AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE

10.1002/2017EF000606

Special Section:
Avoiding Disasters: Strengthening Societal Resilience to Natural Hazards

Adaptation to flood risk: Results of international paired flood event studies

Heidi Kreibich[1], Giuliano Di Baldassarre[2], Sergiy Vorogushyn[1], Jeroen C. J. H. Aerts[3], Heiko Apel[1], Giuseppe T. Aronica[4], Karsten Arnbjerg-Nielsen[5], Laurens M. Bouwer[6], Philip Bubeck[7], Tommaso Caloiero[8], Do T. Chinh[1], Maria Cortès[9], Animesh K. Gain[1], Vincenzo Giampá[10], Christian Kuhlicke[11], Zbigniew W. Kundzewicz[12], Maria Carmen Llasat[9], Johanna Mård[2], Piotr Matczak[13], Maurizio Mazzoleni[14], Daniela Molinari[15], Nguyen V. Dung[1], Olga Petrucci[10], Kai Schröter[1], Kymo Slager[6], Annegret H. Thieken[7], Philip J. Ward[3], and Bruno Merz[1]

[1]Section 5.4 Hydrology, GFZ German Research Centre for Geosciences, Potsdam, Germany, [2]Department of Earth Sciences, Centre of Natural hazards and Disaster Science (CNDS), Uppsala University, Uppsala, Sweden, [3]Department of Water and Climate Risk, Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands, [4]Department of Engineering, University of Messina, Messina, Italy, [5]Urban Water Systems Section, Department of Environmental Engineering, Bygningstorvet, Technical University of Denmark, Kgs. Lyngby, Denmark, [6]Deltares, Delft, The Netherlands, [7]Institute of Earth and Environmental Science, University of Potsdam, Potsdam, Germany, [8]CNR-ISAFOM National Research Council, Institute for Agricultural and Forest Systems in the Mediterranean, Rende, Italy, [9]GAMA, Department of Applied Physics, University of Barcelona, Barcelona, Spain, [10]CNR-IRPI National Research Council, Research Institute for Geo-Hydrological Protection, Rende, Italy, [11]Department Urban & Environmental Sociology, UFZ Helmholtz Centre for Environmental Research, Leipzig, Germany, [12]Institute for Agricultural and Forest Environment, Polish Academy of Sciences, Poznań, Poland, [13]Institute of Sociology, Adam Mickiewicz University, Poznan, Poland, [14]Integrated Water Systems & Governance, IHE Delft Institute for Water Education, Delft, The Netherlands, [15]Department of Civil and Environmental Engineering, Politecnico di Milano, Milan, Italy

Key Points:
- Across different socio-economic and hydro-climatic contexts there is high potential to adapt to future flood risk
- Focusing events act as triggers for raising risk awareness, preparedness and improvements of emergency management which reduce vulnerability
- Vulnerability reduction is key for successful adaptation but the challenge remains to stimulate risk reduction when no extreme events occur

Supporting Information:
- Supporting Information S1

Corresponding author:
H. Kreibich,
heidi.kreibich@gfz-potsdam.de

Citation:
Kreibich, H. et al (2017), Adaptation to flood risk: Results of international paired flood event studies, *Earth's Future*, *5*, 953–965, doi:10.1002/2017EF000606.

Received 29 APR 2017
Accepted 24 JUL 2017
Accepted article online 26 JUL 2017
Published online 3 OCT 2017

Abstract As flood impacts are increasing in large parts of the world, understanding the primary drivers of changes in risk is essential for effective adaptation. To gain more knowledge on the basis of empirical case studies, we analyze eight paired floods, that is, consecutive flood events that occurred in the same region, with the second flood causing significantly lower damage. These success stories of risk reduction were selected across different socioeconomic and hydro-climatic contexts. The potential of societies to adapt is uncovered by describing triggered societal changes, as well as formal measures and spontaneous processes that reduced flood risk. This novel approach has the potential to build the basis for an international data collection and analysis effort to better understand and attribute changes in risk due to hydrological extremes in the framework of the IAHSs Panta Rhei initiative. Across all case studies, we find that lower damage caused by the second event was mainly due to significant reductions in vulnerability, for example, via raised risk awareness, preparedness, and improvements of organizational emergency management. Thus, vulnerability reduction plays an essential role for successful adaptation. Our work shows that there is a high potential to adapt, but there remains the challenge to stimulate measures that reduce vulnerability and risk in periods in which extreme events do not occur.

1. Introduction

Damage due to floods is increasing in large parts of the world [*IPCC*, 2012]. More knowledge about whether flood risk increases over time in specific regions, and if so, why, is essential for policy response in terms of flood risk management and adaptation strategies [*Merz et al.*, 2010; *Bouwer*, 2011]. According to the IPCC SREX concept, risk depends on hazard, exposure, and vulnerability [*IPCC*, 2012]: In this context, hazard is defined as the potential occurrence of a natural or human-induced physical event that may cause adverse effects to social elements. Exposure is defined as the presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events. Vulnerability is defined generically as the propensity or predisposition to be adversely affected [*IPCC*, 2012]. Such predisposition constitutes an internal characteristic of the affected element, and it includes the characteristics of a person or society and the situation that influences their capacity to anticipate, cope with, resist, and recover from the adverse effects of physical events [*Wisner et al.,* 2004].

The observed increase in flood damage in many regions of the world is dominated by exposure increase, while an impact of changes in flood hazard due to anthropogenic climate change has hardly been observed to date [*Bouwer*, 2011; *Merz et al.,* 2012]. The climate signal might be masked by a counteracting decrease in vulnerability, as suggested by studies at global [*Jongman et al.,* 2015] and regional [*Di Baldassarre et al.,* 2015; *Mechler and Bouwer*, 2015] scales. However, knowledge is still scarce about the underlying processes that drive changes in flood risk, particularly in respect to vulnerability [*UNISDR*, 2015].

The vulnerability of societies may be influenced by flood risk management, other formal measures like land use planning, societal changes, as well as spontaneous processes that influence flood risk. "Focusing events," that is, events that provide a sudden, strong push for action, often trigger flood risk mitigation and improvements of risk management [*Kingdon*, 1995; *Kreibich et al.,* 2011]. For example, the 1953 North Sea flood disaster lead to the Delta Works in The Netherlands [*Van Koningsveld et al.,* 2008] and the construction of the Thames Barrier [*McRobie et al.,* 2005] in the UK. Several studies are available on various aspects of societal vulnerability [e.g., *Tapsell et al.,* 2002; *Brouwer et al.,* 2007; *Kuhlicke et al.,* 2011] and learning [e.g., *Birkland*, 1998; *Pahl-Wostl*, 2009; *Armitage et al.,* 2008]. However, we believe that our study provides empirical evidence adding essential information about how extreme flood events stimulate changes in flood risk management and how these manifest during a subsequent flood in the same region.

The objective of our study is to gain knowledge on how flood events trigger adaptation to future flood risk. We assess eight paired flood events, which are real-world examples for successful risk reduction. This allows us to derive robust conclusions from commonalities and differences between the case studies, across a wide range of hydro-climatic and socioeconomic conditions.

2. Compilation of Paired Flood Event Studies

This study is based on a selection of success stories of risk reduction, that is, case studies, collected from around the world where societies effectively implemented flood risk management or other measures and societal changes, which significantly mitigated potential flood damage (Figure 1). Besides such success stories there are, unfortunately, examples of developments which lead to an increase of flood risk. Examples concern higher exposure due to urbanization or asset value increase [e.g., *Domeneghetti et al.,* 2015; *Faccini et al.,* 2015; *Ferguson and Ashley*, 2017]; an increase in vulnerability due to a lack of maintenance of protection structures [e.g., *Orlandini et al.,* 2015; *IKSE*, 2001]; or fading of preparedness of administration and affected parties [e.g. *Kreibich and Merz,* 2007; *Nkwunonwo et al.,* 2016]. However, such cases are not considered in this study, since we aim to show how successful flood risk mitigation can be achieved. The approach is based on the analysis of paired flood events in different river basins across different socioeconomic and hydro-climatic conditions. Paired flood events were defined as consecutive floods that occurred in the same region. Such paired events are natural experiments where processes which change flood risk can be analyzed. The approach is analogous to the concept of "paired catchment studies" in hydrology, which is widely used to determine the magnitude of water yield changes resulting from changes in vegetation [*Brown et al.,* 2005].

To assess changes in flood risk and its drivers, detailed case study analyses were undertaken (see Supporting Information S1). On this basis, hazard, exposure, and vulnerability indicators were derived and evaluated for each case study. Inherently, the characterization of risk and its components combines both quantitative and qualitative aspects. For this study, hazard is described using the following indicators: the event preconditions (e.g., antecedent catchment wetness, saturated or frozen soils, etc.), the frequency and intensity of precipitation, the hydrological severity (e.g., return period of the flood discharge, affected length of the river network, inundation extent, etc.) and the failure of protection measures (like dikes, dams, etc.). To characterize exposure, the following indicators are used: the number of people affected, the area affected (e.g., settlement area, agricultural land, assets affected, etc.) and the presence of exposure hotspots, which shall indicate if there was particularly high exposure in the flooded area, for example, due to affected cities or industrial areas. There are various concepts and definitions of "Vulnerability" [*Thywissen*, 2006], many of which consider a quite broad context [e.g. *Nakamura and Llasat,* 2017; *Brooks et al.,* 2005; *Turner et al.,* 2003;

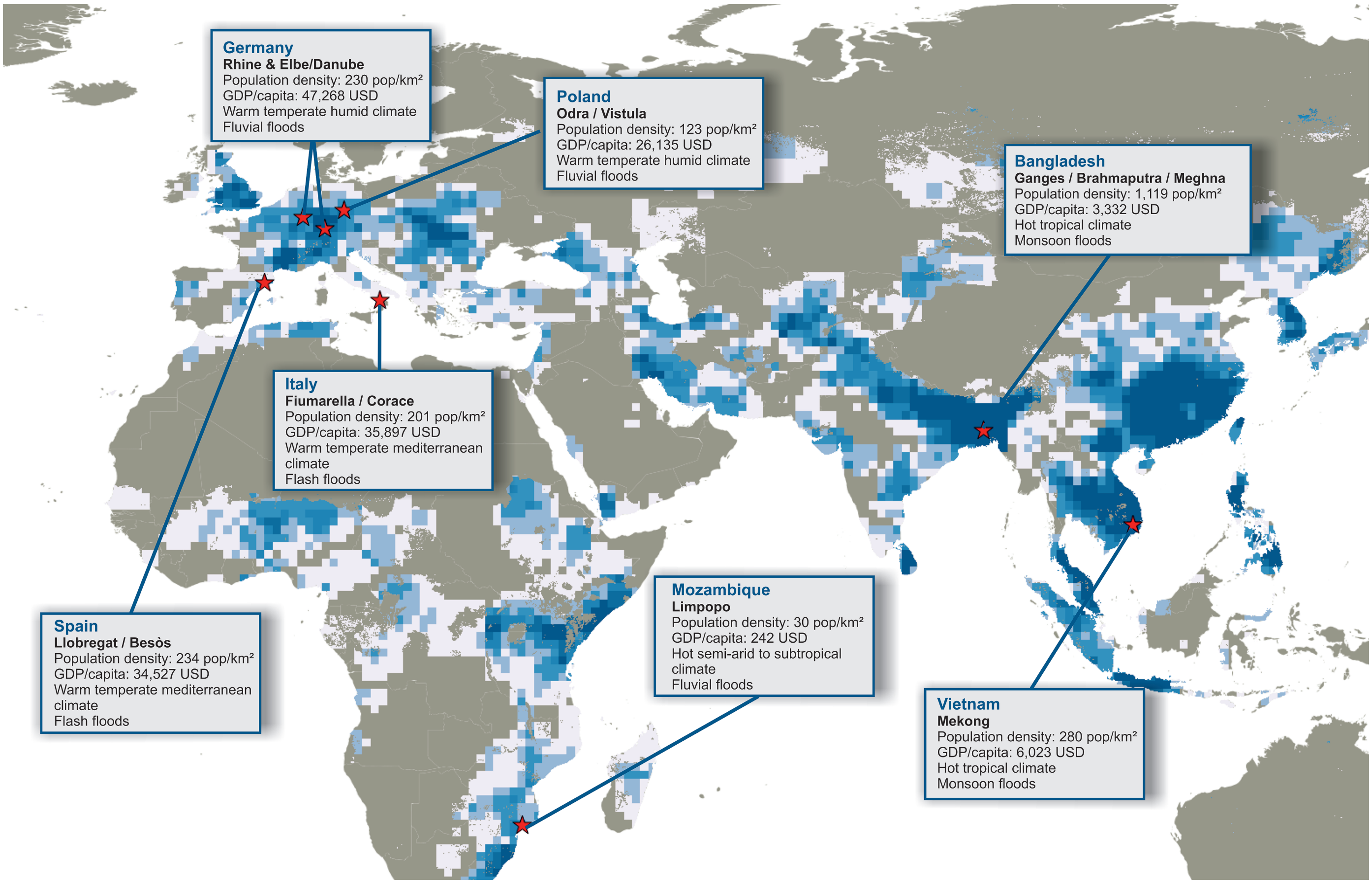

Figure 1. Case studies across different socioeconomic (e.g., population density, gross domestic product per capita [*World Bank*, 2016]) and hydro-climatic (e.g., climate, flood type) contexts (for detailed information on the individual case studies see Supporting Information S1 (texts S1–S8)). The distribution of global flood frequency in the period 1985–2003 is shown using a blue scale. The flood frequency grid was classified into 10 classes of approximately equal number of grid cells. The darker blue the grid cell is, the higher the relative frequency of flood occurrence [*CHRR and CIESIN*, 2005].

Kelly and Adger, 2000]. For our case study comparison, we narrow the few and focus on the following vulnerability indicators: lack of awareness (e.g., lack of flood experience, information campaigns, precautionary measures), lack of preparedness (e.g., lack of early warning, lead times, risk communication during event, private emergency measures) and insufficient organizational emergency management (e.g., performance of the governmental crisis management, civil protection, emergency plans, evacuation, etc.). The negative form (e.g., lack of) is chosen to have a positive correlation with vulnerability and to be consistent with the effects of the hazard and exposure indicators so that a reduction in an indicator leads to a reduction in flood risk and as such reflects a positive development. For instance, a reduction of lack of awareness relates to a reduction of vulnerability and as such to a reduction in flood risk. This is particularly important for our compilation of all paired event studies in Figure 2.

Detailed analyses of the individual paired flood events are based on case study research, literature review, and expert knowledge about the impacted regions. These detailed analyses are provided in Supporting Information S1 (texts S1 to S8). Based on these results, the hazard, exposure and vulnerability indicators were derived. When available, quantitative empirical evidence from case study research was used for a quantification of indicators. Where no empirical evidence was available, a qualitative assessment based on the literature review and expert knowledge was used. For each case study, we examine how these indicators manifested during both floods and particularly how they changed from the first flood to the second flood. Particularly important is how their changes influenced the difference in the resulting damage, that is, number of fatalities and monetary damage. These results were abstracted and compiled in Figure 2 to achieve a homogenous cross-case study comparison and as such more generic results than

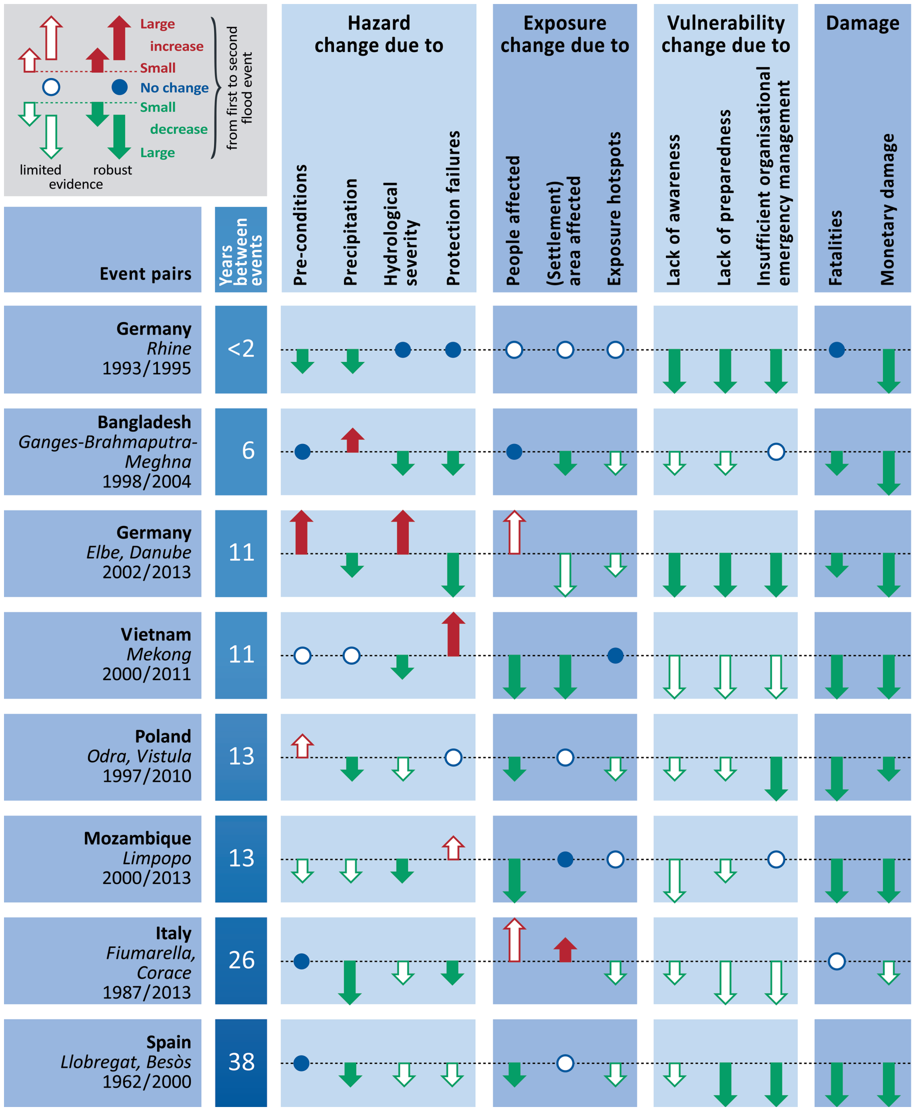

Figure 2. Analysis of the eight paired flood events (for more detailed information see Table 1 and Supporting Information S1, texts S1–S8). The figure shows the difference of the primary drivers of flood risk change as well as of fatalities and economic damage between the first flood event, used as baseline, and the second event. Drivers are expressed using hazard, exposure, and vulnerability indicators.

on the basis of individual case study analyses only. Changes of the hazard, exposure, and vulnerability indicators as well as of the resulting damage (fatalities and monetary damage) from the first flood used as baseline to the second flood are indicated by upward and downward arrows for increase and decrease, respectively (or circles for no change). In case of quantitative comparisons (e.g., precipitation intensities, monetary damage) a change of less than 50% is indicated by a small arrow, and larger changes by large arrows. The diversity of amount and quality of available information about the change of the individual indicators are indicated by hollow and filled arrows/circles for limited and robust evidence. This distinction is based on expert judgment inspired by the IPCC concept of treatment of uncertainties [*Mastrandrea et al.*, 2010]. Generally, evidence is evaluated to be robust when there is one (or preferably more consistent) good-quality measurement, analysis, or study available from a reputable source (e.g., scientific study or governmental report) which indicate(s) the change of indicator.

Our approach of analyzing pairs of events as well as undertaking a comparative analysis of various event pairs yields generic results. A problem of extreme event or catchment studies is that every event, catchment, region, situation, etc. is unique and has its own characteristics and processes which make it challenging to draw general, transferable conclusions. Transferring the established approach of paired catchment studies [*Brown et al.,* 2005; *Prosdocimi et al.,* 2015] to event comparisons and complementing it with (semi-)qualitative data on exposure and vulnerability enable a comprehensive attribution of changes in risk, as demonstrated for floods in this study and as suggested for droughts by *Van Loon et al*. [2016]. Another approach to reach universal results is comparative analysis, which aims to find general patterns by analyzing a large set of case studies (e.g., catchments) from all over the world [*Duan et al.,* 2006; *Blöschl et al.,* 2013]. Combining these two approaches in collecting a large number of paired events seems a promising way forward for attributing changes in risk of hydrological extremes. Thus, the eight paired event studies compiled in this study may be the starting point for an international effort to collect and analyze paired events, for example, in the framework of the IAHSs Panta Rhei initiative.

3. Flood Risk Change

The compilation of paired events shows that in all cases, reductions in flood damage between the first and second flood occurred mainly along with large reductions of the three main elements of vulnerability, that is, lack of risk awareness, lack of preparedness, and insufficient organizational emergency management. In some cases additionally structural flood protection and reduction in exposure played a role (Figure 2). Clearly, the different drivers of risk change (vulnerability, exposure and hazard) act simultaneously. In integrated flood risk management, flood protection is complemented with nonstructural measures such as land-use planning to reduce exposure, and improved private preparedness or organizational emergency management to reduce vulnerability [*Klijn et al.,* 2015]. The German Elbe, Danube 2002/2013 case is a good example of the combined effects of structural and nonstructural measures. Although the hydrological severity of the second event in 2013 was much larger (hydrological severity index: 75 in 2013, 35 in 2002 [*Schröter et al.,* 2015]), the monetary damage was reduced by about 50% and the fatalities by 33% due to improved structural protection, as well as reduced vulnerability due to timely flood warning and better awareness and preparedness of affected people and emergency managers [*Thieken et al.,* 2016b].

3.1. Hazard Changes

Catchment preconditions and precipitation differ from event to event and cannot be influenced by flood risk management. In all paired event cases, these factors are either insignificantly different between the events or slightly lower for the second event with only a few exceptions (Figure 2). In the German Elbe, Danube case, the hydrological severity in terms of the magnitude and spatial coverage of the second event was higher and driven by strong catchment wetness [*Schröter et al.,* 2015]. Still, a strong damage reduction for the second event was achieved, which underscores the decisive roles of reductions in vulnerability and exposure. Largely lower precipitation is observed in the Italian case for the second event, which partly explains reductions of damage along with the reduced vulnerability.

There is a general tendency to improve structural flood defenses and increase the protection level after major flood events. For instance, in the German Elbe, Danube 2002/2013 case, massive investments in the reinforcement of dikes after the 2002 flood were undertaken. The federal state of Saxony in Germany alone allocated more than €800 million for structural flood defenses after the 2002 flood [*Müller*, 2010]. The reinforced protection infrastructure has led to reductions in protection failures: only 30 dike failures occurred in 2013, compared to over 130 failures in 2002. Monetary damage was reduced by about 50% (Table 1). Some reduction in damage as a result of reduced protection failures is also noted in the Bangladesh, Italian, and Spanish case studies. For these case studies, no evidence for massive investments into structural flood protection is reported. It could be the case that fewer failures occurred during the later floods due to smaller hydrological severity and lower hydrological load on flood protection structures. The causality is different in the Vietnamese case: Many protection dikes, which are designed to protect farmland from flood throughout the year, were built quickly on relatively weak soil foundations in the years following the 2000 flood. The dike system in 2011 led to confined stream flow, causing higher flow velocities and water levels than might have been considered for dike construction and stability. This led to many dike failures during the flood in 2011. However, since many dikes were newly built after the 2000 flood, the dike system (despite the failures) still caused a reduction of affected agricultural area by 78% (Table 1). Given the hydrological severity of the 2000 event, it has to be expected that many more dikes would have failed, if they were in place. Construction of dikes is costly and time consuming; hence, if the time lag between two flood events is short, as was the case for Germany Rhine 1993/1995, it is unlikely that defenses are sufficiently repaired or upgraded. However, where we have an indication of substantial investments into the flood protection infrastructure (Elbe/Danube and Mekong basins), a strong evidence of risk reduction is present (Figure 2).

3.2. Exposure Changes

Across the eight case studies, the role of changes in exposure differs, with positive and negative trends reported (Figure 2). In single cases, changes in exposure have clearly contributed to lower damage. For example, in Vietnam 200,000 households were relocated to protected grounds after the flood in 2000. Thus, the number of affected people was reduced by 88% (Table 1). Similarly, for the Mozambican case the number of affected people was reduced by 93% mainly due to decreasing the number of settlements in flood-prone areas after the event in 2000. The monetary damage was reduced by 94% and the fatalities by 83% (Table 1).

In contrast, in the Italian case, industry moved out of the affected areas after the first flood, but was then substituted by private residents over a longer time (Table 1). This lead to an increase of exposure, particularly the number of affected people increased by 86% (Table 1). This case highlights the necessity of keeping flood risk awareness at a high level over long time periods.

In the German Elbe, Danube case the change of exposure is rather unclear. While *EM-Dat [*2015*]* reported an increase of affected people by 82%, the affected area of residential and mixed use was calculated to be reduced by 74% (Table 1). This combination appears very unlikely and points to high uncertainties associated with the exposure information (Figure 2).

During short time periods of a few years, exposure changes are hardly possible, as observable for the Rhine floods in 1993 and 1995 in Germany (Figure 2). Large reductions in exposure are only observed in case studies in which the time interval between the paired events is more than 10 years (Figure 2). Thus, it takes time until spatial planning programs, settlement protection (e.g., by hard engineering works) or relocation are implemented.

3.3. Vulnerability Changes

In almost all paired event cases, that is, success stories of risk reduction, a medium to large reduction in vulnerability indicators is seen. Large reductions in all three vulnerability indicators occurred in both German cases and in the Vietnamese case, indicating effective learning by societies, that is, of administrative/governmental, commercial, and private sectors, after the focusing events using these as windows of opportunity [*Kreibich et al.,* 2011; *Kingdon*, 1995]. Apparently, measures to reduce vulnerability can be readily implemented and unfold their positive effects quickly. For instance, after the Rhine flood in Germany in 1993, the number of precautionary measures that were implemented by private households, such as securing oil tanks or the deployment of mobile flood barriers, more than doubled [*Bubeck et al.,* 2012]. Large reductions in vulnerability were achieved between the floods in 1993 and 1995, resulting in a 67% lower monetary damage in the latter (Table 1). Also in the other German paired flood event case in the Elbe and Danube catchment, affected parties and authorities reduced their vulnerability after the extreme flood in 2002. Many governmental flood management programs and initiatives were launched, for instance, the German Weather Service (DWD) has significantly improved its numerical weather forecast models and its warning management [*Kreibich and Merz,* 2007; *Thieken et al.,* 2016b]. Also a high percentage of the private households and companies adopted precautionary measures and were much better prepared for emergency actions [*Kreibich et al.,* 2011; *Kienzler et al.,* 2015]. The comparison of the Mekong flood events in 2000 and 2011 in Vietnam showed that considerable improvements regarding the vulnerability were possible, supporting a significant reduction of monetary damage by 58% and of fatalities by 81% (Table 1).

In the Italian and Spanish cases, large reductions occurred in two vulnerability indicators and a small reduction in the third one. However, the time between the events was so long, that not only the effects of learning after the first flood event can be observed during the second event; improved awareness and preparedness, as well as an improved emergency management, are probably also due to general vulnerability decreasing developments stimulated by policies such as the European Flood Directive [*European Commission*, 2007] and the Hyogo/Sendai frameworks by UN-ISDR. In the Spanish case, monetary damage was reduced by 83% and fatalities by even 99% mainly due to a significantly improved early warning by the meteorological services, based on advances in hydro-meteorological monitoring and modeling. Additionally, the activation

Table 1. Information on Risk Drivers and Resulting Damage of the Individual Success Stories of Risk Reduction, that is, Paired Flood Events (for Detailed Information see Supporting Information S1, Texts S1–S8)

		Germany Rhine (Supporting Information S1, Text S1)		Bangladesh (Supporting Information S1, Text S2)		Germany Elbe, Danube (Supporting Information S1, Text S3)		Vietnam (Supporting Information S1, Text S4)	
		1993	1995	1998	2004	2002	2013	2000	2011
Hazard	Preconditions	Wetness-index: 49.2 [*Schröter et al.*, 2015]	Wetness-index: 30.8 [*Schröter et al.*, 2015]	Saturated soils due to regular monsoon rainfall	Saturated soils due to regular monsoon rainfall	Wetness-index: 47 [*Schröter et al.*, 2015]	Wetness index: 114 [*Schröter et al.*, 2015]	ND[a]	Saturated soils
	Precipitation	Precipitation index: 21.97 [*Schröter et al.*, 2015]	Precipitation index: 8.6 [*Schröter et al.*, 2015]	1870 mm	2000 mm	Precipitation index: 30 [*Schröter et al.*, 2015]	Precipitation index: 17 [*Schröter et al.*, 2015]	ND[a]	High continuous rainfall combined with high number of typhoons
	Hydrological severity	Severity index: 44.4 [*Schröter et al.*, 2015], lower Rhine mainly affected	Severity index: 51.2 [*Schröter et al.*, 2015] lower Rhine mainly affected	68% of Bangladesh inundated	40% of Bangladesh inundated	Severity index: 35 [*Schröter et al.*, 2015]	Severity index: 75 [*Schröter et al.*, 2015]	Bivariate probability of peak discharge and volume: 0.05 [*MRC*, 2015]; 0.01 [*Dung et al.*, 2015]	Bivariate probability of peak discharge and volume: 0.1 [*MRC*, 2015]; 0.02 [*Dung et al.*, 2015]
	Protection failures	0	0	4500 km dikes partially/totally damaged	3100 km dikes partially/totally damaged	131 dike failures	30 dike failures including 3 major breaches [*DKKV*, 2015]	1270 km dikes failed/were over-topped [*DMC-CCFSC*, 2016]	3370 km dikes failed [*DMC-CCFSC*, 2016]
Exposure	People affected	100,000 [*EM-Dat*, 2015]	ND[a]	30,000,000	36,000,000	330,000 [*EM-Dat*, 2015]	600,000 [*EM-Dat*, 2015]	~5 million people, 895,499 houses affected [*DMC-CCFSC*, 2016]	590,000 people, 176,588 houses affected [*DMC-CCFSC*, 2016]
	(Settlement) area affected	ND[a]	ND[a]	100,250 km^2	54,720 km^2	52.6 km^2 (own calculation, see S3)	13.7 km^2 (own calculation, see S3)	615,704 ha [*DMC-CCFSC*, 2016]	137,599 ha [*DMC-CCFSC*, 2016]

Table 1. continued

		Germany Rhine (Supporting Information S1, Text S1)		Bangladesh (Supporting Information S1, Text S2)		Germany Elbe, Danube (Supporting Information S1, Text S3)		Vietnam (Supporting Information S1, Text S4)	
		1993	1995	1998	2004	2002	2013	2000	2011
	Exposure hotspots	Cologne, Koblenz, Bonn	Cologne, Koblenz, Bonn	Eastern part of Dhaka City.	Sylhet city, eastern part of Dhaka City	Dresden (Cultural heritage)	Passau, Deggen-dorf, Halle (Saale)	No particular hotspots	No particular hotspots
Vulnerability	Lack of awareness	Last severe floods in 1926 and 1970	Experience with flood event just 13 months before [*Bubeck et al.*, 2012]	High awareness due to annual flooding, last severe floods in 1987 and 1988	Increased coping capacity due to decreasing poverty, increasing access to education	Last severe floods in 1974 and 1954 [*Kreibich et al.*, 2011; *Kreibich and Thieken*, 2009]	Several recent floods in 2002, 2005, 2006, 2010, 2011 [*Kienzler et al.*, 2015]	Last severe flood 22 years ago	Experience with 2000 flood
	Lack of preparedness	Low preparedness [*Bubeck et al.*, 2012; *Engel et al.*, 1999]	Improved early warning and sign. Increased preparedness [*Bubeck et al.*, 2012; *Engel et al.*, 1999]	Good preparedness and early warning (forecasts for 24 and 48 h lead times) [*Gain et al.*, 2015]	After 1998, further improved forecast-ing/warning (forecasts for 72 h lead time)	Warnings relatively late and imprecise, low preparedness [*Kreibich and Merz*, 2007]	Sign. Improved warning and preparedness [*Thieken* et al., 2016b]	Low preparedness	Medium to high preparedness, good early warning
	Insufficient organizational emergency management	Public flood management badly prepared	Public management sign. Improved due to learning in 1993 [*Engel et al.*, 1999]	Weak disaster preparedness and response planning	Weak disaster preparedness and response planning	Exercises within individual relief organizations	Every 2 years trans-organizational national crisis management exercise (LÜKEX) [*Thieken et al.*, 2016b]	Unprepared and not well organized	Much better organized, frogm communal to governmental level
Damage	fatalities	5	5	1050	730	21 [*DKKV*, 2015; *Thieken et al.*, 2016a]	14 [*DKKV*, 2015; *Thieken et al.*, 2016a]	481 [*DMC-CCFSC*, 2016]	89 [*DMC-CCFSC*, 2016]
	Monetary damage[b]	EUR 767 million	EUR 256 million	US$ 5000 million	US$ 2200 million	EUR 14.6 billion [*DKKV*, 2015; *Thieken et al.*, 2016a]	EUR 6 to 8 billion [*DKKV*, 2015; *Thieken et al.*, 2016a]	US$ 500 million [*Chinh et al.*, 2016]	US$ 208.9 million [*Chinh et al.*, 2016]

Table 1. continued

		Poland (Supporting Information S1, Text S5)		Mozambique (Supporting Information S1, Text S6)		Italy (Supporting Information S1, Text S7)		Spain (Supporting Information S1, Text S8)	
		1997	2010	2000	2013	1987	2013	1962	2000
Hazard	Preconditions	Saturated soils after 1st intense precipitation event	(Decisively) saturated soils	Saturated soils	Less saturated soils	Wind and storm surge caused backwater effects	Wind and storm surge caused backwater effects	Event after 4 months without rainfall	Event after some weeks without rainfall
	Precipitation	Extreme rainfall	Rainfall less extreme than in 1997	5 weeks of heavy persistent rainfall	1 week of heavy rainfall	24-h rainfall—return period: >50 years (3 h rp: 11 years)	24-h rainfall rp: 30 years (3 h rp: 20 years)	Rainfall max. 6 mm/min; 250 mm in less than 3 h [*Llasat et al.*, 2003]	Rainfall max. 100 mm/h, 150 mm in 3 h [*Llasat et al.*, 2003]
	Hydrological severity	Catastr., rare flood	Catastr., rare flood, but less severe than 1997	Flood level 13 m (Chokwe)	Flood level 10 m (Chokwe)	Smaller area affected than 2013	Larger area affected than 1987	Llobregat River discharge at gauge Martorell: 1.550 m^3/s	Llobregat River discharge at gauge Martorell: 1.400 m^3/s
	Protection failures	Approximately 460 km dikes damaged	37 dike breaches	ND[a]	Dike failure in Chokwe	1200 m dikes failed	Several dikes over-topped	Destruction of bridges and hydraulic structures	Destruction of bridges
Exposure	People affected	160,000 people evacuated [*Butts et al.*, 2007]; 46,000 houses affected	14,565 families evacuated; 18,194 residential buildings affected	4,500,000	315,910	About 7000	About 13,000	>50,000	>20,000
	(Settlement) area affected	665,000 ha [*Kundzewicz et al.*, 2012]	682,894 ha	140,000 ha	170,000 ha	Industries, cultivated fields	Urban area, roads, cultivated fields	509,35 km^2 highly affected area	5037,42 km^2 affected area
	Exposure hotspots	Klodzko, Raciborz, Opole, Wroclaw	Sandomierz, Tarnobrzeg, Wilkow, Swiniary.	Gaza province (Chokwe town, Xai Xai City)	Gaza province (Chokwe town, Xai Xai City)	Urban areas, hospitals, roads, railways, industries	Urban areas, hospitals, roads, railways	Vallès county industrial area, Barcelona	Montserrat touristic region, Barcelona

10.1002/2017EF000606

Table 1. continued

		Poland (Supporting Information S1, Text S5)		Mozambique (Supporting Information S1, Text S6)		Italy (Supporting Information S1, Text S7)		Spain (Supporting Information S1, Text S8)	
		1997	2010	2000	2013	1987	2013	1962	2000
Vulnerability	Lack of awareness	Long time without major floods	Experience with 1997 flood	Last floods in 1975, 1977, 1981, 1996	Experience with 2000 flood	Low awareness	High attention due to severe flood in Sardinia the day before	Very low awareness, particularly among migrant population	Civil protection campaigns increased awareness
	Lack of preparedness	Organizational deficiencies at first, improved forecasting and warning next	Forecasting and warning systems significantly improved after 1997	Qualitative early warnings were issued	Early warning system implemented after 2000 [*Di Baldassarre et al.*, 2015]	Civil protection did not issue early warnings.	Successful information spread by mobile phone and social networks.	Early warning system did not exist.	Meteorological services issued good early warnings
	Insufficient organizational emergency management	Deficient, particularly at central level, missing legal basis, ambiguous division of responsibility	Sign. Improvement due to 2007 Crisis Management Act	ND[a]	ND	Emergency management was relatively poor: people felt "abandoned from authorities"	Emergency management improved considerably	Civil protection did not exist, emergency management plans were not available	INUNCAT Plan (Civil Protection Plan for floods) was activated
Damage	fatalities	54 [*Kundzewicz et al.*, 2012]	19 [*EM-Dat*, 2015; *Kundzewicz et al.*, 2012]	800	136	0	0	815	5
	Monetary damage[b]	EUR 2.7 – 5.4 billion	EUR 3.0 billion	US$ ~541 million	US$ 30 million	EUR > 3 million	EUR 514,022 first aid restoration costs	EUR 375 million	EUR 65 million

[a]ND, no data or information available.
[b]Monetary damage for comparison calculated as at year of second flood.

of the INUNCAT Civil Protection Plan for floods supported damage reduction (Table 1). Technical developments can also support improved preparedness: For instance, early warning information was successfully spread through mobile phone and social networks during the 2013 flood in Italy (Table 1).

Vulnerability did not decrease much in Bangladesh between 1998 and 2004 (Figure 2). Yet, an extraordinary reduction of vulnerability had already taken place in the previous decades. For instance, the 1974 flood killed about 29,000 people, 40 times more than the number of fatalities caused 30 years after by the 2004 flood, which had a similar magnitude [*Mechler and Bouwer*, 2015]. This reduction of people's vulnerability is explained by a number of factors, such as the emergence of spontaneous or informal processes (e.g., flood experience leading to increased awareness and preparedness) or the implementation of deliberate and formal measures like the implementation of building codes. Bangladesh also had external assistance and invested about 10 billion USD over the last five decades into disaster risk reduction [*World Bank*, 2010]. During the flood of 1998, the Flood Forecasting and Warning Centre of Bangladesh provided flood forecasting for 24 and 48 h lead-times with accompanying warning messages [*Gain et al.,* 2015]. After this flood, further improvements were undertaken with the project "Consolidation and Strengthening of Flood Forecasting and Warning Services". During the 2004 flood, the early warning system provided forecasts with a 72-h lead-time (Table 1).

In Poland, most improvements occurred in the administrative/governmental sector. Since the 1997 flood, the forecasting and warning systems of Poland have been significantly improved both technically and organizationally. In 2007, the Crisis Management Act constituted the organizational structure of the emergency management. This clarification of the legal basis for operations and division of responsibility lead to significant improvements of the organizational emergency management, which was proven during the 2010 flood. In Mozambique, vulnerability reduction is mainly attributed to increased awareness and preparedness. This has been achieved primarily by promoting educational programs on flood risk at different levels [*Lumbroso et al.,* 2008]. Educational tools included: (1) material on sustainable flood risk management for organizations involved in water planning; (2) posters and pamphlets to raise flood awareness at community level; and (3) "living with floods" manual and card game to raise awareness among young people and less literate adults, which were distributed to rural and urban communities throughout Mozambique [*Lumbroso et al.,* 2008].

Overall, across the paired event cases, the observed reduction in vulnerability is in line with the observed decrease in flood damage, which suggests an important role of vulnerability in adaptation to flood risk.

However, the majority of the changes in vulnerability are based on limited evidence (depicted in Figure 2 by open symbols), which is in contrast to the majority of trends in hazard and damage, the latter being mainly based on robust evidence (Figure 2). For exposure, the underlying evidence is somewhere in between, with about half of the observed changes being based on limited evidence. This is on the one hand due to the fact that many hazard parameters, like precipitation or discharge, can be measured and are often continuously monitored, in contrast to vulnerability indicators such as awareness or preparedness, which cannot be easily measured and are only recorded occasionally, mostly after extreme damaging events. On the other hand, this also reflects the fact that far more event analyses focus on the hydrological processes of floods than on exposure or vulnerability. Thus, our knowledge on vulnerability is far more limited. Both German cases are exceptions, as detailed vulnerability analyses were undertaken based on postevent surveys of affected parties (Table 1).

4. Conclusions

This first study of paired flood events shows how societies adapt to flood risk through a variety of actions. There is a clear signal that the first event acted as a trigger for raising risk awareness, preparedness, and improvements of organizational emergency management, which in turn reduced vulnerability and damage. Also, reinforcing flood protection infrastructures reduced flood damage. Exposure can also be reduced, but it requires policy and legal changes and enforcement in the area of land use planning, and its effects mostly occur on a longer (decadal) time scale. Our analysis underlines the essential role of reducing vulnerability for effective adaptation, but also the need for an improved understanding of vulnerability, in the sense of its changes and effects on damage and risk. We believe that our compilation of paired flood events can be the starting point for a broader international initiative to collect and analyze a large number of paired event studies, for example, in the framework of the IAHSs Panta Rhei initiative. Generally, the challenge remains to stimulate adaptation processes without the occurrence of disastrous floods and make risk reduction persistent over long time scales.

Acknowledgments
The present work was developed by the Panta Rhei Working Group "Changes in flood risk" within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS). All data and information used for this study are available in Appendix S1 (texts S1 to S8).

References

Armitage, D., M. Marschke, and R. Plummer (2008), Adaptive co-management and the paradox of learning, *Global Environ. Change*, *18*, 86–98.

Birkland, T. A. (1998), Focusing events, mobilization, and agenda setting, *J. Public Policy*, *18*(3), 53–74.

Blöschl, G., M. Sivapalan, T. Wagener, A. Viglione, and H. Savenije (2013), *Runoff Prediction in Ungauged Basins. Synthesis across Processes, Places and Scales*, Cambridge Univ. Press, New York.

Bouwer, L. M. (2011), Have disaster losses increased due to anthropogenic climate change? *Bull. Am. Meterol. Soc.*, *92*(1), 39–46.

Brooks, N., W. N. Adger, and P. M. Kelly (2005), The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation, *Global Environ. Change*, *15*(2), 151–163. https://doi.org/10.1016/j.gloenvcha.2004.12.006.

Brouwer, R., S. Akter, L. Brander, and E. Haque (2007), Socioeconomic vulnerability and adaptation to environmental risk: A case study of climate change and flooding in Bangladesh, *Risk Anal.*, *27*(2), 313–326.

Brown, A. E., L. Zhan, T. A. McMahon, A. W. Western, and R. A. Vertessy (2005), A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, *J. Hydrol.*, *310*, 1–4. https://doi.org/10.1016/j.jhydrol.2004.12.010.

Bubeck, P., W. J. W. Botzen, H. Kreibich, and J. C. J. H. Aerts (2012), Long-term development and effectiveness of private flood mitigation measures: An analysis for the German part of the river Rhine, *Nat. Hazards Earth Syst. Sci.*, *12*(11), 3507–3518.

Butts, M., A. Dubicki, K. Stronska, G. Jorgensen, A. Nalberczynski, A. Lewandowski, and T. vanKalken (2007), Flood forecasting for the upper and middle Odra River basin, in *Flood Risk Management in Europe*, edited by S. Begum, M. J. F. Stive and J. W. Hall, Springer, Dordrecht, The Neth.

Chinh, D. T., N. V. Dung, H. Kreibich, and P. Bubeck (2016), The 2011 flood event in the Mekong Delta: Preparedness, response, damage and recovery of private households and small businesses, *Disasters*, *40*(4), 753–788. https://doi.org/10.1111/disa.12171.

CHRR (Center for Hazards and Risk Research, Columbia University), and CIESIN (Center for International Earth Science Information Network, Columbia University) (2005), *Global Flood Hazard Frequency and Distribution*, NASA Socioecon. Data and Appl. Center (SEDAC), Palisades, N. Y. https://doi.org/10.7927/H4668B3D.

Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, K. Yan, L. Brandimarte, and G. Blöschl (2015), Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes, *Water Resour. Res.*, *51*, 4770–4781.

DKKV (German Committee for Disaster Reduction) (2015), Das Hochwasser im Juni 2013: Bewährungsprobe für das Hochwasserrisikomanagement in Deutschland. *DKKV-Schriftenreihe* Nr. 53, Bonn, ISBN 978-3-933181-62-6, 207 S (in German).

DMC-CCFSC (Disaster Management Center - Central Committee for Flood and Storm Control) (2016), 25 Jun. 2017. [Available at http://www.dmc.gov.vn, http://118.70.74.167:8081/DesInventar/profiletab.jsp?countrycode=vnn&continue=y].

Domeneghetti, A., F. Carisi, A. Castellarin, and A. Brath (2015), Evolution of flood risk over large areas: Quantitative assessment for the Po River, *J. Hydrol.*, *527*, 809–823. https://doi.org/10.1016/j.jhydrol.2015.05.043.

Duan, Q., J. Schaake, V. Andréassian, S. Franks, G. Goteti, H. V. Gupta, Y. M. Gusev, F. Habets, A. Hall, L. Hay, et al. (2006), Model parameter estimation experiment (MOPEX): An overview of science strategy and major results from the second and third workshops, *J. Hydrol.*, *320*, 3–17.

Dung, N. V., B. Merz, A. Bárdossy, and H. Apel (2015), Handling uncertainty in bivariate quantile estimation – An application to flood hazard analysis in the Mekong Delta, *J. Hydrol.*, *527*, 704–717. https://doi.org/10.1016/j.jhydrol.2015.05.033.

EM-Dat (2015), Data from "International Disaster Database" 1 Oct. 2015. [Available at http://www.emdat.be/].

Engel, H., N. Busch, K. Daamen, J. Helm, M. Keller, J. Ottens, B. Parmet, and E. Sprokkereef (1999), Eine Hochwasserperiode im Rheingebiet: Extremereignisse zwischen Dez. 1993 und Febr. 1995, , *Bericht Nr. I-17*, Int. Komm. für die Hydrol. des Rheingebietes (KHR).

European Commission (2007), Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks (Floods Directive). Eur. Comm., Brussels, Belgium.

Faccini, F., F. Luino, A. Sacchini, and L. Turconi (2015), Flash flood events and urban development in genoa (Italy): Lost in translation, in *Engineering Geology for Society and Territory*, vol. *5*, edited by G. Lollino, A. Manconi, F. Guzzetti, M. Culshaw, P. Bobrowsky and F. Luino, Springer, Basel, Switz., 797–801.

Ferguson, A. P., and W. S. Ashley (2017), Spatiotemporal analysis of residential flood exposure in the Atlanta, Georgia metropolitan area, *Nat. Hazards*, *87*(2), 989–1016. https://doi.org/10.1007/s11069-017-2806-6.

Gain, A. K., V. Mojtahed, C. Biscaro, S. Balbi, and C. Giupponi (2015), An integrated approach of flood risk assessment in the eastern part of Dhaka City, *Nat. Hazards*, *29*(3), 1499–1530. https://doi.org/10.1007/s11069-015-1911-7.

IKSE (Internationale Kommission zum Schutz der Elbe) (2001), *Bestandsaufnahme des vorhandenen Hochwasserschutzniveaus im Einzugsgebiet der Elbe*. Magdeburg, Jan. 2001, 74 pp, 23 Jun. 2017. [Available at http://www.ikse-mkol.org/fileadmin/media/user_upload/D/06_Publikationen/02_Hochwasserschutz/2001_IKSE-Bestandsaufnahme_Hochwasserschutzniveau.pdf]

IPCC (Intergovernmental Panel on Climate Change) (2012), *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, Cambridge Univ. Press, New York.

Jongman, B., H. C. Winsemius, J. C. J. H. Aerts, E. C. dePerez, M. K. vanAalst, W. Kron, and P. J. Ward (2015), Declining vulnerability to river floods and the global benefits of adaptation, *Proc. Natl. Acad. Sci. U. S. A.*, E2271–E2280 https://doi.org/10.1073/pnas.1414439112.

Kelly, P. M., and W. N. Adger (2000), Theory and practice in assessing vulnerability to climate change and facilitating adaptation, *Clim. Change*, *47*(4), 325–352. https://doi.org/10.1023/A:1005627828199.

Kienzler, S., I. Pech, H. Kreibich, M. Müller, and A. H. Thieken (2015), After the extreme flood in 2002: Changes in preparedness, response and recovery of flood-affected residents in Germany between 2005 and 2011, *Nat. Hazards Earth Syst. Sci.*, *15*, 505–526.

Kingdon, J. W. (1995), *Agendas, Alternatives, and Public Policies*, 2nd ed., Longman, Harlow, U. K.

Klijn, F., H. Kreibich, H. deMoel, and E. Penning-Rowsell (2015), Adaptive flood risk management planning based on a comprehensive flood risk conceptualization, *Mitig. Adapt. Strateg. Global Change*, *20*(6), 845–864.

Kreibich, H., and B. Merz (2007), Lessons learned from the Elbe river floods in August 2002 - With a special focus on flood warning, in *Extreme Hydrological Events: New Concepts for Security*. NATO Science Series 78, edited by O. F. Vasiliev, P. H. A. J. M. Gelder, E. J. Plate and M. V. Bolgov, Springer, Dordrecht, The Neth., 69–80.

Kreibich, H., and A. H. Thieken (2009), Coping with floods in the city of Dresden, Germany, *Nat. Hazards*, *51*(3), 423–436.

Kreibich, H., I. Seifert, A. H. Thieken, E. Lindquist, K. Wagner, and B. Merz (2011), Recent changes in flood preparedness of private households and businesses in Germany, *Reg. Environ. Change*, *11*(1), 59–71.

Kuhlicke, C., A. Scolobig, S. Tapsell, A. Steinfuhrer, and B. deMarchi (2011), Contextualizing social vulnerability: Findings from case studies across Europe, *Nat. Hazards*, *58*(2), 789–810.

Kundzewicz, Z. W., A. Dobrowolski, H. Lorenc, T. Niedźwiedź, I. Pinskwar, and P. Kowalczak (2012), Floods in Poland, in *Changes in Flood Risk in Europe*, edited by Z. W. Kundzewicz , IAHS Press and CRC Press/Balkema, Wallingford, U. K., 319–334.IAHS Special Publication, 10

Llasat, M. C., T. Rigo, and M. Barriendos (2003), The "Montserrat-2000"flash-flood event: A comparison with the floods that have occurred in the north-eastern Iberian peninsula since the 14th century, *Int. J. Climatol.*, *23*, 453–469.

Lumbroso, D., D. Ramsbottom, and M. Spaliveiro (2008), Sustainable flood risk management strategies to reduce rural communities' vulnerability to flooding in Mozambique, *J. Flood Risk Manage.*, *1*, 34–42.

Mastrandrea, M. D., C. B. Field, T. F. Stocker, O. Edenhofer, K. L. Ebi, D. J. Frame, H. Held, E. Kriegler, K. J. Mach, P. R. Matschoss, G.-K. Plattner, G. W. Yohe, and F.W. Zwiers (2010), *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*, Intergovernmental Panel on Climate Change (IPCC). 14 Apr. 2016. [Available at http://www.ipcc.ch].

McRobie, A., T. Spener, and H. Gerritsen (2005), The big flood: North Sea storm surge, *Philos. Trans. R. Soc. A*, *363*, 1263–1270. https://doi .org/10.1098/rsta.2005.1567.

Mechler, R., and L. M. Bouwer (2015), Understanding trends and projections of disaster losses and climate change: Is vulnerability the missing link? *Clim. Change*, *133*(1), 23–35.

Merz, B., J. Hall, M. Disse, and A. Schumann (2010), Fluvial flood risk management in a changing world, *Nat. Hazards Earth Syst. Sci*, *10*, 509–527, www.nat-hazards-earth-syst-sci.net/10/509/2010/.

Merz, B., Z. W. Kundzewicz, J. Delgado, Y. Hundecha, and H. Kreibich (2012), Detection and attribution of changes in flood hazard and risk, in *Changes in Flood Risk in Europe*, edited by Z. W. Kundzewicz, IAHS Special Publication, 10, IAHS Press and CRC Press/Balkema, Wallingford, U. K., 435–454.

MRC (Mekong River Commission) (2015), Annual Mekong Flood Report 2011. Mekong River Comm., 72 pp.

Müller, U. (2010), *Hochwasserrisikomanagement. Theorie und Praxis*, Vieweg+Teubner Verlag, Berlin, Germany. ISBN: 978-3-8348-1247-6.

Nakamura, I., and M. C. Llasat (2017), Policy and systems of flood risk management: a comparative study between Japan and Spain, *Nat. Hazards*, *87*(2), 919–943. https://doi.org/10.1007/s11069-017-2802-x.

Nkwunonwo, U. C., M. Whitworth, and B. Baily (2016), Review article: A review and critical analysis of the efforts towards urban flood risk management in the Lagos region of Nigeria, *Nat. Hazards Earth Syst. Sci.*, *16*(2), 349–369. https://doi.org/10.5194/nhess-16-349-2016.

Orlandini, S., G. Moretti, and J. D. Albertson (2015), Evidence of an emerging levee failure mechanism causing disastrous floods in Italy, *Water Resour. Res.*, *51*, 7995–8011. https://doi.org/10.1002/2015WR017426.

Pahl-Wostl, C. (2009), A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes, *Glob. Environ. Change*, *19*, 354–365.

Prosdocimi, I., T. R. Kjeldsen, and J. D. Miller (2015), Detection and attribution of urbanization effect on flood extremes using nonstationary flood frequency models, *Water Resour. Res.*, *51*, 4244–4262.

Schröter, K., M. Kunz, F. Elmer, B. Mühr, and B. Merz (2015), What made the June 2013 flood in Germany an exceptional event? A hydro-meteorological evaluation, *Hydrol. Earth Syst. Sci.*, *19*, 309–327.

Tapsell, S. M., E. C. Penning-Rowsell, S. M. Tunstall, and T. L. Wilson (2002), Vulnerability to flooding: Health and social dimensions, *Philos. Trans. R. Soc. Lond. A*, *360*(1796), 1511–1525. https://doi.org/10.1098/rsta.2002.1013.

Thieken, A. H., T. Bessel, S. Kienzler, H. Kreibich, M. Müller, S. Pisi, and K. Schröter (2016a), The flood of June 2013 in Germany: How much do we know about its impacts? *Nat. Hazards Earth Syst. Sci.*, *16*, 1519–1540.

Thieken, A. H., S. Kienzler, H. Kreibich, C. Kuhlicke, M. Kunz, B. Mühr, M. Müller, A. Otto, T. Petrow, S. Pisi, et al. (2016b), Review of the flood risk management system in Germany after the major flood in 2013, *Ecol. Soc.*, *21*, 2.

Thywissen, K. (2006), *Components of risk – A comparative glossary*. Source, vol. *2*.

Turner, B. L., P. A. Matson, J. J. McCarthy, R. W. Corell, L. Christensen, N. Eckley, G. K. Hovelsrud-Broda, J. X. Kasperson, R. E. Kasperson, A. Luers, et al. (2003), A framework for vulnerability analysis in sustainability science, *Proc. Natl. Acad. Sci. U. S. A*, *100*(14), 8080–8085. https://doi.org/10.1073/pnas.1231334100.

UNISDR (United Nations International Strategy for Disaster Reduction) (2015), *GAR 2015 Making Development Sustainable: The Future of Disaster Risk Management*, UN Int. Strat. for Disaster Reduction Secretariat, Geneva, Switz.

Van Koningsveld, M., J. P. M. Mulder, M. J. F. Stive, L. Van der Valk, and A. W. Van der Weck (2008), Living with sea-level rise and climate change: A case study of the Netherlands, *J. Coast. Res.*, *24*, 367–379.

Van Loon, A. F., K. Stahl, G. Di Baldassarre, J. Clark, S. Rangecroft, N. Wanders, T. Gleeson, A. I. J. M. Van Dijk, L. M. Tallaksen, J. Hannaford, et al. (2016), Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches, *Hydrol. Earth Syst. Sci.*, *20*, 3631–3650. https://doi.org/10.5194/hess-20-3631-2016.

Wisner, B., P. Blaike, T. Cannon, and I. Davis (2004), *At Risk: Natural Hazards, People's Vulnerability and Disasters*, Routledge, London.

World Bank (2010), *Economics of Adaptation to Climate Change. Synthesis Report*, World Bank, Washington, D. C.

World Bank (2016), Data from "GDP per capita, PPP (current international $)" World Development Indicators database. 14 Apr. 2016. [Available at http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators].