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Article

Discharge Alterations of the Mures River, Romania under Ensembles of Future Climate Projections and Sequential Threats to Aquatic Ecosystem by the End of the Century

Anastasia Lobanova *, Judith Stagl, Tobias Vetter and Fred Hattermann

Potsdam Institute for Climate Impact Research (PIK), Telegraphenberg A 31, Potsdam 14473, Germany; E-Mails: stagl@pik-potsdam.de (J.S.); vetter@pik-potsdam.de (T.V.); hattermann@pik-potsdam.de (F.H.)

* Author to whom correspondence should be addressed; E-Mail: lobanova@pik-potsdam.de; Tel.: +49-331-288-207-53.

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Abstract: This study aims to assess the potential alterations in the hydrological regime attributed to projected climate change in one of the largest rivers in the Carpathian Area, the Mures River, and to estimate associated threats to riverine ecosystem. The eco-hydrological model, Soil and Water Integrated Model (SWIM), was applied on the Mures River basin, calibrated and validated against records at a gauging station in Alba-Julia town. A set of nine future projections for climatic parameters under one emissions scenario A1B over the period 1971–2100 were fed into the SWIM model. To provide functional link between hydrological regimes and riverine ecosystems, each of the nine simulated discharge time series were introduced into the IHA (Indicators of Hydrological Alterations) tool. Triggered changes in hydrological patterns of the Mures River were assessed at the basin and sub-basin scales. The obtained results present a strong agreement through all nine climate projections; suggesting an increase in the discharge of Mures River for the winter season; a decrease in summer and prolongation of the low flow periods by the end of the century. Anticipated changes would pose threats to aquatic ecosystems; altering normal life-cycles; and depleting natural habitats of species.

Keywords: SWIM; hydrological modeling; ensembles of climate projections; Mures River; climate change; indicators of hydrological alteration

1. Introduction

The state, functionality and health of the aquatic ecosystems are heavily dependent on the hydrological regimes in a river basin, and their seasonal variability is of great importance for the normal life-cycle of the local species [1]. As Poff and Ward [1] suggest, the modifications and shifts in hydrological regimes alone, apart from other relevant biological factors, like water temperature, oxygen levels or reach morphology, can have destructive impacts on the health of the aquatic ecosystems. Future changes in climate are expected to have significant influence on the hydrological cycle through the alteration of the precipitation patterns, melting of the glaciers, temperature rise and other factors [2,3]. All regions of Europe are expected to experience mainly negative impacts of climate change, however, their vulnerability as well as their adaptation capacity to such impacts strongly depend on their economical state [4]. The Danube River Region is one of the largest river basins in Europe. The enhancement of the basin related scientific research and development was proposed by the European Commission Report [5], following various EU (European Union) directives involving the water resources management and global change, e.g., the EU Water Framework Directive and the White Paper—Towards Adaptation to Climate Change [6,7]. The necessity to assess the impacts of climate change and anthropogenic pressures to preserve and restore good environmental conditions of the region was clearly emphasized in the directives, calling for identification of adaptation measures.

The Carpathian region is one of the most important areas with unaltered natural conditions within Danube catchment. The region is rich in biodiversity, providing habitat for many endangered species [8,9].

The collapse of the industrial activities after the breakdown of the Soviet Union had a positive influence on the preservation of good environmental conditions in Tisza River and Mures River tributaries, yet the Carpathian area is now considered one of the most exposed to future climate impacts due to its poor economic state [9,10]. Increasing temperatures and the degradation of water resources will set additional stresses to the region, possibly resulting in conflicts for water resources between users (including ecology) and neighboring countries [11].

The Carpathian region has recently drawn broad scientific interest, resulting in several studies aiming to assess the impacts of climate change on the precipitation patterns, temperature, hydrological cycle and runoff conditions of the region [6,7,12–15]. However, these studies focused on the estimations of the changes in hydrological cycle components in the whole Carpathian region [7,12], or made use of only one or two coupled GCM-RCM (General Circulation Model-Regional Climate Model) climate simulations when focusing on a specific river (e.g., [15]).

The purpose of this study is to assess the alterations of hydrological patterns in the upper part of the Mures River Basin, triggered by projected climate changes by employing an eco-hydrological basin-scale model driven by ensemble of nine different future climate projections obtained from different coupled GCM-RCM simulations. The "ensembles" approach was proposed by Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report [2] as a method to reveal and decrease uncertainties associated with climate change modeling. To evaluate the rate of change in the hydrological patterns the IHA (Indicators of Hydrological Alterations) method was used. This method provides insights into potential threads to aquatic ecosystem, by establishing the functional link between the habitat area and the alteration of the flow regimes. This investigation is the first to apply the IHA method at the sub-basin level in the context of assessment of hydrological impacts of climate change, to investigate the spatial patterns of projected changes. Such mapping of hydrological impacts might be used to focus on climate impacts in the areas of specific interest within the catchment areas, e.g. national parks, protected areas *etc*.

2. Study Area

The Mures River has a total length of 789 km, of which 762 km lies in the territory of Romania and is one of the most important rivers in the Carpathian region. It has a total drainage area of 28,310 km^2, of which 93.5% lies in Romania with the rest in Hungary. The basin topography is mostly formed by mountains (25%) and hills (55%); only 15% lies in valley and 5% in lowland areas [8,16]. Basin topography is presented in Figure 1. The mean discharge at the joint to Tisza is 155 m^3/s [16] and there are four important tributaries of the Mures River: the Tarnava Mica (115 km), Tarnava Mare (43 km), Niraj (78 km), and Gurghiu (55 km) [17].

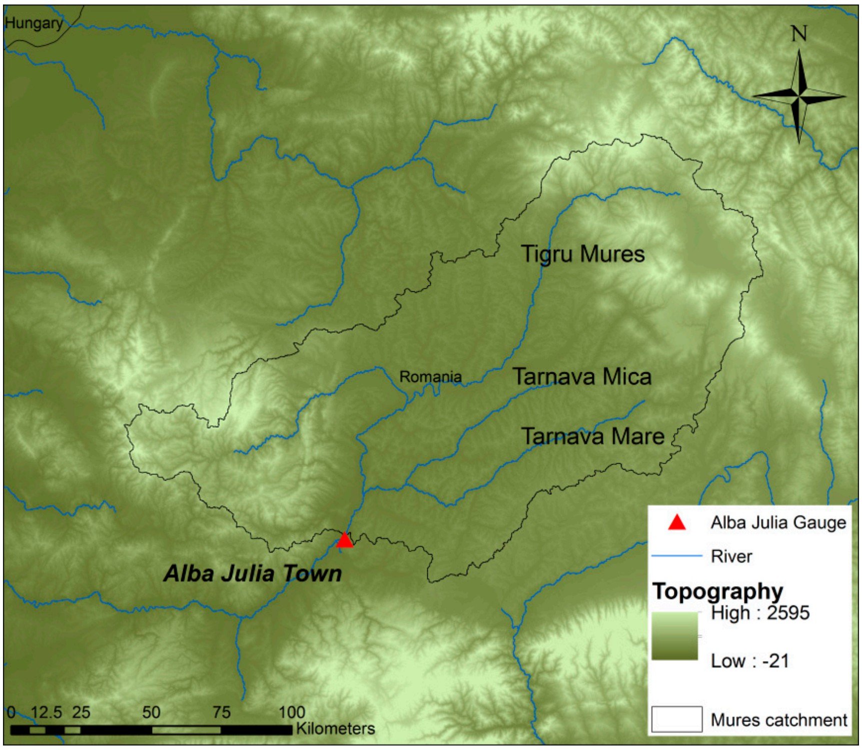

Figure 1. Mures River basin.

Hamar and Sarkany-Kiss [8] and United Nations Economic Commission for Europe (UNECE) [16] state that climatic variables of the basin temperature and precipitation bear mainly upon air masses from Atlantics, Mediterranean and Eastern Europe. The annual mean precipitation in the mountains reaches 1200 mm/year, whereas in the Hungarian plane this value drops to 500–600 mm/year, due to the impact of the Carpathian mountain chain. The topography of the area also influences the temperature conditions in the catchment. The annual mean temperature for the lowlands is around 11 °C, whereas for mountainous areas it decreases to 3–4 °C [8,16]. In general, there are two distinguishable climatic periods: the wetter period from April to August and a long, drier period from

September to March. The spring floods are mostly caused by snowmelt in mountainous areas around mid-February, rather than high precipitation patterns [8]. There are number of reservoirs in the Mures catchment, serving for flood protection and hydropower production.

In total, the Mures River is home to 52 species of fishes, which densely populate all of its tributaries. In recent years, some fish species have been in danger, mainly as a consequence of deteriorated water quality conditions [8]. The Mures Region, due to its mineralized waters, rich biodiversity and mountainous landscapes, has become a significant tourist attraction in the past few years, both nationally and internationally [17], improving the economical state of the region.

3. Methods

To fulfill the assessment of future climate change impacts on the hydrology of the Mures River basin the eco-hydrological, process-based, semi-distributed catchment scale SWIM model [18] was set-up, calibrated and validated against observed discharge data at Alba Julia gauging station on a daily time step. The climate projections were obtained from nine different coupled GCM-RCM runs and used as input data in the SWIM model. The coupled GCM-RCM simulations were carried out within the ENSEMBLES: Climate change and its impacts Project and included simulation results of six different Regional Climate Models (RCMs) using boundaries of three different General Circulation Models (GCMs) under one IPCC Scenario of socio-economic development A1B [19].

The simulation of Mures catchment was performed for the period between 1971 and 2100. The resulting discharge series were separated into three different time periods as: (i) a reference period between 1971 and 2000; and (ii) two future periods between 2021–2050 and 2071–2100, respectively. The projected hydrological variability was assessed by the IHA approach after Richer *et al*. [20], which performs statistical comparison of two time periods based on 32 flow characteristics, so-called indicators, which have functional link to the aquatic ecosystem and habitat area. The analysis for the whole basin was carried out as a comparison of discharges over two periods, producing a relative signal of change between the reference period and each of the two future periods for all nine future climatic projections. A set of sixteen indicators were selected: percentage deviation in median monthly flows (twelve indicators), low pulse duration, high pulse duration, low pulse count, and high pulse count (four indicators). The spatially distributed assessment of hydrological alterations was performed with the IHA tool. The analysis was conducted for fourteen indicators: mean monthly percentage deviation, which later were grouped and averaged by season (autumn, winter, spring, summer) and low/high pulse duration, since in this study those indicators showed higher sensitivity to future changes. The output for each of the selected indicators and for each nine projections was calculated on the sub-basin level, averaged among the nine projections and plotted as sub-basin maps, indicating the relative percentage of change between the corresponding reference period and each of the two future periods in each sub-basin. To address the inter-model uncertainty, the standard deviation of nine future projections for each season and high and low flow pulse duration was calculated and mapped in the same manner as the results for the indicators. A diagram, presenting a workflow process of the study described in this paper is presented in Figure 2.

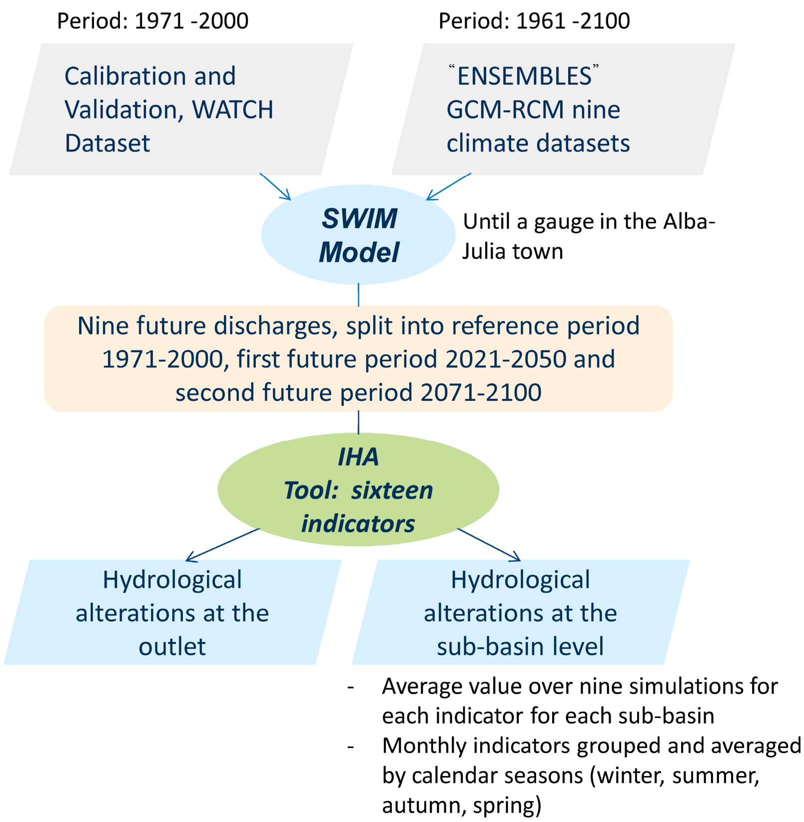

Figure 2. Diagram of the workflow process.

3.1. SWIM Model Description

The SWIM model is a process-based, semi-distributed, eco-hydrological basin-scale model [18], and it is based on two previously developed models: SWAT [21] and MATSALU [22]. SWIM integrates hydrology, erosion, vegetation and nutrients dynamics at the river-basin scale using topographical, agricultural and climate data as forcing datasets.

The detailed description of the SWIM model can be found in, e.g., Krysanova *et al*. [18] or Krysanova *et al*. [23]. The SWIM model is a complex system incorporating several sub-modules, including hydrological modules for soil profile, groundwater and river routing, a vegetation model and biogeochemical sub-models for nitrogen, phosphorous and carbon with different levels of complexity. The SWIM model incorporates the disaggregation scheme from MATSALU model [22]: basin to sub-basin, and sub-basin to so-called Hydrological Response Unit (HRU) or hydrotopes. To obtain hydrotopes the soil, sub-basins and land use maps are overlaid and then disaggregated into elements within which the soil type and land use are of one type; HRUs with the same "soil type–land use type" structures are assumed to have similar hydrological behavior. The HRUs are later combined into the hydrotopes classes within each sub-basin. During the simulation the water flow, nutrient flow and crop growth are calculated for each hydrotope. The lateral flows of water, sediments and nutrients are later summarized for each sub-basin and routed based on the Muskingum Method, considering the transmission losses [23,24].

3.2. IHA Method

The intra-annual variability of flows is essential for the life-cycle of many wetland and riparian species, which are used to certain patterns of hydrological regimes in terms of seasonality, duration of high and low flow events, relation between amount of water and habitat area, and they are highly sensitive to shifts in these patterns [1]. The understanding of potential links between the degree of alteration of the hydrological regimes and functionality of aquatic ecosystem is essential to sustain and improve environmental conditions in river basins [20]. There is a number of different methods used for the assessment of such links, as reviewed by Acreman and Dunbar [25]. They state that there is no common rule to identify which method is generally better or might be more appropriate for any specific basin. It is clarified that the main driver for choosing the assessment method should be based on individual issues present in the basin, e.g., river restoration, basin planning in terms of resources allocations.

The IHA Method [26] employed in this study is classified by Acreman and Dunbar [25] as a desktop method. It was designed to evaluate the rate of change in flow regimes due to a dam's introduction in the river basins and consequential impact of such changes on the river ecosystem. To assess changes in the flows regimes, the IHA method provides a set of 32 indicators, which characterize the hydrological regimes of a river in terms of magnitude, duration, frequency, timing and rate of change of a hydrologic event [20]. The ability to compare time-periods makes the IHA method suitable for evaluation of the hydrological alterations resulting from climate change in terms of impacts on aquatic ecosystem [27].

Nevertheless, this method also has significant limitations as it considers only hydrological conditions of the river, whereas other factors such as water temperature, river morphology, water quality, turbidity, *etc*., which may have a strong influence on the aquatic ecosystem, are not accounted for. In this study, sixteen indicators, summarized in Table 1, are considered. The functional link between flow characteristics and functionality of aquatic ecosystem is also provided in Table 1, based on the work of Richter and Thomas [28].

Table 1. List of selected IHA indicators and their functional link to aquatic ecosystem (Richter and Thomas [28]).

IHA Group	Hydrological Parameters	Functional Link to the Aquatic Ecosystem
Magnitude of monthly water conditions	Median monthly discharge (twelve indicators)	Provide adequate habitat area; Maintain water temperature, dissolved oxygen; Drinking water for terrestrial animals; Groundwater tables, soil moisture
Timing of annual extremes	Average duration of low pulse event (below 25 percentile) Average duration of high pulse event (exceeding 75 percentile) No. of high pulses each year No. of low pulses each year	Induced velocities, sediment transport and erosion; Water temperature; Connection to flood plains Water availability for habitat area; Ensure migration and spawning paths for fishes Trigger new life-cycles; Provide floodplains with nutrients, ensure connection of floodplain with main channel
Total	16 Indicators	-

3.3. Data

The Digital Elevation Model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM) of Consultative Group for International Agricultural Research (CGIAR) Database. This dataset has been made available to the public on the CGIAR website [29]. The data has a resolution of 90 m × 90 m at the equator and is provided as 0.5° × 0.5° mosaic sets.

Land Use dataset was acquired from the Coordination of information on the environment CORINE Database [30] of Land Use Data Centre of European Environment Agency, and has a resolution of 100 m × 100 m for the year 2000. The main source for mapping the land use types are ortho-corrected images made by the Earth observation satellite Landsat 7.

Soil information data has a resolution of 1000 m × 1000 m and was obtained from the Harmonized World Soil Database FAO70 created by the Food and Agriculture Organization of the United Nations.

SWIM uses daily precipitation; average, minimum and maximum temperature; solar radiation; and relative humidity as meteorological input data. Often, the density of climatic stations appears to be unsatisfactory for hydrological modeling, or the data series have serious gaps in records, or some parameters do not exist at all, which was also the case for the Mures basin. The only available data on Mures basin was from several climatic stations located close but still out of the basin area. Therefore, the Global Meteorological Water and Global Change WATCH Dataset was used in this study. The WATCH Meteorological Data set was created as a driving force for hydraulic/hydrological and land models, used to assess the hydrological cycle under the scope of WATCH Project [31,32]. This dataset, with regular spatial resolution (0.5° longitude/latitude), encompasses the whole 20th century, from 1901 to 2001, on a daily time step and contains synthetically generated meteorological data. These meteorological data were obtained from the European Centre for Medium Range Weather Forecasting (ECMWF) Re-Analysis ERA-40 reanalysis dataset and include all the meteorological variables needed for modeling input. The ERA-40 dataset was derived from a GCM simulation and incorporates satellite data, atmospheric surroundings, and is corrected to land- and sea-surface observations.

3.4. Model Calibration and Validation

The calibration of the SWIM model was performed with use of the measured discharge data at the outlet of the basin at Alba Iulia Town gauging station. Data at this station were recorded on a daily time step and embrace the period from 1960 till the end of 2008. The period between 1985 and 1994 was chosen for the calibration, whereas the validation was conducted over the period between 1996 and 2001.

The evaluation of the SWIM model performance was performed with the use of the Nash-Sutcliffe Efficiency (NSE) [33] and Relative Volume Difference (RVD) methods. The NSE represents the relation of the difference between the observed and simulated discharge to the variance of the observed discharge values. It varies between 1.0 and $-\infty$, where 1.0 indicates a perfect fit [34]. The RVD represents the global variation between simulated and observed discharge in percentage [35].

3.5. Climate Scenarios

Future climate projections are normally derived from numerical simulations [2]. As Tebaldi and Knutti [36] stated, internal climate variability and the high complexity of the natural climate system complicates the modeling work. The authors also argue that, at the moment, it is impossible to include all the processes involved in the climate formation within a model, due to either lack of knowledge on the physics behind those, or associated extensive computations. Therefore, the decisions on the inclusion or exclusion of the physical processes and the extent/complexity of their parameterization within the climate models are made based on the expert knowledge and special needs addressed to model outputs. Such assumptions introduce uncertainties into the modeling process, leading to possibly erroneous outputs [36]. The ensembles modeling approach generally considered as correct and promoted by the IPCC Third Assessment Report [2] which advocates the idea that using different sets of independently developed models will help to cancel out some of the errors, decreasing uncertainty [36,37]. Following this assumption, the ENSEMBLES Project was enhanced to provide a set of climate forecasts, obtained from different GCM-RCM coupled simulations [17,38].

The present study employs the future daily climate datasets obtained from ENSEMBLES Project. Only 9 out of 25 existing coupled GCM-RCM runs were chosen, which covered the whole 21st century (Table 2). Horizontal resolution of the RCMs employed is 25 km and further downscaling was performed into each sub-basin, in the same manner as the WATCH dataset.

Table 2. Coupled GCM-RCM simulations from ENSEMBLES Project used in this study.

RCM	GCM			Name Used in This Study
	MPIMET	NERSC	CNRM	
DMI	x			DMI
DMI		x		DMI-NERSC
DMI			x	DMI-CNRM
HadRM	x			HadRM
ICTP	x			ICTP
KMNI	x			KMNI
MPI	x			MPI
SMHI	x			SMHI
SMHI		x		SMHI-NERSC

It should be noted that no bias-correction with respect to observed climatic, or in this case to the WATCH dataset, was performed in this study.

4. Results and Discussion

4.1. Model Performance

The initial visual examination of the simulated discharge showed some significant time lags in the spring and late winter for the peak flows, occurring earlier than the observed ones. It can be proposed that in the higher mountainous areas, the snowmelt process is hindered and starts at higher temperatures due to high altitudes, resulting in delayed high-flow events during spring. On the other hand, the WATCH dataset does not include orographic corrections on the two-meter-temperatures, which can also have influence on the climatic trends represented in the area [31]. After the correction of the snow-related parameters in the SWIM model, in particular increasing the temperature threshold at which the snowmelt starts and decreasing the rate of snow melt per degree-day, simulated spring peaks fit the observed ones and the model performance improved, resulting in the NSE of 0.64 and the RVD of –6.3% for the calibration period and NSE of 0.61 and the RVD of 1.7% for validation period ("good", according to classification given in Moriasi and Arnold [39]), as presented in Figures 3 and 4.

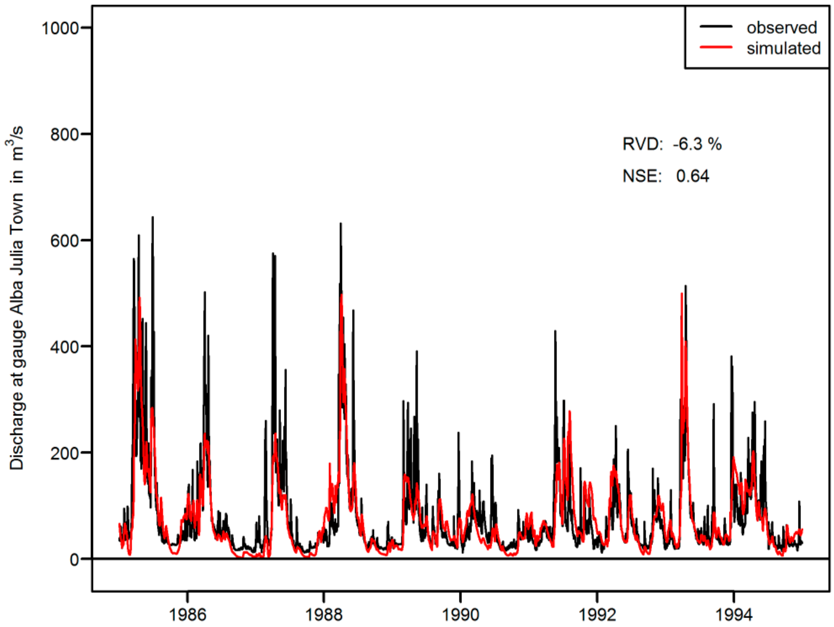

Figure 3. Calibration of Mures River model until Alba Julia gauge, over period from 1986 to 1994.

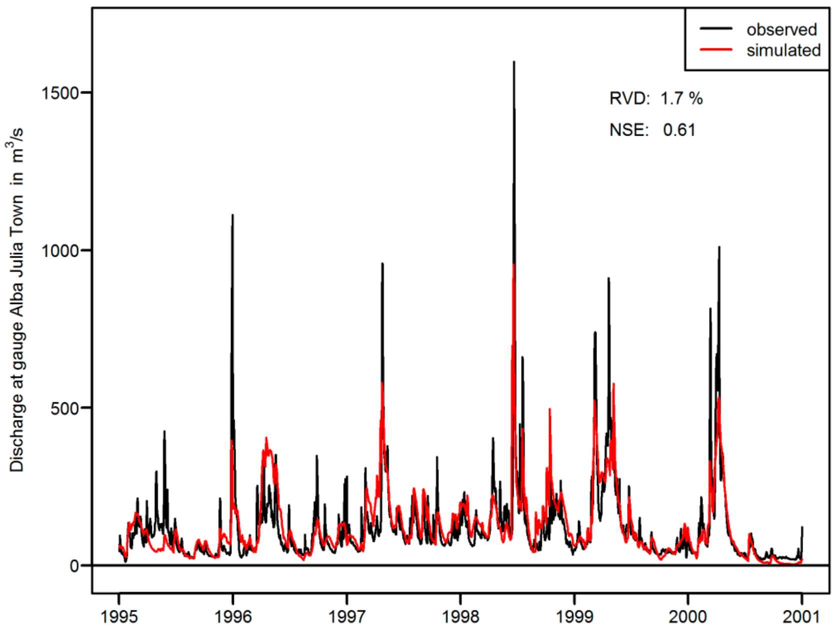

Figure 4. Validation of Mures River model until Alba Julia gauge, over period from 1996 to 2001.

4.2. Future Climate Projections in the Context of Hydrological Modeling

As, by the end of the century, the climate signal becomes more and more uncertain, there is a higher need for the inclusion of more GCM simulations, rather than different RCMs [17]. In this study, only three different GCMs were employed, and, under those, the Max-Planck-Institute for Meteorology (MPIMET) model was overrepresented, providing boundary conditions for six RCMs. This can be seen as a limitation of this study, but the deviations in discharges, as presented in Figure 4, show that the future climate projections obtained from different RCM driven by one GCM-MPIMET trigger different deviations in hydrological patterns of Mures River, which suggests that the usage of different RCMs is as important as the usage of different GCMs.

On the other hand, the ENSEMBLES GCM-RCM simulations matrix is still relatively sparse [17,40], with some coupled model runs covering the period until 2050 only.

The seasonal dynamics of river runoff modeled by the SWIM model driven with climate scenario input agreed for the reference period (1971–2000) with the one observed in the Mures River basin, although the mode tends to overestimate the absolute values. In order to make the comparison as consistent and transparent as possible, only relative changes in hydrology are considered in this study and no bias correction was carried out on the future climate data [41].

4.3. IHA Analysis for Monthly Median Discharge, High and Low Flow Events Alterations

Initially, the IHA assessment was fulfilled for a set of sixteen indicators. However, the count of low and high flow events per year, as well as the rise and fall rates of a high flow event, did not show any variability in the future. Therefore, the results for these indicators are not presented in this paper.

In Figures 5 and 6, the deviations in median monthly discharge for two future periods, 2021–2050 [42] and 2071–2100, are shown, expressed in percentage of change. The deviations in monthly median discharge were calculated as relative change between the reference and the projected values of discharge, as presented in Equation (1), where, DEV refers to Deviation, Q_{ref} and Q_{proj} indicate median monthly discharge during the reference and future periods, respectively.

$$\text{DEV} = \frac{(Q_{proj} - Q_{ref})}{Q_{ref}} \times 100, \quad (\%) \tag{1}$$

There was a strong agreement among all nine future climate projections for the relative monthly median discharge alterations of the Mures River basin, suggesting an increase in winter discharge for both future periods and a decrease of summer discharge for the second future period. The fact that all RCMs and GCMs were assumed to be developed independently from each other suggests that this trend can be seen as robust. However, until the mid of the century, little agreement among the projections on trends in discharge alterations in summer and autumn was found.

Approaching the year 2100, the results (Figure 6) become more pronounced, such that all models show an increase in the flow rate for winter and decrease for the late spring (May) and summer. On the other hand, the results for the autumn are not as certain as for winter and summer, such that for November a decrease in the discharge was projected for the first future period, and an increase for second future period.

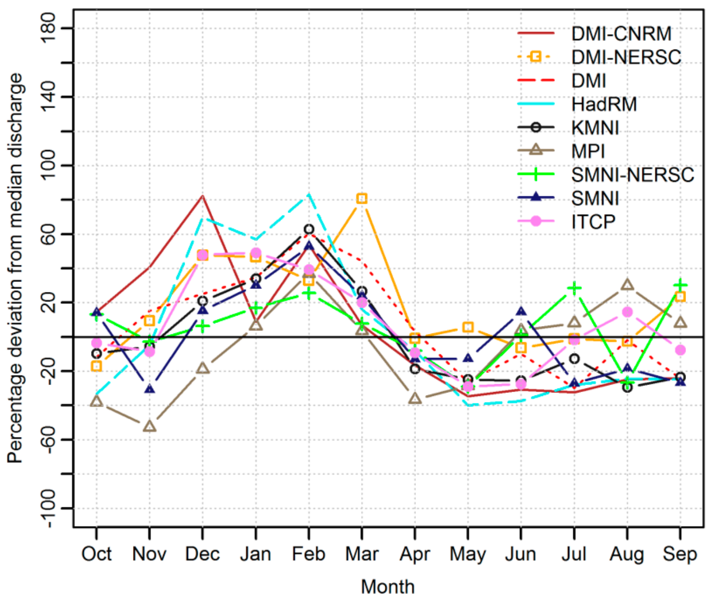

Figure 5. Deviation in monthly median discharge of Mures River for 2021–2050 [42].

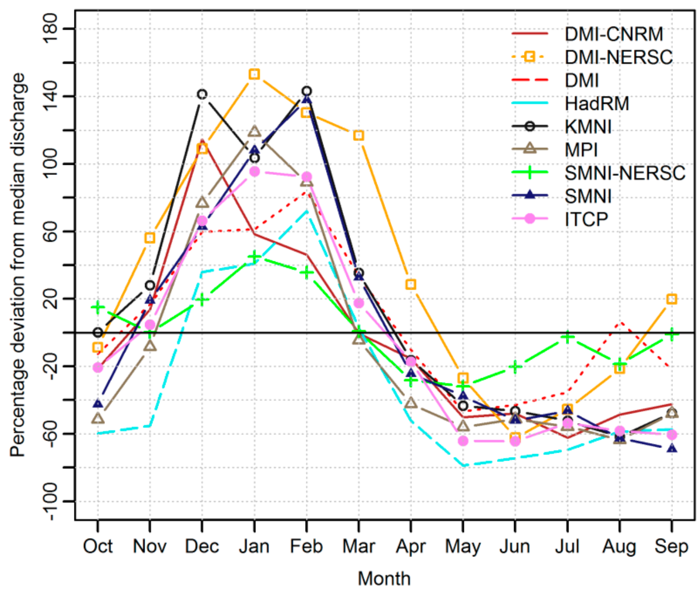

Figure 6. Deviation in monthly median discharge of Mures River for 2071–2100.

Within approximately half of the simulations (five out of nine) for the duration of the high flow event, a slight increase in median and maximum values for the number of days for the first future period was observed, as presented in Figure 7, suggesting that it is about as likely as not that flood events will become longer by 2050. For the second future period, results follow the same trend: six out of nine models show an increase in median number of days. The same behavior was found for the duration of low flow events, shown in Figure 8: for the first future period, five model runs showed an increase in the median and in the maximum number of days. Only for the second future period, seven models out of nine supported the trend, indicating that it is likely that drought events will become prolonged by the year 2100.

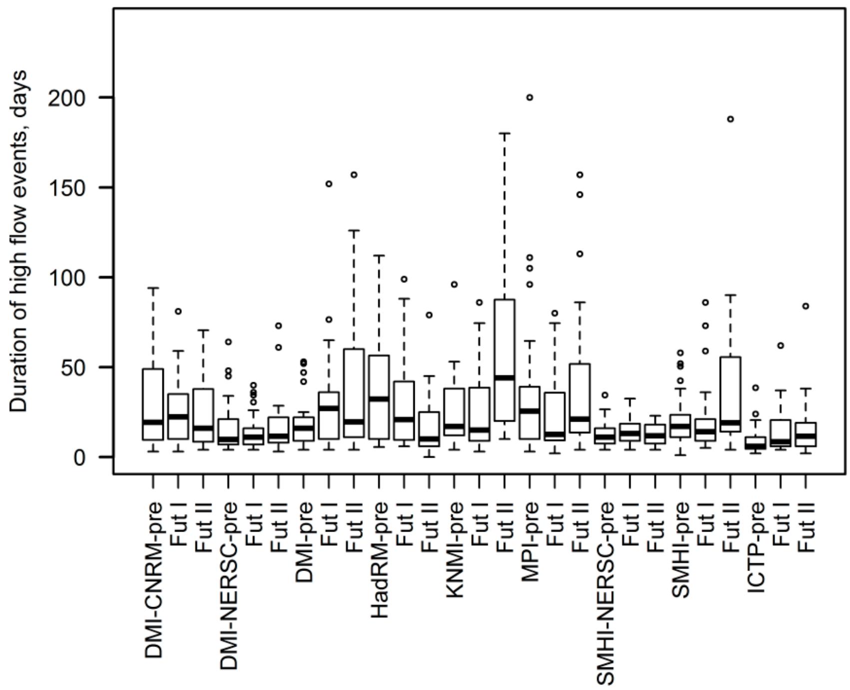

Figure 7. Duration of high flow event in days for reference and two future periods for all nine future projections, respectively.

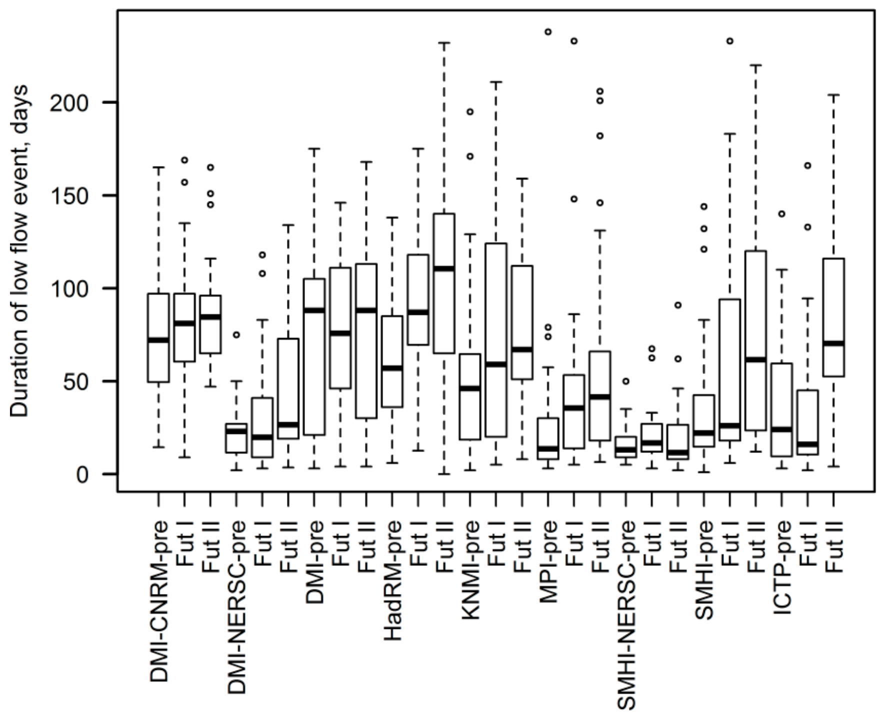

Figure 8. Duration of low flow event in days for reference and two future periods for all nine future projections, respectively.

Projections for the number of the low and high flow events per year did not show any significant change, such that for both first and second future periods there was no substantial change in median values for those indicators.

4.4. Spatial Assessment of Expected Changes

The maps presented in Figure 9 show the deviations of the selected indicators: the percentage deviation (twelve indicators) in median monthly discharge and in the low pulse duration. The percentage deviations in median monthly discharge were firstly grouped and averaged by seasonality (autumn, winter, spring and summer) and then over all nine model runs for each of 186 sub-basins of the Mures River model. A similar procedure was applied to low pulse duration. The results for each sub-basin were obtained as average of nine model runs. The associated values of standard deviation are mapped in the same manner, as a measure of "agreement" between the projections.

A significant agreement over the whole basin area was found for the increase in flow rate in winter and for decrease in summer. The associated low standard deviation values indicate a high certainty.

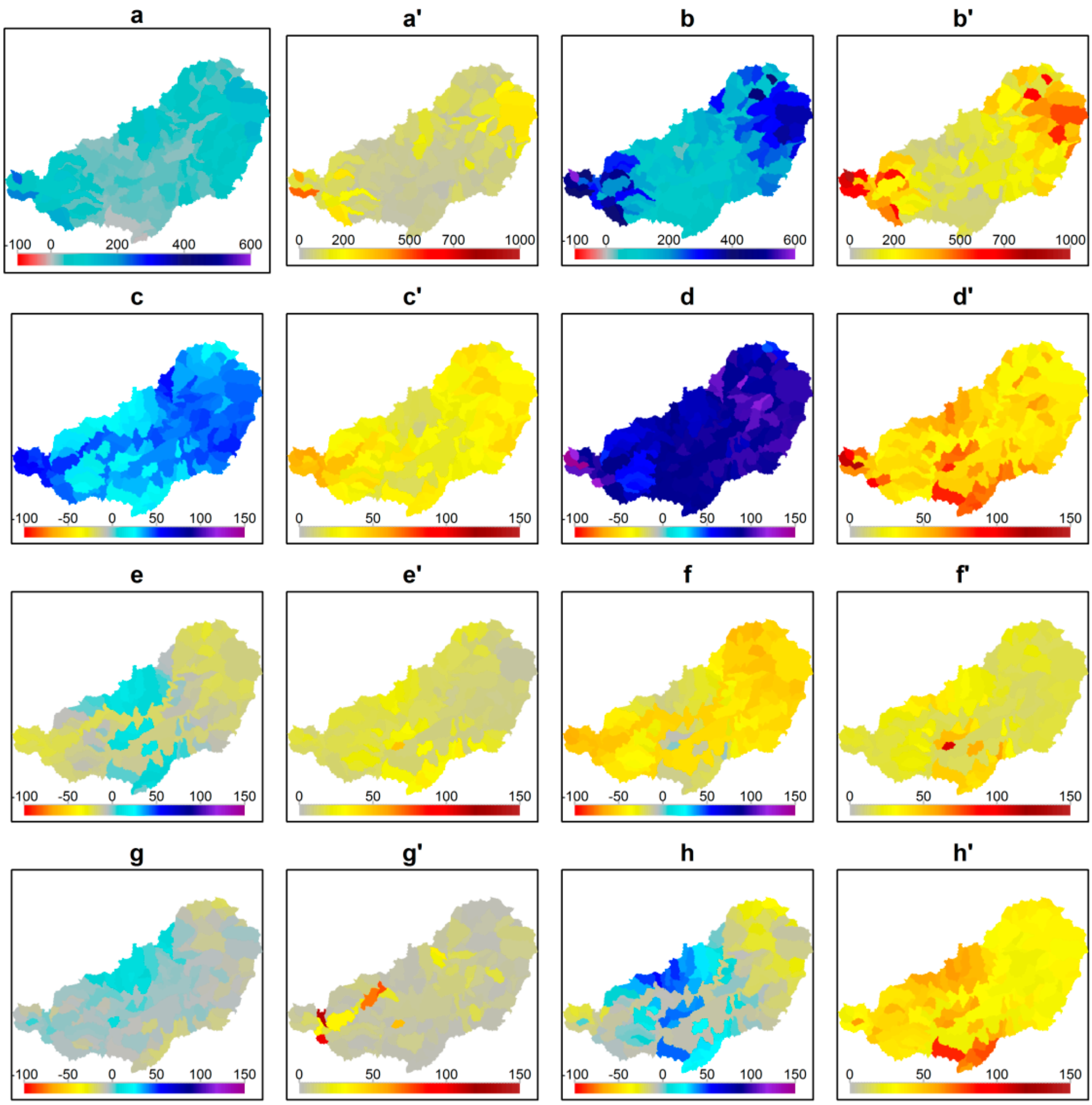

Figure 9. *Cont.*

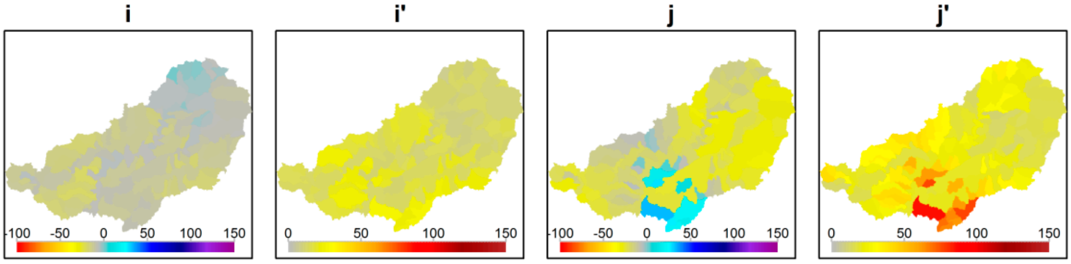

Figure 9. Mapping of percentage deviations in number of selected indicators on the sub-basin level: (**a**, **a'**), Percentage deviation in the duration low flow event for the first future period with respect to reference period and associated standard deviation for nine model runs; (**b**, **b'**) Percentage deviation in the duration low flow event for the second future period with respect to reference period and associated standard deviation for nine model runs; (**c**, **c'**) Percentage deviation in the monthly discharged during calendar winter; (**d**, **d'**) Percentage deviation in the monthly discharge during calendar winter months for the second future period with respect to reference period and associated standard deviation for nine model runs d' months for the first future period with respect to reference period and associated standard deviation for nine model runs; (**e**, **e'**) Percentage deviation in the monthly discharge during calendar summer months for the first future period with respect to reference period and associated standard deviation for nine model runs; (**f**, **f'**) Percentage deviation in the monthly discharge during calendar summer months for the second future period with respect to reference period and associated standard deviation for nine model runs; (**g**, **g'**) Percentage deviation in the monthly discharge during calendar autumn months for the first future period with respect to reference period and associated standard deviation for nine model runs; (**h**, **h'**) Percentage deviation in the monthly discharge during calendar autumn months for the second future period with respect to reference period and associated standard deviation for nine model runs; (**i**, **i'**) Percentage deviation in the monthly discharge during calendar spring months for the first future period with respect to reference period and associated standard deviation for nine model runs; (**j**, **j'**) Percentage deviation in the monthly discharge during calendar spring months for the second future period with respect to reference period and associated standard deviation for nine model runs.

On the other hand, the autumn and spring flow changes were not uniform over the basin area, projecting an increase in discharge for some areas and a decrease for others. The standard deviation values also indicated high variety among the outputs of nine future climate projections for each sub-basin for those indicators. The same was observed for the duration of high and low flow events: less agreement among the models regarding the prediction of prolongation of those events was represented by high values of standard deviation. A shortening of low flow events was projected for the first future period and an increasing for the second future period for some sub-basins. Associated high standard deviations values also indicated increased uncertainty in the results for these indicators.

It is observed that the maps of the duration of low flow events indicate that in mountainous areas of the region the drought events are expected to be more prolonged than in the valley. The same spatial variation can also be seen for seasonal changes: the increase in winter discharge is projected to be higher in mountainous areas compared to valleys, and for the autumn and summer, *vice versa*, a slight increase in discharge in the valley and a decrease for the higher altitudes are projected.

5. Conclusions

The simulations of climate change incorporate significant uncertainty and it can be stated that it is not feasible to propose practical, solid measures to enhance the proper management and adaptation strategy to the projected changes now. However, even minor climate changes may trigger a drastic alteration in the hydrological cycles, and these risks should be accounted for in an adaptation strategy [43]. Uncertainties associated with the processes incorporated in the climate change modeling and coupling with hydrological models should be understood and have to be taken into account when interpreting results of modeling and creating adaptation strategies for river basins.

The study of hydrological alterations triggered by climate change in Mures River Basin was performed by employing scenarios obtained from nine coupled runs of GCM-RCM model driven by A1B socio-economic development scenario till the end of the century. Majority of models agreed on projecting increase in the discharge for the winter months and a decrease for late spring, summer and early autumn by year 2100. Since all models are assumed to be developed independently from each other, this future trend can be seen as robust.

These findings also resemble those obtained in CARPIVIA Project [7] and support some findings reported in "Danube River Basin—Climate Change Adaptation" Report [14], such as increase in discharge during winter and decrease during late spring and autumn. The potential prolongation of low flow events can be seen as likely only by the end of the century.

Following the description of the functional link between flow characteristics and aquatic ecosystem proposed by Richter and Thomas [28], projected increase of discharge during winter and the prolongation of high-flow events may result in the increased water velocities, leading to a change of morphology in the river reach, displacement of small organisms like plankton or fish eggs, increased turbidity and therefore disturbance of the photosynthesis, disturbing the functioning of the riparian ecosystem. Furthermore, reduced flow rates during summer and spring and projected prolongation of low flow events could lead to an increase in water temperature and growing levels of dissolved nutrients and pollutants, changing the physical, chemical and biological patterns to which river inhabitants are used to. The prolonged duration of the low flow events and projected decrease in summer discharge may also decrease the habitat area and the minimum required water depth for fishes, resulting in a reduced area for fulfillment of aquatic organisms' life cycle.

The ENSEMBLES Scenarios, applied in this study, allowed revealing the likely future trends in hydrological cycle in the focal area. On the other hand, as was discussed before, these scenarios had their limitations, and can be seen only as first approximation of possible future changes. The estimation of any specific values of deviation in discharges triggered by climate change in the Mures River Basin is beyond the scope of this study.

The mapping of the indicators might be useful for allowing managers to assess the most vulnerable areas, and the areas where the first action to sustain the environmental conditions should be taken. The IHA method applied in this study is appropriate to fulfill a first assessment of the basin state in the future, while making a bridge between the decision makers and scientists.

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Author Contributions

All authors contributed significantly to the development of the methodology applied in this study. Anastasia Lobanova performed set-up, calibration and validation of the model, as well as scenario simulations and analysis with the IHA method. The paper was written and finalized by Anastasia Lobanova. All authors contributed significantly to the analysis of the results, contents of this paper and creation of the figures.

Conflicts of Interest

The authors declare no conflict of interest.

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