Hydroclimatic Projections for the Upper Vistula Basin

Mikolaj Piniewski, Mateusz Szczesniak, Abdelkader Mezghani and Zbigniew W. Kundzewicz

Abstract In this study, we apply a previously calibrated SWAT model of the Vistula and Odra basins in order to assess hydrological impacts of climate change in the Upper Vistula Basin. Raw projections from an ensemble of nine EUR-11 CORDEX climate model runs (precipitation and minimum and maximum temperatures) assuming an intermediate greenhouse gas emission scenario of 4.5 W/m^2 were adjusted using a quantile-mapping correction approach. We analysed changes between two future horizons 2024–2050 (near future) and 2074–2100 (far future) and a reference period (1974–2000). We found that, for the near future, all climate models agree well about ubiquitous warming on both seasonal and annual scales, while eight models agree about an increase in projected mean annual precipitation and total runoff. For the far future, an increase in temperature, in mean annual precipitation, as well as in the total runoff, is projected using all climate models. Results also highlighted a higher temperature increase in winter than in other seasons and a higher increase in minimum temperature than in maximum temperature. The highest runoff increase is projected in winter, consistently, by all climate models. In addition, we assessed projected changes in high streamflow indicator based on the 90th monthly flow percentile (Q90). Based on the median of climate model simulations, we found that the mean basin-wide increase in monthly Q90 is 6.4 and 15 % for the near future and the far future, respectively. Nevertheless, the range of projected changes in precipitation, runoff and high flows calculated across the whole ensemble remains relatively high and spatial patterns are not fully consistent across different climate models.

M. Piniewski (✉) · M. Szcześniak
Warsaw University of Life Sciences, Warsaw, Poland
e-mail: M.Piniewski@levis.sggw.pl

M. Piniewski · Z.W. Kundzewicz
Potsdam Institute for Climate Impact Research, Potsdam, Germany

A. Mezghani
Norwegian Meteorological Institute, Oslo, Norway

Z.W. Kundzewicz
Institute for Agricultural and Forest Environment, Polish Academy of Sciences, Poznań, Poland

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1 Introduction

Anthropogenic global warming has clearly manifested itself as an increase of mean air temperature at various spatial scales, ranging from local to national, regional, continental, hemispheric, and global. The globally averaged combined land and ocean surface temperature has increased by about 0.85 (0.65–1.06) °C, over the period from 1880 to 2012 (IPCC 2013). All 15 individual years of the 21st century (2001–2015), have been among the 16 globally warmest years on record. The year 2015 proved to be the warmest on record, with the global mean temperature exceeding the previous record (established in 2014) by as much as 0.13 °C. Also in Central Europe and Poland, many temperature records were set in 2014 and 2015. Indeed, the heat goes on (Graczyk et al. 2016). The year 2015 has been the first and only year analyzed in thermal classification (since 1966) at the observation station Warsaw-Okecie (cf. www.imgw.pl) marked as "anomally warm", as compared to the reference period 1971–2000.

Since the attribution of the observed warming is well understood and persuading (IPCC 2013), it is possible to produce model-based climatic projections for the future.

The hydroclimatic projections performed in this study used the bias-corrected output from EUR-11 CORDEX experiments, assuming RCP 4.5, (cf. Moss et al. 2010). A quantile mapping method (QMAP) developed by the Norwegian Meteorological Institute was applied as a bias correction procedure for both historical and RCP 4.5 scenario runs (Mezghani and Dobler 2015). Three climate variables (precipitation, minimum and maximum temperature) from nine GCM-run-RCM combinations were available. All data were interpolated on the 5-km grid, regardless of the original RCM resolution. This was the same grid as the one of the CHASE-PL Forcing Data Gridded Daily Precipitation and Temperature Dataset 5 km (CPLFD-GDPT5) (Berezowski et al. 2015a, b), that was used as the forcing data for calibration of the hydrological model SWAT (Soil and Water Assessment Tool) for the Vistula and Odra basins (Piniewski et al. 2016a, Piniewski and Szcześniak 2016).

All bias-corrected data were available for the following three time slices: 1971–2000, 2021–2050, and 2071–2100. Since SWAT requires three years of warm-up period (the period for which different unknown water storages can stabilise and which is not taken into account in model output), all model simulations is available for three 27-year-long time slices: 1974–2000 (hereafter referred to as "historical period"), 2024–2050 ("near future"), and 2074–2100 ("far future"). In this chapter we focus on the projections extracted for the area of the Upper Vistula Basin, i.e. the Vistula upstream of the confluence with the river San. This part of the Vistula River Basin includes nearly the entire Polish part of the Carpathian mountains, with three important right-hand tributaries: Dunajec, Wisłoka and San.

2 Projections of Temperature

Climate model projections agree well about the direction of change of temperature leading to an overall ubiquitous warming across the Upper Vistula Basin and Poland. This refers to both projections for the near future, and for the far future. There is a fairly consistent signal of mean temperature increase for the whole Upper Vistula Basin in all models considered, with a likely range of 0.5–1.7 °C in the near future and 1.2–3.2 °C in the far future. In both future horizons, spatial distribution of change is not pronounced and there are slight differences between the regions when considering individual models albeit, the difference does not exceed 0.5 °C. The increase in minimum temperature is consistently larger (by 0–0.5 °C) than the increase in maximum temperature.

Seasonal projections of temperature change also show ubiquitous warming. Mean temperature change is the highest in winter (DJF) according to the median RCM: 1.3 and 2.9 °C for the near and far future, respectively. For all other seasons the magnitude (for the median RCM) is comparable and is slightly lower than in winter: between 0.8 and 1.1 °C for the near future, and between 1.7 and 1.9 °C for the far future.

3 Projections of Precipitation

Mean annual precipitation in the whole Upper Vistula Basin is projected to increase by 1.0–11.8 % in the near future (with an exception of one climate model for which the mean projected change is negative, −0.1 %) and by 3.8–11.5 % in the far future. This change is not spatially uniform and the spatial patterns differ between individual climate models. Eight out of nine models project an increase in precipitation that accelerates with time. In the far future, only three climate models show a decrease in precipitation for certain sub-basins but the area for which it happens is negligibly small. The magnitude of projected precipitation change for the Upper Vistula Basin is in general lower than for the entire Vistula Basin.

Models do not agree about changes in mean annual precipitation for the Upper Vistula Basin, in the near future. While, in general, most models show increase of mean annual precipitation, with the median change of 3.8 %, there are subareas in the basin where precipitation decrease is projected, in particular in the southern mountainous part. For the far future, all models tend to show increase of mean annual precipitation for the Upper Vistula Basin (median change by 8 %), with some models showing small areas of projected precipitation decrease.

Precipitation change is not seasonally uniform. For different seasons, seasonal distribution of changes is different. For the near future, the median RCM results suggest an increase of winter and spring precipitation by 10.6 and 7.1 %, respectively, while for summer and autumn only by 0.1 and 1.2 %, respectively. In winter and spring, precipitation increase is uniform for individual climate models, whilst in summer and autumn, the direction of change is very uncertain. The magnitude of mean changes in the Upper Vistula Basin is similar to that calculated on the entire Vistula and Odra basins for winter, spring and summer, whilst for autumn it is considerably lower.

For the far future, the median of the RCM simulations suggests an increase for winter and spring precipitation by almost 16 %, while for summer and autumn only by 1.5 and 4.5 %, respectively. Similarly to near future projections, changes in summer and autumn are more uncertain than for winter and spring. Summer seems to be the only season for which the magnitude of changes is significantly lower for the Upper Vistula Basin than for the entire Vistula and Odra basins.

Rising winter temperatures and increasing winter precipitation lead to non-trivial changes in the amount of precipitation falling as snow (assessed based on the SWAT model output). Considering the median of the projections, there is a sharp latitudinal gradient related to elevation change: in southern mountainous parts projected decrease in snowfall is relatively small (approximately 5 and 10 % in the near and far future), while in the northern part it is higher by the factor of four, reaching 20 and 40 %, respectively.

4 Projections of Runoff

Piniewski and Szcześniak (2016) produced hydrological projections driven by nine aforementioned climate models for the Vistula and Odra basins, consisting of 2633 sub-basins, using the SWAT hydrological model, which was calibrated and validated against daily discharge data from 80 "benchmark" catchments (Piniewski et al. 2016a). Figures 1 and 2 show projected changes in mean annual total runoff (i.e. the sum of baseflow, subsurface and surface runoff) for both near and far future, respectively.

Similarly to precipitation, mean annual runoff in the Upper Vistula Basin is projected to increase for eight out of nine climate models in the near future (Fig. 1) and for all nine models in the far future (Fig. 2). Most climate models project an increase in runoff by approximately more than 10 % in the near future, but one model projects a decrease in runoff (by 3.8 %). However, for the far future, the number of models showing an increase in runoff higher than 10 % reaches eight (out of nine in total), four of which project an increase above 20 %. Moreover, projected changes are not spatially uniform and the spatial patterns differ between models. Interestingly, for both future time slices and for all nine models, the Upper Vistula Basin faces a drier (or "less wet") future than the whole Vistula and Odra basins (Figs. 1 and 2). While in the near future there are areas in which runoff decreases (most frequently SE Poland), in the far future this is much less common and is limited mainly to small parts of the mountainous areas in the south.

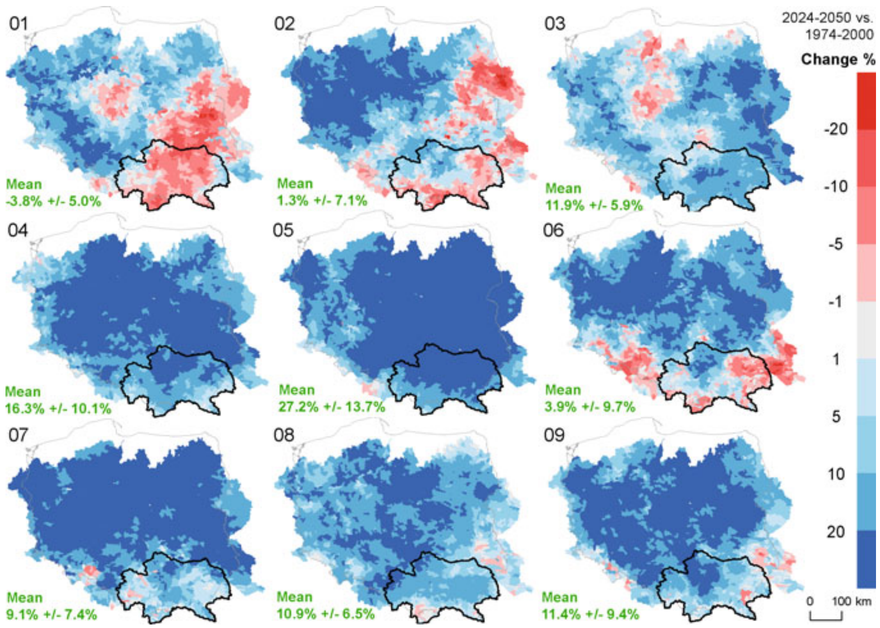

Fig. 1 Mean annual runoff projections for the near future (relative change between 2024 and 2050 and 1974–2000). *Black thick line* delineates the Upper Vistula Basin, whereas *green* labels denote mean and standard deviation of percent changes over sub-basins inside the Upper Vistula Basin (color figure online)

Surprisingly, the highest increase of mean annual runoff for one model in the near future is slightly higher than for the far future (27.2 %, with less uncertainty and 26.2 %, with more uncertainty, respectively).

The seasonal increase in runoff in the Upper Vistula Basin is the largest in winter (17.3 and 37.2 %, respectively) according to the median RCM. In summer and autumn, the projected changes are similar (5–6 % for the near future and 16 % for the far future), whereas spring is the only season in which the change is similar in both periods (increases by 7.7 and 8.9 %, respectively). Comparing these values with the projected increases in seasonal precipitation, one can note that spring is the season for which a response in runoff to increasing precipitation is considerably lower than for other seasons. It is presumably related to the fact that in the historical period the annual runoff peak occurs in spring, while in the future periods (particularly far future) it is shifted towards winter due to decreasing snow melt.

In all seasons apart from winter, runoff projections for the Upper Vistula Basin are considerably different than for the entire Vistula and Odra basins. In particular, in the southern mountainous part in all these three seasons there are substantial areas of runoff decrease, which occurs much less frequently elsewhere.

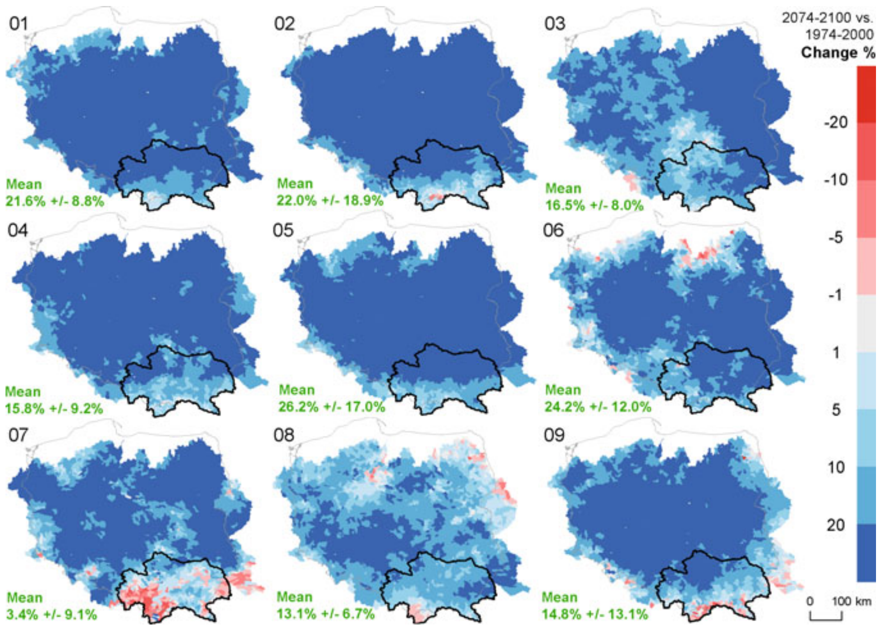

Fig. 2 Mean annual runoff projections for the far future (relative change between 2074–2100 and 1974–2000). *Black thick line* delineates the Upper Vistula basin, whereas *green* labels denote mean and standard deviation of change over sub-basins inside the Upper Vistula Basin (color figure online)

5 Changes in High Flow

Figure 3 shows projected changes in high streamflow indicator, the 90th daily flow percentile (Q90), for the near and far future, respectively, according to the median RCM, for the Upper Vistula Basin. The mean basin-wide increase is 6.4 % and 15 % for the near future and the far future, respectively. Spatial pattern of changes in Q90 is similar for both periods: small increases are prevailing for the right-hand tributaries of the River Vistula, draining high elevation catchments, and higher (for the far future even above 20 %) for the left-hand tributaries characterized by lower elevation. The magnitude of Q90 increase in the Upper Vistula Basin is lower than in the entire Vistula and Odra basins, while the uncertainty related to the direction of change is higher.

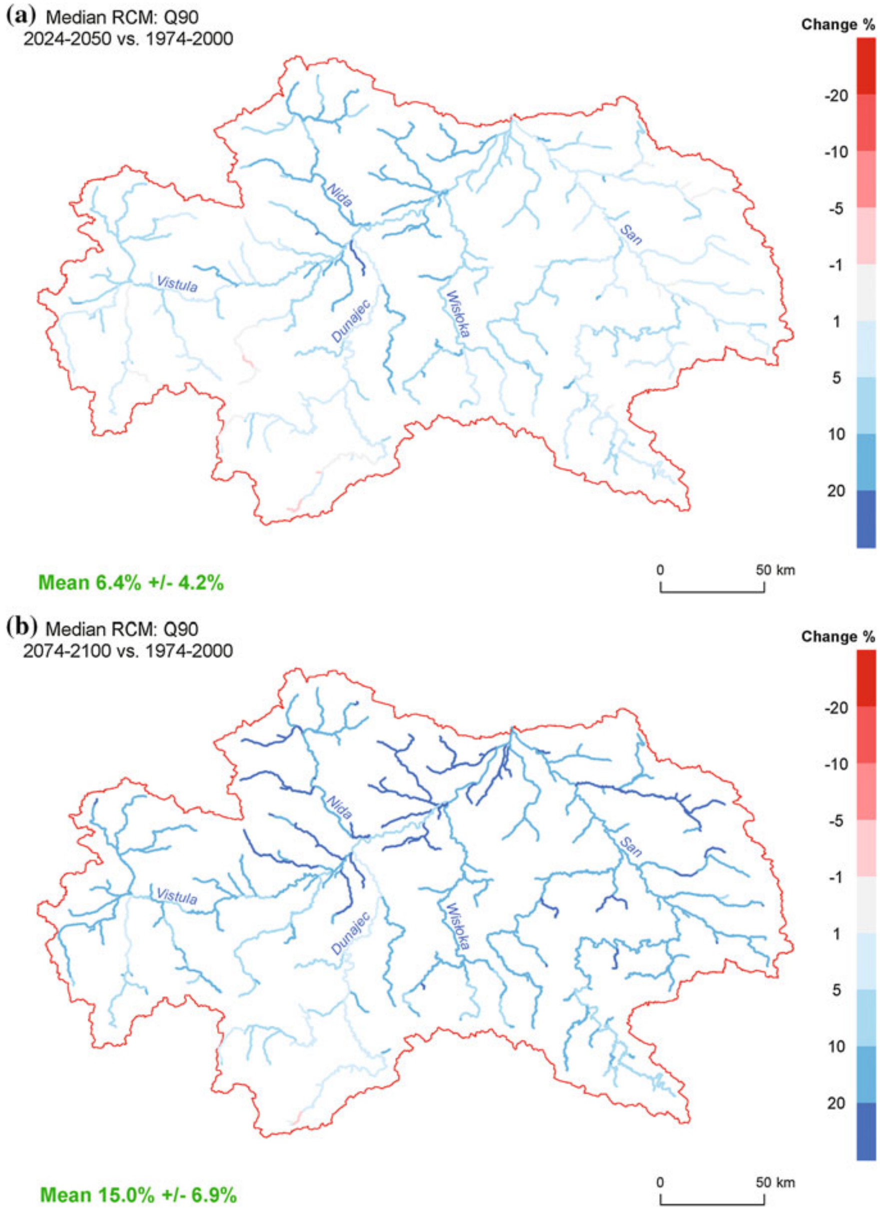

Fig. 3 High (Q90) monthly flow indicator projections for the near (**a**) and far (**b**) future for median RCM

6 Concluding Remarks

Projections of changes in hydroclimatic variables: temperature, precipitation, runoff and high flow, for the Upper Vistula Basin from an ensemble of bias-corrected RCM experiments and the SWAT model show several robust signals:

1. A ubiquitous mean temperature increase in the near and far future, with low spatial variability.
2. A higher temperature increase in winter than in other seasons.
3. A higher increase in minimum temperature than in maximum temperature.
4. An increase in mean precipitation and runoff projected by the majority of climate models in both future periods considered. The relative magnitude of increase (in percent) in runoff is generally higher than the corresponding increase in precipitation, so that an amplification effect can be observed. The change accelerates with time.
5. Smaller magnitude of precipitation and runoff changes in the southern mountainous part of the Basin than in its northern highland part.
6. Seasonally variable precipitation changes according to most of the models: in both future periods the increase is largest in winter and spring.
7. The highest runoff increase is projected in winter, consistently, by all climate models.
8. Changes in precipitation and runoff for the Upper Vistula Basin are different in comparison to the entire Vistula and Odra basins (a smaller magnitude of increase, in general).
9. An increase in high flow projected mainly in the northern highland part of the Basin.

Nevertheless, the range of projected changes based on the climate model ensemble remains relatively high and spatial patterns are not fully consistent across different climate models. For example, although the mean runoff increase is projected consistently by all models in the far future, its range is very wide: from 3.4 to 26.2 %.

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