



## Differences in flood hazard projections in Europe – their causes and consequences for decision making

Z. W. Kundzewicz, V. Krysanova, R. Dankers, Y. Hirabayashi, S. Kanae, F. F. Hattermann, S. Huang, P. C. D. Milly, M. Stoffel, P. P. J. Driessen, P. Matczak, P. Quevauviller & H.-J. Schellnhuber

To cite this article: Z. W. Kundzewicz, V. Krysanova, R. Dankers, Y. Hirabayashi, S. Kanae, F. F. Hattermann, S. Huang, P. C. D. Milly, M. Stoffel, P. P. J. Driessen, P. Matczak, P. Quevauviller & H.-J. Schellnhuber (2017) Differences in flood hazard projections in Europe – their causes and consequences for decision making, *Hydrological Sciences Journal*, 62:1, 1-14, DOI: [10.1080/02626667.2016.1241398](https://doi.org/10.1080/02626667.2016.1241398)

To link to this article: <https://doi.org/10.1080/02626667.2016.1241398>



© 2016 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



Published online: 25 Oct 2016.



[Submit your article to this journal](#)



Article views: 5434



[View related articles](#)



[View Crossmark data](#)



Citing articles: 23 [View citing articles](#)

## Differences in flood hazard projections in Europe – their causes and consequences for decision making

Z. W. Kundzewicz<sup>a,b</sup>, V. Krysanova<sup>b</sup>, R. Dankers<sup>c</sup>, Y. Hirabayashi<sup>d</sup>, S. Kanae<sup>e</sup>, F. F. Hattermann<sup>b</sup>, S. Huang<sup>f</sup>, P. C. D. Milly<sup>g</sup>, M. Stoffel<sup>h,i,j</sup>, P. P. J. Driessen<sup>k</sup>, P. Matczak<sup>a,l</sup>, P. Quevauviller<sup>m</sup> and H.-J. Schellnhuber<sup>b</sup>

<sup>a</sup>Institute for Agricultural and Forest Environment, Polish Academy of Sciences, Poznań, Poland; <sup>b</sup>Potsdam Institute for Climate Impact Research, Potsdam, Germany; <sup>c</sup>Met Office, Exeter, UK; <sup>d</sup>Institute of Engineering Innovation, University of Tokyo, Tokyo, Japan; <sup>e</sup>Department of Mechanical and Environmental Informatics, Tokyo Institute of Technology, Tokyo, Japan; <sup>f</sup>The Norwegian Water Resources and Energy Directorate, Oslo, Norway; <sup>g</sup>US Geological Survey, Princeton, NJ, USA; <sup>h</sup>Climatic Change and Climate Impacts, Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland; <sup>i</sup>Department of Earth Sciences, University of Geneva, Geneva, Switzerland; <sup>j</sup>dendrolab.ch, Institute of Geological Sciences, University of Berne, Berne, Switzerland; <sup>k</sup>Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands; <sup>l</sup>Institute of Sociology, Adam Mickiewicz University, Poznań, Poland; <sup>m</sup>Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Brussels, Belgium

### ABSTRACT

This paper interprets differences in flood hazard projections over Europe and identifies likely sources of discrepancy. Further, it discusses potential implications of these differences for flood risk reduction and adaptation to climate change. The discrepancy in flood hazard projections raises caution, especially among decision makers in charge of water resources management, flood risk reduction, and climate change adaptation at regional to local scales. Because it is naïve to expect availability of trustworthy quantitative projections of future flood hazard, in order to reduce flood risk one should focus attention on mapping of current and future risks and vulnerability hotspots and improve the situation there. Although an intercomparison of flood hazard projections is done in this paper and differences are identified and interpreted, it does not seem possible to recommend which large-scale studies may be considered most credible in particular areas of Europe.

### ARTICLE HISTORY

Received 1 July 2016  
Accepted 21 September 2016

### EDITOR

D. Koutsoyiannis

### ASSOCIATE EDITOR

not assigned

### KEYWORDS

flood hazard; climate change; projections; science–policy interactions; decision making; Europe

## 1 Introduction

Flood damage has grown considerably in Europe as wealth in flood-prone areas has accumulated. Many destructive floods have been recorded in recent decades, with the costliest one in August 2002 affecting several European countries. Other destructive flood locations include: Italy in November 1994 and October 2000; the UK in October 2000, summer 2007, and winters 2013/14 and 2015/16; Central Europe in July 1997, summer 2010, and June 2013; the Balkan region in May 2014; and, most recently, Germany, France and Belgium in June 2016. Recent floods have set new stage and discharge records (e.g. on the Oder/Odra in July 1997, on the Elbe and its tributaries in August 2002, on the Vistula and its tributaries in May and June 2010, on the Upper Danube in July 2013 and on many UK rivers in January 2016), so there is widespread concern that not only flood damage but also flood hazard could be on the rise.

In the past decade there has been a multitude of studies providing future projections of changes in flood

hazard and risk in Europe. The European Floods Directive (EU 2007) generalizes: “*the scale and frequency of floods are likely to increase in the future as a result of climate change, inappropriate river management and construction in flood risk areas.*” However, especially at the regional and local scale the projections provided by different studies are not always in agreement. Often, the changes projected into the future are not supported by observed trends: observational records do not indicate a robust and ubiquitous increase in the amplitude and frequency of high river flows throughout Europe (Kundzewicz 2012), though an increasing tendency in the number of floods with large magnitude and severity has been noted in Europe (Kundzewicz *et al.* 2013).

The present paper aims to identify and interpret differences in flood projections over Europe from a process perspective and to discuss implications for management and for science–policy interactions.

## 2 Differences between flood hazard projections and their interpretation

### 2.1 Comparison of projections

There have been many publications devoted to large-scale projections of changes in flood frequency and intensity, covering the European continent. Lehner *et al.* (2006), Dankers and Feyen (2009), Rojas *et al.* (2011, 2012), Alfieri *et al.* (2015) and Roudier *et al.* (2016) reported projections for Europe only, while Hirabayashi *et al.* (2008, 2013), Dankers *et al.* (2014), Giuntoli *et al.* (2015) and Arnell and Gosling (2016) covered the whole globe. Projections for specific European regions and countries differ between these 11 studies (Table 1). Projections from most European-scale studies (except Lehner *et al.* 2006, reporting largely different results) show some robustness and similarity, in general. However, there is much less agreement on projections of flood hazard in Europe (i) between the European-scale and global-scale studies, as well as (ii) between different global-scale studies. There is a systematic difference between projections of changes in flood hazard in southeastern Europe (Italy, Greece, Iberian Peninsula) in most European and most global studies. European-scale studies (except Lehner *et al.* 2006) are mostly based on the same hydrological model, LISFLOOD, while Roudier *et al.* (2016) additionally included two other hydrological models. Differences between projections in the earlier suite of models were indicated by Kundzewicz *et al.* (2010). Comparing projections, one can find areas of agreement and of disagreement. In general, flood frequency projections for Europe reported by Alfieri *et al.* (2015) differ from those by Hirabayashi *et al.* (2013) and Dankers *et al.* (2014) which, in turn, differ from earlier projections produced by Hirabayashi *et al.* (2008) and Dankers and Feyen (2009). Also, differences in recent projections by Roudier *et al.* (2016) and Giuntoli *et al.* (2015) are considerable. In brief, projections of changes in flood hazard in Europe, resulting from large-scale studies, are seemingly not robust. The reasons for this will be explored in Section 2.2.

Alfieri *et al.* (2015) concluded that, for European countries, global warming would increase  $Q_{100}$  (100-year flow, i.e. river discharge with exceedence probability in any one year being 0.01) by 18–256% between 1990 and 2020. On average, in Europe,  $Q_{100}$  established for the control period is projected to double in frequency within three decades. Changes for further time horizons are less consistent. Rojas *et al.* (2011, 2012) illustrated a dominant increase of frequency of  $Q_{100}$  for much of Europe. In contrast, recent projections of change in flood hazard reported by Hirabayashi *et al.*

(2013) indicate flood frequency decrease in much of Northern, Central, and Southern Europe. Only for part of Europe (British Isles, northern France, and part of Benelux), are prevailing increases in frequency of  $Q_{100}$  projected. A multi-model intercomparison by Dankers *et al.* (2014) found agreement on projected increases in flood frequency ( $Q_{30}$ ) only for the British Isles.

Projections by Rojas *et al.* (2012) and Alfieri *et al.* (2015) agree across most of Western Europe, but considerable differences exist for much of Poland, the eastern part of Germany, part of Romania and Bulgaria, Spain and Finland. The most recent work on Europe by Roudier *et al.* (2016) largely corroborates the findings of Alfieri *et al.* (2015).

Uncertainty also shows up at the national scale (cf. Madsen *et al.* 2014). Figure 1 illustrates two projections of changes in flood hazard over Germany that agree over many areas but disagree over considerable areas as well. Where the two projections agree on the direction of change, they may still differ (at places, strongly) in the amplitude of the projected change.

Even though understanding of climate and water systems as well as flood risk in Germany is well advanced (see Hattermann *et al.* 2014, 2016), with multiple studies and rich observational records available, the uncertainty in the projections is still notable.

The projections presented in Fig. 1 correspond to two generations of emissions scenarios available with a time gap of a little over a decade only (Special Report on Emissions Scenarios, SRES A1B in Fig. 1(a) and representative concentration pathways, RCP 8.5 in Fig. 1(b); see Nakicenovic *et al.* (2000) for SRES and Moss *et al.* (2010) and Meinshausen *et al.* (2011) for RCP), driving an ensemble of climate models, and the SWIM hydrological model, well tested for German conditions (Krysanova *et al.* 2015). The ensemble of climate models for the A1B scenario corresponds to the European ENSEMBLES project (van der Linden *et al.* 2009), while models for the RCP 8.5 scenarios stem from the CORDEX (Coordinated Downscaling Experiments) initiative (Jacob *et al.* 2014). The time horizon of projections presented in Fig. 1 is 2071–2099 or 2071–2100 (some scenarios only last until 2099), while the common reference period is 1971–2000.

### 2.2 Interpretation of differences between projections

#### 2.2.1 Causes of differences

Studies of projections of changes in flood hazard differ with respect to emissions scenarios, driving climate models (general circulation models, GCMs, and regional climate models, RCMs) and downscaling techniques, as well

**Table 1.** Comparison of studies on large-scale projections of changes in flood frequency and intensity.

Paper	Number of climate model scenarios	Number of hydrological models	Variable	Time period	Emissions scenario	Central Europe	WE: British Isles	EE: Eastern Europe	NE: Scandinavia, Finland	SE: Iberia	SE: Italy, Greece
<i>European-scale studies</i>											
Roudier <i>et al.</i> 2016	5 RCM/GCM combinations	3: LISFLOOD, E-HYPE, VIC	Q <sub>100</sub>	+2°C*	RCP 2.6, 4.5, 8.5	↑	↑	↓N ↑C, S	↓↑	↑	↑
Alfieri <i>et al.</i> 2015	7 EURO-CORDEX	1: LISFLOOD	Q <sub>100</sub>	2080s	RCP 8.5	↑↓	↑JN	JN ↑S	↓↑	↑N ↓S	↑
Rojas <i>et al.</i> 2012, 2011	1: HIRHAM5-ECHAM5	1: LISFLOOD	Q <sub>100</sub>	2070–2099	A1B	↑JNE	↑	↓↑S	↑ Jmix	↑ Jmix	↑↓
Dankers and Feyen 2009	5 RCMS	1: LISFLOOD	Q <sub>100</sub>	2071–2100	A2, B2	↑ NW SE↑C	↑	↓↑	↓↑	↑ Jmix	↑ Jmix
Lehner <i>et al.</i> 2006	2 GCMS	1: WATERGAP	Q <sub>100</sub>	2070s	A1B	↓↑	↑ Jmix	↓↑	↑	↑↓	↑ Jmix
<i>Global-scale studies</i>											
Giuntoli <i>et al.</i> 2015	5 GCMS	6 GHMs	Frequency of high-flow days	2066–2099	RCP 8.5	–	–	–	↑	–	–
Dankers <i>et al.</i> 2014	5 GCMS	9 GHMs	Q <sub>30</sub>	2070–2099	RCP 8.5	↑ W ↑E	↑	↓	↓↑	↓	↓
Arnell and Gosling 2016	21 GCMS	1: Mac-PDM.09	Q <sub>100</sub>	2050s	A1B	↓↑W	↑	↓↑	↑ Jmix	↑N ↓S	↑
Hirabayashi <i>et al.</i> 2013	11 GCMS	11 AOGCMS	Q <sub>100</sub>	2071–2100	RCP 8.5	↑NW↑SE	↑	↓↑	↓↑	↓↑NW	↑
Hirabayashi <i>et al.</i> 2008	1: MIROC	1: MATSIRO LSM	Q <sub>100</sub>	2071–2100	A1B	↑↓	↑	↑↓	↓↑	↓ C ↑ SN	↑ Jmix

↑ mostly increase

↑ partly (in sub-areas) increase

↓ mostly decrease, in sub-areas increase

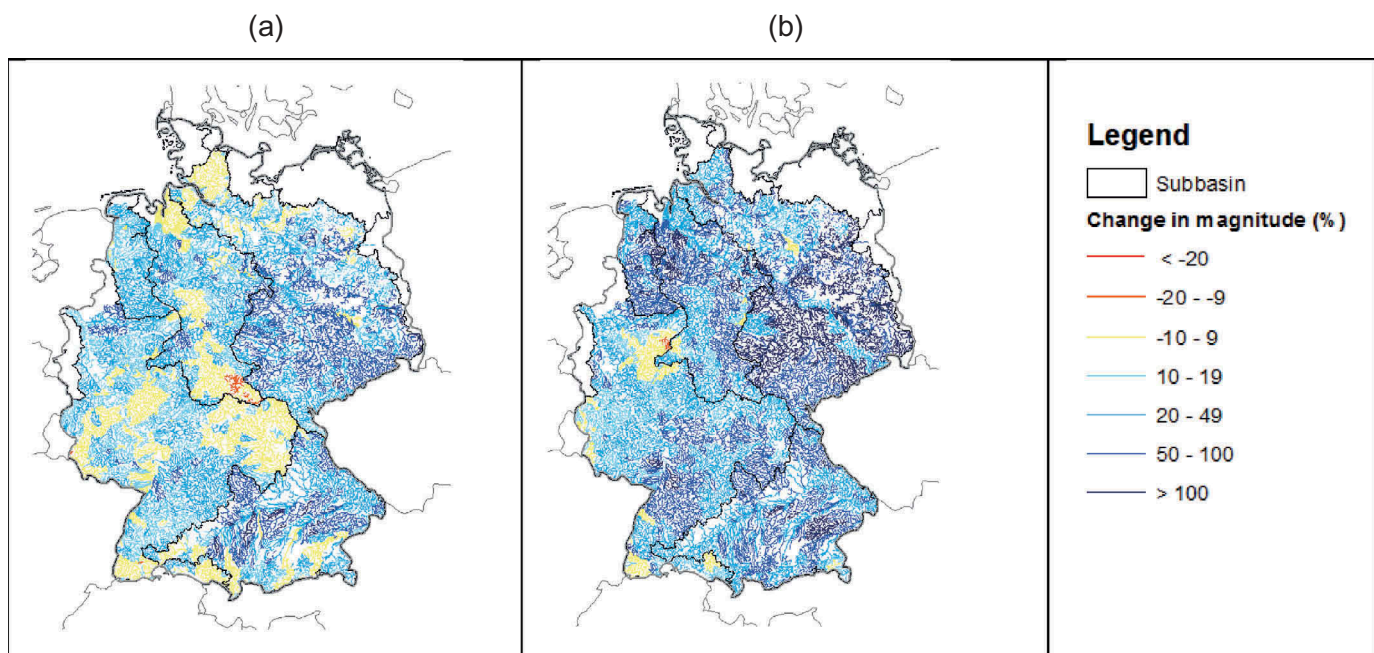
↓ mostly decrease, in some sub-areas increase

JN ↑S decrease in N, increase in S

↑ Jmix: mixed patterns

– no significant changes

\*reference to time instant when the global warming reaches 2°C above the pre-industrial level



**Figure 1.** Projected change in  $Q_{100}$  in Germany: (a) mean from 13 A1B scenarios and (b) mean from 15 RCP 8.5 scenarios. The GCMs used are: (a) HadCM (three realizations), ARPEGE, ECHAM5 (two realizations) and BCM; and (b) MPI-ESM-LR, CNRM-CM5-LR, EC-EARTH, IPSL-CM5A-MR and HadGEM2-ES. Source: unpublished results obtained at Potsdam Institute for Climate Impact Research (PIK).

as bias correction methods. Further, there are differences in simulation of hydrological processes by global hydrological models (GHMs) and regional hydrological models (RHMs) and their performance, especially for extremes, as well as general problems related to extreme value techniques applied for time series that are not long enough. Differences can also be found in the time horizons of future projections, as well as resolution of impact models, and return period. Also the control (reference) intervals often differ between studies, being 1901–2000 for Hirabayashi *et al.* (2008), 1961–1990 for Rojas *et al.* (2011, 2012), 1971–2000 for Hirabayashi *et al.* (2013), Dankers *et al.* (2014) and Roudier *et al.* (2016), 1972–2005 for Giuntoli *et al.* (2015) and 1976–2005 for Alfieri *et al.* (2015). Table 1 includes information on the differences in technicalities of recent studies that can explain, to some extent, the differences in flood hazard projections.

### 2.2.2 Different scenarios of greenhouse gas emissions

One clear reason for differences in projections is related to emissions scenarios. Typically, flood hazard projections are based on either SRES scenarios, in older papers, or RCPs, in newer papers, except for a recent paper by Arnell and Gosling (2016), still based on SRES scenarios. Differences between particular SRES and between particular RCP scenarios are substantial, while the overall difference between a selected SRES

scenario and the nearest RCP scenario may be not large. Despite the difference in applied scenarios (A1B and RCP 8.5, respectively), studies by Hirabayashi *et al.* (2013) and Arnell and Gosling (2016), based on many GCMs, show similar results except for Scandinavia.

### 2.2.3 Different driving climate models

Selection of GCMs is a large source of uncertainty in climate impact studies, in general. In studies before Dankers and Feyen (2009) mostly one GCM output was used, whereas more recently model ensembles have been applied. Dankers and Feyen (2009) used two RCMs. Hirabayashi *et al.* (2013) and Dankers *et al.* (2014) analysed results driven by eleven GCMs and five GCMs, respectively, while Alfieri *et al.* (2015) used three GCMs downscaled by four RCMs (seven Euro-Cordex scenarios). Roudier *et al.* (2016) used five GCM/RCM combinations and Giuntoli *et al.* (2015) used five GCMs. This can clearly explain a major portion of the differences in flood hazard projections.

These differences arise from the different climate models for a number of reasons; the most obvious one being that they do not agree in themselves on the projected changes in heavy rainfall events (Nicholls and Seneviratne 2015). Although 1-day precipitation extremes may not be immediately relevant to flooding in large river basins, a recent increase in record-breaking precipitation events has been observed (Lehmann *et al.* 2015). Indeed, a warmer atmosphere can retain more

moisture in line with the Clausius-Clapeyron law, and model-based projections indicate a likely increase in frequency of heavy precipitation. However, model skill in reproducing extreme storm events, given a change in forcing, is not persuasive. The underestimation of historical rainfall extremes by the climate models may suggest underestimation of precipitation in projections.

#### 2.2.4 Multiple runs to reflect natural variability

To some extent the results are also affected by the simulated natural variability and sequence of events (the “weather”) in the individual climate model simulations. Dankers and Feyen (2008) showed how individual runs of the same climate model, starting from different initial conditions, can result in different projections, especially at the local scale. This finding suggests that, ideally, studies looking into changes in hydro-meteorological extremes should use multiple realizations of a single model (rather than just one realization), in addition to multi-model ensembles, in order to take account of natural variability. However, this is done rarely.

#### 2.2.5 Bias correction

Climate models show large biases in their simulations of the present-day climate, in particular intense precipitation. If a raw GCM/RCM output is used to drive hydrological models, the resulting output is not realistic relative to observations. Hence, some form of bias correction is needed (see Rojas *et al.* 2011) to anchor the model control period to observations. The bias correction of the climate model, accomplished prior to being used as input to a hydrological model, plays an important role in the projections of flood frequency and magnitude and it can be an additional source of uncertainty in Table 1. There exist a number of bias correction methods that alter the mean, variance, distribution and extremes of climate model output (typically temperature and precipitation), and flood statistics are sensitive to the selected bias correction method.

#### 2.2.6 Different types of flooding

Flood hazard may be specifically connected, regionally or locally, to particular flood types and temporal/spatial scales that are not adequately covered by the conceptualization of the processes in the large-scale models. Even if projections refer to river flood hazard, they do not comprehensively take account of the complex typology of floods (e.g. inundations caused by convective or frontal rainfall, snowmelt, ice-jam, rain-on-snow, rain-on-ice). Hence, the results of the projections could more appropriately be seen as indicators of changes in flood hazard. Flood typology relies on meteorological inputs and also

on catchment controls and flood time scales (elevation, catchment scale, river scale etc.) (see Gaál *et al.* 2015).

Major discrepancies in projections seem to occur in Northern Europe, where different types of flooding exist (snowmelt floods and rainfall floods). Depending on how climate models project changes in variables relevant for the different flood-generation processes and how hydrological models simulate snowmelt and runoff processes, this may result in diverging projections (see Rojas *et al.* 2012, Giuntoli *et al.* 2015, Roudier *et al.* 2016). Another problem in snow-dominated regions is that, according to the principles of extreme value theory, one cannot pool extreme events originating from different mechanisms. Hence, snowmelt high flows should be treated separately from rain-fed high flows, but for the time being, large-scale modelling studies that treat them separately barely exist.

#### 2.2.7 Different types of hydrological models

The studies listed in Table 1 use a range of hydrological modelling approaches. Dankers *et al.* (2014) examined nine global hydrological models (GHMs), finding that the different models sometimes provide surprisingly contrasting projections of changes into the future, even though they were driven by the same climate input. This suggests that, in addition to climate model uncertainty, hydrological modelling uncertainty can also be important (Dankers *et al.* 2014). In this vein, Roudier *et al.* (2016) used three large-scale hydrological models and Giuntoli *et al.* (2015) used six GHMs. This can also explain a significant portion of the differences in projected flood hazard.

Another important reason for uncertainty of results is that, in large-scale studies, global hydrological models are usually applied without any calibration/validation at the catchment scale. Hirabayashi *et al.* (2008, 2013) presented some model evaluations of the MATSIRO model (Hirabayashi *et al.* 2008, Figures 2–4) and 11 AOGCMs (Hirabayashi *et al.* 2013, Figures S1 and S2), all based on probability plot correlation coefficients. Three other, more recent, global-scale papers applying GHMs, i.e. Dankers *et al.* (2014), Giuntoli *et al.* (2015) and Arnell and Gosling (2016), did not include any evaluation or validation. Uncalibrated global models may still provide consistent and coherent simulations across very large scales and are useful for obtaining global overviews, but they have to compromise the model performance in individual catchments to obtain simulation results over global and continental scales. This can also be responsible for some of the differences in flood hazard projections.

However, all European-scale studies include a description of the calibration and evaluation of the models being used, and focus on flood characteristics in their model

evaluation. Lehner *et al.* (2006) calibrated and evaluated the WaterGAP model for 15/39 stations, Dankers and Feyen (2009): LISFLOOD for 209 stations, Rojas *et al.* (2011, 2012): LISFLOOD for 258 stations, Alfieri *et al.* (2015): LISFLOOD for 693 stations, and Roudier *et al.* (2016): LISFLOOD, VIC and E-HYPE for 428 stations.

Hence, all European-scale studies since 2008 are based on calibrated and evaluated models, and are mostly in good agreement for all studies since Lehner *et al.* (2006). However, it is worth noting that these studies are based on the same hydrological model, LISFLOOD. Only the last study (Roudier *et al.* 2016) additionally includes two other models, E-HYPE and VIC (providing projections that mostly agree with the previous ones based on LISFLOOD only). The LISFLOOD and E-HYPE models are based on the basin-scale model versions applied to a larger (continental) scale.

The projections of the global-scale studies, based on non-validated global hydrological models, are quite different from the European-scale studies, with calibrated and validated models, and they also differ from each other. Projections by Giuntoli *et al.* (2015) are different from European studies for all regions (except for Scandinavia in the study by Lehner *et al.* 2006); those by Dankers *et al.* (2014) are similar only for the British Isles, Scandinavia and Finland; those by Arnell and Gosling (2016) are similar only for Western and Eastern Europe, and to Rojas *et al.* (2012) also for Northern Europe.

It could be expected that models calibrated and validated for a particular gauging station provide more realistic simulations under historical control conditions; yet the assumption that the calibrated model parameters will remain constant for future climate is unlikely to be true (Merz *et al.* 2011). A hydrological model that is well tuned to historical conditions may not always provide plausible projections under significantly different future climate.

Also, good model performance in simulating discharge at the catchment outlet may mask variable performance across the catchment, and in other variables. Representing spatial patterns on maps assumes that the model has some skill, ideally demonstrated through validation at intermediate gauges. Likewise, if climate change impacts on extremes are investigated, the model performance for extremes needs to be evaluated. However, these rules are not always followed strictly by modellers. Therefore, under a high-end climate change scenario (RCP 8.5) for the end of the century and for extreme events, modelling is connected with a high uncertainty.

### 2.2.8 Climate vs hydrological model uncertainty

A discussion on climate model vs hydrological model uncertainty, in view of the recent multi-model (GCM

and GHM) studies, was presented by Hagemann *et al.* (2013), who showed that uncertainties in projected runoff are predominantly associated with GCMs; Wada *et al.* (2013), who projected future irrigation water demand and showed that GHMs dominate in the overall uncertainty in some regions; Schewe *et al.* (2014), who concluded that both GCMs and GHMs contribute essentially to uncertainty; and Giuntoli *et al.* (2015), who showed that climate model uncertainty dominates at the global scale, but that GHMs are the greatest source of uncertainty in snow-dominated regions. Also, Roudier *et al.* (2016) found a better agreement for three applied models in Central and Southern Europe compared to Fennoscandinavia.

### 2.2.9 Different return periods

In studies of changes in river flood frequency, the notion of  $Q_{100}$  is widely used, but some authors use other return periods or high flow percentiles. Giuntoli *et al.* (2015) made projections for changes in frequency of high river flows (runoff equalled or exceeded 5% of the time). Dankers *et al.* (2014) studied 30-year 5-day peak flow, i.e. a moderately extreme river discharge. Estimates of extreme river flows are often based on extreme value distributions, and are increasingly uncertain at more extreme discharge levels. This uncertainty is well known in the field of statistics, but in many hydrological studies it is not taken into account. In this respect, an estimate of  $Q_{30}$  based on 30 years of simulations (as in Dankers *et al.* 2014) is obviously more robust than an estimate of  $Q_{100}$  based on 30 years of simulations. Roudier *et al.* (2016) compared  $Q_{100}$  and  $Q_{10}$  for Europe, obtaining a similar broad pattern as far as direction of change is concerned, yet the percentage changes in  $Q_{100}$  are stronger than in  $Q_{10}$ .

### 2.2.10 Presentation of results

The results of different studies are also presented differently. With the increasing uptake of ensemble-based approaches, it is necessary to synthesize the results across multiple model runs, with regard to flood frequency and magnitude. One study may show a set of maps (e.g. for individual GCMs and/or different scenarios), either incorporated in the body of the paper, or available as supplementary information. Alternatively, a single aggregate map can be presented (e.g. for central tendency, such as mean or median of projections), possibly with indication of inter-model spread/variability. Such a map may get broader recognition, such as inclusion in the IPCC (Intergovernmental Panel on Climate Change) material—a map by Hirabayashi

*et al.* (2013) was used in Jiménez *et al.* (2014) and Doell *et al.* (2015). The question then emerges as to how representative the mean model is when discussing frequencies of very different model projections and how an ensemble is summarized for a region. Rich discussion of this issue from a climate modelling perspective may be found in the literature (see Knutti *et al.* 2010).

### 3 Discrepancies between observed trends and projections

Increases in heavy precipitation have been noted in many regions, but the impact on floods has been difficult to detect in observation records. Long time series of high-discharge data show no convincing upward trend in Europe (e.g. Mudelsee *et al.* 2003, Kundzewicz *et al.* 2005, Kundzewicz 2012), while some model-based projections for the future simulate increases over large areas (see Table 1).

The lack of consistency between observations and projections is perhaps not surprising, because stronger anthropogenic climate change started relatively recently. The far-future trend can be different from the past/current trend, because the warming projected until the end of the 21st century is likely to be much stronger than observed so far, especially under the high-end climate change scenarios.

The trend cannot be detected in the observations because the signal-to-noise ratio is low and the natural variability is strong. To put this into context, the probability of exceeding  $Q_{100}$  at least once in a 100-year period is about 63%, so there is still a chance of 37% of not observing  $Q_{100}$  at all. However, a robust identification of trends in  $Q_{100}$  will ideally require multiple exceedences of very extreme river flow levels, and the probability of exceeding  $Q_{100}$  at least three times in any period of 100 years is only about 8% (Cloke and Pappenberger 2009).

The failure to detect a ubiquitous rising trend has apparently been a surprise to some experts regarding recent flood events as possible harbingers of climate-related flood risk rise, for example, a sarcastic and exaggerated title chosen by Schiermeier (2003): “*Analysis pours cold water on flood theory*”, when referring to failure to detect trends by Mudelsee *et al.* (2003).

However, because of the interplay between long-term trends, decadal-scale natural variability, nonlinearities and thresholds in the climate system, flood hazard does not have to change monotonically over a long time scale. Alfieri *et al.* (2015) published projections for various time horizons. On average, in Europe,  $Q_{100}$  is projected to double in frequency within three decades. For all 37 European countries considered,

$Q_{100}$  is projected to increase between time horizon 1990 and 2020. However, for most countries, there is no monotonic increase of annual exceedence frequency of the 100-year flood for two further time horizons, 2050 (2036–2065) and 2080 (2066–2095). Also, Kay and Jones (2012) found that changes are unlikely to occur linearly over the coming century and that large changes in flood frequency in the UK can occur over a relatively short time interval, which is something that policy makers need to consider.

#### 3.1 Data issues

Reliable determination of flood frequency trends requires a long time series of good quality river flow data. Often, time series of records are not long enough for trend detection and hydrological networks have typically been shrinking, for budget reasons. Scarcity of ground data of adequate quality and quantity is also a reason for uncertainty in projections, because the material for calibration and validation is not satisfactory.

If trend detection is carried out by considering multiple river stations covering a large region, data limitations in time could be substituted partly by abundance in space, with the caveat that trends may well be influenced by other factors, many of which will be location specific.

Free international hydro-meteorological data exchange, albeit existing in principle, as per resolutions of the World Meteorological Organization, is in fact very limited. Many studies are restricted to pilot sites from individual countries, because acquisition of compatible, harmonized and quality controlled international data can be very difficult within a project time span. Even if a few flood databases do exist, their use for specific goals of international projects is usually limited (see Gaume *et al.* 2009). Beyond laudable bottom-up initiatives to solve the problem, there is a need for a truly European solution (Gaume *et al.* 2009, Hall *et al.* 2015). Suggestions as to how to address the economic barriers of data exchange have not brought the expected effects in the European context thus far (see Viglione *et al.* 2010). Merz *et al.* (2014) called for efforts towards accounting for factors that contribute to changes in all three risk components (hazard, exposure, vulnerability) in order to contribute to the understanding of the interactions between society and floods. They advocated an international multidisciplinary collaboration and data-sharing initiative, which would support the understanding of links between climate and flooding and advance flood research.



#### 4 Attribution

One cannot attribute the occurrence of a specific flood event to climate change. A different framing is needed, demonstrating that the probability of exceedence of a concrete flood discharge (i.e. one that actually occurred) would be different in two cases: without climate change and with climate change due to increased atmospheric greenhouse gas concentrations.

In their rigorous attribution study looking at the flood events in England and Wales in autumn 2000, Pall *et al.* (2011) concluded that the probability of occurrence of this type of events has likely increased because of anthropogenic warming.

It is interesting to seek statistical evidence for an increase of flood magnitudes with increasing global atmospheric CO<sub>2</sub> concentration. Such a study for Europe is not known to the authors at present. However, Hirsch and Ryberg (2012) undertook such an attempt for the coterminous United States and did not find such evidence in any of the four regions defined in their study, while in one region they actually found a statistically significant negative relationship between global atmospheric CO<sub>2</sub> concentration and flood magnitudes. Di Baldassarre *et al.* (2010) also did not find a climate signal in flood data for the entire African continent.

A model-based attempt to find a large-scale transfer function from CO<sub>2</sub> concentration to flood magnitudes should consider both changes in heavy precipitation and changes in the functioning of plants and, therefore, of the hydrological behaviour of catchments. Few hydrological models include this process, which is another example of why even an exceptionally well-tuned and well-evaluated catchment model may not give more reliable projections of the future if it misses key processes like this.

For the time being, there is no conclusive and general proof as to how climate change has been affecting flood behaviour. The conventional attribution framework struggles with the small signal-to-noise ratio and uncertain nature of the forced changes (Trenberth *et al.* 2015). Overall, there is low confidence (due to limited evidence) that anthropogenic climate change has affected the magnitude/frequency of floods.

Looking at attribution of changes in flood hazard, one can identify multiple climatic and non-climatic drivers (Kundzewicz *et al.* 2014), whose relative importance can be site-specific. Climatic factors predominantly include changes in intense precipitation (increasing in a warmer Europe). Snowmelt is likely to decrease in much of a warmer Europe, even if warming may not necessarily reduce snowmelt

everywhere, e.g. if it is accompanied by an increase in precipitation during the snow accumulation season. Warming is more likely to bring the snowmelt season (and snowmelt floods) forward to earlier in the year. However, changes in other components of the hydrological cycle (e.g. soil moisture) also play a role. There are considerable uncertainties in projecting future evapotranspiration. Non-climatic factors include changes (mostly anthropogenic) in rivers themselves, such as modification of river channels (e.g. dikes and dams), and changes affecting runoff coefficient and available water storage capacity in catchments, such as urbanization, deforestation and drainage of wetlands (see Hall *et al.* 2014). In some basins, non-climatic factors can be largely responsible for changes in frequency of flood events (see Di Baldassarre *et al.* 2009, Blöschl *et al.* 2013).

#### 5 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 studies (see Dankers *et al.* 2014), stakeholders in regions where no local flood hazard projections are available eagerly look at large-scale maps from different sources that may 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 (IMGW *et al.* 2015). What would a practitioner from the Iberian Peninsula, Italy or Greece think of the robustness and credibility of projections on seeing the results of Roudier *et al.* (2016) that convey information about the increase of flood hazard there, the results of Giuntoli *et al.* (2015) showing no significant changes, and the results of Dankers *et al.* (2014) informing us of a decrease in flood hazard? These three recent large-scale studies, published in high-impact periodicals, show largely different results.

Even if national-level projections exist, a local practitioner, responsible for climate change adaptation or flood risk reduction, seeing considerable differences between projected changes for her/his area of interest, as visualized in Fig. 1, may be puzzled. Adapt to what?

In order to manage flood risk, projections for the future are useful. However, the lack of a clear science message challenges flood risk management. The precautionary principle as the basis for decision making can become politicized (Beven 2011), while public perception of the causes of floods may become detached

from scientific evidence (Calder and Aylward 2006). Flood experts encounter difficulties in communicating a complex message to the public (Hoss and Fischbeck 2016). Ambiguous predictions offered by science increase the role of the cognitive biases of human perceptions in decision making (Merz *et al.* 2015).

Large-scale analyses should be understood as sensitivity studies that help in determining orientation. Regional and local, catchment-specific, studies, tuned to the small-scale conditions and observed discharge, should take account of relevant (climatic and non-climatic) uncertainties, and be used to inform decision makers about adaptation. They could also be compared with large-scale (global or continental) studies for the specific region.

Existence of long-term change violates the stationarity assumption (see the discussions in Milly *et al.* 2008, 2015, Koutsoyiannis and Montanari 2015), yet noise, including multi-decadal natural variability, is dominant. There has never been stationarity in flood frequency—except in the minds of hydrologists. Non-stationarity means that a present-day design flood (e.g.  $Q_{100}$ ) for a particular location, established from historical observations in the reference period, can be dramatically different from a design flood value projected for a future horizon of importance for adaptation.

There is no doubt that better preparedness for existing climate variability is necessary, but this is unlikely to be sufficient for future changes (see Field *et al.* 2012) in areas with increasing flood hazard. Preparedness implies not only adequate knowledge, but also effective governance capacity and a transparent and comprehensive division of responsibilities (Runhaar *et al.* 2016). It is necessary to develop adaptive risk reduction strategies and associated governance arrangements (Hegger *et al.* 2014) in order to keep destructive water away from people and property, and keep people and property away from destructive water in the changing climate. An important element in this respect is to diversify flood risk strategies, i.e. to provide a multitude of flood risk measures—complementing the “classic” flood defence measures with flood prevention, mitigation, preparation and recovery—as a backup in case one strategy fails (Hegger *et al.* 2014). Designing alternative adaptation pathways, based on different scenarios and projections, is key to an adaptive approach (Raadgever *et al.* 2011). Adaptive flood risk management should rely on a sound *ex-ante* policy analysis, establishing whether a policy transition is required, an assessment of alternative flood risk management strategies, and their planning in anticipation without running the risk of regret of doing too little too late or too much too early (Klijn

*et al.* 2015). This should allow the course of action to be reconsidered once new information becomes available. Hence, a long-term commitment is needed to iterative policy revision, flexibility and learning in the broader governance system. Finally, there is a need to develop and apply appropriate science–policy interfaces that stimulate interaction between processes of knowledge production and knowledge utilization (van Enst *et al.* 2016)

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). In parts of Europe, water management specialists are already incorporating the potential effects of climate change into specific design guidelines, by a precaution-based adjustment, acknowledging increases in intense precipitation in the warming climate. An example of a climate change adjustment factor for a design flood is a relative increase of  $Q_{100}$ , incorporated in design guidelines. Madsen *et al.* (2014) compiled information on existing guidelines on climate change adjustment factors for 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). Ideally, it may be possible to identify “no-regret” (or “low-regret”) adaptation options that are open-ended, so that the resultant adaptation strategy can be modified in the face of new scientific evidence or changing societal attitudes to risk (Wilby and Dessai 2010).

Another issue that needs consideration is the mismatch between several projection studies (many of which focus on end of the century time scales) and the time frames relevant for adaptation decisions (more probably the first half of this century).

Besides top-down approaches, which rely heavily on hazard projections, there are also bottom-up approaches that start from the vulnerability of communities (Blöschl *et al.* 2013). The latter are very useful when the uncertainty in projections is large or surprises with high impact (so-called black swans) are possible (Di Baldassarre *et al.* 2016), and low-regret options lend themselves well to application.

As exposure has increased, vulnerability has changed, and both are likely to continue evolving into the future, it will be necessary to reduce flood risk regardless of the trends in the hazard component. This means multiple adaptation strategies need to be considered, as in Alfieri *et al.* (2016), who compared four adaptation options and evaluated them under a high-end global warming scenario. When selecting a particular strategy to reduce current flood risk it is

important that it will be robust to flood hazard changes into the future.

## 6 Science–policy interactions: ensuring soundness of regulatory actions

The existence of large uncertainties in flood hazard projections calls for better interaction between scientific research and practice. Increasing flood risks have led the European Commission to decide on the development of a specific legislative instrument that would complement the Water Framework Directive (WFD). The Floods Directive (EU 2007) requires EU Member States to assess and manage flood risks, with the aim to reduce adverse consequences for human health, environment, cultural heritage and economic activity in Europe. It has to be coordinated with the implementation of the WFD. The action lines provide a comprehensive mechanism for assessing and monitoring increased flood risk, also due to climate change, and for developing appropriate adaptation approaches. This EU instrument provides Member States with a general framework which has to be implemented by National Flood Risk Management programmes that take into consideration specific risks at regional and local levels. The key to success of this framework is closely related to efficient exchanges among the main actors, and this has to take place at European (EU), national, regional and local levels. At the EU level, the so-called Common Implementation Strategy (CIS) enables flood experts from Member States, including scientists, flood risk managers and stakeholders, to gather through the Flood Working Group (WGF of the CIS), meeting regularly to exchange views on technical/scientific challenges for the implementation of the Directive. In this context, science–policy interactions are an essential component for efficient and state-of-the-art action programmes which, in the EU regulatory framework, will have to be implemented in the second river basin management plan (2015–2021).

Several EU-funded projects have contributed to strengthening of the science–policy interactions considered to be an essential component of the success of any policies, in particular in the water sector (Quevauviller 2010). At the early stage of the policy formulation, the need to have access to the scientific state-of-the-art was tackled in the Sixth Framework Programme (FP6) in 2002–2007 by the FLOODsite (Integrated flood risk analysis and management methodologies) project, which provided the scientific foundation reflected in the directive text adopted in 2007. This was complemented by enhanced knowledge on

climate change impacts by the WATCH (Water and global change) project and regional assessments, e.g. in the Mediterranean area with the CIRCE (Climate change and impact research: the Mediterranean environment) project.

In the Seventh Framework Programme (FP7) in 2007–2013, research was more focused on implementation issues, e.g. projects related to improved early warning of flash floods with IMPRINTS (Improving preparedness and risk management for flash floods and debris flow events), flood resilience with CORFU (Collaborative research on flood resilience in urban areas), technologies to improve safety with FLOODPROBE (Technologies for improved safety of the built environment in relation to flood events), culture of risk prevention KULTURisk (Knowledge-based approach to develop a culture of risk prevention) and flood risk governance with STAR-FLOOD (Strengthening and redesigning European flood risk practices: towards appropriate and resilient flood risk governance arrangements). Details about some of these projects are available in Quevauviller *et al.* (2012) and about the STAR-FLOOD project in Hegger *et al.* (2014, 2016). The important feature is that the EU regulatory framework, supported by the CIS working group, and the various EU-funded projects provide a valuable architecture that should permit a multidisciplinary (including socio-economic) scientific and multi-sectoral dialogue. What is at stake here is whether these projects, while responding to expressed policy needs, are actually establishing operational links with practitioners (in particular civil protection units). While these interactions with “end users” have been increasingly incorporated in FP7 projects, critical comments from various stakeholders (including civil protection units and other first responders) have encouraged the European Commission to explicitly require concrete involvement of first responders in projects funded by the Horizon2020 Framework Programme (2014–2020). Such involvement has been attempted e.g. in the ANYWHERE Innovation Action (see <http://www.anywhere-h2020.eu/>).

Communication of the main findings of these EU projects to policy makers outside the direct study areas and translating these into policies had not always been very effective. A broader involvement of EU Member State representatives in digesting the project outcomes would allow the results to have Europe-wide impacts and create synergies at both European and regional levels.

## 7 Research gaps, recommendations and concluding remarks

There is a considerable spread of river flood hazard projections for several regions of Europe among different large-scale (global and pan-European) model-based studies. This spread, illustrated and interpreted in the present paper, raises caution, especially among decision makers in charge of climate change adaptation, flood risk reduction and water resources management at the regional to local scales. However, flood hazard projections for the future, despite the inherent uncertainty, are important to inform decision making processes, sketching the range of possible futures.

We can formulate recommendations and research gaps related to flood hazard projection studies. Using RCPs (representative concentration pathways) in conjunction with SSPs (shared socio-economic pathways) is recommended, as this opens up the opportunity to study changes in flood risk as a consequence of climate change as well as societal change. It is advisable to use multi-GCM ensembles, and also multiple realizations of the same models. However, while it is necessary to balance the application of ensembles with computational costs, it should be kept in mind that there will always be some incongruity between studies if only a few climate models are used and/or if the selected models are not representative of the current large suite of GCMs, RCMs and hydrological models. It should also be kept in mind that even large multi-model ensembles may not necessarily sample the full uncertainty range, and that unexpected surprises are therefore still a possibility. Expert opinion and advice in interpreting the flood hazard projections is therefore paramount, especially when making local adaptation decisions.

Regions, such as Central and Eastern Europe, where GCM projections show high uncertainties warrant more attention from climate modellers. As far as hydrological models are concerned, using multi-model ensembles—following the path initiated by Dankers *et al.* (2014)—is also recommended. Scale-specific assessments are needed—using global hydrological models for global/continental overviews, but not for projection of the regional-scale impacts and adaptation, where calibrated and validated continental or regional hydrological models (also for extremes) should be used, with appropriate treatment of the uncertainty arising from (calibrated) model parameters and missing processes.

In some regions, rain floods and snow floods both influence projections. Researchers have to look into the relevant processes, to separately investigate different

mechanisms of floods and to determine which of these are dominant in each river basin (for present and future conditions).

More understanding is necessary of the influence of bias correction schemes, parameter uncertainty and calibration stability within hydrological models, and uncertainty related to extreme value estimation. All these are also relevant at the local scale.

Given the problem with detecting changes in  $Q_{100}$ , a better benchmark could be  $Q_{30}$  or  $Q_{10}$ , since they have a higher frequency of occurrence, and hence our ability to detect changes is also higher. However,  $Q_{100}$  directly plays the role of a design flood more often than  $Q_{30}$  or  $Q_{10}$ .

Even if an intercomparison of flood hazard projections is done, as in this paper, and differences are identified and interpreted, it does not seem possible to recommend which large-scale studies may be considered most credible in particular areas of Europe. The science behind flood projections and impact assessments is not strong enough to justify stronger conclusions. Some authors, noting discrepancy in projections, have questioned the dominant research path on future climate impacts (e.g. Koutsoyiannis *et al.* 2009, 2011, Anagnostopoulos *et al.* 2010, Kundzewicz and Stakhiv 2010). As an alternative, a bottom-up approach that starts with the vulnerability of the system has often been proposed and may be more appropriate for adaptation studies at the local scale.

Perhaps a new, international project is needed that can systematically and rigorously evaluate different climate and hydrological models and downscaling/bias correction methods, while holding constant metrics such as the control period, projection time frame and return interval of interest. This could form a FloodMIP project, *per analogiam* to WaterMIP, IS-MIP (Inter-Sectoral Impact Model Intercomparison Project) and other model intercomparison projects.

Because it is naïve to expect availability of trustworthy quantitative projections of future flood hazard (as some practitioners clearly do), in order to reduce flood risk, one should focus attention on identification of current and future risks and vulnerability hotspots and improve the situation in areas where such hotspots occur. For decision making, it is necessary to develop an approach based on mapping vulnerabilities, and then try to estimate the probability that these are being affected. Decision making under uncertainty requires identification and quantification of the uncertainty involved, and then improvement of a framework for decision making, including the risk of action *vs* the risk of inaction.

It is hoped that, in EU-funded research projects, practical cooperation will gradually be strengthened

and made effective among policy makers, scientists and first responders, as well as with industry (technology developers and providers), for the sake of improved flood risk management practices in Europe.

## Acknowledgements

The authors are grateful to the reviewers, Jan Szolgay, Giuliano Di Baldassare and Jay Alder, as well as the Co-editor, Demetris Koutsoyiannis, whose useful, constructive comments considerably improved the quality of this manuscript.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

The authors wish to acknowledge support of: the EU FP7 STAR-FLOOD (STrengthening And Redesigning European FLOOD risk practices: Towards appropriate and resilient flood risk governance arrangements) Project, which received funding from the European Commission under grant agreement no. 308364 (PPJD, ZWK, PM) and was co-financed by the Ministry of Science and Higher Education of the Republic of Poland within grant agreement no. 2749/7.PR/2013/2 for international projects in the period 2013–2016 (ZWK, MS); and the FLORIST (FLOod RISK on the northern foothills of the Tatra Mountains) Project, which received funding (PSPB No. 153/2010) from Switzerland through the Swiss Contribution to the enlarged European Union. This study also received funding as grants S-10 and S-14 from the Environment Research & Technology Development Fund by the Ministry of the Environment, Japan (YH, SK).

## References

- Alfieri, L., Feyen, L., and Di Baldassare, G., 2016. Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. *Climatic Change*, 136 (3–4), 507–521. doi:10.1007/s10584-016-1641-1
- Alfieri, L., et al., 2015. Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, 19, 2247–2260. doi:10.5194/hess-19-2247-2015
- Anagnostopoulos, G.G., et al., 2010. A comparison of local and aggregated climate model outputs with observed data. *Hydrological Sciences Journal*, 55 (7), 1094–1110. doi:10.1080/02626667.2010.513518
- Arnell, N.W. and Gosling, S.N., 2016. The impacts of climate change on river flood risk at the global scale. *Climatic Change*, 134 (3), 387–401. doi:10.1007/s10584-014-1084-5
- Beven, K., 2011. I believe in climate change but how precautionary do we need to be in planning for the future? *Hydrological Processes*, 25, 1517–1520. doi:10.1002/hyp.v25.9
- Blöschl, G., et al., 2013. The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods. *Hydrology and Earth System Sciences*, 17 (12), 5197–5212. doi:10.5194/hess-17-5197-2013
- Calder, I.R. and Aylward, B., 2006. Forest and floods: moving to an evidence-based approach to watershed and integrated flood management. *Water International*, 3 (4), 541–543.
- Cloke, H.L. and Pappenberger, F., 2009. Ensemble flood forecasting: a review. *Journal of Hydrology*, 375 (3–4), 613–626. doi:10.1016/j.jhydrol.2009.06.005
- Dankers, R. and Feyen, L., 2008. Climate change impact on flood hazard in Europe: an assessment based on high resolution climate simulations. *Journal of Geophysical Research – Atmospheres*, 113, D19105. doi:10.1029/2007JD009719
- Dankers, R. and Feyen, L., 2009. Flood hazard in Europe in an ensemble of regional climate scenarios. *Journal of Geophysical Research – Atmospheres*, 114, D16. doi:10.1029/2008JD011523
- Dankers, R., et al., 2014. First look at changes in flood hazard in the inter-sectoral impact model intercomparison project ensemble. *Proceedings of the National Academy of Sciences*, 111, 3257–3261. doi:10.1073/pnas.1302078110
- Di Baldassarre, G., Castellarin, A., and Brath, A., 2009. Analysis of the effects of levee heightening on flood propagation: example of the River Po, Italy. *Hydrological Sciences Journal*, 54 (6), 1007–1017. doi:10.1623/hysj.54.6.1007
- Di Baldassarre, G., Brandimarte, L., and Beven, K., 2016. The seventh facet of uncertainty: wrong assumptions, unknowns and surprises in the dynamics of human-water systems. *Hydrological Sciences Journal*, 61 (9), SI 1748–1758. doi:10.1080/02626667.2015.1091460
- Di Baldassarre, G., et al., 2010. Flood fatalities in Africa: from diagnosis to mitigation. *Geophysical Research Letters*, 37, L22402. doi:10.1029/2010GL045467
- Doell, P., et al., 2015. Integrating risks of climate change into water management. *Hydrological Sciences Journal*, 60 (1), 4–13. doi:10.1080/02626667.2014.967250
- EU (European Union), 2007. Directive 2007/60/EC of the European parliament and of the council of 23 October 2007 on the assessment and management of flood risks. *Official Journal of the European Union*, L288, 27–34.
- Field, C.B., et al., eds., 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation*. Cambridge, UK: Cambridge University Press, Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC).
- Gaál, L., et al., 2015. Dependence between flood peaks and volumes: a case study on climate and hydrological controls. *Hydrological Sciences Journal*, 60 (6), 968–984. doi:10.1080/02626667.2014.951361
- Gaume, E., et al., 2009. A compilation of data on European flash floods. *Journal of Hydrology*, 367 (1–2), 70–78. doi:10.1016/j.jhydrol.2008.12.028
- Giuntoli, I., et al., 2015. Future hydrological extremes: the uncertainty from multiple global climate and global hydrological models. *Earth System Dynamics*, 6 (1), 267–285. doi:10.5194/esd-6-267-2015
- Hagemann, S., et al., 2013. Climate change impact on available water resources obtained using multiple global

- climate and hydrology models. *Earth System Dynamics*, 4, 129–144. doi:10.5194/esd-4-129-2013
- Hall, J., et al., 2014. Understanding flood regime changes in Europe: a state-of-the-art assessment. *Hydrology and Earth System Sciences*, 18, 2735–2772. doi:10.5194/hess-18-2735-2014
- Hall, J., et al., 2015. A European flood database: facilitating comprehensive flood research beyond administrative boundaries. *Proceedings of IAHS*, 370, 89–95. doi:10.5194/piahs-370-89-2015
- Hattermann, F.F., et al., 2014. Modelling flood damages under climate change conditions a case study for Germany. *Natural Hazards and Earth System Sciences*, 14 (12), 3151–3168. doi:10.5194/nhess-14-1-2014
- Hattermann, F.F., et al., 2016. An update of the article “Modelling flood damages under climate change conditions – a case study for Germany”. *Natural Hazards and Earth System Sciences*, 16 (7), 1617–1622. doi:10.5194/nhess-16-1617-2016
- Hegger, D., Driessen, P., and Bakker M., with input from all STAR-FLOOD researchers, 2016. *A view on more resilient flood risk governance: key conclusions of the STAR-FLOOD project*. Final STAR-FLOOD project report. Available from: <http://www.starflood.eu/documents/2016/03/d6-4-final-report-webversion.pdf>
- Hegger, D.L.T., et al., 2014. Assessing stability and dynamics in flood risk governance—an empirically illustrated research approach. *Water Resources Management*, 28 (12), 4127–4142. doi:10.1007/s11269-014-0732-x
- Hirabayashi, Y., et al., 2008. Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sciences Journal*, 53 (4), 754–772. doi:10.1623/hysj.53.4.754
- Hirabayashi, Y., et al., 2013. Global flood risk under climate change. *Nature Climate Change*, 3, 816–821. doi:10.1038/nclimate1911
- Hirsch, R.M. and Ryberg, K.R., 2012. Has the magnitude of floods across the USA changed with global CO<sub>2</sub> levels? *Hydrological Sciences Journal*, 57 (1), 1–9. doi:10.1080/02626667.2011.621895
- Hoss, F. and Fischbeck, P., 2016. Increasing the value of uncertain weather and river forecasts for emergency managers. *Bulletin of the American Meteorological Society*, 97 (1), 85–97. doi:10.1175/BAMS-D-13-00275.1
- IMGW, et al., 2015. *Plany zarządzania ryzykiem powodziowym dla obszarów dorzeczy i regionów wodnych Projekt planu zarządzania ryzykiem powodziowym dla obszaru dorzecza Odry*. Draft. No. WBS: 1.6.4.2. Warsaw: IMGW.
- Jacob, D., et al., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, 14, 563–578. doi:10.1007/s10113-013-0499-2
- Jiménez, B.E.C., et al., 2014. Freshwater resources. In: C.B. Field, et al., eds. *Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [online]. Cambridge: Cambridge University Press, 229–269.
- Kay, A.L. and Jones, D.A., 2012. Transient changes in flood frequency and timing in Britain under potential projections of climate change. *International Journal of Climatology*, 32 (4), 489–502. doi:10.1002/joc.v32.4
- Klijn, F., et al., 2015. Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. *Mitigation and Adaptation Strategies for Global Change*, 20, 845–864. doi:10.1007/s11027-015-9638-z
- Knutti, R., et al., 2010. Challenges in combining projections from multiple climate models. *Journal of Climate*, 23 (10), 2739–2758. doi:10.1175/2009JCLI3361.1
- Koutsoyiannis, D. and Montanari, A., 2015. Negligent killing of scientific concepts: the stationarity case. *Hydrological Sciences Journal*, 60 (7–8), 1174–1183. doi:10.1080/02626667.2014.959959
- Koutsoyiannis, D., et al., 2009. Climate, hydrology and freshwater: towards an interactive incorporation of hydrological experience into climate research—Discussion of “The implications of projected climate change for freshwater resources and their management”. *Hydrological Sciences Journal*, 54 (2), 394–405. doi:10.1623/hysj.54.2.394
- Koutsoyiannis, D., et al., 2011. Scientific dialogue on climate: is it giving black eyes or opening closed eyes? Reply to “A black eye for the hydrological sciences journal” by D. Huard. *Hydrological Sciences Journal*, 56 (7), 1334–1339. doi:10.1080/02626667.2011.610759
- Krysanova, V., et al., 2015. Modelling climate and land-use change impacts with SWIM: lessons learnt from multiple applications. *Hydrological Sciences Journal*, 60 (4), 606–635. doi:10.1080/02626667.2014.925560
- Kundzewicz, Z.W., ed., 2012. *Changes in flood risk in Europe*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Special Publ. 10.
- Kundzewicz, Z.W., Pińskwar, I., and Brakenridge, G.R., 2013. Large floods in Europe, 1985–2009. *Hydrological Sciences Journal*, 58 (1), 1–7. doi:10.1080/02626667.2012.745082
- Kundzewicz, Z.W. and Stakhiv, E.Z., 2010. Are climate models “ready for prime time” in water resources management applications, or is more research needed? *Hydrological Sciences Journal*, 55 (7), 1085–1089. doi:10.1080/02626667.2010.513211
- Kundzewicz, Z.W., et al., 2005. Trend detection in river flow time series: 1. Annual maximum flow. *Hydrological Sciences Journal*, 50 (5), 797–810. doi:10.1623/hysj.2005.50.5.797
- Kundzewicz, Z.W., et al., 2010. Assessing river flood risk and adaptation in Europe—review of projections for the future. *Mitigation and Adaptation Strategies for Global Change*, 15 (7), 641–656. doi:10.1007/s11027-010-9213-6
- Kundzewicz, Z.W., et al., 2014. Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, 59 (1), 1–28. doi:10.1080/02626667.2013.857411
- Lehmann, J., Coumou, D., and Frieler, K., 2015. Increased record-breaking precipitation events under global warming. *Climatic Change*. doi:10.1007/s10584-015-1434-y

- Lehner, B., *et al.*, 2006. Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated assessment. *Climatic Change*, 75, 273–299. doi:10.1007/s10584-006-6338-4
- Madsen, H., *et al.*, 2014. Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. *Journal of Hydrology*, 519, 3634–3650. doi:10.1016/j.jhydrol.2014.11.003
- Meinshausen, M., *et al.*, 2011. The RCP greenhouse gas concentrations and their extension from 1765 to 2300. *Climatic Change*, 109 (1–2), 213–241. doi:10.1007/s10584-011-0156-z
- Merz, R., Parajka, J., and Blöschl, G., 2011. Time stability of catchment model parameters: implications for climate impact analyses. *Water Resources Research*, 47 (2), W02531. doi:10.1029/2010WR009505
- Merz, B., *et al.*, 2014. Floods and climate: emerging perspectives for flood risk assessment and management. *Natural Hazards and Earth System Sciences*, 14, 1921–1942. doi:10.5194/nhess-14-1921-2014
- Merz, B., *et al.*, 2015. Charting unknown waters—On the role of surprise in flood risk assessment and management. *Water Resources Research*, 51. doi:10.1002/2015WR017464
- Milly, P.C.D., *et al.*, 2008. Stationarity is dead: whither water management? *Science*, 319, 573–574. doi:10.1126/science.1151915
- Milly, P.C.D., *et al.*, 2015. Commentary on critiques of “Stationarity is dead: whither water management?” *Water Resources Research*, 51 (9), 7785–7789. doi:10.1002/2015WR017408
- Moss, R.H., *et al.*, 2010. The next generation of scenarios for climate change research and assessment. *Nature*, 463 (7282), 747–756. doi:10.1038/nature08823
- Mudelsee, M., *et al.*, 2003. No upward trends in the occurrence of extreme floods in central Europe. *Nature*, 425, 166–169. doi:10.1038/nature01928
- Nakicenovic, N., *et al.*, 2000. *IPCC special report on emissions scenarios*. Cambridge, UK: Cambridge University Press.
- Nicholls, N. and Seneviratne, S.I., 2015. Comparing IPCC assessments: how do the AR4 and SREX assessments of changes in extremes differ? *Climatic Change*, 133 (1), 7–21. doi:10.1007/s10584-013-0818-0
- Pall, P., *et al.*, 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, 470 (7334), 382–385. doi:10.1038/nature09762
- Quevauviller, P.H., ed., 2010. *Water systems science and policy interfacing*. Cambridge, UK: The Royal Society of Chemistry. ISBN: 978-1-84755-861-9.
- Quevauviller, P.H., *et al.*, 2012. Integration of research advances in modelling and monitoring in support of WFD river basin management planning in the context of climate change. *Science of the Total Environment*, 440, 167–177. doi:10.1016/j.scitotenv.2012.07.055
- Raadgever, T.C., *et al.*, 2011. Uncertainty management in practice: lessons from the regional implementation of the water framework directive in the Netherlands. *Environmental Science and Policy*, 14 (1), 64–75. doi:10.1016/j.envsci.2010.11.001
- Rojas, R., *et al.*, 2011. Improving pan-European hydrological simulation of extreme events through statistical bias correction of RCM-driven climate simulations. *Hydrology and Earth System Sciences*, 15, 2599–2620. doi:10.5194/hess-15-2599-2011
- Rojas, R., *et al.*, 2012. Assessment of future flood hazard in Europe using a large ensemble of bias-corrected regional climate simulations. *Journal of Geophysical Research – Atmospheres*, 117, D17109.
- Roudier, P., *et al.*, 2016. Projections of future floods and hydrological droughts in Europe under a +2°C global warming. *Climatic Change*, 135 (2), 341–355. doi:10.1007/s10584-015-1570-4
- Runhaar, H.A.C., *et al.*, 2016. Prepared for climate change? A method for the ex-ante assessment of formal responsibilities for climate adaptation in specific sectors. *Regional Environmental Change*, 16 (5), 1389–1400. doi:10.1007/s10113-015-0866-2
- Schewe, J., *et al.*, 2014. Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences USA*, 111, 3245–3250. doi:10.1073/pnas.1222460110
- Schiermeier, Q., 2003. Analysis pours cold water on flood theory. *Nature*, 425, 111. doi:10.1038/425111a
- Trenberth, K.E., Fasullo, J.T., and Shepherd, T.G., 2015. Attribution of climate extreme events. *Nature Climate Change*, 5 (8), 725–730. doi:10.1038/nclimate2657
- van der Linden, P., *et al.*, 2009. *ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project*. Exeter, UK: Met Office Hadley Centre.
- van Enst, W.I., Runhaar, H.A.C., and Driessen, P.P.J., 2016. Boundary organisations and their strategies: three cases in the Wadden Sea. *Environmental Science & Policy*, 55 (SI), 416–423, Part 3. doi:10.1016/j.envsci.2015.08.016
- Viglione, A., *et al.*, 2010. Barriers to the exchange of hydro-meteorological data in Europe: results from a survey and implications for data policy. *Journal of Hydrology*, 394 (1–2), 63–77. doi:10.1016/j.jhydrol.2010.03.023
- Wada, Y., *et al.*, 2013. Multimodel projections and uncertainties of irrigation water demand under climate change. *Geophysical Research Letters*, 40, 4626–4632. doi:10.1002/grl.50686
- Wilby, R.L. and Dessai, S., 2010. Robust adaptation to climate change. *Weather*, 65 (7), 180–185. doi:10.1002/wea.v65:7