Changes in river flood hazard in Europe: a review

Zbigniew W. Kundzewicz, Iwona Pińskwar and G. Robert Brakenridge

ABSTRACT

Despite costly flood risk reduction efforts, material damage and death toll caused by river floods continue to be high in Europe. In the present review paper, after outlining a process-based perspective, we examine observed and projected changes in flood hazard. Spatial and temporal variability of large floods is analyzed, based on a time series of flood information, collected by the Dartmouth Flood Observatory in 1985–2016. Model-based projections of future flood hazard are critically reviewed. It is difficult to disentangle the climatic change component from strong natural variability and direct human impacts. The climate change impact on flood hazard is complex and depends on the river flood generation mechanism. It has not been possible to detect ubiquitous changes in flood characteristics in observation records in Europe, so far. However, we found an increasing tendency in the number of floods with large magnitude and severity, even if year-to-year variability is strong. There is a considerable spread of river flood hazard projections in Europe among studies, carried out under different assumptions. Therefore, caution must be exerted by practitioners in charge of climate change adaptation, flood risk reduction, risk insurance, and water resources management when accommodating information on flood hazard projections, under considerable uncertainty.

Key words | change detection, Europe, flood hazard, observations, projections

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INTRODUCTION

Despite massive flood risk reduction efforts and high expenditures on structural defenses, floods continue to be an acute problem throughout Europe, causing high material damage and death toll. There have recently been several flood events with material damage up to tens of billions of euros. After the flood-rich decade of the 1990s, with several disastrous flood events in Europe, the 21st century has continued to witness many destructive floods. There is persuasive evidence that the damage caused by river flooding is on an upward trend.

Although the term 'risk' has several interpretations, it is typically considered as a combination of hazard (measured via frequency or probability of high river stage and discharge) and adverse consequences. Flood risk has clearly been intensified by humans, who have caused increase in the 'load' and decrease in the 'resistance' of the system (from the parlance of mechanics). Anthropogenic changes may thereby increase the river flood magnitude for a particular design precipitation, and amplify the flood damage, because growing wealth has been accumulated in high flood-risk areas. This is apart from any anthropogenic increase in the actual load: through, for example, a warmer atmosphere with potential to carry more moisture, and facilitating more intense and/or prolonged rainfall.

Increasing flood damage has intensified concern among European nations. Non-stationarity in extreme precipitation and high river discharge due to climatic change has become an active research area, high on research agendas in the European Union (EU) and in individual EU member countries, with abundant recent research projects and publications. Numerous recent studies of changes in river flood hazard and risk include Europe-wide studies, larger regional

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studies covering several countries, national studies, as well as sub-national and local studies. For review, see Kundzewicz (2012) and Madsen *et al.* (2014).

The aim of this paper is to review changes in flood risk hazard in Europe. After adopting a process-based perspective on flood risk and flood hazard, observed and projected changes in flood hazard in Europe are examined. Spatial and temporal variability of large floods is analyzed, as based on a time series of flood information, collected by the Dartmouth Flood Observatory (DFO) over the past 32 years. Finally, model-based projections for the future are discussed, including indications of their uncertainty and lack of robustness.

INCORPORATING A PROCESS-BASED PERSPECTIVE

Flood risk is affected by flood hazard, flood exposure, and flood vulnerability, which themselves depend (Figure 1), in an interconnected way, on the relevant climatic, surface process, and socio-economic systems (cf. Kundzewicz *et al.* 2014). There are multiple factors controlling flood risk and a change in any one of them can lead to increases or decreases.

River discharge is the integrated result of hydrological processes in the drainage basin – from precipitation, snowmelt, and groundwater, to river flow. Socio-economic systems, driving land use and land cover and interventions in the river channel and floodplains also play a role.

Climate-system factors determining flood risk via river flood hazard include the water-holding capacity (and water vapor content) of the atmosphere and the characteristics of intense precipitation, such as its amount and distribution in space and time. According to the Clausius–Clapeyron law, there is more room for water vapor in a warmer atmosphere, hence an increased potential for intensive precipitation. However, climate-driven changes in flood frequency may exhibit huge complexity and depend on the specific generating mechanisms. Under a warmer atmosphere in European latitudes, flood magnitudes are expected to rise where floods result from increasingly heavy rainfalls, but may decrease where snowmelt is the principal flood-generating mechanism: winter snow cover may decrease, and the time of greatest flood risk may shift ahead in time from spring towards winter. However, warming may not reduce snowmelt flooding everywhere; as winter precipitation increases in much of the continent, snow cover may increase in areas where the winter temperature still remains below the freezing point. Hence, direct climatic determinants of flood hazard include: precipitation amounts (in particular, heavy precipitation), snow cover amounts, and winter-spring temperature regime (e.g., rapid snowmelt, river ice break-up, etc.).

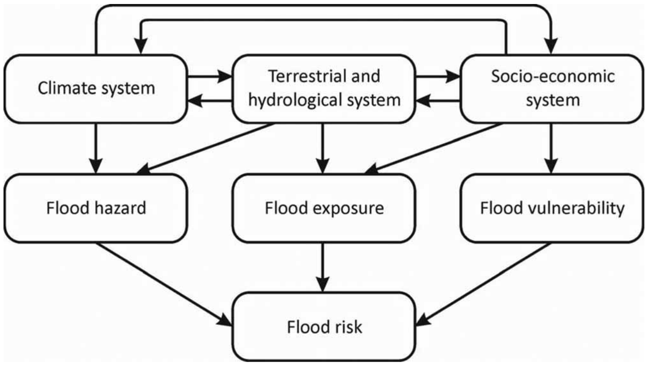

Figure 1 | Factors affecting flood risk and its components.

Watershed characteristics also drive flood risk via flood hazard. Important hydrological and terrestrial characteristics include: catchment size, slope, elevation, geology, land cover, topography, and soils. All may affect the frequency and size of flood hydrographs, which vary in shape but may be characterized by characteristics at a cross-section of interest, e.g., flow amplitude, frequency of exceedance, seasonality. Standard flood frequency analyses commonly incorporate series of annual flood peak discharges (Klingeman 2005).

Changes in the land surface related to land-use and land-cover changes (LUCC), such as decreased retention, increased drainage rate increase, and reduced surface permeability, affect runoff and flood hydrographs. LUCC, e.g., caused by socio-economic factors, condition the transformation of rainfall into runoff. If land use is modified within a catchment (e.g., resulting in conversion of forested land into urban land), then downstream water levels and discharges in response to a given precipitation input may increase, as runoff coefficient is much higher over paved land than vegetated land. Hence, under assumption of the same size and topography of a basin, an urban and a rural catchment react differently to the same precipitation; the peak discharge in the urban area is higher, while the time-to-peak is shorter. However, the river stage and thus the risk of flooding also depend on engineered changes to the course of rivers, e.g., dikes constructed for river valley development. Besides urbanization, other types of land-use change are important to the generation of floods. Deforestation, drainage of flood plains, wetlands, lakes, ponds, and other surface retention areas diminish the available water storage capacity in a basin and adversely affect flood risk; however, in some cases, engineered drainage may remove flood water quickly from low-relief land and reduce local flooding there. Existing flood defenses should be re-evaluated regarding the flood characteristics change due to LUCC (Yang *et al.* 2016).

Finally, the third group of flood risk drivers includes strictly socio-economic factors, including exposure, vulnerability, adaptive capacity, risk awareness and damage potential (driven by the size of the population and its wealth), the state of the economic development of flood-prone areas, and risk perception. Particularly relevant is the number of inhabitants in flood-prone areas, economic growth (increase in wealth, leading to growth of the damage potential), and the susceptibility of objects or persons to hazard (elevated structures will experience less damage).

While the increase in flood risk may be an unwelcome and unintended side effect of human activities, in contrast, flood risk reduction is most often from deliberate activity. In general, construction of river engineering structures (e.g., embankments, dikes, and dams) and river regulation (e.g., channel straightening and shortening, and narrowing, channelization, construction of by-pass channels) alters the transformation of precipitation into river runoff and resulting flood hydrographs. In particular, the response time of the system to rainfall or snowmelt is affected. Counter-intuitively, flood damage in many parts of the world has been increasing because of structural defenses such as dikes and levees. Typically, dikes offer adequate protection against small and medium size floods, i.e., the number of damaging floods in this range decreases when dikes are in place. Hence, the positive effects of dikes against floods lower than the design flood are evident, but the protection thereby provided encourages more development, setting the stage for extreme losses and fatalities when a rare storm causes levee-overtopping discharges or even levee breaches (Brakenridge *et al.* 2017).

In summary, there are important interlinkages between climate, terrestrial, and socio-economic systems as regards flooding; we consider floods not simply as particular peak discharges with certain expected return periods and measured frequency, but as the final result of the interplay of these various processes. Then, remains the quality of the observational data used to measure floods. For example, some workers infer a 'CNN effect'; improvements in flood news reporting can lead falsely to conclusions of increased flooding. Today, when a major flood strikes anywhere (almost), it is reported quickly on television and other electronic media news sources worldwide; such coverage was not so complete only some decades ago. As we examine flood trends in Europe, therefore, we must attempt to correct for the effects of increasingly better information and/or refer to more objective streamflow records.

OBSERVATIONS FOR EUROPE

Large floods have been recorded in Europe since the beginning of history, yet information about very old floods is, at best, fragmentary (cf. Brázdil *et al.* 2012). However, in some countries, such as Italy, very long records of damaging floods exist. Salvati *et al.* (2012) collected a list of over 2,600 flood events with fatalities in Italy, since the year 589. They reported 1,124 flood fatalities in 1950–2010 (less than in 1900–1949 but more than in 1850–1899).

There is no doubt that costs related to flood damage have been increasing, and partly due to the increasing exposure of people and assets (Kundzewicz *et al.* 2014). Kron (2012) shows an increase in the number of large flood events and also in economic losses and insured losses. Such analyses require careful adjustment for inflation (change in actual value of the currency units used). For example, the nominal loss of 21.9 billion euros caused by an August 2002 flood would correspond to 26.5 billion euros in 2010 values. The amplification is much higher for older flood events, e.g., the damage caused by the large flood in Italy in 1966 (nominal loss of 4 billion euros, converting Italian liras to euros with the exchange rate valid when the common European currency, euro, was introduced, in 2002) would inflate to 28 billion euros in 2010 values (Kron 2012, p. 461). However, the quantitative assessment of flood losses is inevitably uncertain (see Chorynski *et al.* 2012), hence one can only provide broad ranges of estimates of material damage. In this regard, a major new report by the United Nations Food and Agriculture Organization ('The impact of disasters on agriculture and food security', FAO 2015) separates flood 'damage' (immediate dollar impacts on, for example, crops, buildings, other infrastructure) from flood 'losses', in which the sustained impacts on local economies are assessed through a standard econometric methodology. Sudden losses are those most commonly covered by insurance schemes; it requires more detailed analyses to understand long-term impact.

With regard to the immediate losses, Barredo (2009) found no detectable sign of human-induced climate change in normalized flood losses in the (then) member states of the EU and some other countries in Europe, for the period 1970–2006. They normalized flood losses by considering the effects of changes in population, wealth, and inflation at the country level and removed inter-country price differences by adjusting the losses for purchasing power parities. Thus, although losses increased, this would have occurred whether or not climate change (or other anthropogenic factors) were also underway.

Regarding direct measurements of meteorology and hydrology, precipitation records allow investigations as to whether the frequency and/or magnitude of precipitation events are also changing and exhibiting trends, or are instead varying about a mean (the stationarity assumption). There is a large number of studies of changes in flood hazard reported in the book edited by Kundzewicz (2012) and in the paper by Madsen *et al.* (2014). Increases in heavy precipitation have been noted in many regions, but the impact on floods is more difficult to detect directly in the available streamflow records. In particular, time series of heavy precipitation events show that the frequency and intensity of observed extreme precipitation are indeed increasing in many European locations. Also, anthropogenic warming has likely contributed to a global-scale intensification of heavy precipitation (IPCC 2013). For winter, a change to wetter conditions and more extreme precipitation was noted in north and central Europe, while drier conditions were detected in the south, with a slight increase in the occurrence of extreme events.

Domination of large inter-annual and inter-decadal variability in European records of maximum river flow was reported by Kundzewicz *et al.* (2005), but such variabilities are difficult to quantify in short time series (e.g., extending over a few decades). Typically, trends are not robust and largely depend on the start year and the end year of analysis. Several extraordinary events have been observed. For instance, the flood in Austria in the summer of 2002 was unprecedented over 100 years, yet the 2005 flood was of similar magnitude (Bloschl *et al.* 2012). 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; Madsen *et al.* 2014). In brief, there is no conclusive evidence for a ubiquitous and homogeneous climate-related increasing trend at larger-scale, regional or national level, so far, in observed extreme streamflow in Europe. There are no clear national or larger-scale regions in Europe which uniformly exhibit statistically significant increases in flood discharges. However, for smaller regions in Europe, apparent increases in extreme streamflow are found, including alpine basins and some maritime-influenced catchments (Madsen *et al.* 2014). In many cases, individual stations in a country or within larger regions may have both positive and negative trends (commonly – piecewise) or no evident trend. In some areas, where snowmelt is an important flood generation mechanism, Madsen *et al.* (2014) noted decreases in extreme streamflow and earlier spring snowmelt peak flows, likely caused by increasing temperature.

There remains only low confidence in the claim that anthropogenic climate change has affected the frequency and magnitude of river floods in Europe. There is a complex interplay between long-term trends, inter-annual and inter-decadal natural variability, nonlinearities and thresholds in the climate system. We also note that most such analyses have used series of annual peak discharges, yet some of the most damaging floods occur due to sustained maintenance of overbank flow conditions. Hence, other descriptive statistics regarding floods may need to be used to capture warming-related trends over time.

SPATIAL AND TEMPORAL VARIABILITY OF EUROPEAN FLOODS, 1985–2016

A useful open-access source of information on floods in recent decades is the DFO (http://floodobservatory.colorado.edu.) The Observatory provides global coverage and uses both news reports and orbital remote sensing to detect, measure, and map floods. Usage of remote sensing renders it possible to measure and compare inundation events (cf. Kundzewicz *et al.* 2013). The event listing (the Active Archive of Large Floods, http://floodobservatory.colorado.edu/Archives/index.html) provides first-order characterization of flood events worldwide, from 1985 to the present. Figures 2 and 3 plot the number of events per year included within the European countries (Figures 4 and 5). The Archive includes these categories: DFO registry number, Glide number, Nation, Other nations affected, Detailed (text) locations, Validation, Begin date, End date, Duration in days, Fatalities, Displaced,

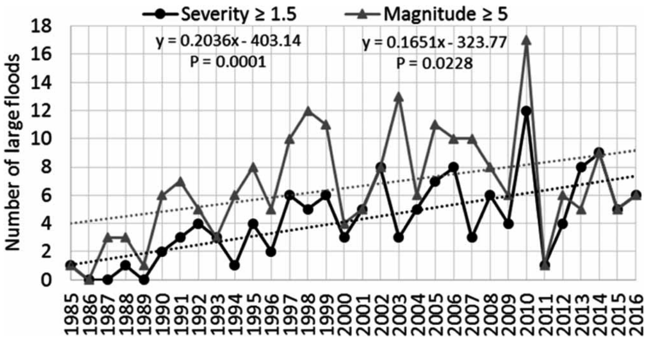

Figure 2 | Numbers of large floods of severity $\geq$1.5 (black line) and magnitude $\geq$5 (grey line) in Europe each year during 1985–2016, based on DFO records. This present figure updates Kundzewicz *et al.* (2013), covering the interval 1985–2010.

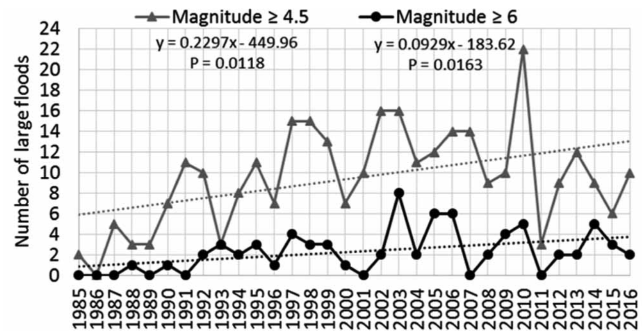

Figure 3 | Numbers of large floods of magnitude $\geq$4.5 and $\geq$6 in Europe each year during 1985–2016, based on the DFO records.

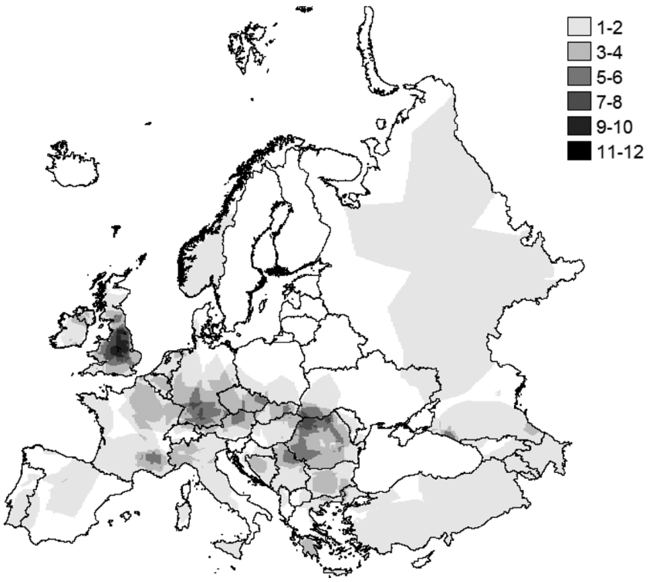

Figure 4 | Spatial distribution of the number of large floods in Europe, based on data from the DFO over the entire 32-year time interval, 1985–2016, for which records are available. The threshold for classification of large floods is severity equal to or greater than 1.5. This present figure updates a map in Kundzewicz *et al.* (2013), covering the interval 1985–2010. Different shades of grey refer to the number of large floods reported, as explained in the legend.

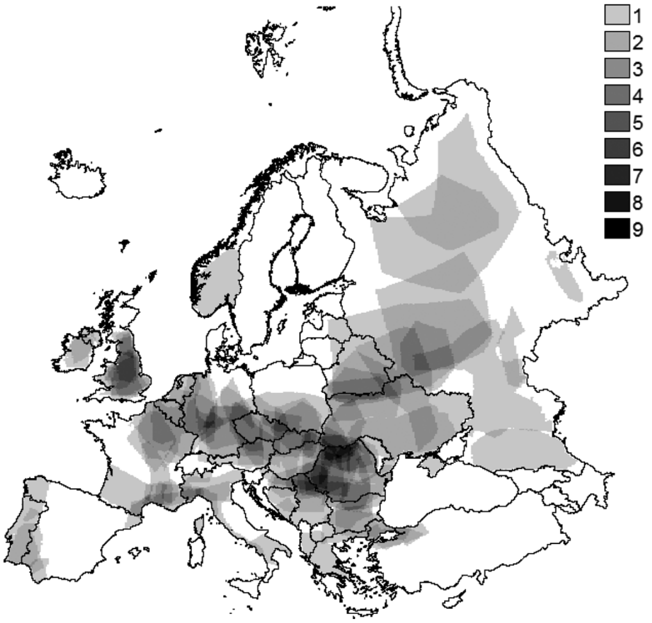

Figure 5 | Spatial distribution of the number of large floods in Europe, based on data from the DFO over the entire 32-year time interval, 1985–2016, for which records are available. The threshold for classification of large floods is magnitude equal to or greater than 6. Different shades of grey refer to the number of large floods reported, as explained in the legend.

Damage estimate in USD, Causation, Severity, Affected km^2, calculated 'Flood magnitude' (LOG[Duration × Severity × Affected Area], see below), GIS polygon of affected area, and Latitude and Longitude of polygon centroids. An archive number is assigned to any flood that caused significant damage to structures or agriculture, is an infrequent event, and/or is accompanied by fatalities. Floods are assigned severities as: Class 1: large flood events, significant damage to structures or agriculture, fatalities, and/or one to two decades-long reported interval since the last similar event; Class 1.5: very large events, greater than 20-year but less than 100-year recurrence interval; and Class 2: extreme events, with an estimated recurrence interval greater than 100 years. Thus, Class 2 floods with long duration over large areas result in the highest flood magnitude values (e.g., ~6–8), Class 1 floods of short duration over small areas provide relatively small calculated magnitudes (e.g., ~3–4). Over the years, severity classes were assigned by different workers and information quality about recurrence intervals vary greatly; DFO considers such classes only rough estimates and the calculated magnitudes also are thus approximate.

Finally, flood causation categories are the following: Heavy rain, Tropical cyclone, Extra-tropical cyclone, Monsoonal rain, Snowmelt, Rain and snowmelt, Ice jam/breakup, Dam/levy break or release, Brief torrential rain, Tidal surge, Avalanche-related. In Europe, all of these causes except tropical cyclone and monsoonal rain are attributed proximal causes for the archived history of large floods.

Changes in large flood characteristics in Europe based on this information for 1985–2010 (Kundzewicz *et al.* 2013) are now updated to 2016. Despite the approximate nature of the severity and thus magnitude estimates, the number of large floods above a certain threshold of severity and magnitude can be used to study changes over time. Kron (2012) examined several flood indices in Europe, such as number of large floods, total damage, and insured damage and found increases in all of them. However, definition of a large flood in Kron (2012) differs from that here; that paper considers a flood event to be large if the affected country requested international assistance. As well, one difficulty with our description of the number of floods above a certain magnitude threshold is that events adjacent to each other in time could be subjectively either grouped, as one event – possibly a super flood, or counted separately, as two smaller floods of lower magnitude; a heuristic 'lump or split' decision is needed. As for the estimate of severity, this introduces possible errors into the accounting. The largest floods in particular are time-transgressive in character; flooding may occur first in upstream tributaries and then move downstream, as flooding receded upstream. Finally, and despite the extensive coverage in recent years of major floods by news media and online, geographic representation may certainly vary. European portions of Russia in particular may not be well-documented due to local reports appearing in only Russian language outlets that are not as easily retrieved by online key word search procedures.

According to the data behind Figures 2–5, there were 304 major flood events in Europe in 1985–2016 with $M > 4.5$ and 74 events with $M > 6$, as well as 11 floods with $M > 7$. This corresponds to incidence rates of ~9.8/yr, 2.4/yr, and 1/2.8 yr or rounding to, respectively ~10/year, 2/year, and 1 ($M > 7$ flood) every 3 yr. The maximum magnitude observed was 8.1 (an extended snowmelt flood with affected area of 1.43 million km^2). Four floods are reported with over 100 fatalities each: two events in Russia, one in Italy (1998) and one in Poland and Czech Republic (1997).

Inter-annual variability in the number of large floods, as illustrated in Figures 2 and 3, is strong. In particular, the difference between the consecutive years, 2010 and 2011, was striking. There were 22 large flood events in Europe (with $M > 4.5$) in 2010 and only three just one year after, in 2011. Also, Figures 4 and 5 highlight the large number of very severe reported flood events in Romania.

PROJECTIONS FOR THE FUTURE

Kundzewicz *et al.* (2010, 2017) described considerable differences in flood hazard projections over Europe, identifying likely sources of discrepancy. The lack of agreement in flood hazard projections requires caution, especially among practitioners, at the regional to local scales. Clearly, the need for reliable prediction is strong, and thus there have been many studies and publications devoted to large-scale projections of changes in flood frequency and intensity, covering the European continent. Some studies provide projections for Europe only and others report projections on a global basis. This work is still in its early stages as workers learn to inter-compare and further test the models required. There is not strong agreement on predictions for flood hazard in Europe for the next decades (i) between the European-scale and global-scale studies, as well as (ii) between different global-scale studies (Kundzewicz *et al.* 2017). Comparing the results, one can find areas of agreement and of disagreement. Rojas *et al.* (2012) illustrate a dominant increase in frequency of high river discharges for much of Europe. In contrast, predicted changes 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 increases in flood frequency projected. A multi-model intercomparison by Dankers *et al.* (2014) found agreement on projected increases in flood frequency 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. Roudier *et al.* (2016) largely corroborate the findings of Alfieri *et al.* (2015).

Alfieri *et al.* (2015) present projections of changes in mean annual exceedance frequency of the 100-year (recurrence interval) river flow (Q100) for particular countries of Europe for three future time horizons. They conclude that, on average, Q100 is projected to increase by 18–256% between time horizons 1990 (1976–2005) and 2020 (2006–2035). This means that, on average, in Europe, exceedance of Q100 established for the control period is projected to become twice more frequent within three decades, between time horizon 1990 and 2020 (the latter year, in fact – the center of a 30-year interval, is very close to now). Changes for further time horizons are less consistent. For all 37 European countries considered, Q100 is projected to increase. However, for most countries, there is no monotonic increase of annual exceedance frequency of the 100-year flood for two further future time horizons, 2050 (2036–2065) and 2080 (2066–2095).

Differences between model results occur for many reasons, and are examined by Kundzewicz *et al.* (2017). Predicted changes in flood hazard differ with respect to assumed scenarios of greenhouse gas emissions, driving climate models (general circulation models and regional climate models) and downscaling techniques, as well as bias correction methods. Further, there are essential regional differences in simulation by global hydrological models and regional hydrological models, especially for extremes, as well as general problems related to extreme value techniques applied for relatively short time series. Differences in conditions backing various studies reported in the literature can also be found in the assumed time horizons of future projections, as well as spatial and temporal resolution of hydrological impact models, and return period of relevance. Also the control (reference) intervals and characteristics (indices) of high flow often differ between studies. Intercomparisons for identical conditions are badly needed; a path forward needs to be identified to bring these potentially powerful methods to bear in producing more secure prediction of future flood hazard.

CONCLUDING REMARKS

In Europe, wealth in flood-prone areas, hence damage potential, has undoubtedly increased and so has flood damage. In regard to climate, a trend towards higher and more intense precipitation has been reliably detected in many regions of Europe and this trend is expected to strengthen with a warmer atmosphere, thus surely affecting rain-caused river flood risk.

However, so far, changes in flood characteristics have been difficult to detect in observation records. As demonstrated in this review paper, no robust and ubiquitous increase in the amplitude and frequency of high river flows throughout Europe could be detected, although an increasing tendency in the number of floods with large magnitude and severity can be noted, as reported in this present paper, based on records from the DFO. In general, it is difficult to disentangle the climatic change component from strong natural variability and direct human impacts. The impact of climate forcing on river flood hazard is complex and largely depends on the flood generation mechanism.

There is a considerable spread of river flood hazard projections in Europe, among different large-scale (global and pan-European) model-based studies. Lack of robust projections means that caution must be exerted by national, sub-national, or local decision-makers in charge of climate change adaptation, flood risk reduction, risk insurance, and water resources management. However, despite the inherent uncertainties, flood hazard projections for the future will increasingly be able to inform decision-making processes as the models and observational data improve. To reduce flood risk in Europe, focused attention could also make use of observed geographic distribution of the most damaging events, together with the modeled predictions. Also, climate change does not increase flood risk everywhere and in all seasons; for example, a general decrease in flood magnitude and earlier spring floods has been predicted for catchments with snowmelt-dominated peak flows, and this prediction is broadly consistent with observation.

Existing procedures for designing structural flood defenses – dikes, dams, spillways, and reservoirs, etc., are typically based on the assumption of stationarity of river discharge process (Kundzewicz & Kaczmarek 2000). Thus, the design flood (that should be withstood by the structure), such as 100-year flood, is assumed constant. However, the assumption of stationarity is not applicable due to changes in climate, in hydrological regime (e.g., LUCC, urbanization, and wetland draining), and in river infrastructure. Common-sense changes to design rules have been introduced in some EU countries, based on precautionary principle taking nonstationarity into account (Kundzewicz *et al.* 2014, 2017). If a new flood is the flood of record, larger than any observed prior, extrapolation of our relatively short flow series, using the standard probability distributions and the stationarity assumption, may indicate such event to be exceptionally rare, e.g., 'the 1,000 year flood'. Yet, our scientific understanding actually supports this flood as 'the new normal'; a rare event, perhaps, but one that must now be incorporated into the flow series, and with corresponding shorter calculated recurrence intervals.

Flood hazard projections are a challenge for hydrological scientists, whose duty (cf. Watts 2016) is to inform many socially important decisions that affect human well-being and livelihoods. Efficient transfer of information contained in projections (including their uncertainty and lack of robustness) to practitioners warrants serious consideration.

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