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Flood Risk in a Range of Spatial Perspectives–from Global to Local

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Abstract

The present paper examines flood risk (composed of hazard, exposure and vulnerability) in a range of spatial perspectives – from the global to the local scale. It deals with observed records, noting that flood damage has been increasing. It also tackles projections for the future, related to flood hazard and flood losses. There are multiple factors driving flood hazard and flood risk and there is a considerable uncertainty in our assessments, and particularly in projections for the future. Further, this paper analyses options for flood risk reduction in several spatial dimensions, from global framework to regional to local scales. It is necessary to continue examination of the updated records of flood-related indices, trying to search for changes that influence flood hazard and flood risk in river basins.

Key words: flood risk; flood hazard; flood risk reduction; global scale; regional scale; local scale

1. Introduction

River flooding is a major natural disaster, manifesting itself at a range of spatial and temporal scales – from floods on large international rivers conveying huge masses of water (cubic kilometres) lasting over weeks or months to, potentially violent, destructive and killing, inundations in small, often urban, basins, lasting hours. It is estimated that, globally, floods constitute 43% of the total number of natural disasters and 47% of all weather-related disasters, affecting 2.3 billion people in 1995-2015, with the total damage of the order of 662 billion US$. About 800 million people worldwide are currently living in flood-prone areas and about 70 million of those people are, on average, exposed to floods each year (UNISDR, 2015).

The nature of disastrous floods seems to have changed, in recent decades, with increasing frequency and amplitude of heavy precipitation, flash and urban floods, as well as acute riverine and coastal flooding. Urbanization and sealing of ground surface have significantly increased surface water runoff in many areas. In some countries, recurrent flooding of crop land has taken a heavy toll in terms of lost agricultural production, food shortages, interrupted food supplies and under-nutrition. However, some deleterious impacts of floods are preventable or at least can be reduced, because of the opportunity of primary prevention through existing, and - in many places – affordable, technologies such as early warning systems and some flood defenses, while awareness raising and education can also be effective in protecting people from adverse impact of floods.

The spatial perspective on floods ranges from a global view by multi-national stakeholders, international organizations, reinsurance institutions, and think-tanks, interested in global affairs to regional (group of countries, river basins which cross national borders, where 40% of global population live and where trans-boundary water issues should be addressed), national, and sub-national (river basins) scales. The local point of view is, for instance, the one of a family of a person who lost life in the flood, of a family that lost their house or workplace in the flood, or of persons responsible for local flood protection. The local scale pertains to the locality and community in flood-prone area, where flood damage incurred and/or where flood risk reduction measure has to be implemented. The global consideration may include aggregation of observation records, model-based projections, as well as international policies aimed at flood risk reduction.

In the present paper, reviewing flood risk in a range of spatial perspectives (from global to local), we start from examination of observed records, noting that flood damage has been increasing. Further, we discuss projections for the future – flood hazard and flood losses, and then review flood-risk reduction strategies, starting from the global framework to regional to local.

2. Observed records – flood damage has been increasing

European Academies' Science Advisory Council (see EASAC, 2018), presented the trends in the number of different types of natural catastrophes worldwide in 1980–2016 (with 1980 levels set at 100%), based on the data from MunichRe NatCatSERVICE. The number of hydrological events (floods and mass movements) has increased much stronger than the number of geophysical, meteorological and climatic events. The number of hydrological events in an average year has now more than quadrupled since 1980 (exceeds 500% in some years). Global flood damage, after Munich Re, has been growing in last years with record high damages in 2017, both insured (some 120 US$ billion) and non-insured (some 179 US$ billion) due to a suite of three disastrous hurricanes and deluges from August to September in the USA and the Caribbean (Fig. 1). In July 2018, there were heavy rainfalls in Japan, causing major floods with dozens of fatalities, massive evacuation and high material damage.

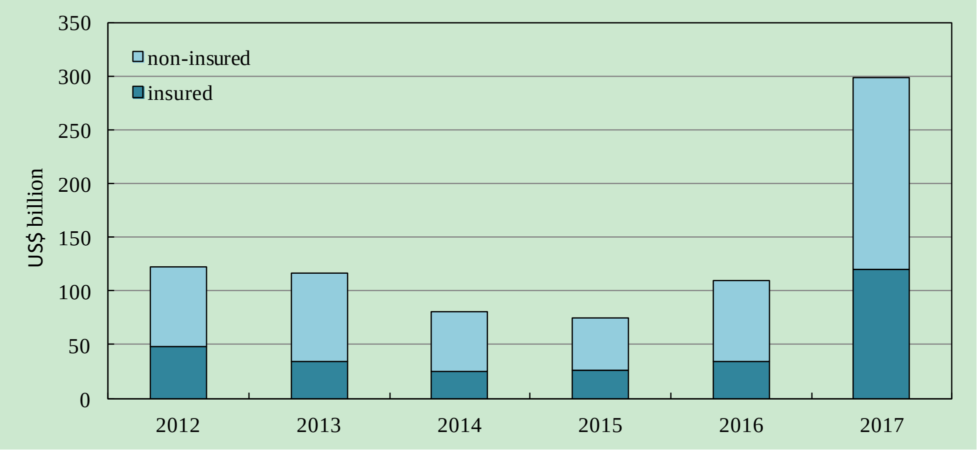

Fig. 1 Global flood damage, in billions US$ (Source: www.munichre.com/natcatservice).

Flood risk can be assumed to depend on flood hazard, flood exposure and flood vulnerability, which, in turn, are driven by a complex interplay of climate system, terrestrial and hydrological system, as well as the socio-economic system (Fig. 2). Kundzewicz et al. (2014) indicated that increasing exposure of population and assets has been primarily responsible for the recent increase in flood losses.

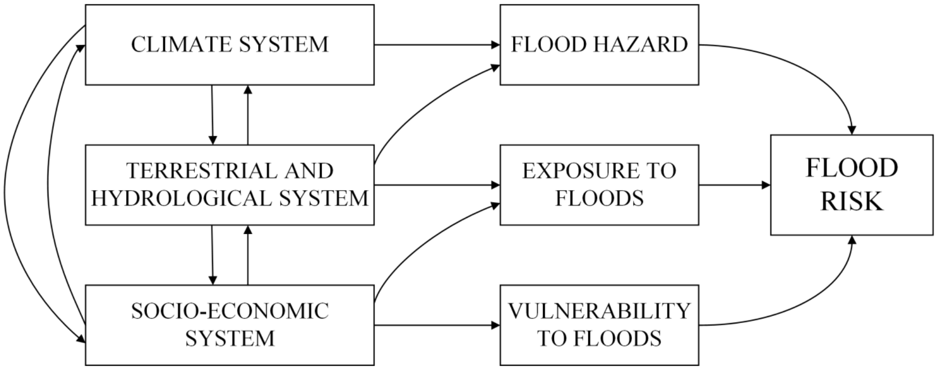

Fig. 2 Conceptual sketch of components of flood risk and its drivers (after: Kundzewicz et al., 2017a, modified).

Economic losses in monetary units (yet, adjusted for inflation and PPP, i.e. purchase power parity) caused by floods have been on the rise at any spatial scale. They are higher, in absolute terms, in industrialized countries, while relative economic losses expressed as a proportion of GDP and fatality rates are higher in less developed countries. This has grave security implications. This observation holds for natural disasters in general. From 1970 to 2008, over 95% of natural-disaster-related deaths occurred in developing countries (Field et al, 2012).

Typically, disaster losses associated with hydrological extremes can typically be well buffered in high-income countries (accounting less than 0.1% of GDP), while being much higher, considerably exceeding 1% of GDP in small exposed and less developed countries (Field et al, 2012).

Several factors may explain a perceived increase in flood risk:

- higher frequency and/or intensity of flood events;
- increased exposure of population and assets;
- increase of property value;
- generally, degraded awareness about natural risks, due to less natural lifestyle;
- increased vulnerability; and – not least
- improved and expanded reporting of disasters (sometimes called CNN effect).

There are countries in the world (see Kundzewicz et al., 2014), where more than 10% of the population and/or more than 10% of the Gross Domestic Product (GDP) were exposed to floods in an average year. In absolute terms, the highest number of people exposed was in India and Bangladesh (over 10 million each), then in China, Vietnam and Cambodia, while the highest mass of GDP exposed was in USA and China (over 10 billion US$ per year in each country), while in India and Bangladesh, it was nearly 10 billion US$. In relative terms, the highest percentage of people exposed was in Bangladesh and Cambodia (each, over 10% of the total population), then in Vietnam, while the highest relative share of economy exposed to floods was estimated in Cambodia and Bangladesh (over 10% in each country), then in Vietnam.

Dartmouth Floods Observatory (http://floodobservatory.colorado.edu/) has been compiling information about large floods, worldwide, since 1985. A short list of most deadly floods (including coastal surges), after the Dartmouth Floods Observatory is presented in Table 1. Among the main causes of the most destructive floods (with more than 1000 fatalities per event) were: tropical and extra-tropical cyclones, monsoonal rains, tropical storms, torrential rains, heavy rains, tsunamis, coastal surges, typhoons. Floods with heavy human toll were recorded in many locations in: Asia (India, China, Bangladesh, Philippines, Afghanistan, Pakistan, Japan, Burma), Central and South Americas (Honduras, Venezuela, Dominican Republic, Haiti, Salvador, Nicaragua, Costa Rica) and Africa (Tanzania and Sudan).

Table 1. Six most deadly floods (including coastal surges, but excluding tsunamis), worldwide since 1985. Information from Dartmouth Floods Observatory

Countries	Flood beginning	Flood end	Dead [thousand]	Main cause
Thailand	26.12.2004	29.12.2004	160	Coastal surge
Bangladesh	29.04.1991	10.05.1991	138	Tropical cyclone
Burma	03.05.2008	25.05.2008	100	Tropical cyclone
Venezuela, Colombia	15.12.1999	20.12.1999	20	Brief torrential rain
Honduras, Panama	24.10.1998	05.11.1998	11	Brief torrential rain
India	29.10.1999	12.11.1999	9.8	Tropical cyclone

Frequency and intensity of heavy precipitation have grown in many, but not all, areas of the globe. However, no gauge-based evidence has been identified so far for a clear, widespread, observed change in the magnitude and/or frequency of river floods (see Kundzewicz et al., 2005). Hodgkins et al. (2017) examined climate-driven variability in the occurrence of major floods across North America and Europe, in minimally altered catchments, finding that the number of significant trends was approximately equal to the number expected due to chance alone. Several authors report that temporal changes in the occurrence of major floods are dominated by natural variability rather than by long-term trends. It is possible that temporally-varying connections exist between indices of climate variability and variability of the likelihood of destructive abundance of water.

3. Projections for the future – flood hazard and flood damage

Climate projections show ubiquitous warming for all seasons and most models project increase in intense precipitation. Seneviratne et al. (2012) presented regional projections of 20-year 24h precipitation, noting increases over virtually all regions of the Globe.

There have been several global studies of model-based projections of flood hazard, starting from Milly et al. (2002), who covered selected basins worldwide, and Hirabayashi et al. (2008), who covered the global scale. It is worthwhile to compare four more recent papers, published since 2013 by Hirabayashi et al. (2013), Dankers et al. (2014), Arnell and Gosling (2014) and Giuntoli et al. (2015). Table 2 presents assumptions made in the global projection endeavors that considerably differ among studies (there are also slightly different reference periods).

Table 2 Assumptions made in model-based global flood-hazard projection studies.

Paper	Number of climate model scenarios	Number of hydrological models	Variable of interest	Time horizon of concern	Emission scenario
Arnell and Gosling (2014)	21 GCMs	1: Mac-PDM.09	Q100	2050s	SRES A1B
Dankers *et al.* (2014)	5 GCMs	9 GHMs	Q30	2070-2099	RCP8.5
Giuntoli *et al.* (2015)	5 GCMs	6 GHMs	Frequency of high flow days	2066-2099	RCP8.5
Hirabayashi *et al.* (2013)	11 GCMs	1 CaMa-Flood model	Q100	2071-2100	RCP8.5

Projections by Hirabayashi et al. (2013) indicate that what used to be a 100-year flood in the control period in many areas, is likely to occur much more frequently in the future, under changed climate, with return period of 50 years and below. Hirabayashi et al. (2013) project increase of hazard (Q100) in most of Asia (except for Western Asia) and in particular – eastwards of 80oE. They also project flood hazard to increase in Central Africa from 20oS to 10oN and in Central and South America from 20oN to 40oS, also in the north of North America and the East coast of the US. For most of Europe, decrease of flood hazard is projected. Results of Dankers et al. (2014) referring to a different index, Q30 (30-year 5-day peak flow), are broadly similar to those by Hirabayashi et al. (2013) as to the direction of change, except for a large area of decrease of hazard in South America. In turn, Giuntoli et al. (2015) project more frequent days with high river flow conditions over much of the north, from 50oN northwards. However, over most of the area of continents – rather small changes are projected, with absolute value less than 5% (i.e. from -5% to +5%).

Studies of large-scale projections of changes in flood hazard illustrate a considerable degree of uncertainty. There is no wonder, as projections were determined for different assumptions (cf. Table 2). They may differ with respect to:

- greenhouse gas emissions scenarios (SRES, RCP);
- driving climate models: general circulation models (GCMs), and regional climate models (RCMs);
- downscaling techniques and bias correction methods;
- performance of large-scale hydrological models, i.e. global hydrological models (GHMs) and regional hydrological models (RHMs);
- climate and hydrological model resolution;
- time horizons of future projections;
- reference (historic) intervals;
- return period (recurrence interval) of concern;
- low-temperature effects, e.g. snow and ice component in models;
- simulation of extremes;
- general problems related to extreme value techniques applied to time series that are not long enough.

The implications of the changing flood hazard to human society depend on the size of the population at risk of flooding. Under assumption of a fixed population (at the level of scenario from 2005), it was projected that annual global flood exposure would increase by about 4±3 times (under RCP2.6), 7±5 times (RCP4.5), 7±6 times (RCP6.0) and 14±10 times (RCP8.5) from 20th to 21st century (Hirabayashi, 2013). However, such results have to be interpreted with caution, especially considering changing adaptation and risk reduction capacity.

Where rain-floods and snow-floods both influence projections, relevant processes and different mechanisms have to be examined, for present and future conditions.

In addition, future flood risk in coastal zones will increase due to the sea level rise (Paprotny and Terefenko, 2017). As projected by Vousdoukas et al. (2018), taking into account both the socioeconomic pathways and climate change but in absence of further investments in adaptation, annual damage by coastal flood in Europe will increase from current 1.25 € billion to 93 - 961€ billion in the end of 21st century, and current 0.1 million exposed population will reach 1.52 - 3.65 million.

4. Flood risk reduction – global framework

Efforts on flood risk reduction are embedded in the general global framework, including the major documents – Hyogo Framework for Action and Sendai Framework for Disaster Risk Reduction.

"Tragedies will continue to be repeated if we do not address water and disaster issues at all levels," stated Dr. Han Seung-soo, the founding chair of the High-Level Experts and Leaders' Panel on Water and Disaster (HELP) (https://www.unisdr.org/archive/58108), while the UN Special Representative for Disaster Risk Reduction, Ms. Mami Mizutori, remarked that floods which now account for half of all weather-related disasters, highlight how disaster risk reduction is both a long-term development issue and a necessary strategy to prevent disasters and save lives in the short to medium term.

The World Conference on Disaster Reduction held in Hyogo, Japan, in 2005, promoting a strategic and systematic approach to reducing vulnerabilities and risks to hazards, adopted the Framework for Action 2005-2015, identifying ways of building the resilience of nations and communities to disasters (UNISDR, 2007).

Disaster loss has been on the rise with grave adverse consequences for the survival, dignity and livelihood of people, particularly of the poor, and for the hard-won development gains. Disaster risk is increasingly of global concern and its impact in one region can have an impact on risks in another (e.g. broken production links during the 2011 Thailand flood). The Hyogo Framework identified specific gaps and challenges in the following main areas: governance: organizational, legal and policy frameworks; risk identification, assessment, monitoring and early warning; knowledge management and education; reducing underlying risk factors; and preparedness for effective response and recovery.

Disaster risk reduction can be regarded as a cross-cutting issue in the realm of sustainable development and therefore an important element for the achievement of internationally agreed Millennium Development Goals.

The global plan for reducing disaster losses, the Sendai Framework for Disaster Risk Reduction, 2015-2030, was adopted by UN Member States in 2015, at the Third UN World Conference on Disaster Risk Reduction in Sendai, Japan (https://www.unisdr.org/we/coordinate/sendai-framework). It is a voluntary, non-binding, agreement aimed at a substantial reduction of disaster risk and losses in lives, livelihoods and health and in the assets. It emphasizes the importance of risk-informed investment in critical infrastructure, including water facilities, to avoid the creation of new risk. Disaster risk reduction and prevention should be integrated in long-term national planning and education on disaster risk must be advanced. Recognizing the State’s primary role to reduce disaster risk but also noting that responsibility should be shared with stakeholders, the Sendai Framework agreement, aiming to make a difference for poverty, health and resilience is the major document of the recent development agenda, embracing seven targets and four priorities for action.

The global targets include substantial reduction of mortality in flood disasters and the number of affected people, reduction of direct economic loss and damage to critical infrastructure as well as disruption of basic services (among them health and educational facilities), including through enhancing resilience (recovery). They also include work on national and local disaster risk reduction strategies, on international cooperation and on increasing the availability of and access to early warning systems (also dedicated to multiple hazards) and disaster risk information and assessments. Timelines for achieving these targets and reference intervals for measuring the progress were defined.

The priorities for action refer to understanding of disaster risk in its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment. Such knowledge can be used for risk assessment, as well as to various flood risk reduction strategies - prevention, mitigation, preparedness and response, recovery and rehabilitation (see Dieperink et al., 2016, Driessen et al., 2016 and Hegger et al., 2016). Strengthening disaster risk governance at a range of levels (national, regional and global) is another priority. Also investing in disaster risk reduction to enhance the economic, social, health and cultural resilience of persons, communities, countries and their assets, as well as the environment is an identified priority. So is also enhancing disaster preparedness for effective response and “Building Back Better”. Disaster risk reduction has to be integrated into sustainable development measures.

Willner et al. (2018) computed the required increase in flood protection, worldwide for subnational administrative units, in order to keep the historic high-end fluvial flood risk in the next 25 years. They found that most of the United States, Central Europe, and Northeast and West Africa, as well as large parts of India and Indonesia, require strong adaptation effort. For example, more than half of the United States needs to at least double their protection within the next two decades.

5. Flood risk reduction – from regional to local

There is no doubt that flood risk has grown in many places and is likely to grow further in the future, due to a combination of anthropogenic and climatic factors. Intense precipitation grows in the warming climate. However, reliable and detailed quantification of aggregate flood statistics is very difficult to obtain for the past-to-present and is virtually impossible to obtain for the future. Nevertheless, despite of the lack of reliable projections, flood risk reduction endeavors have been carried out at a range of scales, from regional (multi-national) to national, sub-national and local.

European Union (EU) passed a dedicated Directive 2007/60/EC on the assessment and management of flood risks (EU 2007), that required all 28 EU Member States to identify areas at risk from flooding, to map the flood extent as well as assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk. This Directive also reinforces the rights of the public to access information and to participate in the planning process. The Directive aims to reduce and manage the risks that floods pose to human health, economic activity, environment, and cultural heritage. The Directive required EU Member States to establish flood risk management plans focused on prevention, protection and preparedness by 2015.

Presence of people and wealth in flood prone areas can be regarded as an illness. One can prevent the risk, by keeping the destructive water away from people. This is the curation of the symptoms of the illness. One can also proceed with flood defenses, by keeping people away from the destructive water. This is curation of the source of the illness. But, it is also necessary to prepare to living with floods. This embraces flood mitigation – keeping water where it falls, flood preparation – forecasting, warning, as well as preparation for evacuation and recovery (see Dieperink et al., 2016; Driessen et al., 2016; Hegger et al., 2016; Nieland and Mushtaq, 2016).

Since 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 existing risk and vulnerability hotspots and improve the situation in areas where such hotspots occur (Kundzewicz et al., 2017b).

The prerequisite for flood risk reduction is to examine long time series of reliable records on flood-related information. Koç and Thieken (2018) carried out a comparative review of information from three sources: Turkey Disaster Database (TABB), the Emergency Events Database (EM-DAT), and the Global Active Archive of Large Flood Events—Dartmouth Flood Observatory, finding large mismatches in the flood data (on the number of events, number of affected people and economic loss).

Flood protection, i.e. adaptation to variability of discharge, has been developed in China for four millennia, since the quasi-legendary Emperor Yu, who succeeded in taming a long-lasting and disastrous flood in the Yellow River basin by dredging and channelling the rivers to drain the floodwaters and established the Xia dynasty, marking the beginning of Chinese civilization. The level of expenditure on flood protection in China has grown considerably in recent decades. However, despite the massive efforts, it is getting abundantly clear that complete flood control is not possible. Even if there exist powerful embankments along the rivers in China, they may not provide satisfactory protection of the riparians during large floods (cf. Kundzewicz and Xia, 2004). Increasingly, large flood damage has been recently occurring on medium- and small-size rivers. Hence, improvement of flood risk management is needed in the country and ambitious and vigorous attempts to improve flood preparedness have been undertaken, by both structural (“hard”) and non-structural (“soft”) measures. The former refer to such defences as dikes, dams and flood control reservoirs, diversions, etc. The latter include implementing watershed management (source control), zoning; insurance; flood forecasting–warning system; and awareness raising (Surminski et al., 2015; Nieland and Mushtaq, 2016; Adelekan and Asiyanbi, 2016). The coping capacities at a local level can influence the robustness of flood warning system (Daupras et al., 2015).

Structural measures, both dikes and dams of different sizes, have a very long tradition in China and continue to play a vital role in flood prevention also today, and in the foreseeable future. The multi-objective, massive Three Gorges Dam on the River Yangtze, the world’s greatest engineering work, has flood protection as the principal objective. Many large reservoirs, also with flood protection as the main objective, had been built in China, with a total storage capacity of over 0.5 × 1012 m3, accounting for over one fifth of the total estimated annual runoff from the land areas (Guo et al., 2004). Typically, water storage reservoirs serve multiple purposes: flood control, hydropower, irrigation, water supply, navigation, etc. The total number of large dams has increased very strongly since 1960, when only five large dams (higher than 100 m) existed. The number of large dams grew tenfold in 2000 (Xu et al., 2010). In the second half of the 20th century, more than 200 thousand kilometers of dikes have been strengthened for alleviating the impacts of floods in China (Zhang et al., 2002).

In many countries, flood protection is distributed among several agencies, hence effective cooperation and communication among federal, state and local stakeholders is essential. This is inherently difficult, but progress has been achieved in China in flood forecasting integration, data sharing and collaborative problem solving. The China Meteorological Administration (CMA) collects observations of precipitation and other meteorological variables and prepares precipitation forecasts. The Ministry of Water Resources (MWR) of China collects hydrological observations (e.g., of river levels and discharges) and is responsible for flood forecasting and dissemination of the forecast. River basin commissions in China (altogether – seven commissions, including the Yangtze River Basin Commission) are agencies of the MWR. The Flood Prevention Law of 2007 laid out principles and responsibilities for flood prevention planning in China. There is a national standard (GB50201-94) drafted by the Ministry of Water Resources and issued by the Ministry of Construction in 1994 dealing with flood return periods for different categories of location (Gemmer et al., 2011). In 2010, flood hazard mapping guidelines were published as a professional standard by the Ministry of Water Resources.

Gemmer et al. (2011) reviewed climate change adaptation in China, the National Climate Change Programme and China´s White Paper "China's Policies and Actions for Addressing Climate Change". All 34 provinces of China produced a climate change adaptation plan, including flood risk reduction.

It is assumed that occurrence of a disastrous flood event improves awareness and triggers funding of relevant research and investment in flood risk reduction. In brief, people are expected to learn from floods. However, in their study of consequences of the destructive 2011 flood in Thailand, Marks and Thomalla (2017) noted that the government has only made minor efforts to reduce flood risk. The sociopolitical transformations needed to reduce system vulnerability have not occurred. The focus was on structural defenses - building floodwalls to reduce risk to large-scale enterprises, and this has redistributed risk to unprotected areas.

6. Concluding remarks

Many studies of flood hazard projections demonstrate the likely rise of flood hazard in the future. Plausible climate change scenarios indicate the possibility of increases in both the frequency and the magnitude of flooding events in many areas. Yet there has been no conclusive and general finding as to how climate change affects flood behaviour, in the light of data

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observed so far. The natural variability in observation records is overwhelming. However, regional changes in timing of floods have been observed in some areas, with increasing late autumn and winter floods (caused by rain) and less ice-jam-related floods, e. g., in Europe and this is a robust result.

The flood hazard depends on a combination of anthropogenic and natural factors, such as climate, land use, as well as population density and wealth (hence – damage potential) in flood-risk areas and development of flood defenses. Owing to the growing population pressure, activities like deforestation, agricultural land expansion, urbanization (and increasing sealing of the ground surface), construction of roads, as well as reclamation of wetlands and lakes have been progressing. This has reduced the available water storage capacity in river basins, increased the value of the runoff coefficient, and aggravated flood hazard and flood risk. Flood potential has ubiquitously increased – there is simply more to lose.

There are multiple factors driving flood hazard and flood risk and there is a considerable uncertainty in our assessments, and in particular projections for the future. In many places flood risk is likely to grow, due to a combination of anthropogenic and climatic factors. However, in general, it is difficult to disentangle the climatic change component in maximum river flow or flood hazard records from strong natural variability and direct, man-made, environmental changes. There is a large difference in between flood hazard projection results obtained by using different scenarios and different models. Therefore, one should be careful with flat-rate statements on changes in flood hazard and flood risk, and on climate change impact in particular. The impact of climate forcing on flood risk is complex and depends on the flood generation mechanism. Indeed, higher and more intense precipitation has been already observed in many (but not all) areas of the Globe and this trend is expected to strengthen in the warmer world, directly impacting on flood risk. Therefore, common-sense changes to design rules, aimed at flood risk reduction, have been introduced in some countries of Europe, based more on precautionary principle rather than on robust science. The design flood was adjusted upward (and the frequency – adjusted downward) in light of projections for the warmer climate.

However, it is a robust statement that, in general, today’s climate models are still not good enough at producing local climate extremes due to, *inter alia*, inadequate (coarse) resolution. There is hope that, with improving resolution, models will be able to grasp details of extreme events in a more accurate and reliable way (Kundzewicz and Schellnhuber, 2004).

It is necessary to continue examination of the updated records of flood-related indices, trying to search for changes that influence flood hazard and flood risk in river basins. Possibly, there have been and will continue to be changes in intense precipitation; changes in cyclone track; changes in land use; and changes in exposure and vulnerability. Early detection and attribution of changes at any spatial scale would be of vast practical importance.

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REFERENCES

Adelekan, I. O. and Asiyanbi, A. P.: Flood risk perception in flood-affected communities in Lagos, Nigeria. Natural Hazards, 80, 445-469, 2016.

Arnell, N. W. and Gosling, S. N.: The impacts of climate change on river flood risk at the global scale, Climatic Change, 134, 387–401, doi:10.1007/s10584-014-1084-5, 2014.

Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., Heinke, J., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D.: 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, 2014.

Daupras, F., Antoine, J. M., Becerra, S. and Peltier, A.: Analysis of the robustness of the French flood warning system: a study based on the 2009 flood of the Garonne River, Natural Hazards, 75, 215-241, 2015.

Dieperink. C., Hegger, D. L. T., Bakker, M. H. N., Kundzewicz, Z. W., Green, C. and Driessen, P. P. J.: Recurrent governance challenges in the implementation and alignment of flood risk management strategies: a review, Water Resources Management, 30, 4467-4481, doi: 10.1007/s11269-016-1491-7, 2016.

Driessen, P. P. J., Hegger, D. L. T., Bakker, M. H. N., Rijswick, H. F. M. W. V. and Kundzewicz, Z. W.: Toward more resilient flood risk governance, Ecology and Society, 21, 53, https://doi.org/10.5751/ES-08921-210453, 2016.

EASAC (European Academies' Science Advisory Council): Extreme weather events in Europe. Preparing for climate change adaptation: an update on EASAC's 2013 study, https://easac.eu/fileadmin/PDF_s/reports_statements/Extreme_Weather/EASAC_Statement_Extreme_Weather_Events_March_2018_FINAL.pdf, 2018.

EU (European Union): 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, 2007.

Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G. K., Allen, S. K., Tignor, M. and Midgley, P. M.: Managing the risks of extreme events and disasters to advance climate change adaptation, Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), Cambridge, UK: Cambridge University Press, 2012.

Gemmer, M., Wilkes, A. and Vaucel, L. M.: Governing climate change adaptation in the EU and China: An analysis of formal institutions, Advances in Climate Change Research, 2, 1-11, 2011.

Guo, S., Zhang, H., Chen, H., Peng, D., Liu, P. and Pang, B.: A reservoir flood forecasting and control system for China, Hydrological Sciences Journal, 49, 959–972, 2004.

Giuntoli, I., Vidal, J. P., Prudhomme, C. and Hannah, D. M.: Future hydrological extremes: the uncertainty from multiple global climate and global hydrological models, Earth System Dynamics, 6, 267–285, doi:10.5194/esd-6-267-2015, 2015.

Hegger, D. L. T., Driessen, P.P.J., Wiering, M.A., Rijswick, H. F. M. W. V., Kundzewicz, P., Matczak, A., Crabbé, A., Raadgever, G. T., Bakker, M. H. N., Priest, S. J., Larrue, C., Ek, K., Hegger, D., Driessen, P. P. J., Raadgever, T. and Priest, S.: Toward more flood resilience: Is a diversification of flood risk management strategies the way forward?, Ecology and Society, 21, 52-71, https://doi.org/10.5751/ES-08854-210452, 2016.

Hirabayashi, Y, Kanae, S., Emori, S., Oki, T. and Kimoto, M.: Global projections of changing risks of floods and droughts in a changing climate, Hydrological Sciences Journal, 53, 754–772, doi:10.1623/hysj.53.4.754, 2008.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H. and Kanae, S.: Global flood risk under climate change, Nature Climate Change, 3, 816–821, doi:10.1038/nclimate1911, 2013.

Hodgkins, G. A., Whitfield, P. H., Burn, D. H., Hannaford, J., Renard, B., Stahl, K., Fleig, A. K., Madsen, H., Mediero, L., Korhonen, J., Murphy, C. and Wilson, D.: Climate-driven variability in the occurrence of major floods across North America and Europe, Journal of Hydrology, 552, 704-717, https://doi.org/10.1016/j.jhydrol.2017.07.027, 2017.

Koç, G. and Thieken, A. H.: The relevance of flood hazards and impacts in Turkey: What can be learned from different disaster loss databases?, Natural Hazards,91, 375–408, 2018.

Kundzewicz, Z. W. and Schellnhuber, H. J.: Floods in the IPCC TAR perspective, Natural Hazards, 31, 111-128, 2004.

Kundzewicz, Z. W. and Xia, J.: Towards an improved flood preparedness system in China, Hydrological Sciences Journal, 49, 941-944, 2004.

Kundzewicz, Z. W., Graczyk, D., Maurer, T., Pińskwar, I., Radziejewski, M., Svensson, C. and Szwed, M.: Trend detection in river flow series: 1. Annual maximum flow, Hydrological Sciences Journal, 50, 797–810, 2005.

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K. and Sherstyukov, B.: Flood risk and climate change: global and regional perspectives, Hydrological Sciences Journal, 59, 1-28, 2014.

Kundzewicz, Z. W., Pińskwar, I. and Brakenridge, G. R.: Changes in river flood hazard in Europe: a review, Hydrology Research, 49, nh2017016, doi:10.2166/nh.2017.016, 2017a.

Kundzewicz, Z. W., Krysanova, V., Dankers, R., Hirabayashi, Y., Kanae, S., Hattermann, F. F., Huang, S., Milly, P. C. D., Stoffel, M., Driessen, P. P. J., Matczak, P., Quevauviller, P. and Schellnhuber, H. J.: Differences in flood hazard projections in Europe - their causes and consequences for decision making, Hydrological Sciences Journal, 62, 1-14, 2017b.

Marks, D. and Thomalla, F.: Responses to the 2011 floods in Central Thailand: Perpetuating the vulnerability of small and medium enterprises?, Natural Hazards, 87, 1147–1165, 2017.

Milly, P. C. D., Wetherald, R. T., Dunne, K. A. and Delworth, T. L.: Increasing risk of great floods in a changing climate, Nature, 415, 514-517, 2002.

Nieland, C. and Mushtaq, S.: The effectiveness and need for flash flood warning systems in a regional inland city in Australia, Natural Hazards, 80, 153-171, 2016.

Paprotny, D. and Terefenko, P.: New estimates of potential impacts of sea level rise and coastal floods in Poland, Natural Hazards, 85, 1249-1277, 2017.

Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X.: Changes in climate extremes and their impacts on the natural physical environment. In: Field, C. B., et al. (eds) Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, and New York, NY, 2012.

Surminski, S., Aerts, J. C. J. H., Botzen, W. J. W., Hudson, P., Mysiak, J. and Pérez-Blanco, C. D.: Reflections on the current debate on how to link flood insurance and disaster risk reduction in the European Union, Natural Hazards, 79, 1451-1479, 2015.

UNISDR (The United Nations Office for Disaster Risk Reduction): Hyogo Framework for action 2005-2015: Building the resilience of nations and communities to disasters, https://www.unisdr.org/files/1037_hyogoframeworkforactionenglish.pdf, 2007.

UNISDR (The United Nations Office for Disaster Risk Reduction): The human cost of weather-related disasters 1995-2015, https://www.unisdr.org/files/46796_cop21weatherdisastersreport2015.pdf, 2015.

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F. and Feyen, L.: Climatic and socioeconomic controls of future coastal flood risk in Europe, Nature Climate Change, 8, 776-780, 2018.

Willner, S. N., Levermann, A., Zhao, F. and Frieler, F.: Adaptation required to preserve future high-end river flood risk at present levels, Science Advances, 4, eaao1914, doi: 10.1126/sciadv.aao1914, 2018.

Xu, K., Milliman, J. D. and Xu, H.: Temporal trend of precipitation and runoff in major Chinese Rivers since 1951, Glob. Planet. Change, 73, 219-232, 2010.

Zhang, J. Q., Zhou, C. H., Xu, K. Q. and Watanabe, M.: Flood disaster monitoring and evaluation in China, Environmental Hazards, 4, 33-43, 2002.