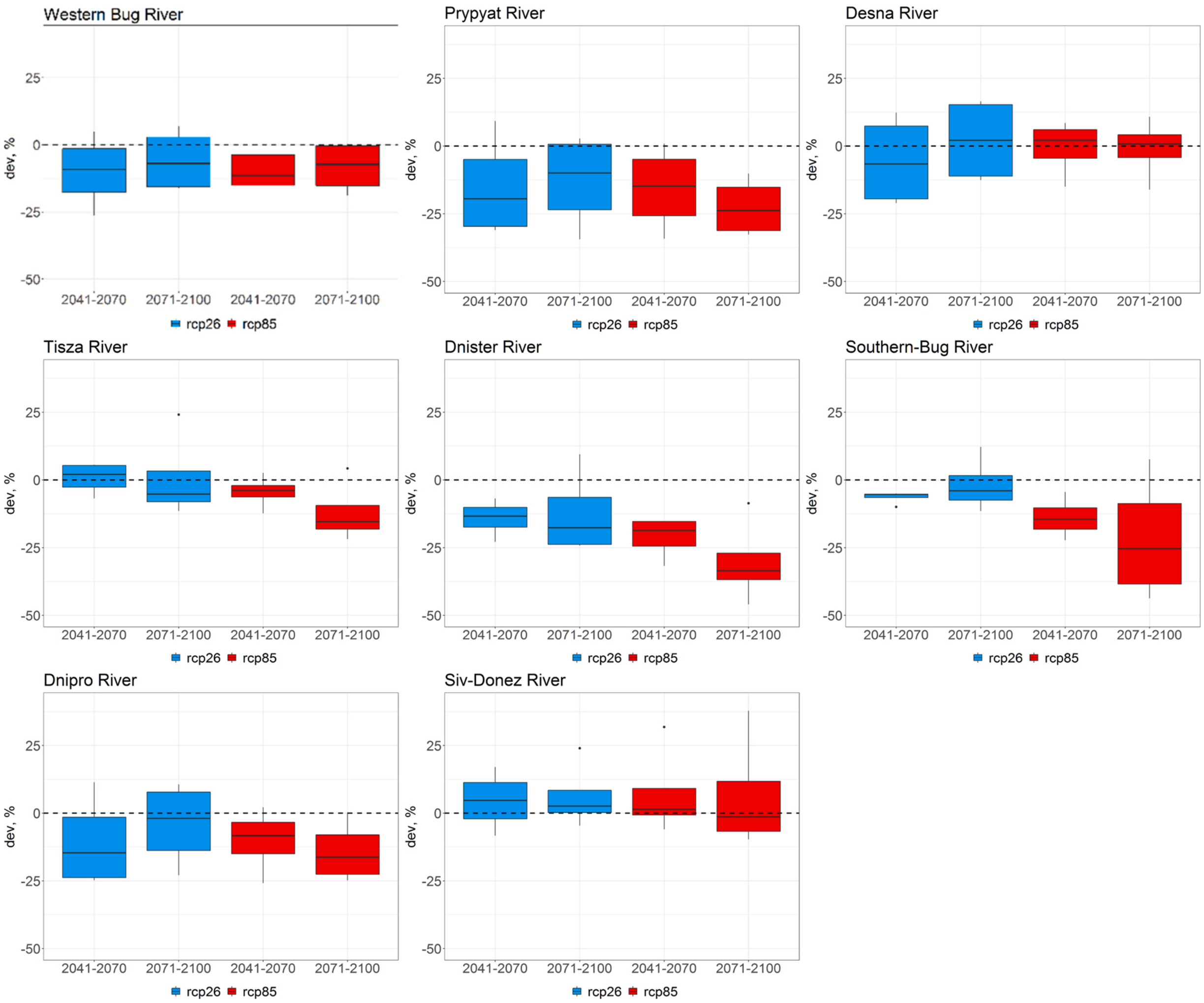


**Fig. 5.** Projected changes in mean annual river discharge simulated by the WaterGAP2 model for eight river basins for two future periods under RCP2.6 and RCP 8.5. Upper box lines indicate 75th percentile, lower – 25th percentile and the middle lines present median; vertical lines show minimal and maximal values.

changes compared to the mid century.

The river discharge in the Western Bug basin is projected to decrease in all months, except February, reaching up to -28 % under RCP 2.6 and up to -30 % under RCP 8.5. The strongest decrease occurs in the fall months under both RCPs. The minor increase in February can be a sign of shift in the peak of river discharge.

Similar but a bit stronger patterns of expected changes were obtained for the Pripyat river, with a general decrease during the year up to -29 % under RCP 2.6, and up to -43 % under RCP 8.5 by the end of the century, except an increase in February in both cases, when discharge is projected to rise up to 10 % under RCP 2.6 and up to 14 % under RCP 8.5.

The river discharge in the Desna basin is projected to increase from January to March in both periods under both RCPs: up to 28 % under RCP 2.6 and up to 42 % under RCP 8.5. During the rest of the months, river discharge is projected to decrease from -3 % to -16 %.

The projections for the Tisza basin show an increase in winter for both future periods from 4 % to 42 % under RCP 2.6 and from 9 % to 42 % under RCP 8.5. In June river discharge increases slightly (by 5 %), and in the rest months, it decreases from -4 % to -17 % in both periods under RCP 2.6. The changes under the RCP 8.5 show a decrease from April to November, ranging from -7 to -21 % in the mid century and from 17 to 35 % in the far future.

In the Dniester basin river discharge is projected to decrease during all months in both time periods under both RCPs, except for February in 2070–2100 under RCP 2.6 (zero changes). The changes vary from -2 % to -20 % under RCP 2.6 and from -5 % to -35 % under RCP 8.5. The river discharge shows a stronger decrease at the end of the century under RCP 8.5.

The river discharge in the Southern Bug is projected to increase in January and February in both periods up to 35 % under RCP 2.6 and up to 30 % under RCP 8.5. During the rest of the year river discharge declines from -3 % to -26 % under RCP 2.6 and from -13 % to -45 % under RCP 8.5 (except a slight increase in one summer month under RCP 2.6). It's notable that changes become higher at the end

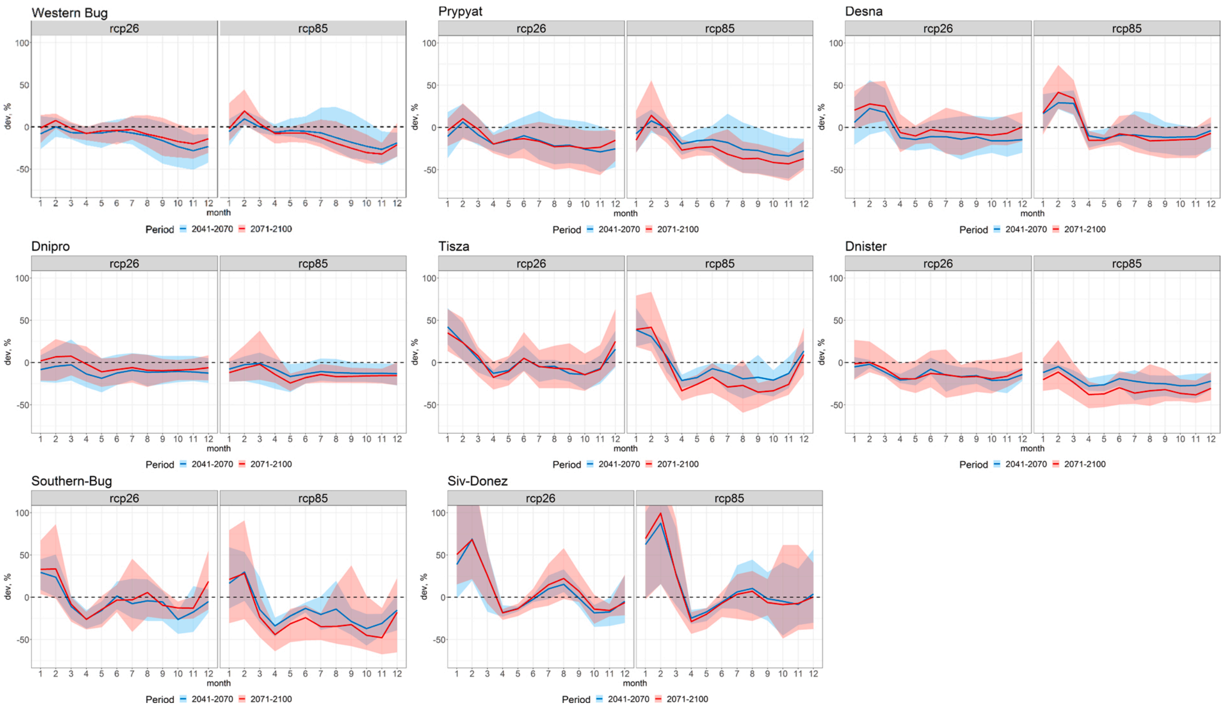


**Fig. 6.** Projected changes in the long-term mean monthly river discharge for two future periods under RCP 2.6 and RCP 8.5. Coloured ranges how model spread and solid lines show multi model mean.

of the century under RCP 8.5.

The simulated changes in the Dnieper basin are homogeneous for both periods and RCPs with a moderate decline of river discharge up to -18 % under RCP 2.6 and up to -24 % under RCP 8.5. An exception is a period from January to March with a small increase up to 7 % in 2070–2100 under RCP 2.6.

The highest positive changes among all catchments are projected for the Siverskyi Donets basin. In January – March river discharge shows an increase up to 69 % under RCP 2.6 and up to 100 % under RCP 8.5, and the highest increase always occurs in February. In July-August river discharge shows an increase up to 22 % under RCP 2.6 and up to 10 % under RCP 8.5, and in the rest months it is projected to decrease up to -28 % under both RCPs.

Annex 6 presents the long-term mean river discharge for two future periods simulated by the ensemble of four models under RCP 2.6 and RCP 8.5. The results show a general decrease during the year with some increase in winter months for the majority of basins under study. The general pattern of changes falls in line of conclusions based on the WaterGAP2, but increases during winter are lower, and the uncertainty of projected discharge is notably higher.

## 5. Discussion

The analysis of model performance showed that the WaterGAP2 model had the best results, and other models had weak or poor performance, where the monthly PBIAS could reach more than 300 % and NSE for the long term monthly discharge – up to -100. The averaged metrics over seven basins under study show the best monthly NSE and seasonal NSE for the WaterGAP2: 0.4 and -0.2 and the best monthly PBIAS and Δσ for the PCR-GLOBWB: – 3.2 and -19.8, accordingly (Annex 7). The good results for the WaterGAP2 can be partly explained by the model calibration (Müller Schmied, 2017), as NSE is to some extent sensitive to the simulated mean, which is likely to be close to the observations in WaterGAP2. In the model evaluation study of Krysanova et al. (2020), the WaterGAP2 was also the best performing model for the set of 57 large river basins. Based on the obtained model evaluation results, and due to the absence of simulation runs for RCP 2.6 or RCP 8.5 for some other models, it was decided to use only the WaterGAP2 model for the impact assessment.

Analysis of projected changes in climate variables performed based on four bias-corrected GCMs under RCP 2.6 and RCP 8.5 shows a gradual temperature increase from the south to the northeast of the study area. Changes in precipitation have no clear patterns across Ukraine under RCP 2.6, but there is a clear decreasing trend in the southern and the southwestern parts under RCP 8.5. It is notable that the differences in precipitation and temperature between 2041–2070 and 2071–2100 periods under RCP 2.6 are much lower in comparison to those under RCP 8.5. It can be explained by temporal distribution of the greenhouse gas concentration during the 21 st century under different RCPs.

A combination of steadily increasing temperature and slightly to moderately increasing or decreasing (depending on the period and RCP) precipitation leads to general decreases of the annual river discharge in the majority of the river basins. Similar to precipitation and temperature, the differences in the projected river discharge between two future periods are higher under RCP 8.5 than under RCP 2.6.

Changes in the long-term mean monthly discharge show an increase during winter months and some decrease in April – May months in the majority of the basins for both periods and RCPs. This can be a result of temperature increase, that provokes earlier snowmelt and shift in the timing of the spring flood. Similar results have been found in Didovets et al. (2017) and Hesse et al. (2015). Also, it can lead to a higher amount of liquid precipitation during winter and further decrease of the magnitude of spring peak discharge. For the rest of the year overall decreases are projected in 5 out of 8 case study basins under RCP2.6 (except for the Tisza, Siverskyi Donets and Southern Bug) and in 7 out of 8 basins under RCP 8.5 (except the Siverskyi Donets) (Fig. 6).

Similar results were obtained in the paper of Didovets et al. (2017), where changes in river discharge in three Ukrainian catchments were analysed using the regional eco-hydrological model SWIM driven by bias-corrected GCMs-RCMs under RCP 4.5 and RCP 8.5. This study showed an increase of river discharge in winter months and a shift of the spring peak discharge in the Samara and Teteriv catchments (tributaries of the Dnieper river). On the other hand, the results for the Upper Western Bug, despite the decreasing precipitation in summer, showed some increase of river discharge during the whole year, which was explained by a higher level of groundwater.

The projected decrease of river discharge during the vegetation period combined with an increase of potential evapotranspiration (see Annex 4) can lead to reduction of water availability for crops across the country. Similar results on a large-scale increase in evapotranspiration in Europe were mentioned in van Vliet et al. (2015). Moreover, a combination of increase in potential evapotranspiration with decrease in actual evapotranspiration (Annex 4 and 5) in southern parts of the study area would increase water demand for irrigation, which is very important for agriculture production in this area.

Besides, the results based on WaterGAP2 show higher discharge increase during winter months compared to the ensemble mean, and in summer months changes in some basins are projected to be opposite in two simulations (e.g. for the Desna river). For example, simulations based on WaterGAP2 show the highest discharge increase in winter up to 100 % in the Siverskyi Donets among all basins, whereas the ensemble mean results show the increase in this basin by 40 %. The increase of discharge in winter months simulated by WaterGAP2 for the Tisza is also notably higher and longer compared to results based on the whole model set (e.g. 24–43 % compared to 5–21 % in January-February). In the case of the Southern Bug changes in January-February are even opposite in two simulations, with an increase up to 28 % simulated by the WaterGAP2 and decrease up to -6 % simulated by the ensemble of models in far future under RCP 8.5. In spite of that, the main direction of change patterns in the long-term mean monthly discharge based on both approaches is similar, with overall decreases during the year except some winter months in the majority of basins.

A more extensive discussion on importance of model performance, model calibration and inclusion of some key processes (e.g. $CO_2$ fertilizations) in the models intended for climate impact studies can be found in Krysanova et al. (2020).

## 6. Conclusions

Climate change will affect water availability of Europe, and Ukraine is not an exception. Future changes will put more stress on water resources and water-related sectors of the countries' economy. In this study, we attempted to produce a general pattern of climate change impacts on river discharge at the country level, and analyse it.

Our results show that even under the „soft "RCP 2.6 scenario river discharge is expected to decrease in the majority of Ukrainian river basins in the middle and end of the 21st century. Under the "business as usual" projections (RCP 8.5) river discharge is projected to decrease more strongly at the end of the century, and in combination with the rising temperature and declining precipitation this may lead to notably lower water availability for the southern part of Ukraine.

This study also demonstrates that the projected impacts and uncertainty of the projections are influenced by selection of hydrological models to be used in the assessment. The model evaluation can help to select only well performing model(s) for impact assessment for improving credibility of impacts and reducing spreads of projections. We would like to emphasize the importance of the analysis of models performance during the historical period using observed data and evaluation of their reliability for climate impact assessment.

Rising temperature provokes changes in hydrological regimes of the rivers. In particular, a shift of the spring river discharge peak to earlier months is projected for the Desna, Southern Bug, Tisza and Western Bug. In summer months, river discharge would decrease in the majority of basins in both periods under both RCPs. This kind of changes could create an additional challenge for the agriculture sector, which is essential for the Ukrainian economy.

In this regard, it is vitally important to develop adaptation strategies at the regional and national levels based on up-to-date scientific knowledge for different sectors.

## CRediT authorship contribution statement

**Iulii Didovets:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization, Writing - review & editing, Data curation. **Valentina Krysanova:** Conceptualization, Writing - original draft, Investigation, Writing - review & editing, Methodology. **Fred Fokko Hattermann:** Conceptualization, Writing - original draft, Investigation, Methodology. **María del Rocío Rivas López:** Writing - original draft, Data curation. **Sergiy Snizhko:** Investigation, Conceptualization. **Hannes Müller Schmied:** Conceptualization, Writing - original draft.

## Declaration of Competing Interest

The authors declare no conflict of interest.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2020.100761.

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