



# 国家气候中心

CHINA METEOROLOGICAL ADMINISTRATION (CMA)  
NATIONAL CLIMATE CENTRE (NCC)

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Prof. Dr. JIANG Tong  
Division of Climate Change Impact Assessment  
Beijing, March 4, 2019

To Editor of  
Natural Hazards and Earth System Sciences

Re: submission of a revised review article

Dear Sir / Madam,

We would like to submit a revised draft of the manuscript "Flood Risk in a Range of Spatial Perspectives – from Global to Local" for publication in *Natural Hazards and Earth System Sciences*.

We really appreciate many interactive comments provided by two anonymous referees, These constructive and useful comments proved to be valuable and allowed us to enrich this paper. We now thank the referees in the Acknowledgments. We have constructively reacted to all the interactive comments. We attach responses to the recommendations of the reviewer.

Do not hesitate to contact us if any further information is needed. We are looking forward to hearing from you.

Sincerely yours,

Jiang Tong  
On behalf of co-authors

**NCC**

**Authors' responses to interactive comments on "Flood Risk in a Range of Spatial Perspectives – from Global to Local" by Z. W. Kundzewicz *et al.***

**Anonymous Referee #1**

Received and published: 16 February 2019

This paper discussed a very important topic, the flood risk at global and regional scales. I appreciate the authors' effort to tackle this issue. But it requires a decent amount of work to solidify some statements.

Thanks for encouraging words. We tried to solidify problematic statements.

I suggest the authors extend and solidify the literature review in this paper. For example, the authors believe that the frequency of flood does not have obvious changes during the past. However, based on previous research, at least in the US, the low-frequency floods do have a significant change, while the high-frequency floods do not have a significant change.

We did our best to extend the literature review, even if there are thousands of source items that could be referred to, so that we had to be selective. Indeed, we introduced additional references from the USA (Links and Slack, 1999, 2005; as well as Shaw & Riha, 2011) that solidify the review and demonstrate the subtleties of findings, demonstrating the lack of a one-size-fits-all result.

The characteristics of floods include are magnitude, frequency and timing. So I also suggest the authors extend a paragraph to discuss the influence of the change of floods' timing, instead of just one sentence in the current version.

We devoted more room to the timing issues, referring to results by Blöschl *et al.* (2017) as well as Hodgkins *et al.* (2017).

Please change the format of latitude and longitude.

We changed the format by using superscripts.

**Anonymous Referee #2**

Received and published: 1 March 2019

I have really enjoyed reviewing this manuscript, which examines flood risk from global to local perspectives. The topic is very relevant, and such a paper is timely. Yet, I think that there are four key aspects that have been neglected (or not sufficiently well discussed). This manuscript would highly benefit from including a critical discussion around the following four major points (A-D).

Many thanks for these kind words and, above all, for excellent, constructive review that helped us enrich our paper. We reacted to all points raised by this referee.

A) Lines 44-53 of the original manuscript / lines 44-54 of the revised manuscript  
This paragraph requires references, as some of these statements are in fact contested by many scholars. Flood trends reported so far are not so strong. For example, in their *Science* paper, Blöschl et al. (1) states that: “Will a warming climate affect river floods? The prevailing sentiment is yes, but a consistent signal in flood magnitudes has not been found.” “A warming climate is expected to have an impact on the magnitude and timing of river floods; however, no consistent large-scale climate change signal in observed flood magnitudes has been identified so far.” “Existing studies have been unable to identify a consistent climate change signal in flood magnitudes.” Blöschl et al. (1) mainly refer to floods in Europe, but similar outcomes were found in other places around the world, such as Africa (2).

Indeed, we are well aware that the climate track in flood hazard is generally weak and by no means it is ubiquitous. We carefully selected the wording used in our paper, in order not to create impression that we see a major climatic pattern in flood hazard. We added one sentence in lines 46-47 but we discuss the climate track in more detail in Section 2 (lines 150-170). We refer to the important work by Blöschl et al. (2017), mainly conveying their principal finding – detection of changes in pattern of flood timing. Indeed, Blöschl’s publication in *Science* is perhaps the highest place where one can find a statement that “a consistent large-scale climate change signal in observed flood magnitudes has not been identified so far”. (Attention: there was also a paper: Mudelsee, M., Börngen, M., Tetzlaff, G. & Grünewald, U. (2003) No upward trends in the occurrence of extreme floods in central Europe, *Nature*, 421, 166-169). However, there have been many other works published before Blöschl et al. (2017), reporting a similar finding (e.g. Lins & Slack, 1999, 2005; the book edited by Kundzewicz, 2012 and cited in Blöschl et al., 2017; as well as Madsen et al., 2014). We could identify some (not persuading) changes in selected indices (Kundzewicz et al., 2005, 2018c). We incorporated both references proposed by referee #2 in part (A) of the review.

B) Line 111 of the original manuscript / line 119 of the revised manuscript

“Increased vulnerability” is listed as a factor for increasing flood risk. It is important to say that in fact at the vulnerability is in fact decreasing at the global scale, as shown for example on the PNAS paper by Jongman et al. (3). At the local scale, there are indeed instances in which vulnerability is increasing, but many authors have shown several examples of decreasing vulnerability (e.g. 4-7 among many others). I am aware that good news and promising trends sell less than bad news and catastrophic trends, but I think these outcomes should still be recognized in a scientific paper. See also my point D below.

Very good point. We added a paragraph (lines 121-126), presenting caveats and explanations, as proposed by referee #2. We incorporated all references proposed in part (B) of the review.

C) Lines 263-268 of the original manuscript / lines 303-318 of the revised manuscript

Previous sections have discussed that flood risk is increasing because more and more people live in flood-prone areas. This is a globally accepted fact. However, in this section the authors suggest increasing protection levels and having even more dykes or levees, which have been shown to attract even more people in flood-prone areas!! There is more than abundant literature on safe-development paradox, residual risk and levee effects (e.g. 8-11 to cite only a few) since the work of Gilbert White in the 1940s (8). Numerous scholars have showed that the introduction or reinforcement of structural protection measures are often associated with negative effects, such as: Increasing exposure to flooding. As protected flood-prone areas are perceived as safer, they attract more assets and people (9). Increasing vulnerability to flooding. As protected flood-prone areas are perceived as safer, people living in these areas have less incentives to take individual precautionary measures (10) Social injustice. Structural measures protecting same areas from frequent flooding, alter the spatial distribution of risk in a way that can affect social groups that are less privileged (11). Preventing relocation. People in highly protected areas are less willing to relocate from risky areas (12). Losses of biodiversity. Levees and dikes that prevent the natural inundation of floodplain also negatively affect biodiversity and ecological functions (13).

Thanks for indicating the areas that require strengthening. We touched upon many points raised by reviewer #2 in part C, i.e. we did not neglect them in the first place. However, indeed we did not discuss them sufficiently well. It is quite a rare case that a reviewer sacrifices a lot of time to produce a set of specific, constructive, remarks with which co-authors agree with delight, so that a win-win situation arises. We introduced a new paragraph in lines 303-318 that discusses the points proposed by reviewer #2 in part C of the review. We also cited all references proposed by reviewer #2 in part C of the review.

D) Lines 352-358 of the original manuscript / lines 407-423 of the revised manuscript

This paragraph, which deals with social learning, is too shallow. "It is assumed: : : " not clear by whom, and in which context. There is abundant literature in this topic, which deserves a better treatment. Instead, a specific example is provided (2011 flood in Thailand) to hint that such a learning is not really happening. In fact, there are many case studies showing learning effects or that the negative impact of an extreme event tends to be lower if such an event occurs shortly after a similar one (e.g. 3-7

among many others): Decreasing flood fatalities have been observed in Bangladesh over the past decades (4). The economic losses of the 1995 Meuse River flooding in Central Europe were remarkably lower than those in 1993, even though the magnitudes of the two events were similar (5). Di Baldassarre et al. (6) show adaptation effects in study areas around the world. Kreibich et al. (7) show multiple examples of learning dynamics in several test sites. Vulnerability to river flooding has been declining over the past decades (3), as a result of adapting response at the local scale.

Again, a very useful comment. Indeed, we did not dare to use the term “social learning”, therefore stating that “[t]his paragraph, which deals with social learning, is too shallow” is an euphemism on the part of referee #2. However, adopting the recommendations of referee #2 we tried to render this paragraph (lines 407-423) a little less “shallow”. Nevertheless, we are aware that there is a vast body of literature on the topic that we do not cite and many aspects that deserve to be tackled and are ignored in this (already quite comprehensive) paper. Prioritization was needed when selecting material for the general review undertaken in our paper. We think that an attempt to offer an objective prioritization would be a *mission impossible*. We cited all references proposed by this reviewer in part (D) of the review.

#### REFERENCES

1. Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A., Merz, B., Arheimer, B., et al. (2017). Changing climate shifts timing of European floods. *Science*, 357(6351), 588-590.
2. Di Baldassarre, G., A. Montanari, H. Lins, D. Koutsoyiannis, L. Brandimarte, and G. Bloeschl (2010). Flood fatalities in Africa: from diagnosis to mitigation, *Geophysical Research Letters*, 37, L22402.
3. Jongman, B., Winsemius, H. C., Aerts, J. C., de Perez, E. C., van Aalst, M. K., Kron, W., & Ward, P. J. (2015). Declining vulnerability to river floods and the global benefits of adaptation. *Proceedings of the National Academy of Sciences*, 112(18), E2271-E2280.
4. Mechler, R., & Bouwer, L. M. (2015). Understanding trends and projections of disaster losses and climate change: is vulnerability the missing link? *Climatic Change*, 133(1), 23-35.
5. Wind, H. G., Nierop, T. M., de Blois, C. J., & de Kok, J. L. (1999). Analysis of flood damages from the 1993 and 1995 Meuse floods. *Water Resources Research*, 35(11), 3459-3465.
6. Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., & Blöschl, G. (2015), Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes, *Water Resources Research*, 51, 4770–4781.
7. Kreibich, H., Di Baldassarre, G., Vorogushyn, S., Aerts, J. C., Apel, H., et al. (2017). Adaptation to flood risk: Results of international paired flood event studies. *Earth's Future*, 5(10), 953-965.
8. White, G.F. (1945). *Human Adjustments to Floods*. Department of Geography. Research Paper No. 29. Department of Geography, University of Chicago, Chicago. 225 pages.
9. Kates, R. W., Colten, C. E., Laska, S., and Leatherman, S. P. (2006), Reconstruction of New Orleans after Hurricane Katrina: A research perspective. *Proceedings of the National Academy of Sciences of USA*, 103(40), 14653-14660.
10. Ludy J., & Kondolf, G. M. (2012). Flood risk perception in lands “protected” by 100-year levees. *Natural Hazards*, 61(2), 829-842.

11. Di Baldassarre, G., Kemerink, J.S., Kooy, M., Brandimarte, L. (2014). Floods and societies: the spatial distribution of water-related disaster risk and its dynamics. *Wiley Interdisciplinary Reviews: Water*, 1(2), 133-139.
12. Mård, J., Di Baldassarre, G., Mazzoleni, M. (2018) Nighttime light data reveal how flood protection shapes human proximity to rivers. *Science Advances*, 4(8), eaar5779.
13. Auerswald, K., Moyle, P., Seibert, S. P., & Geist, J. (2019). HESS Opinions: Socio-economic and ecological trade-offs of flood management—benefits of a transdisciplinary approach. *Hydrology and Earth System Sciences*, 23(2), 1035-1044.

1 **Flood Risk in a Range of Spatial Perspectives—from Global to Local**

2

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19

20 **Abstract**

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

30

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

33

## 34 **1. Introduction**

35

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

44 The nature of disastrous floods seems to have changed, in recent decades, with increasing  
45 frequency and amplitude of heavy precipitation, flash and urban floods, as well as acute riverine  
46 and coastal flooding. The climate track in flood hazard is complex and not ubiquitous (see  
47 Section 2). Urbanization and sealing of ground surface have significantly increased surface  
48 water runoff in many areas. In some countries, recurrent flooding of crop land has taken a heavy  
49 toll in terms of lost agricultural production, food shortages, interrupted food supplies and under-  
50 nutrition. However, some deleterious impacts of floods are preventable or at least can be  
51 reduced, because of the opportunity of primary prevention through existing, and - in many  
52 places – affordable, technologies such as early warning systems and some flood defenses, while  
53 awareness raising and education can also be effective in protecting people from adverse impact  
54 of floods.

55 The spatial perspective on floods ranges from a global view by multi-national  
56 stakeholders, international organizations, reinsurance institutions, and think-tanks, interested in  
57 global affairs to regional (group of countries, river basins which cross national borders, where  
58 40% of global population live and where trans-boundary water issues should be addressed),  
59 national, and sub-national (river basins) scales. The local point of view is, for instance, the one  
60 of a family of a person who lost life in the flood, of a family that lost their house or workplace  
61 in the flood, or of persons responsible for local flood protection. The local scale pertains to the  
62 locality and community in flood-prone area, where flood damage incurred and/or where  
63 implementation of a flood-risk reduction measure is planned. The global consideration may  
64 include aggregation of observation records, model-based projections, as well as international  
65 policies aimed at flood risk reduction.

66 In the present paper, reviewing flood risk in a range of spatial perspectives (from global to  
67 local), we start from examination of observed records, noting that flood damage has been



68 increasing. Further, we discuss projections for the future – flood hazard and flood losses, and  
69 then review flood-risk reduction strategies, starting from the global framework to regional to  
70 local.

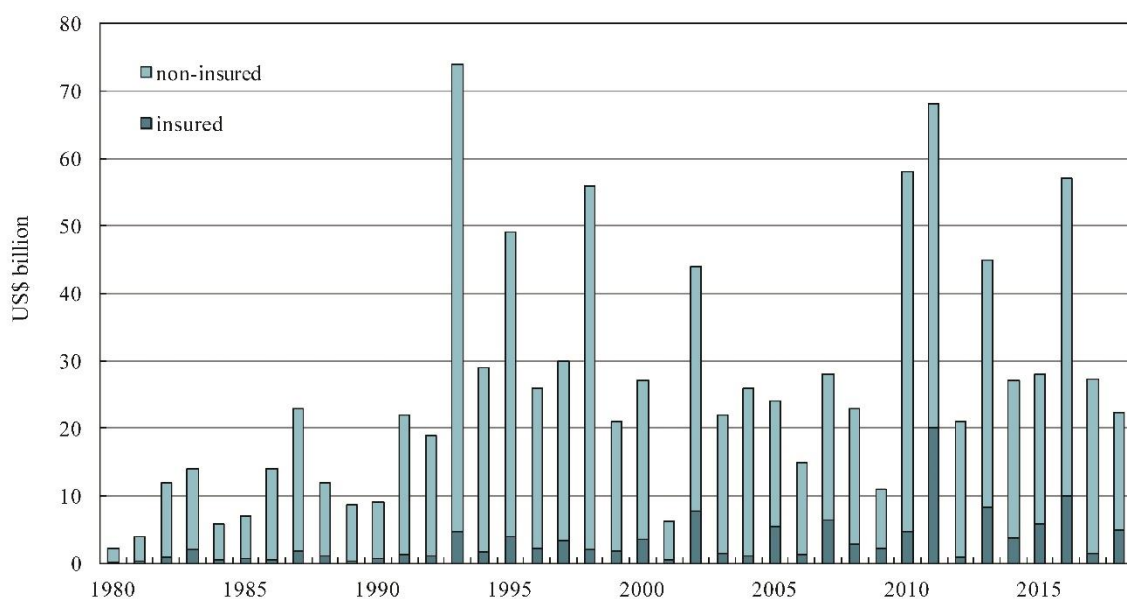
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## 72 2. Observed records – flood damage has been increasing

73 European Academies’ Science Advisory Council (see EASAC, 2018), presented the trends in  
74 the number of different types of natural catastrophes worldwide in 1980–2016 (with 1980  
75 levels set at 100%), based on the data from MunichRe NatCatSERVICE. The number of  
76 hydrological events (floods and mass movements) has increased much stronger than the  
77 number of geophysical, meteorological and climatic events. The number of hydrological  
78 events in an average year has now more than quadrupled since 1980 (exceeds 500% in some  
79 years). Global damage caused by “hydrological events”, after Munich Re, has been growing,  
80 albeit with strong inter-annual variability (Fig. 1).

81 The named hurricanes, such as the most  
82 costly three that occurred in the North Atlantic in just four weeks: Harvey in August 2017, as  
83 well as Irma and Maria (September 2017) are counted as “meteorological events”. However,  
84 the vast majority of the total damage (approximately 95 billion US\$) caused by Hurricane  
85 Harvey was related to flooding. This hurricane, that counts as second-costliest on record (after  
86 Katrina), dropped record levels of rain that inundated the city of Houston, Texas, USA. If the  
87 damage caused by flooding related to Harvey were counted in Fig. 1, the year 2017 would  
88 likely be the outstanding one, with highest flood damage ever.

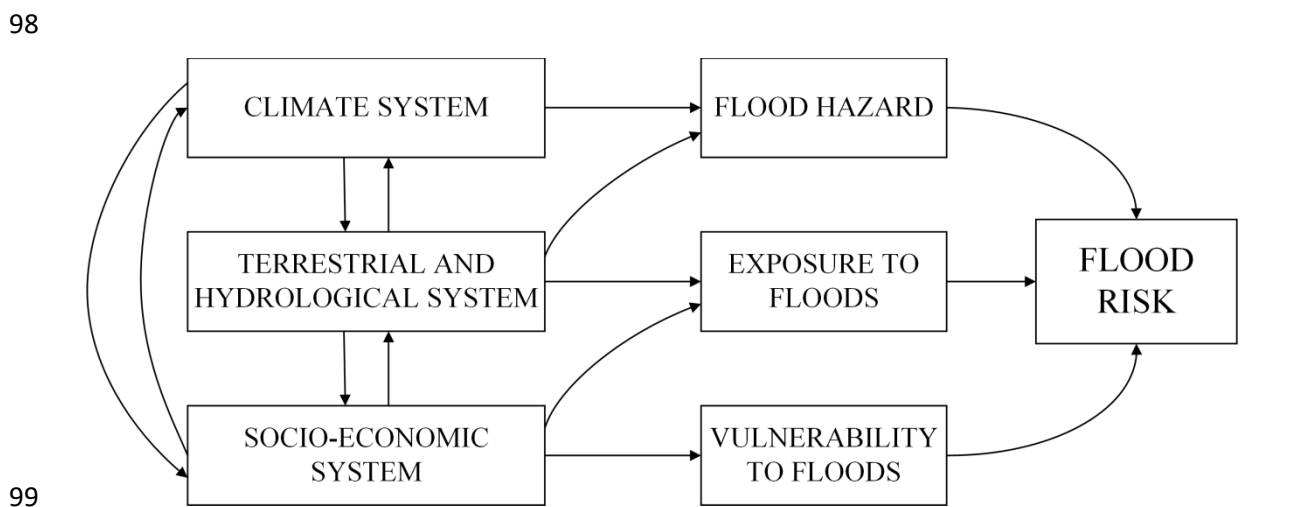
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89

90 **Fig. 1** Global damage by “hydrological events”, in billions US\$ (Source: Munich Re  
91 NatCatSERVICE).

92  
93 Flood risk can be assumed to depend on flood hazard, flood exposure and flood  
94 vulnerability, which, in turn, are driven by a complex interplay of climate system, terrestrial  
95 and hydrological system, as well as the socio-economic system (Fig. 2). Kundzewicz et al.  
96 (2014) indicated that increasing exposure of population and assets has been primarily  
97 responsible for the recent increase in flood losses.



99  
100  
101 **Fig. 2** Conceptual sketch of components of flood risk and its drivers (after: Kundzewicz et al.,  
102 2018c, modified).

103  
104 Economic losses in monetary units (yet, adjusted for inflation and PPP, i.e. purchase power  
105 parity) caused by floods have been on the rise at any spatial scale. They are higher, in absolute  
106 terms, in industrialized countries, while relative economic losses expressed as a proportion of  
107 GDP and fatality rates are higher in less developed countries. This has grave security  
108 implications. This observation holds for natural disasters in general. From 1970 to 2008, over  
109 95% of natural-disaster-related deaths occurred in developing countries (Field et al., 2012).

110 Typically, disaster losses associated with hydrological extremes can be well buffered in  
111 high-income countries (accounting less than 0.1% of GDP), while being much higher,  
112 considerably exceeding 1% of GDP in small exposed and less developed countries (Field et al.,  
113 2012).

114 Several factors may explain a perceived increase in flood risk:

- 115
- higher frequency and/or intensity of flood events;
  - increased exposure of population and assets;
- 116

- 117 • increase of property value;
- 118 • generally, degraded awareness about natural risks, due to less natural lifestyle;
- 119 • increased vulnerability; and – not least
- 120 • improved and expanded reporting of disasters (sometimes called CNN effect).

121 We listed vulnerability increase as one of factors that may explain risk increase, but this  
 122 holds for some areas only. In general, there is a significant decrease in vulnerability at the global  
 123 scale (cf. Kundzewicz et al., 2014; Jongman et al., 2015), largely due to developments in China,  
 124 and “vertical urbanization” in particular. Many examples of decreasing vulnerability at the local  
 125 scale have been reported (e.g. in Di Baldassarre et al., 2015; Mechler and Bouwer, 2015; Wind  
 126 et al., 1999 and Kreibich et al., 2017).

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

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

146

147 **Table 1.** Six most deadly floods (including coastal surges), worldwide since 1985.

148 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      |

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149

150 Frequency and intensity of heavy precipitation have grown in many, but not all, areas of  
151 the globe. However, no gauge-based evidence has been found so far for a clear, widespread,  
152 and consistent change in the magnitude and/or frequency of river floods (see Kundzewicz et  
153 al., 2005; Madsen et al., 2014). Lins and Slack (1999) found that, hydrologically, the  
154 conterminous U.S. had been getting wetter, but less extreme. Later, they (Lins and Slack, 2005)  
155 confirmed the pattern of increasing discharge in the low to moderate range of river flows,  
156 without a concomitant increase in flooding. Relatively few trends in the annual maximum flow  
157 were detected. Hodgkins et al. (2017) examined climate-driven variability in the occurrence of  
158 major floods across North America and Europe, in minimally altered catchments (to eliminate  
159 major non-climatic effects), finding that the number of significant trends was approximately  
160 equal to the number expected due to chance alone. Shaw and Riha (2011) studied three  
161 watersheds in different physiographic regions of New York State, USA and concluded that 20%  
162 or less of annual maximum streamflows were associated with the annual maximum rainfall  
163 events, another 20% - with the annual maximum snowmelt events, while 60% - with moderate  
164 rainfall amounts and very wet soil conditions. Noting that it has not been possible to find  
165 ubiquitous flood hazard changes in observation records in Europe, so far, Kundzewicz et al.  
166 (2018c) detected an increasing trend in the number of large floods, even if the natural variability  
167 is dominating. It is likely that temporally-varying connections exist between indices of climate  
168 variability and variability of the likelihood of destructive abundance of water. Blöschl et al.  
169 (2017) noted no “consistent climate change signal in flood magnitudes” in Europe, while Di  
170 Baldassarre et al. (2010) reported a similar finding for Africa.

171 Blöschl et al. (2017) found climate-induced patterns of change in observed flood timing  
172 in Europe, at the continental scale. They detected earlier spring snowmelt floods throughout NE  
173 Europe (warming-driven change); later winter floods around the North Sea and part of the  
174 Mediterranean coast (related to polar warming) and earlier winter floods in W Europe  
175 (reflecting advancement of soil moisture maxima). In contrast, Lins and Slack (2005) detected

176 no systematic shift in the timing of the maximum flow in any US region on a monthly time  
 177 scale.

178

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

180

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

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

190

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

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

192

193 Projections by Hirabayashi et al. (2013) indicate that what used to be a 100-year flood in  
 194 the control period in many areas, is likely to occur much more frequently in the future, under  
 195 changed climate, with return period of 50 years and below. Hirabayashi et al. (2013) project  
 196 increase of hazard (Q100) in most of Asia (except for Western Asia) and in particular –

197 eastwards of 80°E. They also project flood hazard to increase in Central Africa in latitude range  
198 20°S-10°N and in Central and South America from 20°N to 40°S, also in the north of North  
199 America and the East coast of the US. For most of Europe, decrease of flood hazard is projected.  
200 Results of Dankers et al. (2014) referring to a different index, Q30 (30-year 5-day peak flow),  
201 are broadly similar to those reported by Hirabayashi et al. (2013) as to the direction of change,  
202 except for a large area of decrease of hazard in South America. In turn, Giuntoli et al. (2015)  
203 project more frequent days with high river flow conditions over much of the north, from 50°N  
204 northwards. However, over most of the area of continents, they projected rather small changes,  
205 with absolute value less than 5% (i.e. from -5% to +5%).

206 Studies of large-scale projections of changes in flood hazard illustrate a considerable  
207 degree of uncertainty. There is no wonder, as projections were determined for different  
208 assumptions (cf. Table 2). They may differ with respect to (see Kundzewicz et al., 2018a,b):

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

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

229 Where both rain-floods and snow-floods (as well as ice-jam floods) can influence  
230 projections, relevant processes and different mechanisms have to be examined, for present and  
231 future conditions.

232 In addition, future flood risk in coastal zones will increase due to the sea level rise  
233 (Paprotny and Terefenko, 2017). Taking into account both the socioeconomic pathways and  
234 climate change but in absence of further investments in adaptation, Vousdoukas et al. (2018),  
235 projected the annual damage caused by coastal flooding in Europe to increase from current 1.25  
236 € billion to 93 – 961 € billion in the end of the 21st century, and the exposed population to  
237 increase from the current level of 0.1 million to 1.52 - 3.65 million.

238

#### 239 **4. Flood risk reduction – global framework**

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

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

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

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

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

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

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

286 The priorities for action refer to understanding of disaster risk in its dimensions of  
287 vulnerability, capacity, exposure of persons and assets, hazard characteristics and the  
288 environment. Such knowledge can be used for risk assessment, as well as to various flood risk  
289 reduction strategies - prevention, mitigation, preparedness and response, recovery and  
290 rehabilitation (see Dieperink et al., 2016, Driessen et al., 2016, Hegger et al., 2016 and  
291 Kundzewicz et al., 2018b). Strengthening disaster risk governance at a range of levels (national,  
292 regional and global) is another priority. Also investing in disaster risk reduction to enhance the  
293 economic, social, health and cultural resilience of persons, communities, countries and their  
294 assets, as well as the environment is an identified priority. So is also enhancing disaster  
295 preparedness for effective response and "Building Back Better". Disaster risk reduction has to  
296 be integrated into sustainable development measures.



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

303 However, the increase of flood protection levels to meet the requirements posed by Willner  
304 et al. (2018) would lead to having even more levees, that attract even more people and assets in  
305 flood-prone areas (that are often assumed to be perfectly safe by inhabitants). Since the seminal  
306 work of Gilbert White in the 1940s (White, 1945), many authors reported on safe-development  
307 paradox, residual risk and adverse levee effects (e.g. Kates et al., 2006; Ludy and Kondolf,  
308 2012; Di Baldassarre et al., 2014). It has been shown that the introduction or reinforcement of  
309 structural protection measures are often associated with negative effects. Such effects include  
310 increasing exposure to flooding (Kates et al., 2006) and increasing vulnerability to flooding (as  
311 protected flood-prone areas are perceived as safer, so that inhabitants have less incentives to  
312 take individual precautionary measures; see Ludy and Kondolf, 2012). There is a social  
313 injustice effect - structural flood protection measures may alter the spatial distribution of risk  
314 in a way that affects less privileged social groups (Di Baldassarre et al., 2014). People in  
315 structurally protected areas are less willing to relocate from risky areas (Mård et al., 2018).  
316 Furthermore, levees that prevent natural inundation of floodplains also adversely affect  
317 biodiversity and ecological functions (Auerswald et al., 2019), e.g. via elimination of a “flood  
318 pulse”.

319

## 320 **5. Flood risk reduction – from regional to local**

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

328 At the sub-continental scale, European Union (EU) passed a dedicated Directive  
329 2007/60/EC on the assessment and management of flood risks (EU 2007), that required all EU  
330 Member States (28 at present) to identify areas at risk from flooding, to map the flood extent as

331 well as assets and humans at risk in these areas and to take adequate and coordinated measures  
332 to reduce this flood risk. This Directive also reinforces the rights of the public to access  
333 information and to participate in the planning process. The Directive aims to reduce and manage  
334 the risks that floods pose to human health, economic activity, environment, and cultural  
335 heritage. The Directive required EU Member States to establish flood risk management plans  
336 focused on prevention, protection and preparedness by 2015.

337        Presence of people and wealth in flood prone areas can be regarded as an illness. One can  
338 prevent the risk, by keeping the destructive water away from people and proceeding with flood  
339 defenses. This is the curation of the symptoms of the illness. One can also keep people away  
340 from the destructive water by way of zoning and ban on floodplain development. This is  
341 curation of the source of the illness. But, it is also necessary to prepare to living with floods.  
342 This embraces flood mitigation – keeping water where it falls, flood preparation – forecasting,  
343 warning, as well as preparation for evacuation and the post-flood recovery (see Dieperink et al.,  
344 2016; Driessen et al., 2016; Hegger et al., 2016; Nieland and Mushtaq, 2016, Kundzewicz et  
345 al., 2018).

346        Since it is naïve to expect availability of trustworthy quantitative projections of future  
347 flood hazard (as some practitioners clearly do), in order to reduce flood risk, one should focus  
348 attention on identification of existing risk and vulnerability hotspots and improve the situation  
349 in areas where such hotspots occur (Kundzewicz et al., 2017).

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

357        Flood protection, i.e. adaptation to huge variability of discharge, has been developed in  
358 China for four millennia, since the quasi-legendary Emperor Yu, who established the Xia  
359 dynasty, marking the beginning of Chinese civilization. He succeeded in taming a long-lasting  
360 and disastrous flood in the Yellow River basin by dredging and channelling the rivers to drain  
361 the floodwaters and

362        Flood protection has always been important in China, where hundreds of millions of  
363 people live in river valleys. Structural measures, both dikes and dams of different sizes, have a  
364 very long tradition in China (a term “hydraulic civilization” was coined by Wittfogel, 1956)

365 and continue to play a vital role in flood prevention also today, and in the foreseeable future.  
366 The multi-objective, massive Three Gorges Dam on the River Yangtze, the world's greatest  
367 engineering work, has flood protection as the principal objective. Many large reservoirs, also  
368 with flood protection as the main objective, have been built in China, with a total storage  
369 capacity in excess of  $0.5 \times 10^{12} \text{ m}^3$ , accounting for over one fifth of the total estimated annual  
370 runoff from the land areas (Guo et al., 2004). Typically, water storage reservoirs serve multiple  
371 purposes: flood control, hydropower, irrigation, water supply, navigation, etc. The total number  
372 of large dams has increased very strongly since 1960, when only five large dams (higher than  
373 100 m) existed in China. The number of large dams grew tenfold in 2000 (Xu et al., 2010). In  
374 the second half of the 20th century, more than 200 thousand kilometers of dikes have been  
375 strengthened for alleviating the impacts of floods in China (Zhang et al., 2002).

376 The level of expenditure on flood protection in China has grown considerably in recent  
377 decades. However, despite the massive efforts, it is getting abundantly clear that complete flood  
378 control is not possible. Even if there exist powerful levees along the rivers in China, they may  
379 not provide satisfactory protection of the riparians during large floods (see Kundzewicz and  
380 Xia, 2004). Increasingly, large flood damage has been recently occurring on medium- and  
381 small-size rivers. Hence, improvement of flood risk management is needed in the country and  
382 ambitious and vigorous attempts to improve flood preparedness have been already undertaken,  
383 by both structural ("hard") and non-structural ("soft") measures. The former refer to such  
384 defences as dikes, dams and flood control reservoirs, diversions, etc. The latter include  
385 implementing watershed management (source control), zoning; insurance; flood forecasting–  
386 warning system; and awareness raising (Surminski et al., 2015; Nieland and Mushtaq, 2016;  
387 Adelekan and Asiyanbi, 2016). The coping capacities at a local level can influence the  
388 robustness of flood warning system (Daupras et al., 2015).

389 In many countries, flood protection is distributed among several agencies, hence effective  
390 cooperation and communication among federal, state and local stakeholders is essential. This  
391 is inherently difficult, but progress has been achieved in China in flood forecasting integration,  
392 data sharing and collaborative problem solving. The China Meteorological Administration  
393 (CMA) collects observations of precipitation and other meteorological variables and prepares  
394 precipitation forecasts. The Ministry of Water Resources (MWR) of China collects  
395 hydrological observations (e.g., of river levels and discharges) and is responsible for flood  
396 forecasting and dissemination of the forecast. River basin commissions in China (altogether –  
397 seven commissions, including the Yangtze River Basin Commission) are agencies of the MWR.  
398 The Flood Prevention Law of 2007 laid out principles and responsibilities for flood prevention

399 planning in China. There is a national standard (GB50201-94) drafted by the Ministry of Water  
400 Resources and issued by the Ministry of Construction in 1994 dealing with flood return periods  
401 for different categories of location (Gemmer et al., 2011). In 2010, flood hazard mapping  
402 guidelines were published as a professional standard by the Ministry of Water Resources.

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

407 It is a well established observation that occurrence of a disastrous flood event in a country  
408 or a region improves awareness and triggers investment in flood risk reduction as well as  
409 funding of relevant research. In fact, there are many case studies that report social learning  
410 effects, one of the findings being that the negative impact of an extreme flood tends to be lower  
411 if such an event occurs shortly after another one (e.g. in Jongman et al., 2015; Di Baldassarre  
412 et al., 2015; Mechler and Bouwer, 2015; Wind et al., 1999 and Kreibich et al., 2017). Di  
413 Baldassarre et al. (2015) show adaptation effects in study areas around the world, while Mechler  
414 and Bouwer (2015) noted decreasing number of flood fatalities in Bangladesh over the past  
415 decades. Wind et al. (1999) reported that the economic losses of the 1995 Meuse River flooding  
416 were much lower than those in 1993, even though the magnitudes of the two events were  
417 comparable. Kreibich et al. (2017) illustrated the learning dynamics by way of multi-regional,  
418 paired, flood event studies. However, sometimes deficiencies in learning show up. Marks and  
419 Thomalla (2017) studied consequences of the great 2011 flood in Thailand, noting that only  
420 minor efforts to reduce flood risk were made. The socio-political transformation needed to  
421 reduce system vulnerability has not occurred. The focus was on structural defenses - building  
422 floodwalls to reduce risk to large-scale enterprises, and this results in redistribution of risk to  
423 unprotected areas.

424

## 425 **6. Concluding remarks**

426 Many studies of flood hazard projections demonstrate the likely rise of flood hazard in the  
427 future. Plausible climate change scenarios indicate the possibility of increases in both the  
428 frequency and the magnitude of flooding events in many regions. Yet there has been no  
429 conclusive and general finding as to how climate change affects flood behavior, in the light of  
430 data observed so far, except of some indications of regional changes in timing of floods  
431 observed in some areas, with increasing late autumn and winter floods (caused by rain) and less

432 ice-jam-related floods, e. g., in Europe. The natural variability in observation records is  
433 overwhelming.

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

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

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

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

466

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477

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## 479 **REFERENCES**

- 480 Adelekan, I. O. and Asiyebi, A. P.: Flood risk perception in flood-affected communities in  
481 Lagos, Nigeria. *Natural Hazards*, 80, 445-469, 2016.
- 482 Arnell, N. W. and Gosling, S. N.: The impacts of climate change on river flood risk at the global  
483 scale, *Climatic Change*, 134, 387–401, doi:10.1007/s10584-014-1084-5, 2014.
- 484 Auerswald, K., Moyle, P., Seibert, S. P. and Geist, J.: HESS Opinions: Socio-economic and  
485 ecological trade-offs of flood management–benefits of a transdisciplinary approach.  
486 *Hydrology and Earth System Sciences*, 23(2), 1035-1044, 2019.
- 487 Blöschl, G., Hall, J., Parajka, J., Perdigao, R. A. P., Merz, B., Arheimer, B., Aronica, G. T.,  
488 Bilibashi, A., Bonacci, O., Borga, M., Canjevac, I., Castellarin, A., Chirico, G. B., Claps,  
489 P., Fiala, K., Frolova, N., Gorbachova, L., Gul, A., Hannaford, J., Harrigan, S., Kireeva,  
490 M., Kiss, A., Kjeldsen, T. R., Kohnova, S., Koskela, J. J., Ledvinka, O., Macdonald, N.,  
491 Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C.,  
492 Osuch, M., Ovcharuk, V., Radevski, I., Rogger, M., Salinas, J. L., Sauquet, E., Šraj, M.,  
493 Szolgay, J., Viglione, A., Volpi, E., Wilson, D., Zaimi, K. and Živkovic, N.: Changing  
494 climate shifts timing of European floods, *Science* 357(6351), 588–590.  
495 <https://doi.org/10.1126/science.aan2506>, 2017.
- 496 Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., Heinke,  
497 J., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D.: First look at  
498 changes in flood hazard in the inter-sectoral impact model intercomparison project  
499 ensemble, *Proceedings of the National Academy of Sciences*, 111, 3257–3261,  
500 doi:10.1073/pnas.1302078110, 2014.
- 501 Daupras, F., Antoine, J. M., Becerra, S. and Peltier, A.: Analysis of the robustness of the French  
502 flood warning system: a study based on the 2009 flood of the Garonne River, *Natural*  
503 *Hazards*, 75, 215-241, 2015.
- 504 **Di Baldassarre, G., A. Montanari, H. Lins, D. Koutsoyiannis, L. Brandimarte, and G. Blöschl:**  
505 **Flood fatalities in Africa: from diagnosis to mitigation, *Geophysical Research Letters*, 37,**  
506 **L22402, 2010.**

- 507 Di Baldassarre, G., Kemerink, J.S., Kooy M. and Brandimarte, L.: Floods and societies: the  
508 spatial distribution of water-related disaster risk and its dynamics. *Wiley Interdisciplinary*  
509 *Reviews: Water*, 1(2), 133-139, 2014.
- 510 Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L. and Blöschl, G.:  
511 Perspectives on socio-hydrology: Capturing feedbacks between physical and social  
512 processes, *Water Resources Research*, 51, 4770–4781, 2015.
- 513 Dieperink, C., Hegger, D. L. T., Bakker, M. H. N., Kundzewicz, Z. W., Green, C. and  
514 Driessen, P. P. J.: Recurrent governance challenges in the implementation and alignment  
515 of flood risk management strategies: a review, *Water Resources Management*, 30, 4467-  
516 4481, doi: 10.1007/s11269-016-1491-7, 2016.
- 517 Driessen, P. P. J., Hegger, D. L. T., Bakker, M. H. N., Rijswick, H. F. M. W. V.  
518 and Kundzewicz, Z. W.: Toward more resilient flood risk governance, *Ecology and*  
519 *Society*, 21, 53, <https://doi.org/10.5751/ES-08921-210453>, 2016.
- 520 EASAC (European Academies' Science Advisory Council): Extreme weather events in Europe.  
521 Preparing for climate change adaptation: an update on EASAC's 2013 study,  
522 [https://easac.eu/fileadmin/PDF\\_s/reports\\_statements/Extreme\\_Weather/EASAC\\_Statem](https://easac.eu/fileadmin/PDF_s/reports_statements/Extreme_Weather/EASAC_Statement_Extreme_Weather_Events_March_2018_FINAL.pdf)  
523 [ent\\_Extreme\\_Weather\\_Events\\_March\\_2018\\_FINAL.pdf](https://easac.eu/fileadmin/PDF_s/reports_statements/Extreme_Weather/EASAC_Statement_Extreme_Weather_Events_March_2018_FINAL.pdf), 2018.
- 524 EU (European Union): Directive 2007/60/EC of the European parliament and of the council of  
525 23 October 2007 on the assessment and management of flood risks, *Official Journal of the*  
526 *European Union*, L288, 27–34, 2007.
- 527 Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D.,  
528 Mach, K. J., Plattner, G. K., Allen, S. K., Tignor, M. and Midgley, P. M.: Managing the  
529 risks of extreme events and disasters to advance climate change adaptation, Special Report  
530 of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC),  
531 Cambridge, UK: Cambridge University Press, 2012.
- 532 Gemmer, M., Wilkes, A. and Vaucel, L. M.: Governing climate change adaptation in the EU  
533 and China: An analysis of formal institutions, *Advances in Climate Change Research*, 2,  
534 1-11, 2011.
- 535 Guo, S., Zhang, H., Chen, H., Peng, D., Liu, P. and Pang, B.: A reservoir flood forecasting and  
536 control system for China, *Hydrological Sciences Journal*, 49, 959–972, 2004.
- 537 Giuntoli, I., Vidal, J. P., Prudhomme, C. and Hannah, D. M.: Future hydrological extremes:  
538 the uncertainty from multiple global climate and global hydrological models, *Earth System*  
539 *Dynamics*, 6, 267–285, doi:10.5194/esd-6-267-2015, 2015.
- 540 Hegger, D. L. T., Driessen, P. P. J., Wiering, M., Rijswick, H. F. M. W., Kundzewicz, Z. W.,  
541 Matczak, P., Crabbé, A., Raadgever, G. T., Bakker, M. H. N., Priest, S. J., Larrue, C., Ek,  
542 K.: Toward more flood resilience: Is a diversification of flood risk management strategies  
543 the way forward?, *Ecology and Society*, 21, 52-71, [https://doi.org/10.5751/ES-08854-](https://doi.org/10.5751/ES-08854-210452)  
544 [210452](https://doi.org/10.5751/ES-08854-210452), 2016.
- 545 Hirabayashi, Y., Kanae, S., Emori, S., Oki, T. and Kimoto, M.: Global projections of changing  
546 risks of floods and droughts in a changing climate, *Hydrological Sciences Journal*, 53,  
547 754–772, doi:10.1623/hysj.53.4.754, 2008.
- 548 Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S.,  
549 Kim, H. and Kanae, S.: Global flood risk under climate change, *Nature Climate Change*,  
550 3, 816–821, doi:10.1038/nclimate1911, 2013.

- 551 Hodgkins, G. A., Whitfield, P. H., Burn, D. H., Hannaford, J., Renard, B., Stahl, K., Fleig, A.  
 552 K., Madsen, H., Mediero, L., Korhonen, J., Murphy, C. and Wilson, D.: Climate-driven  
 553 variability in the occurrence of major floods across North America and Europe, *Journal of*  
 554 *Hydrology*, 552, 704-717, <https://doi.org/10.1016/j.jhydrol.2017.07.027>, 2017.
- 555 Jongman, B., Winsemius, H. C., Aerts, J. C., de Perez, E. C., van Aalst, M. K., Kron, W. and  
 556 Ward, P. J.: Declining vulnerability to river floods and the global benefits of adaptation.  
 557 *Proceedings of the National Academy of Sciences*, 112(18), E2271-E2280, 2015.
- 558 Kates, R. W., Colten, C. E., Laska, S., and Leatherman, S. P.: Reconstruction of New Orleans  
 559 after Hurricane Katrina: A research perspective. *Proceedings of the National Academy of*  
 560 *Sciences of USA*, 103(40), 14653-14660, 2006.
- 561 Koç, G. and Thielen, A. H.: The relevance of flood hazards and impacts in Turkey: What can  
 562 be learned from different disaster loss databases?, *Natural Hazards*, 91, 375–408, 2018.
- 563 Kreibich, H., Di Baldassarre, G., Vorogushyn, S., Aerts, J. C., Apel, H., Aronica, G. T.,  
 564 Arnbjerg-Nielsen, K., Bouwer, L. M., Bubeck, P., Caloiero, T., Chinh Do T., Cortès, M.,  
 565 Gain, A. K., Giampá, V., Kuhlicke, C., Kundzewicz, Z. W., Carmen Llasat, M., Mård, J.,  
 566 Matczak, P., Mazzoleni, M., Molinari, D., Dung, Nguyen V., Petrucci, O., Schröter, K.,  
 567 Slager, K., Thielen, A. H., Ward, P. J. and Merz, B.: Adaptation to flood risk: Results of  
 568 international paired flood event studies. *Earth's Future*, 5(10), 953-965. 2017.
- 569 Kundzewicz, Z. W. and Schellnhuber, H. J.: Floods in the IPCC TAR perspective, *Natural*  
 570 *Hazards*, 31, 111-128, 2004.
- 571 Kundzewicz, Z. W. and Xia, J.: Towards an improved flood preparedness system in China,  
 572 *Hydrological Sciences Journal*, 49, 941-944, 2004.
- 573 Kundzewicz, Z. W., Graczyk, D., Maurer, T., Pińskwar, I., Radziejewski, M., Svensson, C. and  
 574 Szwed, M.: Trend detection in river flow series: 1. Annual maximum flow, *Hydrological*  
 575 *Sciences Journal*, 50, 797–810, 2005.
- 576 Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P.,  
 577 Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R.,  
 578 Kron, W., Benito, G., Honda, Y., Takahashi, K. and Sherstyukov, B.: Flood risk and  
 579 climate change: global and regional perspectives, *Hydrological Sciences Journal*, 59, 1-28,  
 580 2014.
- 581 Kundzewicz, Z. W., Krysanova, V., Dankers, R., Hirabayashi, Y., Kanae, S., Hattermann, F.  
 582 F., Huang, S., Milly, P. C. D., Stoffel, M., Driessen, P. P. J., Matczak, P., Quevauviller, P.  
 583 and Schellnhuber, H. J.: Differences in flood hazard projections in Europe - their causes  
 584 and consequences for decision making, *Hydrological Sciences Journal*, 62, 1-14, 2017.
- 585 Kundzewicz, Z. W., Krysanova, V., Benestad, R. E., Hov, Ø., Piniewski, M. and Otto, I. M.:  
 586 Uncertainty in climate change impacts on water resources, *Environmental Science &*  
 587 *Policy*, 79, 1-8, 2018a.
- 588 Kundzewicz, Z. W., Hegger, D. L. T., Matczak, P. and Driessen, P. P. J.: Flood risk reduction:  
 589 structural measures and diverse strategies, *PNAS* (December 4, 2018), 115(49), 12321–  
 590 12325, 2018b.
- 591 Kundzewicz, Z. W., Pińskwar, I. and Brakenridge, G. R.: Changes in river flood hazard in  
 592 Europe: a review, *Hydrology Research* 49(2): 294-302, doi: 10.2166/nh.2017.016280,  
 593 2018c.
- 594 Lins, H. F. and Slack, J. R.: Streamflow trends in the United States, *Geoph. Res. Letters*, 26(2),  
 595 227-230, 1999.



- 596 Lins, H. F. and Slack, J. R.: Seasonal and regional characteristics of U.S. streamflow trends in  
597 the United States from 1940 to 1999, *Phys. Geogr.*, 26(6), 489–501, 2005.
- 598 Ludy J. and Kondolf, G. M.: Flood risk perception in lands “protected” by 100-year levees.  
599 *Natural Hazards*, 61(2), 829-842, 2012.
- 600 Madsen, H., Lawrence, D., Lang, M., Martinkova, M. and Kjeldsen T. R., Review of trend  
601 analysis and climate change projections of extreme precipitation and floods in Europe, *J.*  
602 *Hydrol.* 519, 3634–3650, 2014.
- 603 Mård, J., Di Baldassarre, G. and Mazzoleni, M.: Nighttime light data reveal how flood  
604 protection shapes human proximity to rivers. *Science Advances*, 4(8), eaar5779, 2018.
- 605 Mechler, R. and Bouwer, L. M. Understanding trends and projections of disaster losses and  
606 climate change: is vulnerability the missing link? *Climatic Change*, 133(1), 23-35, 2015.
- 607 Marks, D. and Thomalla, F.: Responses to the 2011 floods in Central Thailand: Perpetuating  
608 the vulnerability of small and medium enterprises?, *Natural Hazards*, 87, 1147–1165, 2017.
- 609 Milly, P. C. D., Wetherald, R. T., Dunne, K. A. and Delworth, T. L.: Increasing risk of great  
610 floods in a changing climate, *Nature*, 415, 514-517, 2002.
- 611 Nieland, C. and Mushtaq, S.: The effectiveness and need for flash flood warning systems in a  
612 regional inland city in Australia, *Natural Hazards*, 80, 153-171, 2016.
- 613 Paprotny, D. and Terefenko, P.: New estimates of potential impacts of sea level rise and coastal  
614 floods in Poland, *Natural Hazards*, 85, 1249-1277, 2017.
- 615 Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y.,  
616 Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X.:  
617 Changes in climate extremes and their impacts on the natural physical environment. In:  
618 Field, C. B., et al. (eds) *Managing the risks of extreme events and disasters to advance*  
619 *climate change adaptation. A special report of working groups I and II of the*  
620 *Intergovernmental Panel on Climate Change (IPCC).* Cambridge University Press,  
621 Cambridge, and New York, NY, 2012.
- 622 Shaw, S. B. and Riha, S. J.: Assessing possible changes in flood frequency due to climate  
623 change in mid-sized watersheds in New York State, USA, *Hydrol. Proc.*, 25(16), 2542-  
624 2550, 2011.
- 625 Surminski, S., Aerts, J. C. J. H., Botzen, W. J. W., Hudson, P., Mysiak, J. and Pérez-Blanco, C.  
626 D.: Reflections on the current debate on how to link flood insurance and disaster risk  
627 reduction in the European Union, *Natural Hazards*, 79, 1451-1479, 2015.
- 628 UNISDR (The United Nations Office for Disaster Risk Reduction): *Hyogo Framework for*  
629 *action 2005-2015: Building the resilience of nations and communities to disasters*,  
630 [https://www.unisdr.org/files/1037\\_hyogoframeworkforactionenglish.pdf](https://www.unisdr.org/files/1037_hyogoframeworkforactionenglish.pdf), 2007.
- 631 UNISDR (The United Nations Office for Disaster Risk Reduction): *The human cost of weather-*  
632 *related disasters 1995-2015*  
633 [https://www.unisdr.org/files/46796\\_cop21weatherdisastersreport2015.pdf](https://www.unisdr.org/files/46796_cop21weatherdisastersreport2015.pdf), 2015.
- 634 Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F. and Feyen, L.:  
635 Climatic and socioeconomic controls of future coastal flood risk in Europe, *Nature Climate*  
636 *Change*, 8, 776-780, 2018.
- 637 White, G. F.: *Human Adjustments to Floods.* Department of Geography. Research Paper No.  
638 29. Department of Geography, University of Chicago, Chicago. 225 pages, 1945.

- 639 Willner, S. N., Levermann, A., Zhao, F. and Frieler, F.: Adaptation required to preserve future  
640 high-end river flood risk at present levels, *Science Advances*, 4, eaao1914, doi:  
641 10.1126/sciadv.aao1914, 2018.
- 642 Wind, H. G., Nierop, T. M., de Blois, C. J. and de Kok, J. L. Analysis of flood damages from  
643 the 1993 and 1995 Meuse floods. *Water Resources Research*, 35(11), 3459-3465, 1999.
- 644 Wittfogel, K. A.: *The hydraulic civilization: Man's role in changing the Earth*, University of  
645 Chicago Press, Chicago, IL, USA, 1956.
- 646 Xu, K., Milliman, J. D. and Xu, H.: Temporal trend of precipitation and runoff in major Chinese  
647 Rivers since 1951, *Glob. Planet. Change*, 73, 219-232, 2010.
- 648 Zhang, J. Q., Zhou, C. H., Xu, K. Q. and Watanabe, M.: Flood disaster monitoring and  
649 evaluation in China, *Environmental Hazards*, 4, 33-43, 2002.