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Hydrological impacts of moderate and high-end climate change across European river basins

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ABSTRACT

Study region: To provide a picture of hydrological impact of climate change across different climatic zones in Europe, this study considers eight river basins: Tagus in Iberian Peninsula; Emån and Lule in Scandinavia; Rhine, Danube and Teteriv in Central and Eastern Europe; Tay on the island of Great Britain and Northern Dvina in North-Eastern Europe.
Study focus: In this study the assessment of the impacts of moderate and high-end climate change scenarios on the hydrological patterns in European basins was conducted. To assess the projected changes, the process-based eco-hydrological model SWIM (Soil and Water Integrated Model) was set up, calibrated and validated for the basins. The SWIM was driven by the bias-corrected climate projections obtained from the coupled simulations of the Global Circulation Models and Regional Climate Models.
New hydrological insights for the region: The results show robust decreasing trends in water availability in the most southern river basin (Tagus), an overall increase in discharge in the most northern river basin (Lule), increase in the winter discharge and shift in seasonality in Northern and Central European catchments. The impacts of the high-end climate change scenario RCP 8.5 continue to develop until the end of the century, while those of the moderate climate change scenario RCP 4.5 level-off after the mid-century. The results of this study also confirm trends, found previously with mostly global scale models.

1. Introduction

Climate change is one of the world's most important global challenges, which will have global as well as regional consequences, and is expected to affect all aspects of modern humanity (IPCC WGII, 2014). The Paris Agreement entered in force at the 21st Conference of Parties (COP21) in 2015 indicated a great success of more than 20 years of negotiations, but also imposed a significant challenge to the contemporary society by setting the goal of limiting the global warming to 2 °C, while aspiring to 1.5 °C (Rogelj et al., 2016; Schellnhuber et al., 2016). This goal is ambitious as now the trajectories of the greenhouse gases emissions are pointing to the high-end climate change scenarios above the agreed threshold, and this development still remains probable, if global actions are not taken urgently.

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The flow regimes of rivers are being modified all over the world by anthropogenic impacts, such as water management operations and land use changes. Some measures put freshwater resources at significant stress, and climate change is expected to alter the hydrological conditions further, posing additional pressure on water resources and aquatic ecosystems. The climate change risks have to be understood, quantified and incorporated into water management strategies at the regional level (Döll et al., 2014). All adaptation measures, including those of "no-regret" type have to be based on a solid understanding of the current situation and possible future trends (Harding et al., 2014), both long-term and short-term. Hydrological modelling is a primary tool to obtain projections on how climate change would impact water resources and hydrological patterns of river basins.

In general, there is a voluminous amount of literature on the impact of climate change on hydrological cycle and water resources covering different scales: from river basins to continental and global scales. Most of the continental and global scale studies employ global scale hydrological models, as the application of a regional model to all river basins in a continent, e.g. in Europe, would result in significant calibration efforts and high input data requirements.

At the scale of Europe, Papadimitriou et al. (2016) conducted a study on impacts of the high-end climate change on river discharge in eight selected European river basins applying the non-calibrated global hydrological model JULES (Best et al., 2011). They have found an increase in the number of days with low flow for Central and Southern Europe (Rhine, Danube, Guadiana), and an increase in low flows for Scandinavia (Kemijoki River). Further, several studies, conducted with different global models (e.g. WaterGAP, Mac-PDM.09), have projected an increase of discharge in the high-latitudes and decrease in the Mediterranean and Southern Europe (Arnell and Gosling, 2013; Hagemann et al., 2013; Schneider et al., 2013), and seasonal changes in the snowmelt driven rivers, where discharge in winter is increasing, while the summer discharge is decreasing (Döll and Schmied, 2012; Wanders et al., 2015).

Uncertainties associated with global-scale hydrological modelling are usually higher as compared with those related to the regional-scale hydrological models (Hagemann et al., 2013; Gosling et al., 2017; Hattermann et al., 2017). This can be explained by coarser resolution of the input data and usually poor performance of global models (most of them are not calibrated) in the historical reference period (Hattermann et al., 2017), as well as inability of most of the global models to take into account water management infrastructure (Abbaspour et al., 2015). Due to this, it makes sense to verify trends by application of the basin-scale models.

Further, there are some continental-scale studies performed with the pan-European models, which are partly calibrated. Donnelly et al. (2016) applied a multi-basin model E-HYPE to the entire Europe, which showed good simulation results, and can be used for climate impact studies after some improvements, regarding input data and additional calibration. Roudier et al. (2016), applying three pan-European models, LISFLOOD (Burek et al., 2012), E-HYPE (Donnelly et al., 2016) and VIC (Liang et al., 1994), found that drought events may increase in Southern Europe, in particular, in Southern France and Spain, and the frequency of flood events may increase in Northern Europe, if the global temperature will increase by +2 °C. A study of Alfieri et al. (2015) applied the distributed hydrological model LISFLOOD driven by the high-end climate change scenario in major river basins across the entire European region. They found decrease of runoff in the Southern Europe and increase of runoff in Northern Europe, and no specific trends for the discharges in the Central Europe. However, the abovementioned analyses were focused on the extreme events frequency analysis or on the validation of the pan-European models, and not on the general picture of the hydrological impacts of projected climate change.

Regarding the hydrological impact assessments performed with the regional scale hydrological models, it usually focuses on individual regions, often single river basins, and studies encompassing large areas are rare (Aich et al., 2014; Vetter et al., 2016). Recently, a Special Issue in Climatic Change (see editorial Krysanova and Hattermann (2017)) addressed the issue of intercomparison of the regional-scale hydrological models and climate change impacts across twelve large river basins around the globe (including two basins in Europe: Rhine and Tagus), fulfilled by the efforts of the ISI-MIP project (Warszawski et al., 2014) group.

Our study aims to close the existing gap and provides an assessment of trends in the long-term mean annual dynamics of river discharge in eight representative European basins triggered by climatic change. For that, an eco-hydrological process-based catchment scale hydrological model was applied, which was calibrated and validated for each case study in advance and accounted for water management operations, where applicable. It used a more elaborated approach, when compared to the previous European-scale studies. We provide an assessment and intercomparison of the moderate and high-end climate change impacts on river discharge across different regions in Europe, focused on eight river basins: Tagus in Iberian Peninsula; Emån and Lule in Scandinavia, Rhine in Central Europe, Danube and Teteriv in Central and Eastern Europe, Tay on the island of Great Britain, and Northern Dvina in North-Eastern Europe. These basins were selected within the European Case Study of the EU funded project "IMPRESSIONS: Impacts and Risks from the high-end scenarios: strategies for innovative solutions".

Our assessment considers two future climate change scenarios of moderate (RCP4.5) and high-end (RCP8.5) global warming, and two future time slices: intermediate (2041–2070) and far future (2071–2100), evaluated with respect to the reference period (1981–2010). Current study complements the picture of the European scale assessments done before, and verifies the trends found in the previous studies fulfilled with the global and pan-European scale models.

2. Case study basins

The river basins considered in this study were selected to represent the variety of conditions in the river basins in Europe. The selected basins:

- are situated in different climatic zones, see Annex 1 in Supplementary Material that provides a map of the basins with respect to climatic zones after the Köppen Geiger classification;
- have different basin areas ranging from *meso*- to macroscale basins (from 4500 km^2 for the Emån to 817000 km^2 for the Danube),

covering large sub-regions of Europe;
- have different topographic conditions, from river basins with flat topography in lowland (like the Northern Dvina) to mountainous regions (like the Tagus basin or the Rhine headwaters);
- have different land use conditions, from areas covered mostly with forest (the Northern Dvina, Emån) to extensively cultivated river basins (the Teteriv, Danube);
- have different levels of anthropogenic influence on river discharge, from highly-regulated river basins with many reservoirs and diversion channels (the Tagus and Lule) to rivers with mostly pristine conditions (the Northern Dvina);
- have different discharge regime characteristics, specific for their climatic areas (like the Tagus River with the Mediterranean type of regime characterized by low discharge in summer and peak discharge in winter, or rivers with different snowmelt driven regimes specific for their climatic regions, e.g. the Norhern Dvina with peak discharge in May, or Lule with peak discharge in June–July).

The basins were also selected based on their significance for the respective regions in Europe. For example, the Danube and Rhine catchments cover the large area of Central and Eastern Europe, and are important for population of many countries there. Further, the Emån, Lule and Tay Rivers are very significant rivers in Sweden and Scotland, the latter two – also for energy production. The Northern Dvina is one of the largest rivers in the North-European part of Russia, with natural flow conditions. The Tagus in the Iberian Peninsula is very important water supplier for Spain and Portugal. And the Teteriv River basins is one of the largest tributaries of the most important river in the Ukraine, Dniepr River. The most important characteristics of the eight river basins under consideration are summarized in Table 1 and in Annex 1 of the Supplementary Material, and the location of river basins is shown in Fig. 1.

3. Methods

3.1. SWIM model

The Soil and Water Integrated Model (SWIM) is a process-based deterministic eco-hydrological model, based on two earlier created models: SWAT (Arnold et al., 1998) and MATSALU (Krysanova et al., 1989). The model is described in Krysanova et al. (1998). The SWIM model can be seen as an assemblage of numerical representations of physical processes of hydrological cycle and related processes (vegetation growth, nutrient cycling and erosion) at the river basin scale. These physical processes are mathematically interpreted with similar levels of complexity, and form four main modules of the model, describing hydrological processes, groundwater, biogeochemical cycles and plant growth. SWIM operates on a daily time step and uses climatic, land use, topographic, vegetation and soil datasets as input files.

The topographical map of a catchment serves as a basis to create a subbasin map, which is later intersected with land use and soil maps to identify the so-called HRUs – Hydrological Response Units or hydrotopes – areas within each subbasin, where a unique combination of land use and soil type is present. The identical HRUs, the ones which have the same land use and soil types in a subbasin, are assumed to have the same hydrological “behaviour”, and are later combined into hydrotope classes within each subbasin, and modelled as one subarea. The components of hydrological cycle, nutrient cycling and sediment loads are calculated at the hydrotope level, and lateral flows are added for subbasins. After that the lateral flows of water, nutrients and sediments are routed through the basin, using conceptual representation of the open channel hydraulics – the Muskingum method, taking into account transmission losses.

More than 20 years of application history of the SWIM include development of model versions for specific processes (wetlands, nutrients in streams, reservoirs, etc.) and many stories of successful application as well as some failure cases, as thoroughly discussed in Krysanova et al. (2015). The SWIM model has been successfully applied for investigation of different hydrological phenomena, like impacts of climatic change on stream flow (Aich et al., 2013; Huang et al., 2013; Lobanova et al., 2016; Stagl and Hattermann, 2015), on agricultural production (Liersch et al., 2013), and on extreme hydrological events (Aich et al., 2016; Hattermann et al., 2012; Huang et al., 2014, 2013), as well as for analysis of the glacier lakes outburst floods (Wortmann et al., 2014) and hydrological impacts of irrigation activities (Huang et al., 2015).

3.2. Reservoir module

The reservoir module of SWIM is a conceptual representation of the storage/release processes at dams and reservoirs (Koch et al., 2013). It is fully integrated in the SWIM model and can represent three management strategies, depending on the minimum discharge from reservoirs (e.g. for environmental needs), minimum and maximum reservoir volumes in a given month, or firm hydropower production target. The reservoir module requires a volume-discharge-surface area relationship for each reservoir, and also the inflow, outflow and stored volume time series for parametrization of the management process. The reservoir module can also simulate the hydropower production, and requires data of the hydropower plant installed as an input for the calculation of the daily produced hydropower.

Each reservoir in the catchment is integrated into the subbasin map of the river basin under consideration as a separate “subbasin”. The precipitation over the reservoirs as well as evaporation rates and seepage of water to the groundwater are considered.

Table 1
Major characteristics of the case study river basins.

Name	Location	Catchment area, km^2	Length, km	Mean discharge, m^3/s	Anthropogenic functions	Anthropogenic alterations considered in SWIM or not	Elevation, max and mean, m	Average annual precipitation, mm	Average temperature	Dominant land use types (% of the total basin area)
Tagus	Iberian Peninsula	80000	1000	500	Hydropower production, irrigation, public water supply	Yes, 16 largest reservoirs and the Tagus-Segura water transfer	1500 599	750	15 °C	Shrubs (19%) Crops (19%) Forest, evergreen (14%)
Tay	Island of Great Britain	5200	188	170	Hydropower production, industrial and public water supply	No	1091 298	1000	10 °C	Shrubs, sparse forest (50%) Grassland (25%) Cropland (10%)
Lule	Scandinavia	25000	350	500	Mainly hydropower production	Yes, 5 major reservoirs	1900 525	750	-2.5 °C	Forest evergreen (35%) Sparse vegetation (30%) Bare soil (10%)
Emån	Scandinavia	4500	220	30	No	No	335 204	680	6.5 °C	Forest evergreen (45%) Forest broadleaved (40%)
Northern Dvina	North-Eastern Europe	350000	744	3500	Navigation	No	421 150	650	- 0.5 °C	Forest evergreen (39%) Forest broadleaved (46%)
Rhine	Central Europe	185000	232	2500	Navigation, irrigation, water supply	No	3753 325	800	6.5 °C	Forest broadleaved (26%) Cropland (26%) Grassland (11%)
Danube	Central and Eastern Europe	817000	2860	7000	Irrigation, hydropower production, navigation	No	3774 314	800	6.4 °C	Cropland (56%) Forest (20%) Grassland (7%)
Teteriv	Eastern Europe	15100	350	33.8	Irrigation, pond-fishing, industrial water supply	No	314 213	620	8.2 °C	Cropland (65%) Forest (25%)

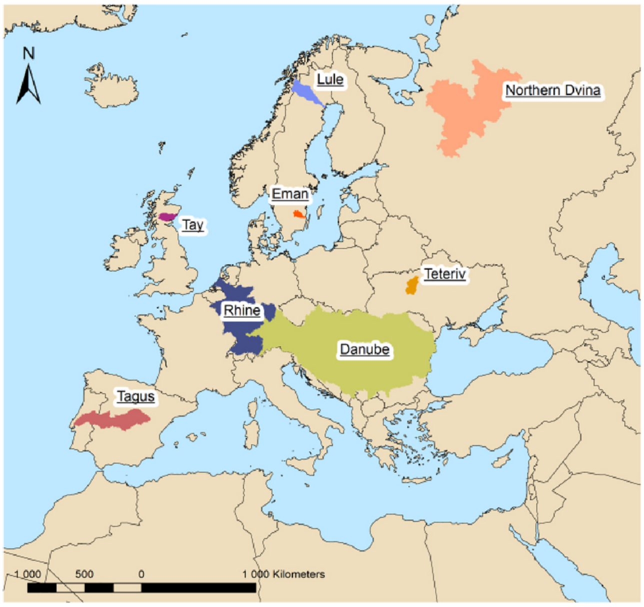

Fig. 1. Coverage of the European Case Study: eight river basins under consideration.

3.3. Water allocation module

The water allocation module (WAM) and its application for the simulation of the Tagus-Segura Water Transfer were described in detail in the work of Lobanova et al. (2017). The WAM simulates water withdrawals by, e.g., irrigation channels and inter- and intrabasin transfers of water, for example for drinking water supply. The module operates on a daily time step, and enables water withdrawal from one subbasin and assignment to the other subbasin within the river basin, or simply outside the basin on the next day, taking into account transmission losses, e.g. due to evaporation. In the case of the Tagus-Segura water transfer, the observed withdrawn values over the calibration and validation periods were applied within WAM, and for the future projections the mean values over the entire observed period were applied, as the projection of the withdrawal evolution was beyond the scope of this study. The analysis of the possible water allocation scenarios in this area under the projected climate change scenarios can be found in Lobanova et al. (2017).

3.4. Input data

The input data needed to set up the SWIM model for a river basin are land use map, soil map, digital elevation model (DEM) and climate data, as well as observed runoff for calibration and validation of the model.

The CORINE2000 land use database and the DEM from the CGIAR database (Jarvis et al., 2008), both with the resolution of 100 m, were used for seven case study basins except the Northern Dvina. The land use types in the CORINE database were then aggregated to match the 15 land use classes of SWIM (Krysanova et al., 2000).

In the case of the Northern Dvina River the input datasets were different. In particular, the land use data was obtained from the global CORINE dataset with a coarser resolution of 250 m, which is covering the European part of Russia. The DEM model used for this catchment was obtained from the ASTER dataset, with the resolution of 30 m, which provides DEM covering the entire globe (Tachikawa et al., 2011). The ASTER dataset was the only one DEM available for the Northern Dvina River, as the CGIAR dataset covers the globe only until 60th latitude.

The soil data for all basins was extracted from the European Soil Data Centre (Panagos et al., 2012). The parameters of each Soil Typological Unit within each Soil Mapping Unit were considered, and weighted according to their percentage shares. The missing parameters, needed for the SWIM model simulation, were derived using the pedo-transfer functions (Krysanova et al., 2000). For the modelling, the vegetation parameters from the SWIM database for 71 vegetation types (23 parameters per type) attached to the model were used, and they were not adjusted for the catchments.

To calibrate and validate the SWIM model, the gridded climate WATCH Era Interim Forcing Data (Weedon et al., 2014) were used. The WATCH Era Interim dataset covers the entire globe and provides synthetically generated climatic variables, corrected to observations. The WATCH ERA Interim dataset is provided on a grid with a resolution of 0.5° and covers time period 1979–2010. The observed discharge data at the outlets of the basins were obtained from the Global Runoff Data Centre (GRDC, Koblenz, Germany) database for all basins except for the Tagus River basin, for which the observed data at the Almourol gauge were taken from the Sistema Nacional de Informação de Recursos Hídricos (SNIRH) database of the Portuguese Ministry of Environment.

Initially, the SWIM model was set up for the Rhine River and described in Huang et al. (2010), for the Danube River – in Stagl and

Hattermann (2015), and for the Teteriv River – in Didovets et al. (2017). For the first two basins SWIM was initially calibrated using WATCH Era 40 (Weedon et al., 2011) data as input, and for the application in this study the models were re-calibrated using WATCH Era Interim data as input.

3.5. Calibration and validation

Two main criteria of fit between the observed and simulated discharges were used: the Relative Volume Error, RVE, and the Nash-Sutcliffe Efficiency, NSE. The RVE is a total deviation in the volume of water discharged, expressed in percent, and the NSE is an efficiency coefficient, which relates a sum of squared differences between the observed and simulated discharges to the variance of the observed values of discharge. The RVE coefficient can vary from -100 to $+\inf$, where 0 indicates a perfect fit, and the NSE coefficient from $-\inf$ to 1.0, where 1 indicates a perfect fit. The specific limits for both criteria, which correspond to a "good" performance of a hydrological model are NSE > 0.65 and PBIAS $< \pm 15\%$, as was specified by Moriasi et al. (2007). In order to test the model performance during the low flow periods, also the log-transformed NSE (logNSE) on the daily simulated and observed values were calculated.

The SWIM model was calibrated and validated against the observed discharge data series on the daily time step for all eight basins. The calibration and validation periods were different for each river basin, subject to discharge data availability. The model calibration was done based on sensitivity analysis for SWIM performed previously for many river basins in Europe. The calibration procedure was performed manually, altering the evapotranspiration correction coefficient, base flow factor, groundwater delay factor, two routing coefficients, Manning coefficient, and saturated conductivity correction coefficient. Also the snow parameters, including threshold temperatures of snowfall and snowmelt as well as snowmelt rate were included in the calibration process in all basins, except the Tagus.

For two of eight selected river basins, the Lule and Tagus, water management infrastructure was included in the model set up. The reservoirs were represented by the SWIM reservoir module, and they were calibrated against the observed inflow, outflow and water storage data, obtained from the country-specific databases. River discharge of the Lule River was found to be the most affected by water regulation, followed by the Tagus River basin. Further, the Tay River basin also includes several natural lakes that are regulated for electricity production. However, these lakes were not included in the model, due to inaccessibility of data on lakes operation. For the same reason, due to absence of data, the reservoirs in the Teteriv River basin were also not considered in the model.

As the aim of this paper was to quantify impacts of climate change on the long-term average monthly discharge, it was decided to calculate the NSE and RVE criteria of fit on the monthly time step for all cases. Additionally, the log-NSE, NSE and RVE were calculated on the daily time step in order to test the model ability to simulate the daily dynamics of discharge, as well as low flows.

The operational rules of the reservoirs in the Tagus and Lule River basins were not altered for the future projections and were preserved as current ones, because the response of water infrastructure operation to changes in water availability was beyond the scope of this paper.

3.6. Climate scenarios

The climate change projections used in this study were developed within the IMPRESSIONS project. The projections were obtained from the CORDEX coupled GCM (Global Circulation Models) – RCM (Regional Climate Models) simulations. The downscaled individual climate variables were bias-corrected to the reanalysis data WATCH Era Interim using the quantile mapping method (Themeβl et al., 2012; Wilcke et al., 2013).

The projections include seven GCM-RCM coupled simulations, forced by RCP4.5 and RCP8.5 scenarios of increase in the radiative forcing. The projections were selected to cover the full range of future climate projections from 1.1 °C to 4.2 °C globally (Kok et al., 2015). The selection of the GCM-RCM coupled simulations was driven in the first place by the expert judgement of their performance in Europe and elsewhere, and in the second place by direct comparison of their ability to represent the reference cycle of temperature and precipitation in Europe. Further, the selected subset was reduced to models that represent different model sensitivity to the greenhouse gases emissions to reproduce the climate model variability. The selected models cover the global increase in temperature up to 4 °C, as the aim of the "IMPRESSIONS" project was to focus on the high-end scenarios (Kok et al., 2015).The Northern Dvina River basin lies exactly at the border of the EURO-CORDEX domain, and therefore the RCM simulation results may not represent this area with sufficient accuracy due to the strong influence of boundary conditions inherited from the GCMs. Therefore, it was decided to use the raw GCM output for this basin, and then to bias-correct it applying the same quantile mapping method as for the other basins.

4. Results and discussion

4.1. Calibration and validation

In general, the performance of the SWIM model during the calibration and validation periods for all selected basins on the monthly time step was satisfactory. However, the model showed lower performance related to low flow conditions in some of the case study river basins. Fig. 2 depicts the long-term average seasonal dynamics observed and simulated with SWIM driven by the WATCH Era Interim data at the outlets of the selected basins over the respective calibration and validation periods together. Table 2 summarizes the NSE and RVE values obtained for the calibration and validation periods with the monthly and daily time steps and the

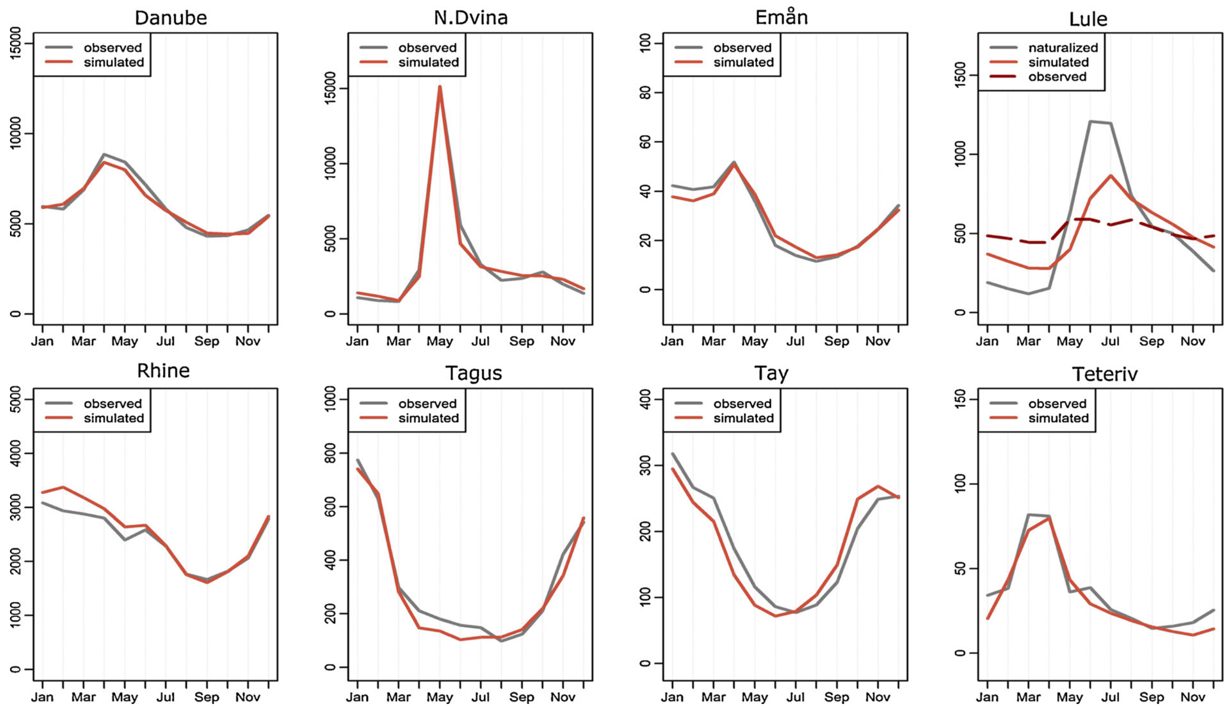

Fig. 2. The long-term mean annual dynamics, observed and simulated with the SWIM model driven by the WATCH Era Interim data for the eight case study basins.

logNSE values on the daily time step for each case study basin. Figures A2–A9 (Annex 3) show the monthly mean time series, the long-term mean annual dynamics, as well as 10th, 50th and 90th flow percentiles of the observed and simulated discharge over the both calibration and validation periods for each case study river basin.

The SWIM model performance was acceptable in all case studies, showing very good to acceptable performance, based on ranges specified in Moriasi et al. (2007). In terms of the NSE values, both on the daily and monthly time steps, the best model fitting was found for the Northern Dvina basin, and the lowest values were estimated for the Tay, Teteriv and Lule River basins. The largest RVE values reaching 10–19% were obtained for the Tagus and Teteriv Rivers. This can be explained by the continuous development of irrigation channels and increase in water consumption for irrigation during the calibration and validation periods in the Tagus, which were not taken into account in the model, as discussed in Lobanova et al. (2016). For the case of the Teteriv River, the situation might be similar to the one described for the Tagus River: the overestimation of the water volumes in the model in the validation period may

Table 2

The Nash-Sutcliffe efficiency and Relative Volume Error values for the calibration and validation periods with the monthly and daily time steps, as well as the log-transformed Nash-Sutcliffe efficiency (logNSE) with the daily time step for the case study basins.

River		Nash-Sutcliffe Efficiency (monthly)	Relative Volume Error, % (monthly)	Nash-Sutcliffe Efficiency (daily)	Relative Volume Error, % (daily)	logNSE (daily)
Danube	Calibration (1990–1999)	0.86	−4.6	0.82	−6.9	0.71
	Validation (2000–2008)	0.87	−5.9	0.79	−7	0.75
Northern Dvina	Calibration (1983–1990)	0.93	−3.2	0.85	−4.6	0.8
	Validation (1991–1998)	0.95	−8	0.9	−3.4	0.83
Emån	Calibration (1991–1995)	0.86	8.6	0.82	8.6	0.79
	Validation (1996–2001)	0.78	−9.5	0.73	−9.5	0.83
Lule (naturalized flow)	Calibration (1999–2005)	0.69	−0.9	0.61	−1.7	0.48
	Validation (2006–2010)	0.62	−0.3	0.59	0.8	0.51
Rhine	Calibration (1981–1991)	0.84	−0.1	0.75	−7.7	0.74
	Validation (1992–1999)	0.88	−0.1	0.81	−0.2	0.74
Tagus	Calibration (1987–1993)	0.82	15	0.72	15	0.8
	Validation (1994–1999)	0.81	−12	0.81	−12	0.33
Tay	Calibration (1980–1992)	0.85	1.6	0.63	3.8	−0.14
	Validation (1992–2001)	0.88	1	0.69	3.6	0.39
Teteriv	Calibration (1999–2003)	0.82	−10.5	0.75	−10.8	0.01
	Validation (2004–2008)	0.56	10	0.53	9.6	−0.04

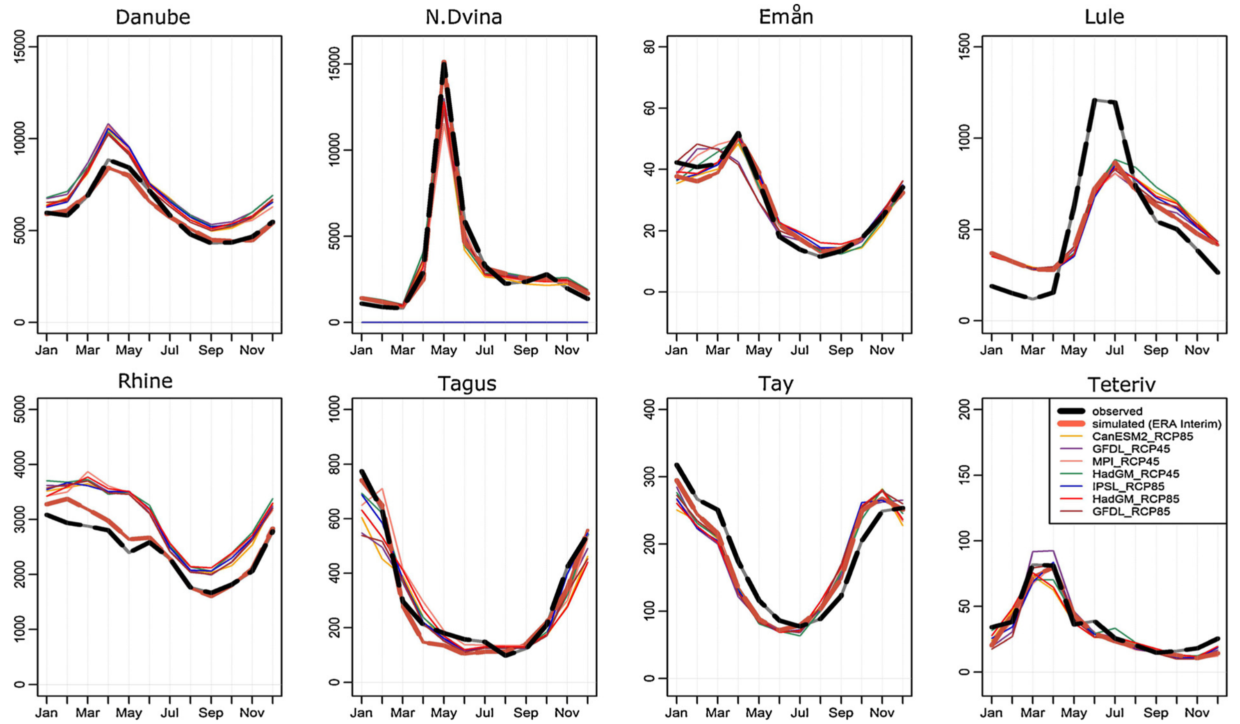

Fig. 3. The long-term mean annual dynamics of river discharge observed and simulated with SWIM driven by the WATCH Era Interim data and seven climate models outputs over the reference period 1981–2100 for the eight case study basins.

reflect the water withdrawals effects which were not taken into account. However, in this case due to the absence of data on water management no solid conclusion can be drawn.

When looking at the seasonal dynamics, one can observe that the SWIM model simulations reproduce observed dynamics well in most cases, but also exhibit some deviations in certain sub-periods in some cases. In the case of the Tay River, the timing of flow was not properly met, probably, due to absence of the regulated lakes integration into the model set up.

In the case of the Tagus River, the low flows during summer were underestimated, possibly due to similar reasons, as this river is one of the most highly regulated in Europe, there are more than 40 large reservoirs in the catchment, whereas in our model only 16 major reservoirs were included. Still, the inclusion of reservoirs has increased the performance of SWIM in this case significantly, as discussed in Lobanova et al. (2016), but some uncertainty due to water management infrastructure, which was not taken into account, is left.

However, the most explicit example of the effects of anthropogenic activities on river flow in this study is the Lule River Basin. In Fig. 1 one can see discharge measured at the outlet of the river, the naturalized flow of the river simulated with the HYPE model (Lindström et al., 2010), and discharge simulated with the SWIM model considering four major reservoirs. One can observe that the natural dynamics of the river was completely transformed, eliminating the flow variability, making flow nearly constant throughout the year. By introducing the reservoirs in the SWIM model the dynamics could be brought closer to the observed one, however still it is far from the perfect fit.

When looking at the logNSE values that are more sensitive to the low flow conditions, one can observe that the model performance for low flow varies between basins: it is quite good for the Emån, Northern Dvina and Danube, satisfactory for the Rhine and Lule, but quite poor for the regulated rivers, such as Tagus (validation period), Tay and Teteriv, where the existing flow regulation was not considered or considered only partly (Tagus). In the case of the Lule logNSE was still high, as the goodness of fit was calculated for the naturalized flow, i.e. without the implementation of the reservoirs, simulated with the HYPE model and naturalized flow simulated with the SWIM model. The reservoirs were added to the SWIM model setup after the calibration of the naturalized flow conditions.

The calibration and validation results, especially the results with the logNSE criterium indicate that inclusion of the water management infrastructure is essential, especially when aiming at the assessment of the low and high flows in addition to the average flow conditions in the rivers.

4.2. Representation of the historical discharge dynamics by SWIM driven by climate models

To check the performance of the bias-corrected climate data in the historical period, the observed discharge was additionally compared with discharge simulated by SWIM driven by the selected GCM-RCM projections (Fig. 3). The systematic overestimation of flows with SWIM driven by the GCM-RCM climate runs was found in two cases: for the Rhine and Danube River basins. In all other

Table 3
Changes in the Budyko aridity index (PET/PP), precipitation (PP), runoff (RO) and actual evapotranspiration (AET) in the case study basins for the far future time slice (2071–2100).

Basin	Aridity Index		PP		RO		AET	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Danube	+	+	−	−	−	minor	−	−
Northern Dvina	minor	+	+ +	+ + +	+	+ +	+ +	+ + +
Emån	minor	minor	minor	+	minor	+ +	minor	+
Lule	minor	minor	+	+ +	+ +	+ + +	+	+ +
Rhine	minor	minor	+	+	+	+ +	minor	minor
Tagus	+ +	+ + + +	−	− − −	− −	− − −	−	− −
Tay	−	−	+ +	+ +	+ +	+ +	minor	minor
Teteriv	minor	minor	+	+ +	+ + +	+ + + +	minor	+

Legend, %	
+ + + +	> 30
+ + +	+21 to +30
+ +	+11 to +20
+	+5 to +10
minor	−5 to +5
–	−5 to −10
–	−10 to −20
—	−21 to −30
—	< −30

cases the simulated dynamics was similar to that driven by the Era Interim data. The long-term mean annual discharge dynamics in the Teteriv River basin was represented satisfactory, even though the catchment is situated in the same region as the Danube. In the cases of the Emån and Tagus there is some uncertainty in representing winter flows, what is indicated by a larger spread of model outputs. As for the Tay, the lag in timing of the high and low flows follows the pattern of the SWIM simulation driven by the Era Interim data and is probably due to the regulated lakes omitted in the model setup.

4.3. Changes in climate and components of hydrological cycle in the case study basins

Figures A10–A13 in Annex 4 depict the long-term mean annual dynamics of temperature and Figures A14 and A15 of precipitation and AET values for the reference, intermediate and far future periods as indicated by the multi-model means of the climate projections under RCP4.5 and RCP8.5 scenarios for the eight case study basins.

When looking at the precipitation patterns for the most southern basin of the Tagus River one can observe a moderate decrease in spring under the RCP 4.5 scenario, and a strong decrease in spring and autumn under the RCP8.5 scenario. Under the low-end scenario precipitation is also projected to decrease in the Rhine basin in summer and early autumn months. Further, precipitation is projected to increase in the Rhine, Danube, Northern Dvina, Tay and Teteriv during the winter and late autumn months under both scenarios. In the Lule and Emån River basins precipitation is expected to increase throughout the year under both scenarios.

Temperature increases in all basins throughout the year, under both scenarios and for the both future time slices with higher increases under the high-end scenario compared to RCP 4.5, and in the far future compared to mid-century. For the rivers located in Northern, Central and Eastern Europe the winter temperatures are projected to become positive approximately one month earlier in spring as compared to the reference period. In the cases of the Danube and Teteriv, the multi-model long-term mean temperature under climate change projections is expected to become positive throughout the year under RCP 8.5 in the far future. The strongest increase in temperature is projected for the Tagus River basin in summer months.

Table 3 provides an overview of changes in the components of the hydrological cycle relative to the reference period by the end of the century, in particular in precipitation (PP), actual evapotranspiration (AET), surface runoff (RO) and the Budyko aridity index (which is potential evapotranspiration divided by precipitation). The aridity index slightly increases under both RCPs in the Danube, and strongly in the Tagus River due to decrease in precipitation and increase in PET, subject to rising temperatures, especially under RCP8.5. Also PP, RO and AET show strong decreases in the Tagus under RCP8.5.

On the contrary, the aridity index is decreasing in the Tay basin. For other basins, the ratio between PET and PP remains practically stable under both climate projections. An increasing trend in precipitation is projected over the Northern Dvina, Tay, Lule, Teteriv and Rhine under both future warming scenarios, and for the Emån under RCP8.5. Similar patterns were found for runoff, which follows trends in precipitation.

The AET shows increases in summer months in the basins of Lule, Nortern Dvina, Emån and Teteriv, which is associated with increased temperatures (see Figs. A10–A13) and increase in precipitation (Figs. A14–A15). In the Tagus and Danube River, on the contrary, the AET decreases, constrained by the reduced water availability. In other catchments changes in AET are less pronounced, but still even slight changes in AET can lead to significant changes in the water balance, especially in the southern catchments, and therefore they have to be considered.

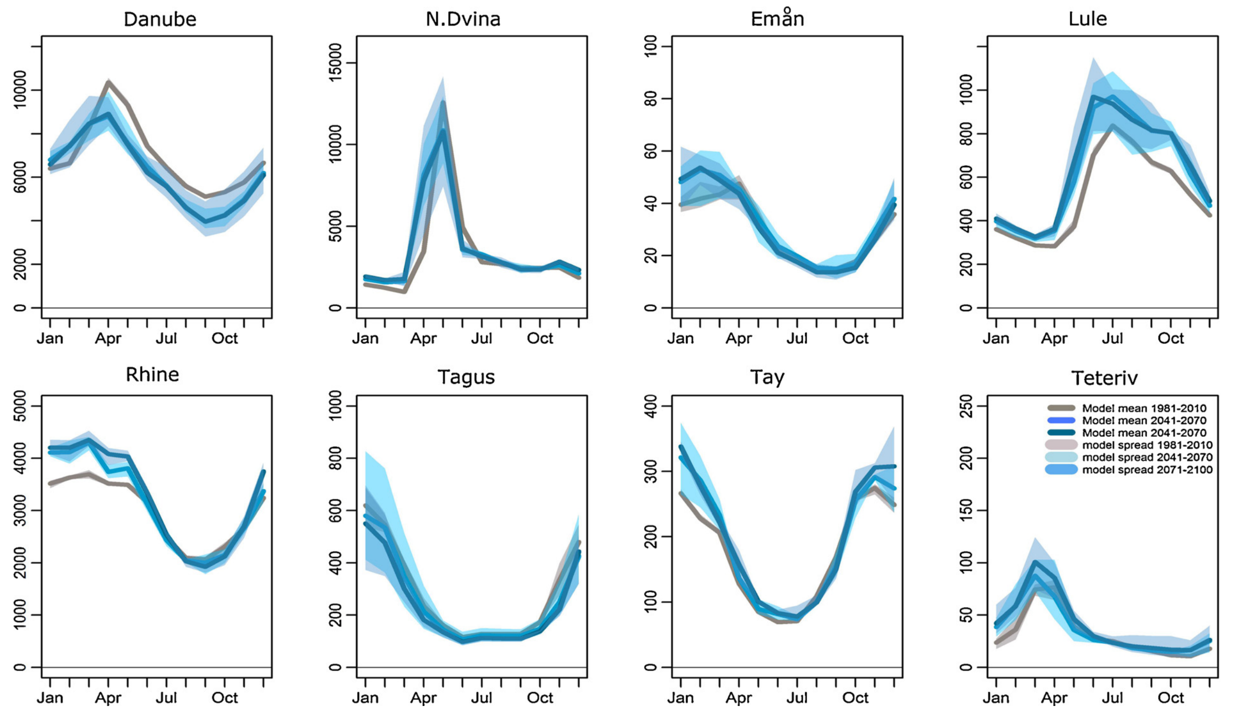

Fig. 4. Comparison of the long-term mean annual dynamics of discharge in the intermediate and far future time slices with that in the reference period (all – simulated with the SWIM model driven by the climate projections under RCP4.5 scenario) for the eight case study basins.

4.4. Changes in river discharge in the basins under climatic change

The impacts of projected changes in climate on the water resources availability in the case study basins were heterogeneous. Figs. 4 and 5 show the multi-model means (three model runs for RCP4.5 and four for RCP8.5) and the model spreads (minimum to maximum values) for the long-term mean annual discharge at the outlets of the basins in two future periods: 2041–2070 (mid-future) and 2071–2100 (far-future) under two global warming scenarios: RCP4.5, moderate, and RCP8.5, high-end global warming, against the model runs in the reference period.

The significance of changes in the monthly discharge of river basins under consideration was evaluated with the Wilcoxon rank test, at the $p = .05$ significance level, comparing reference period to two future periods. Annex 5 provides the *p*-values for each monthly flow in each basin, for the two future periods. Please note that only statistically significant changes are described in this section.

An overall statistically significant increase in discharge throughout the year (all months) was found in the most northern catchment of the Lule River under both warming scenarios and for both future periods. The projected increase in discharge is accompanied by a shift in seasonality; in particular, the peak in discharge is expected to occur approximately one month earlier, shifting from end of July to mid-June, as the average temperature in the catchment will become positive earlier due to increased temperatures in the future. The difference between the intermediate and far future periods is obvious under the RCP8.5 scenario, where the increasing trend is developing further, whereas under RCP4.5 the difference between the far and intermediate future time slices is rather small.

In the case of the Northern Dvina, the spring peak is shifted one month earlier by the end of the century under RCP 8.5, and the peak discharge period is prolonged in time. Under RCP4.5 the high flow period begins already in April and reaches its maximum in May. There is also a slight increase in discharge of the Northern Dvina in late autumn and winter under RCP8.5 in the both time slices, and in the far future under RCP4.5.

In the Emån, Rhine Tay and, Teteriv rivers a statistically significant increase in the winter and early spring discharge is projected under RCP8.5 in both periods (see Annex 5). The increase is the highest in the Teteriv and Emån rivers: reaching up to +60% with respect to the reference period in January for the Emån, and up to two times higher in the Teteriv under RCP8.5. In the Rhine and Tay rivers the increase in winter is up to +30% under RCP8.5 by the end of the century. The same tendency is observed in these four basins under RCP4.5, and in January and February the increase (by 20–25%) is statistically significant in all four basins in both periods. Besides, there are seasonal shifts projected for the Emån and Teteriv under RCP8.5, shifting from April to February for the Emån and from April to March for the Teteriv.

In the case of Danube a decrease in discharge is projected from April until December under RCP4.5, and from April until July under RCP8.5 (based on all model runs). One can see no significant changes of the multi-model mean and a large spread of projections from August to December under RCP8.5. Under the moderate climate change scenario, the peak discharge is shifted from April to March under the high-end climate change scenario.

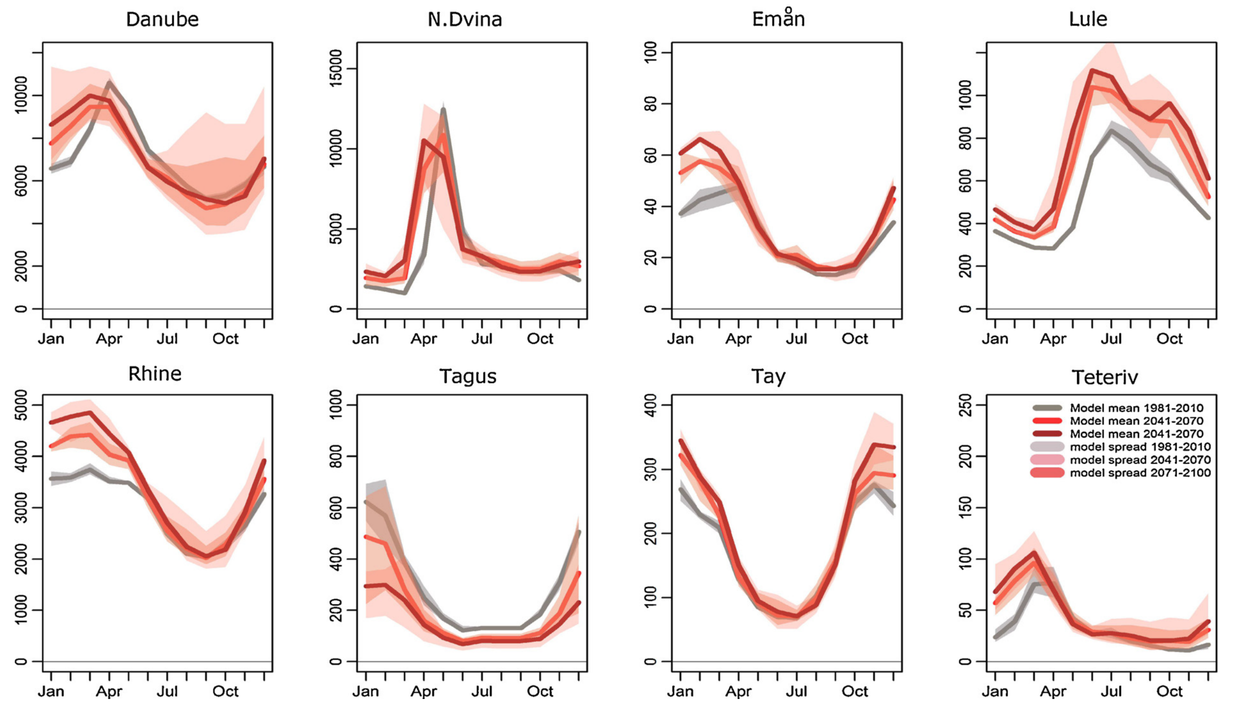

Fig. 5. Comparison of the long-term mean annual dynamics of discharge in the intermediate and far future time slices with that in the reference period (all – simulated with SWIM model, driven by the climate projections under RCP8.5 scenario) for the eight case study basins.

In the southern catchment, the Tagus, an overall decrease in discharge throughout the year was found under both RCP scenarios, based on the multi-model means. The changes are much more pronounced and statistically significant for all months under RCP8.5 in both periods (see Annex 5), resulting in the decrease of discharge by more than 50% throughout the year compared to up to 20% under RCP4.5. The reduction of flows was found to be statistically significant under RCP4.5 only during the low flow period (April–November, except July) for the far future. The model spread was the highest during the high-flow period in January–March for both RCPs. Under RCP4.5 in the winter months some model runs projected an increase, and some decrease, however the multi-model mean still indicates a slight decrease in discharge, and also statistical test showed that this trend is not significant. However, also in the reference period the multi-model spread was much larger during the high-flow period in this basin, as can be seen in Fig. 3.

Figs. 6 and 7 provide an overview of the monthly flow variability over the reference and two future periods depicting the inter-quantile range (from 25th to 75th) of the long-term monthly average flows as box-and-whiskers diagram. It is undoubtedly important to know how the mean of the flow will change, but also it is important (especially for water managers) how the inter-annual flow variability would change in the future, and how far it would deviate from the reference conditions. One can observe that the important changes with respect to the inter-annual flow variability under the moderate scenario RCP4.5 are projected for the Northern Dvina, Tagus and Danube basins. In the Northern Dvina River, the flow variability would increase significantly in the late spring period, when the shift of peak discharge is projected, too. In the Tagus River, the variability of flows will increase significantly during the high flow period in winter, early spring, and slightly during the low flows period. In the Danube River basin, the intra-annual flow variability will increase during the summer and autumn months. When looking at the high-end scenario for the Tagus River basin (Fig. 7), we can see an opposite pattern: the variability of flows significantly decreases in the winter month compared to the reference period. Similar results were found for the late winter and early spring discharges in the Rhine River basin. In the case of the Danube River, the variability remains higher in the late summer and autumn months than in the reference period under RCP 8.5, and in the Emån River, the flow variability slightly increases in the winter months.

5. Discussion

This study aimed to provide an assessment of impacts of the projected climate change on streamflow in the eight representative river basins in Europe. For that we employed the eco-hydrological process-based catchment-scale model SWIM, which was set up, calibrated and validated to the observed data at the outlets of each river basin. The SWIM model included water management infrastructure in two case study basins: Tagus and Lule. The impacts of climate change were explored by applying the bias-corrected GCM-RCM climate datasets, obtained in the framework of the “IMPRESSIONS” project.

The SWIM model was successfully calibrated and validated for all basins, given their climatic, hydrological and physical heterogeneity. However, SWIM has encountered some problems in simulation of the observed discharge in the Lule, Tay, Teteriv and Tagus basins, where anthropogenic influence on discharge was significant. When accounting for water management was introduced

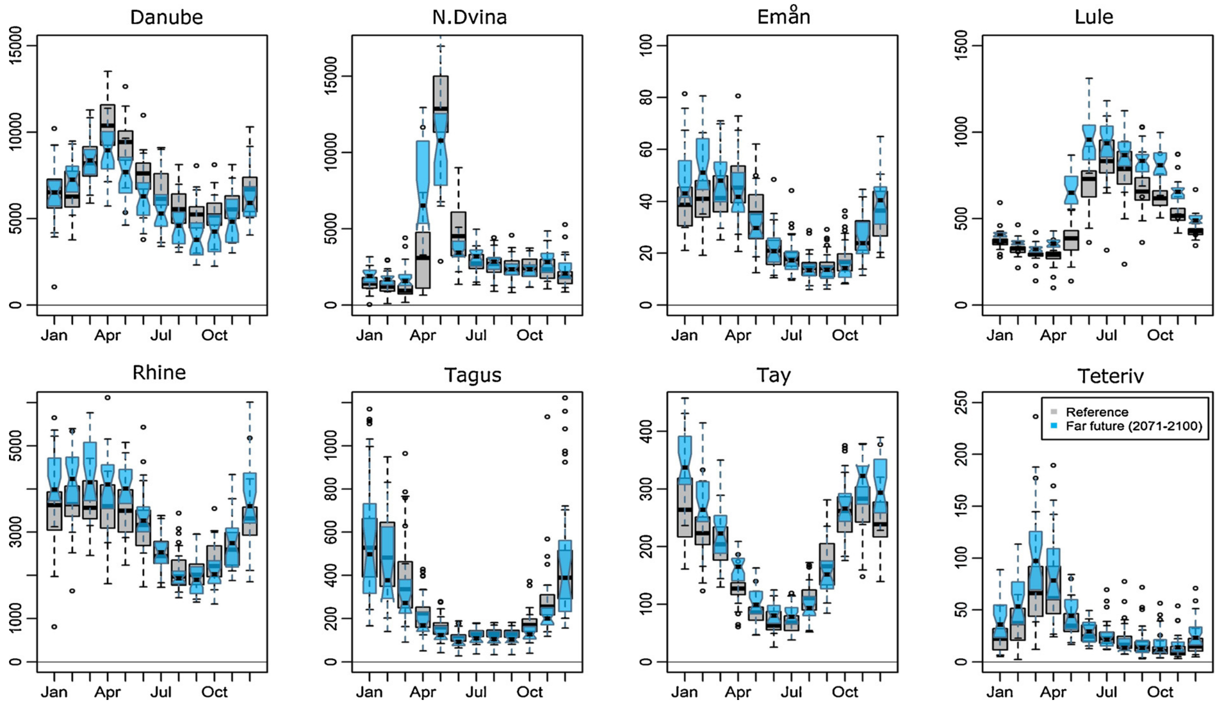

Fig. 6. Long-term monthly variability of river discharge for the reference and far future time slices simulated with SWIM model driven by the climate projections under RCP4.5 scenario for the eight basins under consideration.

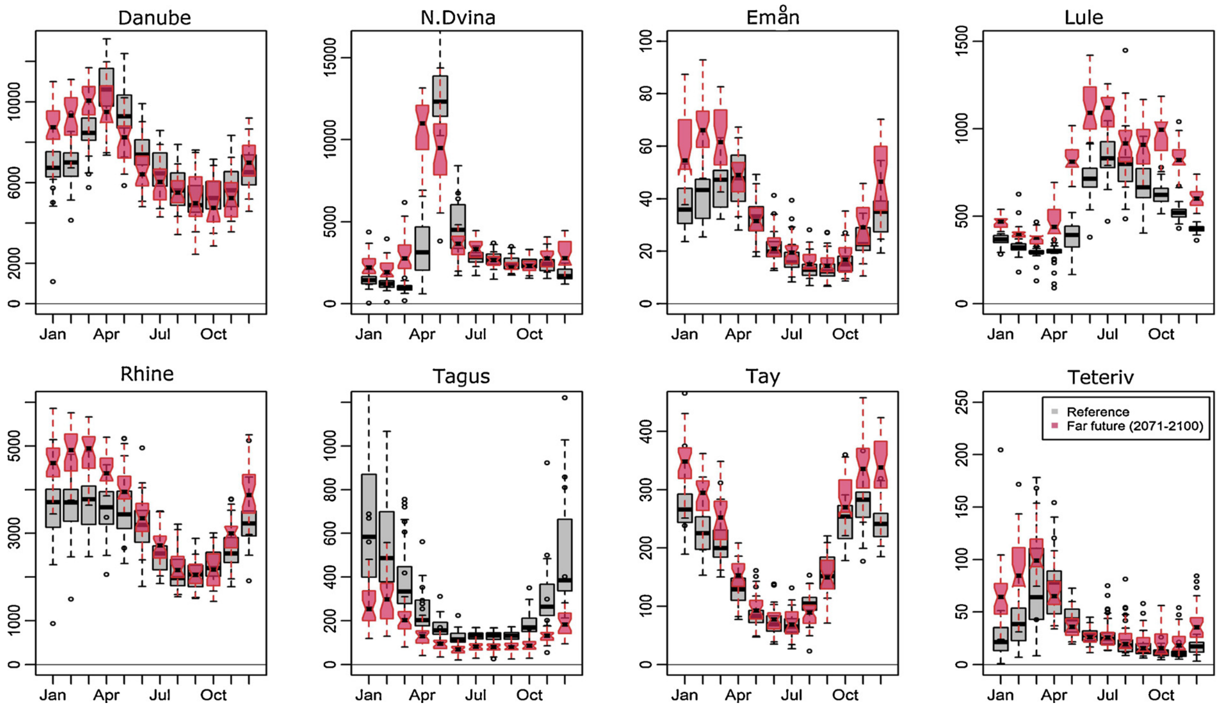

Fig. 7. Long-term monthly variability of river discharge for the reference and far future time slices simulated with SWIM model driven by the climate projections under RCP8.5 scenario for the eight basins under consideration.

by implementing major reservoirs in SWIM in the cases of Lule and Tagus, the model performance in these catchments has improved. Still, the low flow segments in the Tay and Teteriv and in the Tagus during the validation period) were not properly met, as indicated by the log-transformed NSE values (Table 2). In our opinion, when conducting climate change impact assessment, the effects of current water infrastructure operations, if their influence is significant, have to be taken into account.

The bias-corrected climate data were used to drive SWIM in the historical period and were tested for their ability to represent the observed discharge dynamics. The results were satisfactory for all basins, except the Rhine and Danube catchments, where the seasonality was met but the systematic overestimation of flows was found. This is probably associated with the not perfectly performed bias-correction of the GCM—RCM climate data for these regions in the "IMPRESSIONS" Project.

According to our results, the hydrological impacts of climate change will be heterogeneous across the European river basins. One can distinguish the following statistically significant trends based on the projections: a general increase in discharge in the Northern catchments (Lule, Northern Dvina and Tay), and a strong decrease in the Iberian Peninsula (for Tagus, statistically significant under RCP8.5). The largest differences in impacts between the moderate and high-end climate change scenarios were found for the Northern Dvina, Lule and Tagus, characterized by strong inter- and intra-annual variability of flows (see Annex 6). In the Tagus, the deviations in discharge projected under RCP4.5 were practically within the bounds of the historical inter-annual flow variability (as indicated by the Wilcoxon signed rank test) until the year 2070, whereas under RCP8.5 a strong decrease in flows, reaching up to −50%, was found. Therefore, our results show that when accounting for the climate change effects on river discharge in the water management strategies it is important to account for the deviations not only in mean annual flows, but also in the intra-annual variability of flows in the future.

In the Central and Eastern European catchments (Rhine, Danube, Teteriv) as well as in Emån discharge is expected to increase in winter and late autumn. In three northern catchments (N. Dvina, Lule and Emån) and in two Central and Eastern European catchments (Danube and Teteriv) the shifts in seasonality were found at the end of the century under RCP8.5, where the spring peak appears approximately one month earlier.

Our analysis shows that the major drivers behind the projected shifts in seasonality are the projected increases in temperature that will trigger earlier snowmelt, as well as increase in precipitation in the late autumn and winter months. The share of snow to rain in the snowmelt–driven catchments will decrease in spring and autumn (based on the analysis done for the Lule River). In the N. Dvina, Teteriv, Lule and Emån the projected increase in AET will be outweighed by the increase in precipitation (also due to the fact that the increase in AET is projected for summer months and the increase in precipitation would occur in winter and late autumn), leading to increase of discharge in late autumn and winter in these basins. Decrease in precipitation is the main driver behind the overall decrease of discharge in the Tagus River, as well as decrease in discharge of the Danube River in summer and late spring. In those basins, also the AET shows decreasing trends during summer and late spring, due to decreased water availability. On the other hand, an increase in discharge during the January–March period in the Danube is driven by an increase in precipitation.

When looking at the results taking into account location of catchments in the specific climatic zones (Koppen-Geiger classification, Annex 1) one can see similar trends for some of them located in one zone. In particular, an increase in winter discharge under both climate change scenarios was projected for the Rhine, Tay, Emån and Danube river basins, which are situated fully or mostly (large parts of the Emån and Danube) in the temperate oceanic climate zone. For the Lule and Northern Dvina, which belong to the subarctic climate zone, an increase in discharge is projected as well as shifts in seasonality. However, changes in seasonality of discharge for both rivers are slightly different: whereas a general increase in discharge is projected throughout the year for the Lule, discharge is expected to increase in autumn, winter and spring but remain the same in summer in the Northern Dvina.

The impact assessment results of our study go in line in terms of general tendencies in Northern and Southern Europe with the results of studies conducted before (Alfieri et al., 2015; Döll and Schmied, 2012; Papadimitriou et al., 2016; Schneider et al., 2013) using the non-calibrated global-scale models. However, zooming in the global or European maps of previous studies for results related to certain river basins is difficult. One former study (Papadimitriou et al., 2016) presented impacts also for five selected river basins, and they are comparable with our results, except for the Rhine (where no statistically significant trends were found before). In general, our results with the calibrated and validated regional-scale model are probably more credible for all selected eight basins, compared to the outputs of non-calibrated global-scale models often showing poor performance in the historical period (Hattermann et al., 2017; Krysanova et al., 2018). Still, the similarity of impacts is important, as the previous studies involved different types of models and climate change projections. Therefore, the trends found in our study can be considered as robust.

Such modelling chains as applied in this paper are associated with different sources of uncertainty, starting from the uncertainty coming with radiative forcing scenarios (RCPs), following with uncertainty related to climate models and downscaling methods, and finishing with the uncertainty associated with hydrological modelling, arising from model structure, parametrization and calibration. Also, the phenomenon of equifinality is especially important for such large basins as the Danube or Rhine, when the good performance of a hydrological model during the calibration can be reached with different and sometimes physically inadequate sets of parameters values. Though no detailed analysis with quantification of uncertainty sources was conducted in this study, it is doubtless that the results obtained and described in this paper are subject to biases, coming from different sources, as shortly listed above. As was described above, the results for the Rhine and the Danube Rivers are possibly subject to larger biases, as the bias-corrected climate models failed to represent the water volumes of both rivers, and results of this study in absolute units should be referred to with a caution. On the other hand, the small model spreads, obtained for the past dynamics simulated by the SWIM model driven by the GCM – RCM outputs, indicate general agreement between the simulated and observed seasonal dynamics of discharge, and also for the Danube and Rhine the patterns are similar.

Additionally, the uncertainty can potentially be higher for the high and low flow conditions in some of our river basins, e.g. where the SWIM model failed to represent successfully the low flows: in the Tay, Teteriv and Tagus, where streamflow regulation effects on river flow were significant. Potentially, also the selection of the RCP scenarios can be a significant source of uncertainty, as in the case of the Tagus River basin, where the projected changes in discharge remained in the range of the observed intra-annual flow variability under RCP4.5, but were beyond the reference conditions already by the mid-century under RCP8.5. This applies also to the Danube River basin, where the decrease in summer flow was larger under the RCP4.5 scenario than under RCP8.5. However, in the case of the Danube River, the spread due to climate models was large in the summer months under RCP8.5, indicating on larger uncertainty of the results. A large multi-model spread was also found in the high-flow period for the Tagus and Lule River basins under both RCP scenarios, referring to large uncertainty of the results.

6. Conclusions

Climate change will alter the hydrological regimes of rivers in Europe. This will create additional challenges for water resources and aquatic ecosystems which are already stressed due to extensive anthropogenic activities. Therefore, the impacts of the projected climate change have to be understood and incorporated into the regional water management strategies to ensure sustainable approach in governing the water systems.

When looking at the impacts, the South-North gradient can be clearly detected: the results of this study indicate an increase in discharge in the considered Scandinavian and Northern European basins, as well as a strong decrease in the Tagus River basin located in the Iberian Peninsula. In general, apart from the Tagus and Danube, there seems to be no significant changes in the low flow period in other catchments, whereas the flows in the high flow periods in winter and early spring are going to increase across Central, Northern and Eastern Europe. The major driver behind these changes, as our results show, is the increase in precipitation in autumn and winter months (in some cases − also in spring) projected for these rivers. The shifts in seasonality, in particular shifts of the spring peak discharge to earlier time, were found in the snowmelt-driven catchments, like Northern Dvina, Lule, Emån, Danube and Teteriv under RCP8.5, which are associated with the earlier snowmelt due to rising temperatures that will become positive earlier (most pronounced in the Northern Dvina River). The AET is also expected to increase in the summer months in Northern catchments and in the Teteriv River basin; however these changes would be overcompensated by the increases in precipitation.

The differences in deviations between the high-end and moderate climate warming scenarios become evident after the mid-century, where the changes triggered under RCP4.5 level off, but continue to develop further under RCP8.5. The biggest differences between the RCP4.5 and RCP8.5 scenarios were found for the Northern Dvina, Lule and Tagus, where changes under RCP4.5 until the year 2070 were within the bounds of the natural variability of flows in the reference period, and they become more evident only by the end of the century, and under RCP8.5 in both periods.

The global models are useful tools to be applied when general impacts picture is needed at the global and continental scales, and the regional-scale models are absolutely necessary in cases when regional impacts are of interest for certain specific river basins, and also climate adaptation and water management strategies are of interest for them (Hattermann et al., 2017). The local developments in each particular catchment are of a great importance, while considering different scenarios of global warming. Even if the dangerous global warming can be avoided, e.g. by switching to the green sources of energy, the freshwater resources can still be adversely affected by e.g. extension of the hydropower installation (Hermoso, 2017).

The results of this study go in line in terms of general tendencies with the results of the previous studies, conducted mostly with the global or pan-European scale models, and therefore these trends can be considered robust.

Conflicts of interest

None.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ejrh.2018.05.003.

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