

# Projections of Changes in Flood Hazard in Two Headwater Catchments of the Vistula in the Context of European-Scale Studies

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**Abstract** European-scale flood hazard projections do not give a consistent view of future changes in Central Europe, including Poland. Some studies indicate decreases in the magnitude and frequency of high flows, whilst others show increases. In this chapter, we summarize the current state of knowledge on flood perspectives in Central Europe and Poland under future climatic conditions at the background of large-scale European flood hazard projections and we contrast it with a small-scale study. Projections of changes in flood hazard in two catchments are considered in a multi-scale perspective, and against a background of large-scale: global and European projections, through regional (Central Europe) and national, to local. A discussion on causes of differences in flood-hazard projections and their possible interpretation is included. Among other issues, the uncertainties related to the processes taking part in the computational chain leading to the derivation of projections are listed. Specifically, the possible changes in the 30-year and 100-year return period quantiles of the maximum annual flows in the Dunajec and the Upper Wisla basins, two headwater catchments in the Vistula Basin are presented. The analysis is based on seven driving GCM/RCM projections under the

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RCP4.5 scenario. The results for both catchments are consistent with some of the previous European-scale studies, but do not give a coherent image. At this stage, the only explanation of the differences in the projections of future flood changes in both catchments lies in climatic variability and the uncertainty of the results. The results of this study confirm the view that flood hazard assessment is influenced by multiple climatic and non-climatic factors which introduce uncertainties and whose relative importance is site-specific.

**Keywords** Flood hazard · Projections · Uncertainty · River Vistula · Poland

## 1 Introduction

Economic damage caused by river floods has grown considerably in recent decades, at all spatial scales, from local to global. Many river floods with material damage of the order of billions of euros and with multiple fatalities have been recorded in Europe. Since recent floods have reached new heights of stage and discharge records, there is a concern that not only flood damage may have increased, but also flood hazard (Kundzewicz et al. 2016).

Increase of heavy precipitation has been noted in many areas as well but its effect on floods has been difficult to pinpoint. Also studies of change detection in observed high river flows show no convincing and ubiquitous increase of flood hazard, in Europe and world-wide (Kundzewicz 2012; Kundzewicz et al. 2005; Madsen et al. 2014). Nevertheless, some indications of an increasing tendency in the number of large floods in Europe, of considerable magnitude and severity, have been detected recently (Kundzewicz et al. 2013). It is important to stress that reliable determination of flood frequency characteristics requires long-term observations and continuous gauge records. Typically, however, existing time series of records are not long enough, or stations have been re-located over time, which renders analysis and interpretation difficult. In addition, flood trends cannot be easily detected in the observation record because the signal-to-noise ratio is typically low whereas natural variability is high. The failure to detect a ubiquitous rising trend in floods has apparently been a surprise to some experts describing recent flood events as possible harbingers of a rise in flood risk related to climate change. This was exemplified by the sarcastic title chosen by Schiermeier (2003): “*Analysis pours cold water on flood theory*”, when referring to failure to detect an increasing trend in a study reported by Mudelsee et al. (2003).

Model-based large-scale projections of changes in river flood frequency indicate increases in the amplitude and frequency of high river flows in most areas of the world (but not necessarily in Europe) in the warming climate (Hirabayashi et al. 2008, 2013; Arnell and Gosling 2016; Dankers et al. 2014). In addition, and in the case of Europe in particular, considerable disagreement has been reported between projections (Lehner et al. 2006; Dankers and Feyen 2009; Rojas et al. 2011, 2012, Alfieri et al. 2015; Roudier et al. 2016).

In this chapter, projections of changes in flood hazard in the two mountainous catchments situated in headwaters of the River Vistula are considered in a multi-scale perspective, and against a background of large-scale, global and European projections, through regional (Central Europe) and national, to local.

## 2 Review of Large-Scale (Global and European) Flood Hazard Projections

Large-scale, global or continental, projections of changes in flood frequency and intensity have been presented in many publications. Lehner et al. (2006), Dankers and Feyen (2009), Rojas et al. (2011, 2012), Roudier et al. (2016) and Alfieri et al. (2015) report projections for Europe, while Hirabayashi et al. (2008), (2013), Arnell and Gosling (2016), and Dankers et al. (2014) present global projections. It can be noted that large-scale projections may considerably differ between studies (Kundzewicz et al. 2016).

Alfieri et al. (2015) concluded that increases in  $Q_{100}$  dominate in most countries in three future periods studied (2006–2035, 2036–2065, 2066–2095), though the frequency of peak flows over threshold is projected to decrease in some areas (NE Europe and southern Spain). The projected increases are significant in all considered 37 countries in time slice of 2080s with values ranging between 18 % (Finland) and 982 % (Iceland). Rojas et al. (2011, 2012) show a dominant increase of frequency of  $Q_{100}$  at the end of 21st century for British Isles, France, Italy, Balkan and Carpathians, and decrease in eastern Germany, Poland, southern Sweden, Baltic countries and some rivers in the Iberian Peninsula. Roudier et al. (2016) found a clear North to South gradient in changes of flood hazard, with a moderate to strong increase of flood magnitude south of the 60°N parallel, and a strong decrease in northern Scandinavia and NW Russia. For Poland, these three studies suggest an increase, a decrease and a weak increase in floods, respectively.

In contrast, recent projections of change in flood hazard in Europe reported by Hirabayashi et al. (2013) indicate flood frequency decrease in much of Northern, Central and Southern Europe, and only for a part of western Europe (British Isles, northern France, and part of Benelux), prevailing increases in frequency of  $Q_{100}$  are projected. Results of Dankers et al. (2014) show increases in flood frequency ( $Q_{30}$ ) prevailing in projections for British Isles only. For Poland, both studies project a decrease in floods at the end of this century.

## 3 Flood Hazard Projections for Central Europe

In line with the continental-scale studies, flood hazard projections do also differ considerably between studies for Central Europe. For instance, results of projections of changes in flood hazard, reported by Rojas et al. (2012) and Alfieri et al. (2015) do not agree on changes in Poland and Eastern part of Germany, notwithstanding the fact that in

**Table 1** Information on a direction of projected changes of compared large-scale flood hazard projection studies for Central Europe (based on Kundzewicz et al. 2016, updated)

Study	Coverage of the study	Number of climate scenarios	Number of hydrological models	Direction of change
Roudier et al. (2016)	Europe	11 CORDEX	3: Lisflood, E-HYPE, VIC	↑
Alfieri et al. (2015)	Europe	7 CORDEX	1: Lisflood	↑↓
Dankers et al. (2014)	Global	5 GCMs	9 global HMs	↑W ↓E
Arnell and Gosling (2016)	Global	21 GCMs	1: Mac-PDM.09	↑↓W
Hirabayashi et al. (2013)	Global	11 GCMs	11 AOGCMs	↑NW↓SE
Rojas et al. (2012, 2011)	Europe	1 GCM	1: Lisflood	↑↓NE
Dankers and Feyen (2009)	Europe	5 RCMs	1: Lisflood	↑ NW SE↓C
Hirabayashi et al. (2008)	Global	1 GCM	1: MATSIRO LSM	↑↓
Lehner et al. (2006)	Europe	2 GCMs	1: WaterGAP	↓↑

↑ mostly increase

↑ partly increase (in subareas)

↓↑ mostly decrease, in subareas increase

↓↑ mostly decrease, in some subareas increase

↓N ↑S decrease in northern part, increase in southern part

both studies the same hydrological model (LISFLOOD) was used. This is probably due to the different climate scenarios used in these studies: from one GCMs in Rojas et al. (2012) contrasting to seven RCMs in Alfieri et al. (2015).

Uncertainty also shows up in studies at the national scale (Madsen et al. 2014). For instance, disagreements exist between projections of changes in flood hazard over Germany (Kundzewicz et al. 2016) in studies using the same hydrological model, SWIM (Krysanova et al. 2015), but different greenhouse gas scenarios, SRES A1B and RCP8.5, described by Moss et al. (2010), Meinshausen et al. (2011) and Nakicenovic et al. (2000), respectively.

Table 1 summarizes information on projected changes in flood hazard, for the Central European region and illustrates considerable disagreement between particular studies.

## 4 Interpretation of Differences in Flood-Hazard Projections

An increase of observed record-breaking precipitation events has been detected for most of Europe under global warming (Lehmann et al. 2015). However, considerable problems remain, namely those related to projecting intense precipitation.

Indeed, a warmer atmosphere can retain more water vapour in line with the Clausius-Clapeyron law and model-based projections indicate likely increase of frequency of heavy precipitation in the warming Europe. Seneviratne et al. (2012) illustrated that heavy precipitation will become more frequent in the future, i.e. the median of the projected return period of 20-year, 24-h precipitation will decrease for all three sub-regions of Europe. However, model skill in reproducing extreme storm events and trends, given some change in forcing, is not persuasive. Large uncertainties in the projection of precipitation extremes are associated with uncertainties in models, downscaling techniques and natural variability (Nicholls and Seneviratne 2013). The underestimation of rainfall extremes by the models (often observed when models simulate historical data rather poorly) may be also related to the coarse spatial resolution used in model simulations, suggesting that projections of future changes in rainfall extremes in response to anthropogenic global warming may also be underestimated.

Many sources of discrepancy in flood-hazard projections can be identified, such as:

- uncertainty related to differences in General Circulation Models (GCMs);
- uncertainty related to differences in emission scenarios;
- uncertainty due to Regional Climate Models (RCMs) and downscaling techniques;
- deficiency of climate models in representing intense precipitation;
- problems related to bias correction;
- poor performance of models for extremes;
- uncertainty due to differences in global hydrological models (GHMs) and regional hydrological models (RHMs);
- problems related to extreme value techniques.

It is worth identifying basic assumptions in recent work on flood hazard projections, embracing Eastern Europe, listed in Table 1 (Kundzewicz et al. 2016). The particular studies differ with respect to emission scenarios (whether older, drawing from SRES or newer, based on the concept of RCPs), models (climate models—GCMs, RCMs, global and regional hydrological models—GHMs, RHMs), future horizon of interest, as well as spatial resolution, return period, downscaling technique, bias reduction method, just to name a few.

Differences among the projections may be due to the selection of GCMs, which is generally the largest source of uncertainty in the climate impact studies. Older papers by Hirabayashi et al. (2008) or Rojas et al. (2011, 2012), for instance, considered just one GCM, whilst the newer studies—ensembles of several GCMs/RCMs, up to a study based on 21 GCMs (Arnell and Gosling 2016). Hirabayashi et al. (2013) and Dankers et al. (2014) analyzed results from 11 GCMs and five GCMs, respectively, whereas Alfieri et al. (2015) used seven EURO-CORDEX climate scenarios (combinations of three GCMs downscaled with four RCMs).

Studying changes in river flood frequency requires an estimation of extreme river flows. Even if the notion of 100-year flow ( $Q_{100}$ ) is used most frequently (as a typical protection level of structural defences), some authors use other return periods, high flow percentiles, or other variables. For instance, Dankers et al. (2014) studied 30-year 5-day peak flow, i.e. a moderately extreme river discharge, whereas Roudier et al. (2016) used both  $Q_{100}$  and  $Q_{10}$ . Estimates of extreme river flows are often based on extreme value distributions, and are increasingly uncertain at more extreme discharge levels, especially for return periods beyond the length of the data the estimate is based on. This uncertainty is well-known in the field of statistics, and techniques exist to estimate this uncertainty, but in many hydrological studies it is not taken into account. In this respect, an estimate of  $Q_{10}$  based on 30 years of simulations can be considered more robust compared to estimation of  $Q_{100}$  based on 30 years.

The compared papers deal with different future horizons, mostly 2070–2099 or 2071–2100, but Arnell and Gosling (2016) used 2050s whereas Lehner et al. (2006) has chosen 2020s and 2070s as future horizons. Alfieri et al. (2015) used the future horizons of 2020s, 2050s, and 2080s.

One important reason of differences is related to differences in emission scenarios. Impacts are typically modelled, based on climate-model projections using either of two scenario approaches: Representative Concentration Pathways (RCP), cf. Moss et al. (2010), Meinshausen et al. (2011), or the older IPCC Special Report on Emission Scenarios (SRES), cf. Nakicenovic et al. (2000). Typically, flood hazard projections are based on either SRES scenarios, such as A1B, mostly in older papers, such as Lehner et al. (2006), Hirabayashi et al. (2008), Arnell and Gosling (2016), Rojas et al. (2011) also A2 and B2 in Dankers and Feyen (2009). The Representative Concentration Pathways (RCP), in particular RCP 8.5, were used in newer papers, such as Hirabayashi et al. (2013), Dankers et al. 2014 and Alfieri et al. (2015).

Also control (reference) intervals differed in compared studies, being 1901–2000 for Hirabayashi et al. (2008), 1961–1990 for Rojas et al. (2011, 2012), 1971–2000 for Hirabayashi et al. (2013) and Dankers et al. (2014), and 1976–2005 for Alfieri et al. (2015). The differences in underlying assumptions and methods can explain, to some extent, the differences in projections. Bias correction does not necessarily improve climate scenarios, but adds just another non-linear transformation which may affect projection of extreme precipitation, and hence floods.

The recent study by Roudier et al. (2016) does considerably differ from the other papers reported here, as the authors did not select a specific future time horizon but focused on the definition of the hydrological impacts in a world with a +2 °C change in global mean temperature relative to pre-industrial levels (1881–1910). This is important for the policy world, especially in terms of the outcome of the Paris Climate Summit (COP21, i.e. Conference of Parties of the UN Framework Convention on Climate Change) in December 2015. Describing the impacts of a +2 °C (and possibly—also +1.5 °C) has been explicitly requested in France last year. Roudier et al. (2016) considered three RCPs 2.6, 4.5 and 8.5. The time horizons, for which a +2 °C global warming was expected for different

assumptions, were: 2016–2045; 2023–2053; 2027–2056; 2028–2057; 2030–2059; 2042–2071; 2050–2079; 2071–2100.

Usually, in the studies discussed, just one hydrological model was used, except for the work by Dankers et al. (2014), considering nine global hydrological models and Roudier et al. (2016), considering three global hydrological models. Global models can provide consistent and coherent simulations across very large scales and are useful for getting global overviews, but they often have to compromise the model performance at the regional scale and in individual catchments for overall performance. An important reason for uncertainties in projected results is that, in the large-scale studies, usually the global hydrological models are used mostly without any calibration. Some global hydrological models may reproduce the long-term average seasonal dynamics of discharge fairly well, but their ability to reproduce floods seems problematic. Even if some authors show some kind of “validation” for large river basins, they use aggregated results over time and over large spatial areas, where the results may look fairly well. Other authors do not report any validation at all. Should we trust results produced by poorly adjusted tools? Perhaps expecting a consistency is futile.

Some studies rely on land surface models used in GCMs, where issue is about the computation of soil moisture, hillslope runoff, etc. There are some global hydrological models that are not directly coupled with GCMs. But, even those global hydrological models may have computation schemes similar to land surface models of GCMs that are good at representing large-scale water budgets and changes, but less good at representing small-scale peak runoff, i.e. floods in small or upstream rivers. In addition to land surface processes, simulation of rainfall from GCMs and RCMs is better for large spatio-temporal scales of different studies.

Regional Hydrological Models (RHMs) and catchment-specific models, on the other hand, have finer spatial resolution and often incorporate more detailed information on, for example, the topography, soils and water management practices, and it is a standard procedure to calibrate them using observations.

Calibration of hydrological models at catchment-scale is a well-established procedure. Models that are calibrated for a particular gauging station provide more realistic simulations under present and similar climate conditions. However, the assumption that the calibrated model parameters will remain constant into the future may not hold, and is indeed unlikely to be true for parameters that are sensitive to the climate. A hydrological model that is tuned to historic conditions may not always provide plausible projections under different climatic conditions.

Also, good model performance in simulating discharge at the catchment outlet may mask variable performance across the catchment, and indeed in other variables. If a model is calibrated and validated using only a few main criteria (such as Nash and Sutcliffe Efficiency, NSE, and percent bias, PBIAS) and for runoff at the catchment outlet only, then it is, strictly speaking, suitable only for evaluation of the daily, monthly or seasonal dynamics of runoff at the outlet gauge. Representing the results as spatial patterns on maps and also for other variables than runoff assumes the model has some skill which ideally should be demonstrated, for example

through validation at intermediate gauges and for other variables. Likewise, if climate change impacts on extremes are investigated, the model performance needs to be evaluated for these extremes using special criteria. However, these rules are not always followed strictly by modellers. Under high-end climate change scenarios for the end of the century and for extreme events using both types of models (global and catchment-scale) is therefore connected with high uncertainty.

## 5 Flood Hazard Detection and Projections for Poland

Comparing detection of change in individual European countries, Madsen et al. (2014) included Poland, where in general, decreasing trends were detected in both the mean and the variance of annual maximum flow series. The tendency is more pronounced in rivers with a high contribution of winter floods (Strupczewski et al. 2009).

Alfieri et al. (2015) included Poland in their analysis of the projection of change in mean annual exceedance frequency of the 100-year return period peak flow for different European countries and estimation of percentage change between the baseline and the future time slices. In their aggregate view, they would consider the percentage increase between the baseline and the future time slices to read: 127, 86, 94 % for 2020, 2050, and 2080, respectively.

In their inter-comparison of results of national flood projections, Madsen et al. (2014) reported on a Polish study conducted by Osuch et al. (2012) for the Wełna and Orla catchments in western Poland, based on six RCMs from the ENSEMBLES project using the A1B scenario, with quantile mapping applied for the bias correction of climate projections and the lumped, conceptual rainfall–runoff model (HBV). The simulation results by Osuch et al. (2012) showed different directions of change or a lack of statistically significant changes for simulations driven by different RCM/GCMs. That was the only study that applied catchment-scale, lumped hydrological modelling for future flood projections. The other studies mentioned applied pan-European hydrological models Lisflood, E-HYPE and VIC (Rojas et al. 2012; Alfieri et al. 2015; Roudier et al. 2016).

Catchment-scale model projections are important for the adaptation of flood risk management to climate change and may provide different flood indices than the large-scale models. As discussed in Sect. 4, there are many reasons why basin-scale and catchment-scale flood projections may differ. The most important seems to be the uncertainty related to meteorological projections and hydrological modelling at those different scales. The other important issue, related to the scale is spatial and temporal averaging that may have a large impact on estimates of hydrological extremes. The next but not last is the variability of circulation patterns and land-surface-atmosphere feedback depending on local, catchment-scale features of the terrain.

In the next section we illustrate the approach for the derivation of flood hazard projections on a catchment scale for two mountainous catchments situated in the



upper course of the Vistula basin with the aim of showing in practice the reasons for differences between regional and local estimates of projected future changes.

## 6 Flood Hazard Projections for the Two Headwater Catchments of the Vistula

In the foothills of the Tatra Mountains, observational records (Ruiz-Villanueva et al. 2016a, b) do not indicate an increasing flood hazard. Results show, by contrast, evidence of seasonal changes in the magnitude and frequency of high flows in the region. Two headwater catchments of the Vistula, of the rivers Dunajec and Upper Wisla, situated in the same region in the vicinity of the Tatra Mountains are chosen for flood hazard projections at the catchment scale. The catchments belong to the set of semi-natural catchments chosen within the Polish-Norwegian project Climate Change Impact on the Hydrological Extremes (CHIHE) (Romanowicz et al. 2016).

The catchments' locations are shown in Fig. 1. The catchments differ in their flood regime; the Dunajec is rainfall-dominated and the Upper Wisla has a mixed (rainfall and snow-melt) flood regime. Both are mountainous catchments characterized by a large variability of discharge. The geographical characteristics of the catchments are given in Table 2. The averaging of precipitation and streamflow observations was performed over the period 1971–2000.

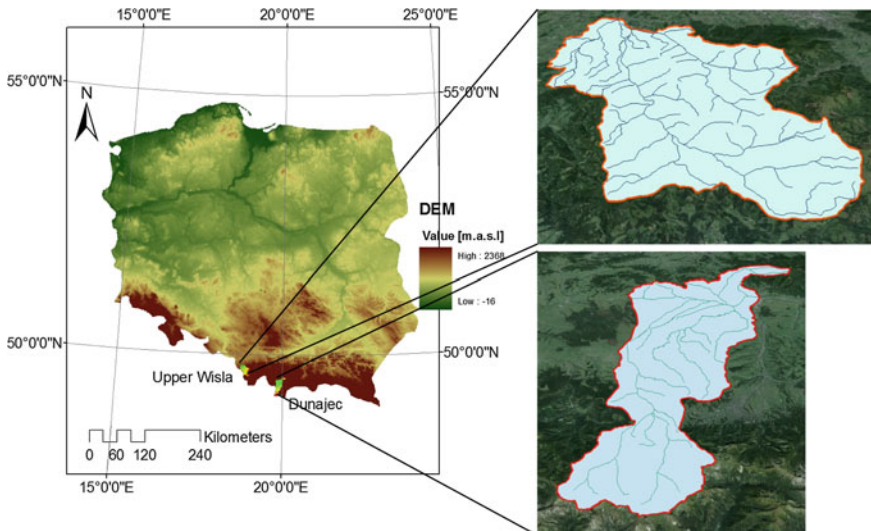
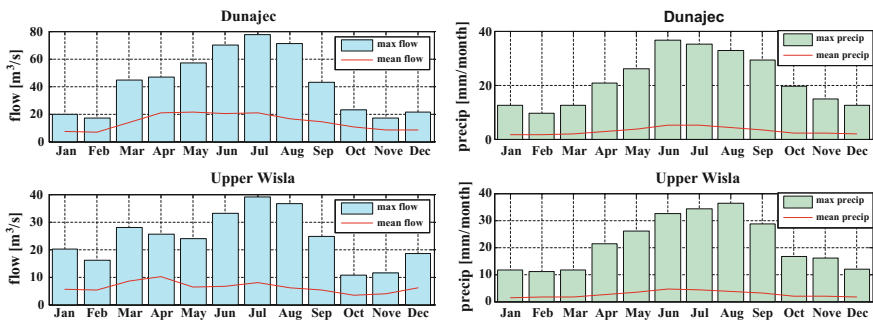


Fig. 1 Location of the Dunajec and the Upper Wisla catchments in Poland

**Table 2** Description of the study catchments

Catchment	Gauging station	Area (km <sup>2</sup> )	Flood regime	PM (mm)	QM (m <sup>3</sup> /s)	Q <sub>max</sub> (m <sup>3</sup> /s)
Dunajec	Nowy Targ-Kowaniec	681.1	Rainfall	3.1	14.5	383
Upper Wisła	Skoczow	296.5	Mixed	2.6	6.1	238

QM is an average daily value of streamflow; PM is an average daily value of precipitation; Q<sub>max</sub> maximum flow in 1971–2000



**Fig. 2** Observed monthly maximum flows (*left column*) and monthly mean precipitation (*right column*) in the Dunajec (*upper panels*) and the Upper Wisla (*lower panels*) in the period 1971–2000

Figure 2 presents monthly maximum flows and monthly mean precipitation patterns in both catchments. There is a visible, two-modal shape of the mean maximum flows for the Upper Wisla catchment, indicating the presence of the snowmelt driven high flows.

The procedure for the derivation of estimates of changes in flood hazard under climate change followed in this study can be summarized in the following main steps:

1. Preparation of climate projection datasets for assumed climate change scenario for the reference period and the chosen time horizon in the future.
2. Calibration and validation of the hydrological rainfall-runoff model using historical observations of hydro-meteorological variables (temperature, precipitation, flow).
3. Simulation of runoff with the model using climate projections.
4. Assessment of flood risk indices, e.g. in the form of  $Q_{100}$  quantiles.
5. Derivation of differences between the future and reference periods.

As explained in Sect. 4, the results of each of these steps contain large uncertainties. In the first step, the uncertainty is related to the choice of climate change scenario, climate model inaccuracy and downscaling techniques. The uncertainty

**Table 3** List of GCM/RCM climate models applied

GCM/RCM	RCA4	HIRHAM5	CCLM4-8-17	RACMO22E
EC-EARTH	1	1	1	1
MPI-ESM-LR	1	0	1	0
CNRM-CM5	0	0	1	0

related to the choice of the scenario of future CO<sub>2</sub> emissions is difficult to reduce (Knutti and Sedláček 2012).

This is why in this study we followed the RCP4.5 (Representative Concentration Pathway) scenario, an “intermediate pathway” in which the global temperature increase in 2100 is estimated to be approximately 2.5 °C relative to the period 1850–1900 (Clarke et al. 2007). The selected combination of climate models consists of three GCMs and four RCMs (Table 3).

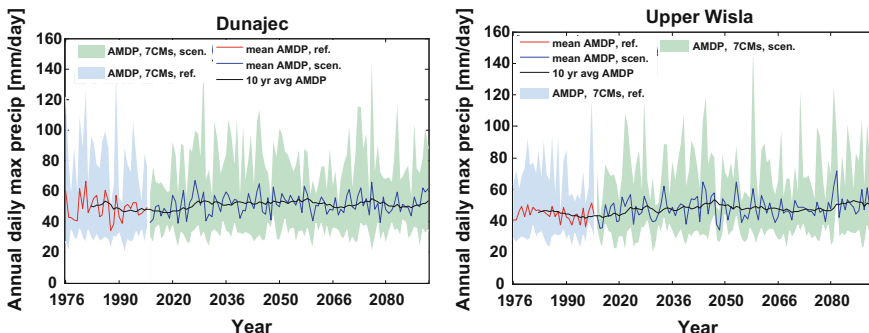
The selected available RCMs/GCMs provide seven projections of climatic variables up to 2100, at a resolution of 12.5 km. Analyses of hydro-meteorological conditions were conducted for the whole 1971–2100 period. We followed the study of Alfieri et al. (2015) in the choice of periods for the comparison. Four time intervals are examined: 1976–2005, the so-called reference period, and three future periods: (2006–2035), (2036–2065) and (2066–2095) periods. These periods are called after their median values: “1990s”, “2020s”, “2050s” and “2080s”, respectively.

As a result of simplifications in the description of processes in global climate models, their spatial resolution and downscaling techniques, projections of temperature and precipitation are biased. As discussed in Sect. 4, the bias correction, or de-biasing, of raw projections might lead to undesirable changes in peak flows (Alfieri et al. 2015). On the other hand, some climate model projections do not reproduce correctly the seasonality of meteorological variables (Osuch et al. 2015), and therefore are not physically realistic without bias-correction. In this study we present the climate impact results using raw projections in order to compare with the results of Alfieri et al. (2015).

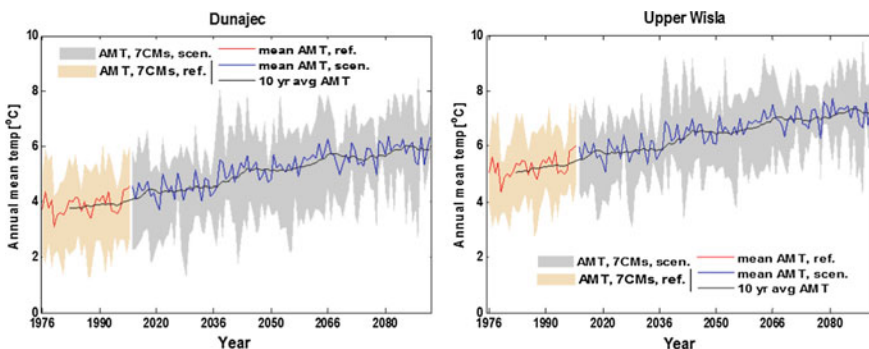
Projections of an annual maximum precipitation for the period 1971–2100 for the Dunajec and Upper Wisla catchments for seven GCMs/RCMs are presented in Fig. 3. The figure illustrates that there are no visible trends in projected precipitation maxima in either catchment.

Figure 4 presents the annual means and spreads of air temperature in the reference and future periods based on seven climate models for the Dunajec and Upper Wisla catchments. In the case of temperature patterns, there are visible positive trends projected for both catchments, with about 1 °C lower temperatures in the Dunajec than in the Upper Wisla. The mean temperature variability shows large similarity between the catchments and rises by nearly 2 °C by the end of 2100 in comparison with the reference period.

The conceptual rainfall-runoff model HBV (Bergström 1995) was applied to model the catchment response to meteorological forcing. The model was calibrated using daily observations of temperature and precipitation from the period



**Fig. 3** Annual maximum daily precipitation (AMDP) for the Dunajec (*left panel*) and the Upper Wisla (*right panel*) in 1976–2100 based on seven climate models (CMs) from the GCMs/RCMs ensemble: *shaded areas* present ensemble spreads: *blue* for the reference period 1976–2005; *green* for the period 2006–2100; *lines* show ensemble means of AMDP: *red line* for the reference period, *blue line* for the future period. The *black line* shows a 10-year moving average AMDP (color figure online)



**Fig. 4** Projected annual mean air temperature (AMT) for the Dunajec catchment (*left panel*) and the Upper Wisla catchment (*right panel*) in 1976–2100 based on seven climate models (CMs) from the GCMs/RCMs ensemble: *shaded areas* present ensemble spreads: *yellow* for the reference period 1976–2005; *grey* for the period 2006–2100; *lines* show ensemble mean temperature: *red line* for the reference period, *blue line* for the future period. The *black line* shows a 10-year moving average temperature (color figure online)

1971–2000, and validated against data covering the period 2001–2010. Model parameters were optimized using the DEGL (Differential Evolution with Global and Local neighbours) method (Storn and Price 1997). As an objective function the Nash-Sutcliffe coefficient was used (Nash and Sutcliffe 1970). The results of calibration and validation of the HBV model were good, and they were presented in Table 1 of Romanowicz et al. (2016). There is a large uncertainty related to the

hydrological model structure and its parameters (Honti et al. 2014) which will not be taken into account in this study, being out of the scope of the present objectives.

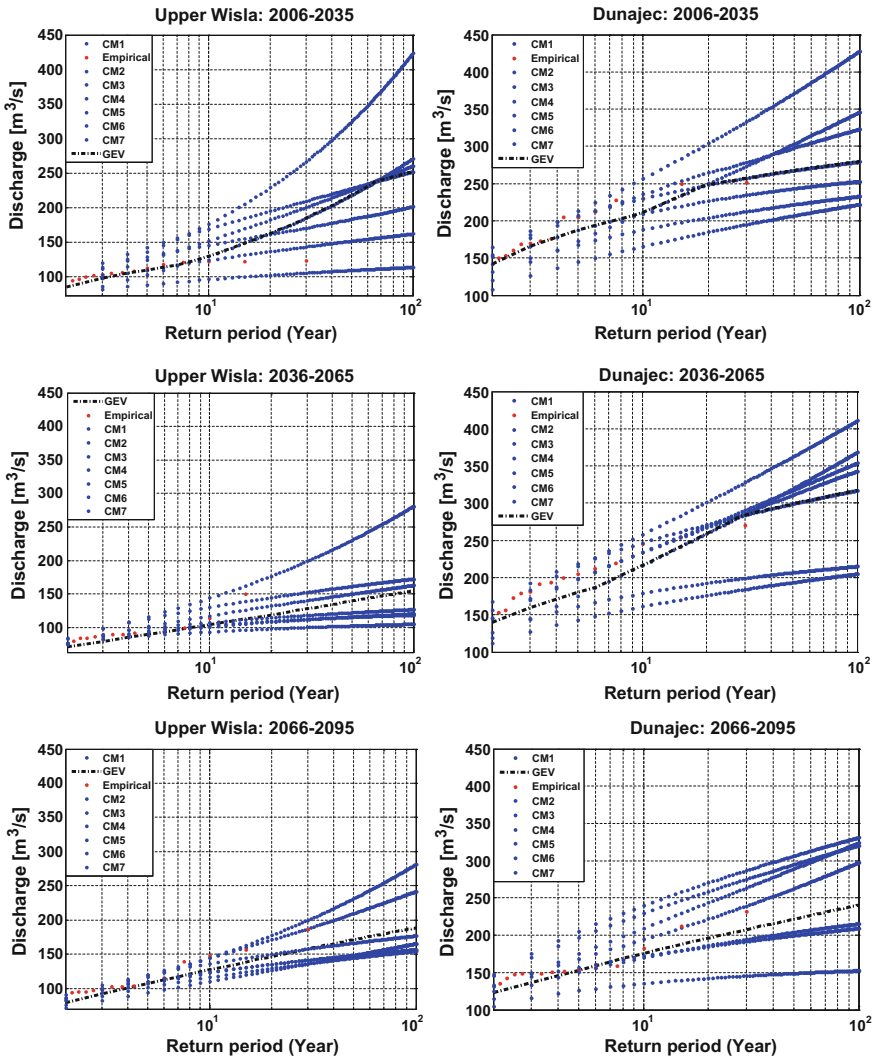
Subsequently, the climate projections from seven model combinations were used to run the HBV model, and the series of flow simulations were obtained for each catchment and GCM/RCM model projection for the whole time horizon 1971–2100. The annual maximum values of daily flows were derived and used in flood frequency analysis. The derivation of 100 return period quantiles requires an extrapolation of empirical cumulative distribution function (cdf) based on 30-year periods. We selected GEV distribution to be fitted to each ensemble of the projected annual maximum flows following the discussion presented by Lawrence and Hisdal (2011). The obtained cumulative distribution functions as a function of a return period for Dunajec and Upper Wisla are presented in Fig. 5. It illustrates a large spread of  $Q_{100}$  quantiles obtained for different ensemble projections.

In the present study flood indices in the form of  $Q_{30}$  and  $Q_{100}$  for three future periods, 2020s, 2050s and 2080s are compared with those for the reference period 1990s.

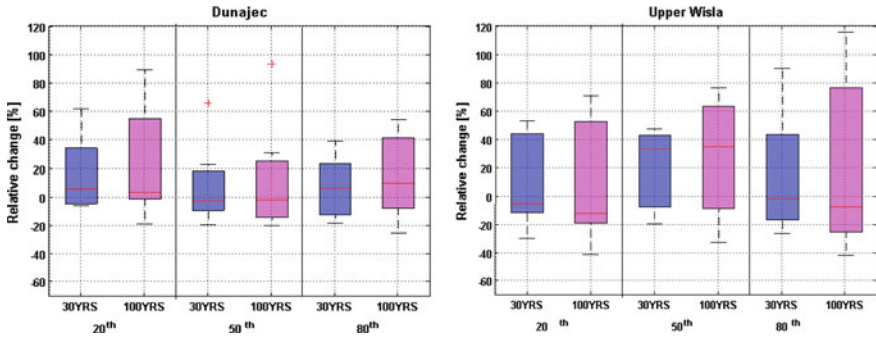
Changes in the  $Q_{30}$  and  $Q_{100}$  quantiles for three future 30-year periods for the Dunajec and the Upper Wisla relative to the reference period 1990s are presented in Fig. 6. The projected changes in both  $Q_{30}$  and  $Q_{100}$  quantiles are consistent with each other but the magnitudes of changes in terms of means and confidence bands differ slightly or moderately between the catchments. Following the medians of quantile changes, the Upper Wisla shows slightly decreasing flood conditions in the 2020s, increasing flood conditions by more than 30 % in the 2050s, and again slightly decreasing in the 2080s. However, if the confidence bands are considered, there is an overall tendency to increasing floods in all three periods.

For the River Dunajec, changes in median values are much smaller (less than 10 % for all but  $Q_{100}$  in the 2080s) and the directions of change are opposite, with a slight increase, minor decrease and subsequent small increase of mean flood quantiles in the three periods studied. However, if the confidence bands are analysed, there is a tendency to increasing floods in all periods also for this catchment. Some differences in behaviour of both catchments can be caused by different flood regimes, with the Dunajec being rainfall-dominated and the Upper Wisla being of mixed regime, but also it can be due to the local atmospheric circulation patterns. However, if we look at the overall picture, most projections of changes in flood quantiles for both catchments show positive changes, with larger variability for the Upper Wisla than for the Dunajec.

Direct comparison of our findings with the results of Alfieri et al. (2015) is not possible because of too large differences in spatial scales. However, we can conclude that our findings support the tendency of positive changes presented by the large-scale analysis in both cases. The annual sums of precipitation show some variability, but these changes are not very well defined. Therefore at this stage, the explanation of some differences in the projections of future flood changes in both catchments lies in the climatic variability and the uncertainty of results.



**Fig. 5** Cdfs for annual maximum daily flows for the Dunajec (*right panel*) and Upper Wisla (*left panel*) obtained for seven driving GCMs/RCMs projections for three 30-year periods: 2020s, 2050s and 2080s; *blue dotted lines* present the GEV fit for each model; *median GEVs* from the ensembles are shown by *black dashed lines*; *red dots* present ensemble median values of projected annual maximum flows (color figure online)



**Fig. 6** Estimated changes in  $Q_{30}$  and  $Q_{100}$  using GEV for 2020s, 2050s and 2080s relative to the reference period 1990s, based on projections from HBV driven by seven GCM/RCMs together with 0.95 confidence bands: Dunajec *left panel* and Upper Wisla *right panel*

## 7 Impact on Climate Change Adaptation and Flood Risk Reduction

The lack of agreement in projections between studies can be interpreted and understood by scientists, but not readily by stakeholders. Despite the caveats accompanying large-scale flood hazard projection studies (Dankers et al. 2014), stakeholders may look at maps of projections from different sources that strongly diverge in the area of their interest, take results at face value, and become confused. This is how the discrepancy in flood hazard projections is regarded by practitioners in Poland (Kundzewicz et al. 2016).

Stationarity is dead (Milly et al. 2008, 2015), yet, the signal-to-noise ratio in flood hazard projections is low. In other words, the noise dominates and overshadows a weak (if any) signal. Non-stationarity means that a design flood (e.g. a 50-year or a 100-year event) for a particular location, established from historical observations in the reference period, can be dramatically different from a, possibly broad, range of values projected for a future time horizon of importance for adaptation. However, despite the huge uncertainty in flood hazard projections, practitioners and water managers in some European countries and regions already try to incorporate the potential effects of climate change into specific design guidelines, by a precaution-based adjustment, acknowledging increase in intense precipitation in the warming climate (Kundzewicz et al. 2008). An example of a climate change adjustment factor for a design flood is a specified relative increase of a 100-year flood in a specified future time horizon, incorporated in design guidelines. Madsen et al. (2014) compiled information on existing guidelines on climate change adjustment factors on design flood and design rainfall in six European countries (Belgium, Denmark, Germany, Norway, Sweden, UK). Such adjustments were also proposed in The Netherlands (Kundzewicz 2012).

Decision-makers responsible for flood protection and climate adaptation have to be aware of the added uncertainty introduced by enhanced greenhouse forcing

(Kundzewicz et al. 2014). According to the Polish Water Law and the EU Floods Directive (2007), flood hazards and flood risk maps were prepared for three different flood return periods (recurrence intervals): short ( $\geq 10$  years), medium ( $\geq 100$  years) and long ( $\geq 500$  years). The main objectives of national flood adaptation strategy in Poland are to minimize the vulnerability to flood risks associated with changes in climate, and include this issue in the planning phase of future investments. The adaptation policy for Poland in future climate conditions was outlined for the time intervals ending in 2020 and 2070 in two separate papers (IOŚ-PIB 2013a, b), both published by the Ministry of Environment and covering all sectors vulnerable to floods, included in the “White Paper”. Vulnerable sectors include water management, urban and rural spatial planning. However, the legislative regulations relating to local spatial planning still have to be established (Doroszkiewicz et al. 2016).

## 8 Outlook and Concluding Remarks

The vast spread of river flood hazard projections for Central Europe and Poland has to be interpreted with caution, especially by decision makers in charge of climate change adaptation, flood risk reduction, and water resources management. At the present stage, there are some differences in the projections of future flood changes in two analyzed catchments in the Upper Vistula Basin that are likely to be due to the climatic variability and the uncertainty of results. We are far from knowing the future reality, but projections for the future, despite the inherent uncertainty, are important to inform processes of flood risk reduction and adaptation to climate change, sketching the range of possible futures. At the same time, there is no doubt that a better preparedness for existing climate variability is necessary, but this is unlikely to be sufficient for future changes (Field et al. 2012; Kundzewicz et al. 2014) in areas with increasing flood hazard.

In some “problematic” regions, such as Central Europe, rain-floods and snow-floods both influence future flood changes. Researchers may be encouraged to separately investigate rain-caused floods and snow-caused floods in the analysis, and to determine which of these are dominant in particular river basins, for present and future conditions.

Projected climate-driven changes in future flood frequency are complex, depending on the generating mechanism, e.g., increasing flood magnitudes where floods result of increasing heavy rainfall and decreasing magnitudes where floods are generated by less abundant spring snowmelt (Kundzewicz et al. 2010).

For the time being, there is no conclusive and general proof as to how climate change affects flood behaviour. There is a scarcity of studies detecting, in a persuasive way, an influence of anthropogenic climate change on rain-generated peak streamflow trends. Natural variability is strong. Detection and attribution research for river flooding is not easy to carry out. The conventional attribution framework



struggles with the low signal-to-noise ratio and uncertain nature of the forced changes (Trenberth et al. 2015).

Flood hazard is influenced by multiple climatic and non-climatic factors, whose relative importance is site-specific. Climatic factors include predominantly changes in intense precipitation and snowmelt, but changes in any component of the hydrological cycle, e.g. precipitation and evaporation also play a role. Non-climatic factors include changes (mostly anthropogenic) in rivers themselves, e.g. modification of river channels, such as construction of water structures—dikes and dams, channel shortening, removal of flood plains, and changes in catchments, such as urbanization, deforestation, drainage of wetlands, and other factors (Hall et al. 2014).

As exemplified by the derived flood indices for two Polish catchments, Upper Wisla and Dunajec, flood hazard projections for future climate are strongly uncertain. However, that uncertainty should not be used as an excuse for a lack of adaptation strategy. In contrast, it should encourage the governments to put more effort in preparing adaptation strategies that can face that uncertainty.

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