

Declining vulnerability to river floods and the global benefits of adaptation

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The global impacts of river floods are substantial and rising. Effective adaptation to the increasing risks requires an in-depth understanding of the physical and socioeconomic drivers of risk. Whereas the modeling of flood hazard and exposure has improved greatly, compelling evidence on spatiotemporal patterns in vulnerability of societies around the world is still lacking. Due to this knowledge gap, the effects of vulnerability on global flood risk are not fully understood, and future projections of fatalities and losses available today are based on simplistic assumptions or do not include vulnerability. We show for the first time (to our knowledge) that trends and fluctuations in vulnerability to river floods around the world can be estimated by dynamic high-resolution modeling of flood hazard and exposure. We find that rising per-capita income coincided with a global decline in vulnerability between 1980 and 2010, which is reflected in decreasing mortality and losses as a share of the people and gross domestic product exposed to inundation. The results also demonstrate that vulnerability levels in low- and high-income countries have been converging, due to a relatively strong trend of vulnerability reduction in developing countries. Finally, we present projections of flood losses and fatalities under 100 individual scenario and model combinations, and three possible global vulnerability scenarios. The projections emphasize that materialized flood risk largely results from human behavior and that future risk increases can be largely contained using effective disaster risk reduction strategies.

flooding | vulnerability | adaptation | climate change | development

Flooding is one of the most frequent and damaging natural hazards affecting societies across the globe, with average annual reported losses and fatalities between 1980 and 2012 exceeding \$23 billion (bn) (in 2010 prices) and 5,900 people, respectively (1). These risks have been shown to negatively affect economic growth on a country level (2). Global trends and regional differences in flood risk result from the dynamics of hazard (i.e., the natural frequency and intensity of floods, without human interference), exposure (i.e., the population and economic assets located in flood hazard-prone areas), and vulnerability (i.e., the susceptibility of the exposed elements to the hazard) (3, 4). Each of these contributing factors can be expected to change over time.

Trends in global flood losses have been increasing over the past decades and have been attributed mainly to increasing exposure due to high population growth and economic development in flood-prone areas (4–9). At the same time, rainfall patterns and intensities may shift under climate change (10, 11), which could influence the flood hazard (12–15). In addition, inter-annual variations in peak discharge, caused by climatic oscillations such as El Niño Southern Oscillation, may lead to strong spatiotemporal fluctuations in the occurrence of floods (16, 17). These hazard and exposure elements can only partly explain spatiotemporal patterns in flood risk, because of the importance of vulnerability (8, 18). There are many different

and competing definitions of vulnerability in literature (see ref. 4, chap. 2, for a discussion on these). Vulnerability is considered in this study to include all man-made efforts to reduce the impact of the natural flood hazard on the exposed elements, including structural flood defenses, building quality early-warning systems, and available health care and communication facilities (19–21). Vulnerability is dynamic and varying across temporal and spatial scales, and may depend on economic, social, geographic, demographic, cultural, institutional, governance, and environmental factors (ref. 4, chap. 2). The level of vulnerability is therefore affected by socioeconomic development (ref. 4, chap. 2; see also ref. 22) and can specifically be influenced by deliberate disaster risk reduction efforts (19, 23). The reduction of vulnerability over time makes countries less prone to the adverse effects of the current and future flood hazard and is therefore considered as a display of adaptation.

For example, two similar tropical cyclones made landfall in eastern India, one in 2013 (Phailin) and one in 1999 (Cyclone 05B). Exposed population was greater in 2013 due to population growth and development in cyclone-prone areas. However, the vulnerability in the region had drastically decreased with the implementation of a disaster management authority; cyclone shelters and early-warning systems ensured that only a small fraction of the population was vulnerable to this event. Because of this, the total reported impacts for the similar event in 2013 were much lower; fewer than 50 lives were lost in 2013, whereas the cyclone in 1999 was responsible for more than 10,000 lives lost (24). A similar study examined the effect of mangrove forests in the 1999 event; controlling for distance from the coast and

Significance

Understanding the vulnerability of societies around the world is crucial for understanding historical trends in flood risk and for producing accurate projections of fatalities and losses. We reproduced historical river flood occurrence using daily climate data for the period 1980–2010 and quantified the natural and socioeconomic contributions to flood risk trends. We show that the fatalities and losses as a share of the exposed population and gross domestic product are decreasing with rising income. We also show that there is a tendency of convergence in vulnerability levels between low- and high-income countries. Projections based on a wide range of climate change and socioeconomic development scenarios demonstrate that amplified adaptation efforts have the potential to largely contain losses from future floods.

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storm surge (exposure and hazard, respectively), they found a differential vulnerability in the number of deaths as a percentage of the potentially exposed population (25).

The level of vulnerability of a community is therefore reflected in the actual losses and fatalities as a share of the people and assets exposed to the flood hazard (26). In vulnerable communities, these mortality and loss rates can be expected to be higher than in less vulnerable communities for the same hazard event.

Understanding the complexity of the risk chain and the resulting past and future trends in flood risk is increasingly important for international decisions on risk financing (13, 27), for the allocation of disaster risk reduction (DRR)-related development aid (28, 29), and for designing effective climate change adaptation policies (4, 30, 31). Recently, disentangling the contribution of hazard, exposure, and vulnerability has once again been emphasized explicitly in the climate change debate, as the acceptance of the Warsaw International Mechanism for Loss and Damage Associated with Climate Change Impacts in December 2013 (32) raises questions of causality, responsibility, and equity (33).

The understanding of climatic and socioeconomic drivers of risk has improved considerably over the past years, and a range of studies have demonstrated that feasible estimates can be made of current and future flood hazard (34, 35) and exposure (19, 36) at a global scale. These scientific advances have recently been combined in first global-scale risk assessments under current and future climate conditions (37–39). However, the understanding of vulnerability remains one of the biggest hurdles in existing continental to global-scale flood risk assessments (33, 37). To disentangle the risk chain and identify the contribution of vulnerability on historical flood losses, it is critical to have consistent information on global flood hazard, exposure, and reported impacts. Previous recent studies (6–9) have tried to unravel reported flood loss patterns from various disaster databases by normalizing the trends using data on gross domestic product (GDP) and population growth (exposure) and, at best, simplistic climate proxies (hazard). Whereas increases in the proxies for hazard and exposure have been statistically linked to rising long-term global trends in losses, they do not represent interannual variability in flood occurrence and offer limited explanatory power for year-to-year global loss patterns. Finding evidence for changes in vulnerability in these long-term trends has therefore been very difficult (8). No previous study has yet been able to quantify the contribution of the individual risk drivers and convincingly disentangle the dynamics of hazard, exposure, and vulnerability on a global scale.

Consequently, little quantitative evidence is yet available about regional differences in human and economic vulnerability to flooding; changes in this vulnerability over time under socioeconomic growth, adaptation, and DRR efforts; and how this relates to observed trends in global disaster risk (8). As a result, past trends in losses and fatalities are not fully understood; the potential effect of climate change-induced increases in flood hazard remains unclear; the global effects of adaptation measures are unquantified; and future projections of fatalities and losses available today are based on simplistic assumptions or do not include vulnerability (8, 13, 40).

Here, we focus on analyzing this missing link in the risk chain. We show that variation and trends in vulnerability can be derived by modeling flood hazard and exposure at a high level of detail and paralleling these to reported impacts over the past decades. We investigate the relationship between GDP per capita and vulnerability, whereby we consider vulnerability to be represented by mortality rates (reported fatalities as a percentage of modeled exposed population) and loss rates (reported losses as a percentage of modeled exposed GDP). We also show how the vulnerability of different world regions has changed over time. Finally, we demonstrate how reducing vulnerability by improved

adaptation efforts may strongly lower the magnitude of human and economic flood losses in the future.

Results and Discussion

Reproducing Risk Trends. To analyze vulnerability to flooding, we reproduced trends in global flood hazard and exposure for each year of 1980–2010 (see *Materials and Methods* for a full description). We forced a global hydrological–hydraulic model (41, 42) with daily climate data (43), to calculate daily discharge and flood volumes. We then derived a time series of annual maximum flood volumes and used these to force a high-resolution global inundation model (34, 37). From this, we produced high-resolution hazard maps (30° × 30°, ~1 km × 1 km at the equator) showing potential maximum inundation extent per year. These maps represent areas that are modeled to be flooded that year if no protection measures were in place, and were validated in past studies (34, 37). We then overlaid these potential inundation maps with spatially explicit annual population density and GDP per capita at purchasing power parity (PPP) data at the same resolution, to derive estimates of annual maximum flood exposure (i.e., estimates of combined annual hazard and exposure, reflecting the number of people and value of GDP exposed to the modeled maximum flood hazard for the respective year) across the globe. This method allows us for the first time (to our knowledge) to compare specific estimates of flood hazard and exposure for each year of analysis and for each country, to reported losses (also converted to PPP) and fatalities (1) (i.e., “risk”) for that country and year.

With these specific estimates of hazard, exposure, and risk, we can derive vulnerability by rearranging the risk equation (Eqs. 1 and 2). The spatiotemporal dynamics of hazard, exposure, and reported impacts (risk) furthermore enable us to quantify spatial differences and temporal trends in vulnerability as follows:

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability}, \quad [1]$$

$$\text{Vulnerability} = \frac{\text{Risk}}{(\text{Hazard} \times \text{Exposure})} \quad [2]$$

In Fig. 1A, we demonstrate how this method is applied to reproduce the potential flood hazard in Pakistan in 1980 [a “regular” year with 11 fatalities and low economic losses reported (1)] and 2010 [a year with extremely widespread flooding causing 1,761 fatalities and \$25bn losses (adjusted at PPP, corresponding to US\$9.5bn in original values) (1)]. Fig. 1B shows the changes in maximum flood volume (i.e., the summed volume of all inundated grid cells) and modeled exposed population between 1990 and 2010 compared with the baseline period (1980–1989). The figure demonstrates that the annual variation in modeled exposed population between 1990 and 2010 corresponds to a certain extent to the variation in reported fatalities ($r = 0.61$). The limited strength of this relationship highlights that variation in annual hazard exposure can explain part of the patterns in reported impacts, but that other factors clearly play a role.

The impact (fatalities) as a ratio of the total exposed population at the annual hazard level (Eq. 2) can be considered as an indicator of vulnerability. This concept was previously explored for tropical cyclone risk (26) and assumes that mortality rates (the number of people killed compared with the size of the number of people exposed) are higher in vulnerable regions than in less vulnerable regions. Similar to these “mortality rates,” “loss rates” are defined here as the economic losses as a percentage of the GDP that the model predicted should have been exposed to the hazard.

The year 1992 was the first year in over a decade with a large flood in Pakistan, leading to 2,000 reported fatalities. In the years 1994–1997, the maximum flood volume and the number of

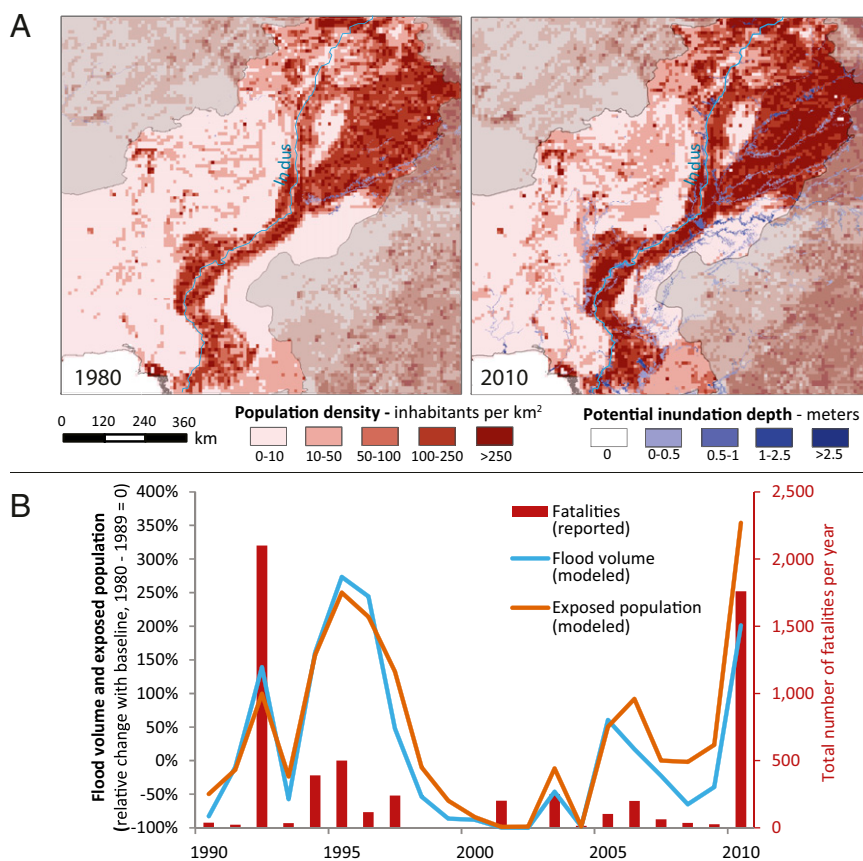


Fig. 1. Patterns in observed flood impacts can be reproduced using a hydrological modeling chain. (A) Population density and modeled potential inundation depth for Pakistan in 1980 (regular year with minor floods) and 2010 (widespread floods reported); (B) patterns in modeled exposed population in Pakistan between 1990 and 2010 (compared with baseline 1980–1989) are very similar ($r = 0.61$) to patterns in reported fatalities (1).

potentially affected people was higher than in 1992, but the number of reported fatalities was much lower. Assuming that the quality of reporting is stable across these years (i.e., the number of fatalities is consistently overestimated or underestimated), one could attribute this difference to a change in vulnerability in this area. This may indicate that vulnerability is dynamic and that improved preparedness could have played a role in (temporarily) lowering vulnerability in the years directly following the major event (44–46). There may be other factors at play in the temporal dynamics of vulnerability, such as the possibilities that not all areas affected in 1992 were fully rebuilt, or that many of the most vulnerable people already suffered fatality or were relocated in 1992. Over the entire time series, we estimate the mean mortality rate in Pakistan at 0.027% (270 fatalities per million exposed to the hazard), with a SD of 0.12%.

The analysis as presented for Pakistan was expanded to the global scale, following the same methodology. The global annual maximum flood volume (blue line in Fig. 2A) shows a clear pattern of interannual variability over the period 1990–2010. The trend in the time series is not significant ($P = 0.11$; Mann–Kendall test) over the entire period 1980–2010. For the period 1990–2010, however, the trend is positive and significant ($P = 0.0041$; Mann–Kendall test). This trend could potentially be a signal of climate change, although the time series is too short to draw strong conclusions on this aspect. Increased reporting of events in later years due to improved telecommunication could also play a role (47). Currently, scientific confidence in the effects of climate change on global flood hazard over the past decades is relatively low (10), but a future increase in global flood occurrence is expected with high confidence (23). In addition

to the overall trend, there is strong interannual variability in flood occurrence. Three years in the 1980–2010 time series (1985, 1988, and 1993; of which 1993 is visible in Fig. 2A) show a difference in maximum global flood volume of more than 35% compared with the previous year. These large fluctuations are linked to natural variability, including climate oscillations such as El Niño Southern Oscillation (17) and could represent significant challenges for disaster risk management and the (re)insurance sector.

Overlaying the annual inundation maps with annual population and GDP data shows that annual global exposure to flooding has fluctuated strongly between 1990 and 2010 (Fig. 2A and B). The total number of people living in potentially flooded areas (i.e., hazard exposure) averaged 123.4 million people with a SD of 32.4 million. Despite the large degree of variability, we do find significant upward trends in both the global exposed population ($P = 0.07$; Fig. 2A) and exposed GDP ($P < 0.001$; Fig. 2B).

As shown in previous research (10), the trends in fatalities and losses (deflated and at PPP) do not demonstrate the same increase as the trends in annual hazard exposure. Fig. 2C–F displays the results for individual income groups, following the present-day income division as used by the World Bank (data.worldbank.org/about/country-and-lending-groups). For the purpose of temporal comparability of results, we assume that countries have not moved from one income group to another. Fig. 2C shows that the number of fatalities in high-income countries is declining, even though the number of potentially exposed people is not declining. In lower middle-income countries, the number of fatalities has been rising, but not as rapidly as the number of potentially exposed people. In low-income

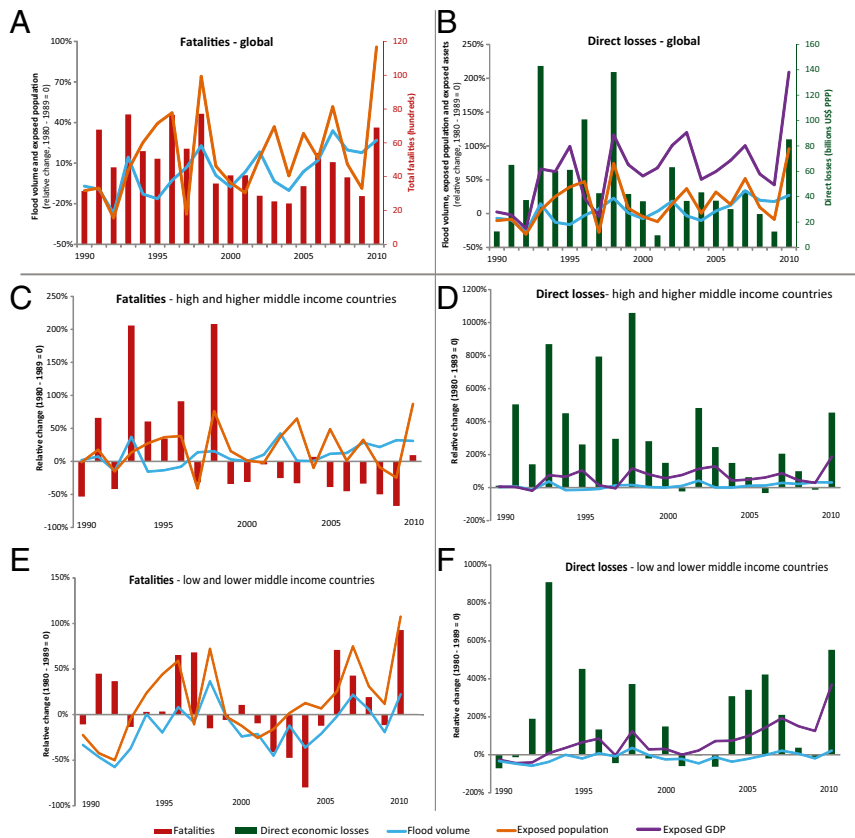


Fig. 2. Relative changes in global modeled flood volume and annual exposure (baseline = 1980–1989) versus absolute fatalities (A) and losses (B). C and E show that the fatalities in high-income countries are declining, despite a range of years with a high number of exposed people, whereas this is not the case in low-income countries. D and F show that both the exposed GDP and reported losses in the period 1990–2010 are higher than the 1980–1989 average for almost each year. Note that the percentage increase in fatalities and losses compared with the baseline may in some years be higher than the percentage increase in exposed population and GDP, but this does not mean that the absolute values are higher. Losses and fatalities as a percentage of exposure are shown in Fig. 3.

countries, there is no clear trend in the number of fatalities, whereas the exposed population showed an increase. For both high- and low-income countries, economic losses have increased between 1990 and 2010 ($P = 0.01$) (Fig. 2 D and F). In the period 1990–2010, there were only a few years in which losses below the 1980s average were reported (3 y in high-income countries, 7 in low-income countries). All other years are characterized by economic losses of up to 1,000% above the 1980s average. These findings show signs of decreasing vulnerability in these countries, which is in line with the findings of the latest *Global Assessment Report on Disaster Risk Reduction* (19). We will investigate this in more detail in the next section.

Globally, the modeled exposed population and exposed GDP can explain only a share of the fatalities and losses ($r = 0.39$ and $r = 0.30$, respectively). One reason for this relatively weak explanatory power is that not all of the modeled potential floods actually occur, because man-made flood protection measures are in place or were realized during the studied period in many populated areas around the world (e.g., ref. 37). Moreover, if the floods do occur, not all of the exposed elements face destruction (assets) or mortality (population), because of disaster preparedness measures that are in place (e.g., evacuation, early warning, flood-proof buildings) and the general resilience of countries, which depends for example on health facilities, government services, transport, and communication (19–21). All of these aspects are reflected in the vulnerability component of the risk chain.

In addition, the model results are not perfect due to uncertainties in various steps of the modeling chain, including in the hydrological modeling, the hydraulic modeling, and the

population and GDP data (e.g., ref. 21). For a discussion on these uncertainties, see refs. 34 and 37. Also, we use only one maximum inundation map per year. If one location in a country got flooded more than once in a single year, this will cause the vulnerability estimate to be an overestimate for that year.

Trends and Patterns in Vulnerability. The vulnerability of people and assets is directly related to the level of development of the specific society and the measures it has taken to prevent floods, which differ regionally and are thought to increase as income levels rise and government effectiveness improves (22, 48). As such, GDP is generally considered to be correlated with vulnerability (e.g., refs. 49 and 50). A higher GDP per capita allows for more investments in DRR measures, better building quality, and better communication of both direct and long-term risks. We investigated the relationship between GDP per capita and vulnerability, whereby we consider vulnerability to be represented by mortality rates (reported fatalities as a percentage of modeled exposed population) and loss rates (reported losses as a percentage of modeled exposed GDP), as demonstrated earlier in this article.

The results clearly show a strong negative relationship between income, on the one hand, and mortality rates (Fig. 3 A and B) and loss rates (Fig. 3 C and D), on the other, for the period 1990–2010. This confirms earlier findings from statistical analyses of loss databases (e.g., ref. 51). Fig. 3A shows that average mortality rates of 0.03–0.1% (300–1,000 fatalities per million modeled exposed people) are very common among countries with a GDP per capita of \$10,000 (PPP) or less, whereas such high vulnerability

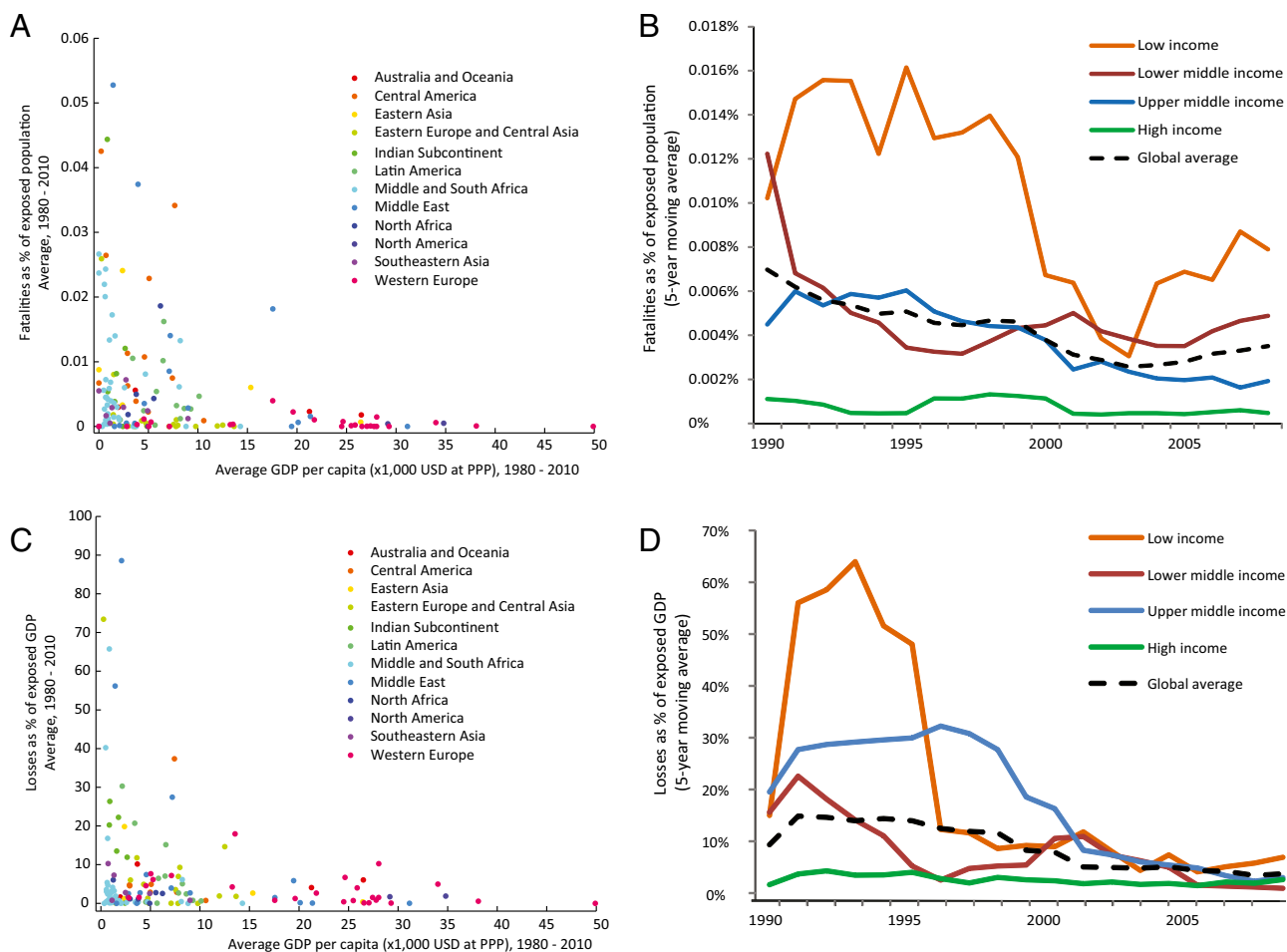


Fig. 3. Rates of loss and mortality due to flooding are shown to be linked to income levels. *A* and *C* show that fatalities and losses, respectively, as a percentage of annual exposure are a negative function of GDP per capita. *B* and *D* show that vulnerability of people and GDP, respectively, have declined over the past two decades, leading to a relative convergence of vulnerability levels between low- and high-income countries.

is no longer found among richer countries. The same relationship holds for losses, with average loss rates varying between less than 1% to over 100% of modeled exposed GDP. Also, for losses, there seems to be a vulnerability threshold around \$10,000 (PPP). This shows that, whereas absolute losses may be higher for high-income countries (8), relative losses as a percentage of modeled exposed GDP decrease with rising income.

The overall vulnerability gap between the income groups is substantial (Fig. 3 *B* and *D*). Although the global average mortality rate is around 0.004% (40 fatalities per million exposed people) and the average loss rate around 6% of GDP at the end of the 2000s, we find a factor 17 (mortality) and 3 (losses) difference between countries currently classified as high- and low-income countries.

The results presented in Fig. 3 *B* and *D* reveal two global temporal trends. First of all, these figures show that the overall vulnerability to flooding has declined in all world regions over the period 1990–2010. On a global scale, the 5-y average mortality and loss rates declined by more than one-half in this period. These global trends are significant at the 99% confidence level (Mann–Kendall test). Second, the average mortality and loss rates in lower income countries have declined relatively faster than the average rates in higher income countries. As a result of low-income countries “catching up,” there is a trend of relative convergence of vulnerability between developing and developed countries. Between 1990 and 2010, the relative dif-

ference in 5-y average loss rates between low- and high-income countries declined from >800% around 1990 to 160% around 2010 (we note that the exact figures are subject to the high variability in the low-income category). Mortality rates also show this convergence pattern, which is especially strong between 1990 and 2000, followed by some degree of divergence thereafter caused by a rise in mortality rates in low- and lower middle-income countries.

Previous studies find an inverted-U-shape function for disaster vulnerability on a national scale (e.g., refs. 50 and 52), indicating that vulnerability may initially increase with rising income before it decreases. However, like other flood-specific studies (22, 53), we do not find clear evidence for such effects for flood vulnerability in any of the aggregated income groups. Our results show a general pattern of decreasing vulnerability over time within all income-classified country groups, and a clear vulnerability gap between the groups.

The vulnerability trends in some world regions demonstrate substantial sudden fluctuations (“steep drops”), especially in the earlier years of the analysis. This may be due to both the model uncertainties highlighted before, and, especially, to the fact that the vulnerability trends are sensitive to the occurrence or absence of single large events, especially given the relatively short period of analysis. Fig. 4 presents the 10 y with the highest number of reported fatalities (Fig. 4*A*) and reported losses (Fig. 4*B*), in descending order. The blue lines in these panels show the

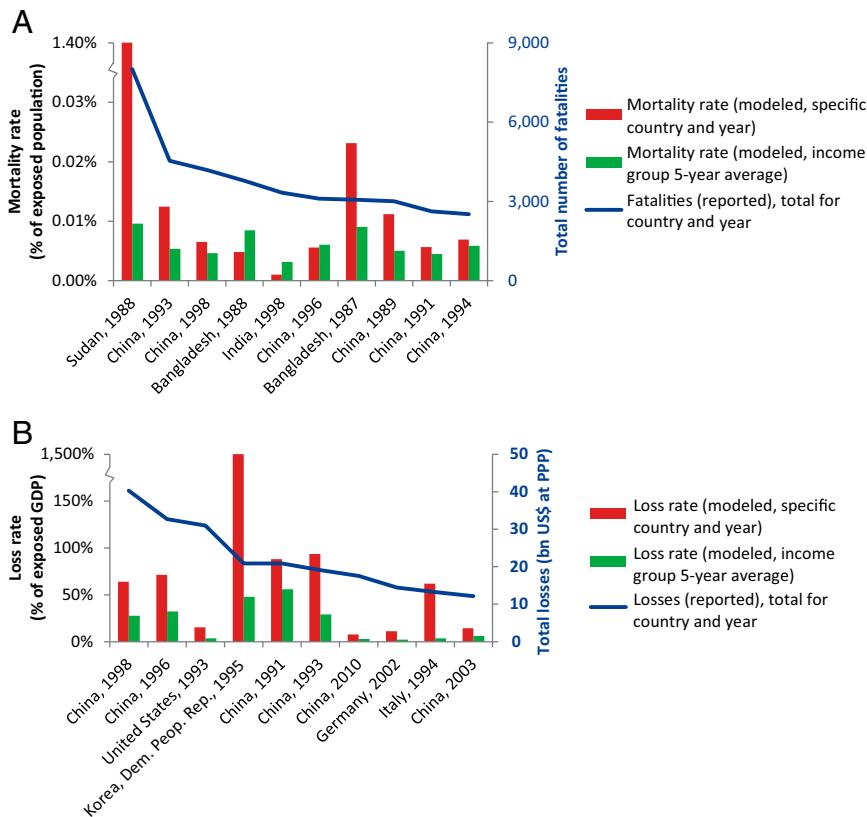


Fig. 4. The 10 recorded events with the largest total number of fatalities (A) and total losses (B), in descending order. The blue lines in both panels show the absolute magnitude of reported fatalities and losses. The red bars display the mortality and loss rates for the specific year and country, which can then be compared with the average mortality and loss rates for the total income group in that year (green bars). The figure shows that the country-specific mortality rates are higher than the income-group average for 7 out of the 10 highest ranking event years in terms of fatalities, and for 10 out of 10 event years in terms of losses.

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In light of these uncertainties, we have analyzed the significance of the vulnerability differences between the income groups (the 5-y average mortality and loss rates over the years 2005–2010, which will later in this paper be applied to produce future

risk projections) using a bootstrapping exercise (*Materials and Methods*). The results show that the mortality rates (Fig. 5A) vary significantly between income groups. The difference in loss rates between income groups (Fig. 5B) is less significant due to the relatively small difference between the income groups and the relatively large interannual fluctuations in these rates.

The intensity of floods thus not only affects the absolute impacts but also the relative impacts as a percentage of the exposure. A key indicator of flood intensity is inundation depth—higher inundation depths are shown to inflict higher economic damages as a percentage of the exposed assets (54) and higher fatalities as percentage of exposed population (55). The choice of the minimum inundation depth threshold used for computing mortality and loss rates may therefore influence these rates. We have computed annual exposure for a variety of depth thresholds to show the sensitivity of the estimated annual exposed population and annual mortality rates to the assumed minimum depth. The number of exposed people is a negative function of the assumed minimum inundation depth (i.e., more people are exposed to depths > 0 than to depths > 1 m or higher; Fig. 5C). Consequently, mortality rates computed at higher inundation depths are also higher than those computed at lower minimum depths (Fig. 5D). Throughout this paper, we use the vulnerability estimates based on all inundation depths > 0 (Fig. 3) because the absence of information about the exact location of the reported fatalities and losses, and the equally lacking academic consensus regarding the relationship between inundation depth and fatality and loss from flooding, make it impossible to define an alternative valid threshold. The resulting uncertainties surrounding the income-group-specific loss and mortality rates mean that

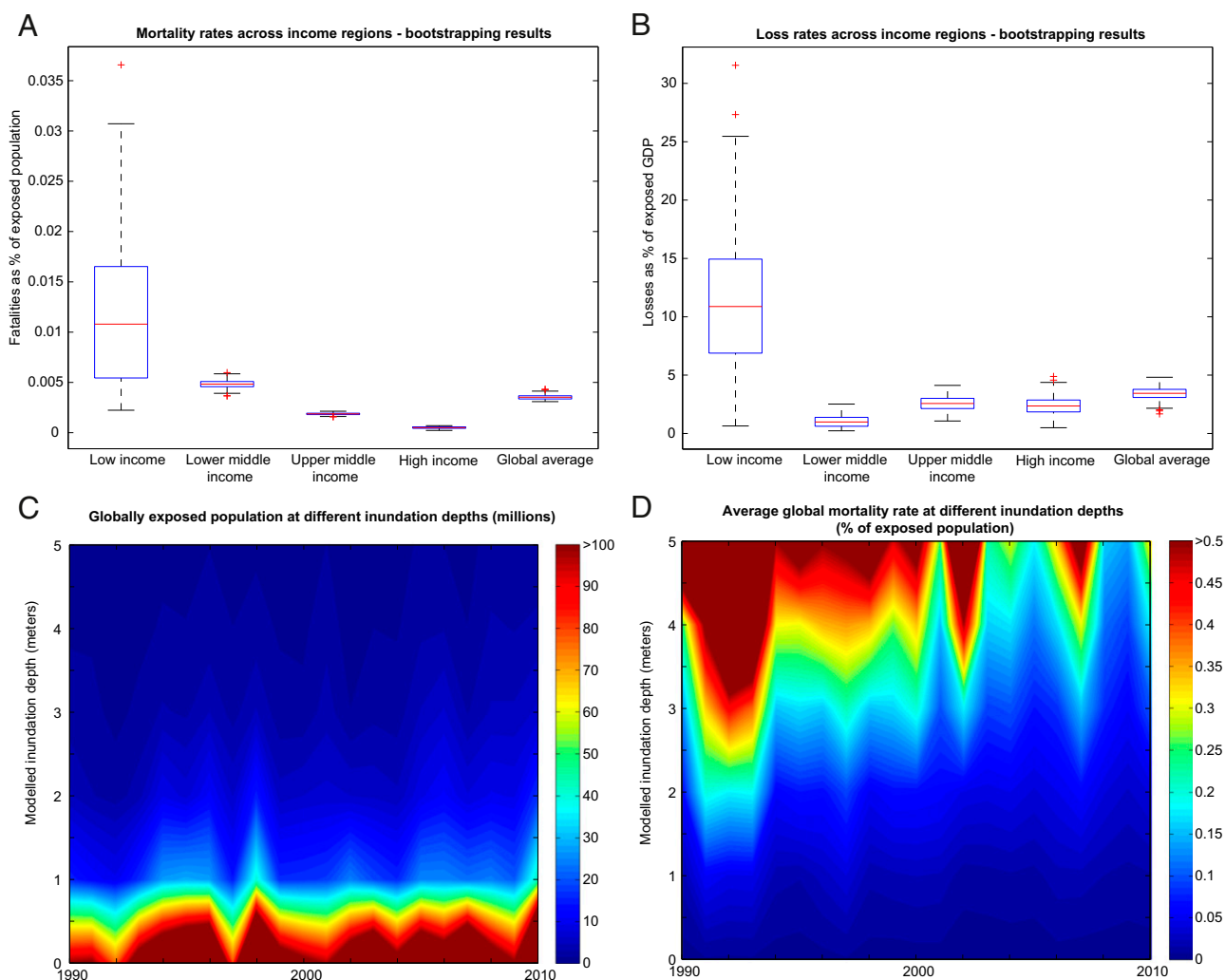


Fig. 5. Test of significance and sensitivity to the specific inundation depth threshold. (A) Results of bootstrapping the average mortality rates per income group ($n = 1,000$; boxes outline the 25th and 75th percentile; whiskers approximate the 1st and 99th percentile; and crossing marks indicate outliers beyond these values); (B) same as A, but for loss rates; (C) global exposed population at minimum inundation depths 0–5 m, for all years 1990–2010; (D) average global mortality rates at minimum inundation depths 0–5 m, for all years 1990–2010.

they should be applied with care. Given that the average rates as presented in this paper are computed across a large number of flood events, they can be considered robust across the board (see the results of the bootstrapping exercise). However, the specific mortality and loss rates from individual extremes may deviate from this, depending on the hydrological characteristics of such an event, including flood depth, flood velocity, water contamination (see, e.g., ref. 56).

In addition to the effect of large events, the results are influenced by the fact that an unknown share of the flood events that occurred over the past decades were either not reported, or poorly reported, in the loss databases, especially in the years before electronic communication became widely used (47). This effect may especially lead to an underestimation of losses in low-income countries, and especially in earlier years of the time series. It is therefore likely that the downward trend in vulnerability for low-income countries is even stronger than our results show.

Future Projections of Global Flood Fatalities and Losses. In practice, vulnerability reduction can be achieved by a range of structural and nonstructural measures and by advancing the underlying capacities of societies. In this paper, we aggregate such developments under the term “adaptation” (to flood risk in general,

not specifically to risks changing due to climate change). Adaptation may have resulted in fewer fatalities and losses than would have been the case without adaptation. Understanding changes in the level of adaptation across world regions will become increasingly important, as flood frequencies and magnitudes may rise under climate change (4) and continuing population and economic growth may lead to greater numbers of people and GDP exposed to floods.

To simulate future trends in flood risk and the effect of scenarios of vulnerability reduction on these trends, we produced global inundation maps for a range of ISI-MIP (57) climate projections [five global climate models (GCMs) and four representative concentration pathways (RCPs)], for the years 2030 and 2080 (*Materials and Methods*). We then combined these with projections of population density and GDP per capita under five shared socioeconomic pathways (SSPs) (ref. 57; *Materials and Methods*), resulting in 100 possible simulations of expected annual exposed population and exposed GDP. Whereas not all of the SSP-RCP combinations are considered equally probable (e.g., a high level of carbon emissions is likely to coincide with high socioeconomic growth), this is difficult to assess and we show the entire range of model outcomes here.

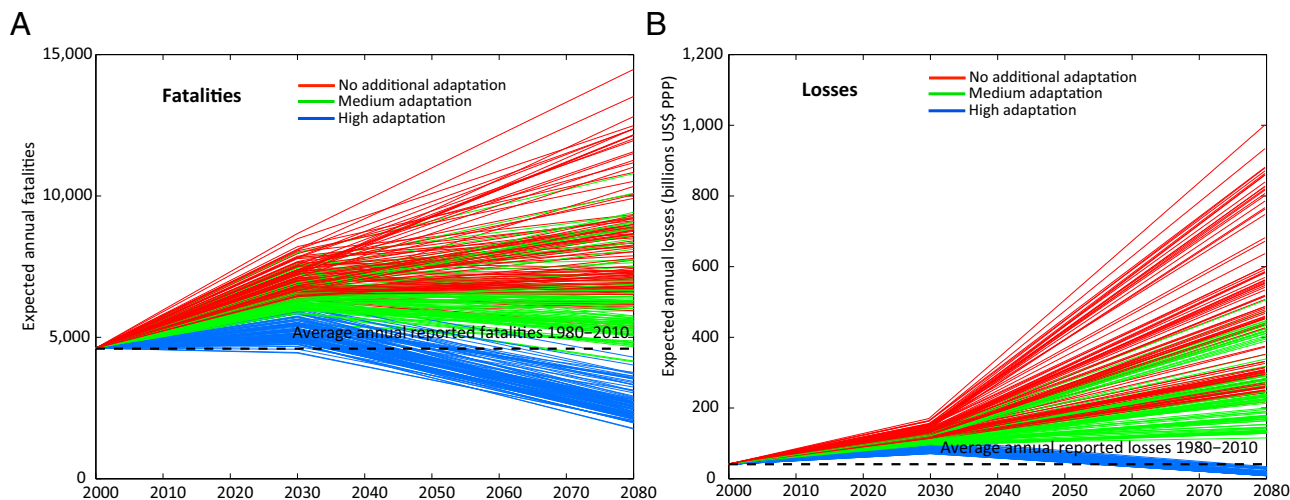


Fig. 6. Projections of fatalities and losses using different climate models, emission scenarios, socioeconomic pathways, and adaptation scenarios. Results were computed for two climatic time slices future time slices (2010–2049, labeled 2030; and 2060–2099, labeled 2080), and interpolated linearly in between. *A* shows that fatalities are expected to increase strongly over the next decades without additional adaptation (red lines) but could be reduced up to 69% under the high-adaptation scenario. *B* demonstrates that expected losses are likely to increase at a faster pace than fatalities without additional adaptation (red lines) and would be reduced to the currently observed loss level only in the high-adaptation scenario.

To translate the projections of annual exposure into the first-ever projections of global fatalities and losses, we applied the 5-year average mortality and loss rates estimated for each income region for the period 2006–2010 (Fig. 3 *B* and *D*; and significance tests in Fig. 5 *A* and *B*). Then, we defined three future vulnerability scenarios: (i) “no additional adaptation” (current vulnerability per income region remains unchanged); (ii) “medium adaptation” [all countries converge to the current (1980–2010) average vulnerability by 2080]; and (iii) “high adaptation” [all countries converge to the current (1980–2010) average vulnerability level in high-income countries by 2080]. These scenarios therefore represent possible levels of future global risk, which depart from the empirically estimated current vulnerability of low- and middle-income countries, and which depend on the pace and nature of economic development as well as the scope and effectiveness of adaptation measures that will be implemented over the course of the next decades.

The estimates of future flood risk within each of the scenarios vary strongly across climate models, emission scenarios, and socioeconomic pathways (Fig. 6). Irrespective of the adaptation scenario, we find a factor 2 (fatalities) to 5 (losses) difference between the highest and lowest projections for by 2080. Under the current vulnerability levels, we estimate that expected annual losses would increase by 433–2,360% (by 2080 compared with 2000). The expected annual number of fatalities increases at a slower pace over the next decades, with estimates ranging from 15% to 214%.

These simulations also show that the degree of vulnerability greatly influences the development of flood risk over the next decades (Fig. 6). If all countries that are currently relatively vulnerable (i.e., loss and mortality rates above global average level) would reach the current global average vulnerability levels by 2080 (medium-adaptation scenario), global fatalities and losses would be reduced by an estimated 2,138 (25%) and US\$233bn (48%), respectively (average of all projections). Under the high-adaptation scenario, the reductions in global fatalities and losses would be as high as 5,960 (69%) and US\$468bn (96%) (average of all projections), respectively. These substantial possible reductions in future risk emphasize that advancing risk reduction could result in vastly lower future impacts.

The results furthermore show that the absolute difference in the expected future levels of losses and fatalities between the

various risk projections (i.e., different GCM, RCP, and SSP combinations) increases with magnitude of the level of risk. This means that the absolute spread in possible future losses will be much wider if no additional vulnerability reduction were implemented, than if all countries converge to the current high-income vulnerability level. This conclusion is similar to an earlier global study on adaptation to coastal flooding (58). Therefore, contingent on the rollout of widespread global adaptation measures for flooding and strengthening of the resilience of countries, there would be less absolute uncertainty in the societal outcomes over the next decades.

Implications and Further Research

To our knowledge, this is the first study that detects spatiotemporal patterns in vulnerability within global flood risk observations. Our results provide enhanced insights in the drivers of risk, geospatially and temporally varying levels of vulnerability, and possible projections of monetary losses and fatalities. The findings emphasize that human behavior determines the difference between a hazard and a disaster and give much needed insights in human vulnerability to climate impacts (8, 59). We show that societies have already been successful in reducing vulnerability to floods and that the global scale-up of adaptation strategies and resilience enhancement, especially in developing countries, has the potential to strongly reduce future harm caused by floods.

The vulnerability trends displayed over the past decades suggest that we see a convergence between low-income and high-income countries, and that the current adaptation approaches have the potential to greatly reduce future flood losses and mortality. The patterns show that developing countries seem to adapt rapidly toward vulnerability levels similar to those seen in developed countries. However, if economic growth continues and if climate change would lead to an increasing frequency and intensity of floods, economic losses from floods would increase drastically unless further adaptation measures are implemented in river basins around the world.

Future research should focus on bridging the gap between global-scale patterns and local-scale solutions. More emphasis should be put on establishing the current causal factors of vulnerability and status of planned risk management and adaptation in different regions, and on quantifying the costs and benefits of different measures available to societies at risk. These costs can

take into account the reduced absolute uncertainty in flood losses that comes with the implementation of robust adaptation policies and measures.

Materials and Methods

Flood Hazard and Exposure Modeling. A physical modeling chain was used to produce flood hazard and exposure maps. First, we used the global hydrological model PCR-GLOBWB (41, 42) and DynRout, its extension for dynamic routing, to simulate discharge and flood volume at a daily time step, and a horizontal resolution of $0.5^\circ \times 0.5^\circ$. These models were forced by meteorological data (precipitation, temperature, potential evaporation) from the Global Precipitation Climatology Project (GPCP) (60) and ERA-Interim reanalysis (43). Temperature, and all fields needed to estimate potential evaporation were taken from ERA-Interim. For precipitation, we used ERA-Interim, rescaled with GPCP. The ERA-Interim inputs were resampled to $0.5^\circ \times 0.5^\circ$, from their original resolution of $0.7^\circ \times 0.7^\circ$, using bilinear interpolation. To calculate annual flood hazard, we then selected the annual peak daily inundation volumes in each grid cell. These values of annual peak inundation volumes per grid cell were used as input in the GLOFRIS inundation downscaling module, described in ref. 34, to produce inundation maps at a horizontal resolution of $30'' \times 30''$ ($\sim 1 \text{ km} \times 1 \text{ km}$ at the equator). Finally, these flood hazard maps were combined with population and GDP per-capita maps, taken from the IMAGE/GISMO models (61). For each year of analysis, this resulted in annual exposure maps, which were then summed on a country level. Note that only one maximum inundation map was produced for each year. Therefore, the occurrence of multiple flood events at the same place in the same year is not accounted for.

Deriving Vulnerability. Vulnerability levels were defined as mortality rates (fatalities as percentage of exposed population) and loss rates (losses as percentage of exposed GDP). To be able to calculate this, detailed data on reported fatalities and direct losses were kindly made available by Munich Re (1). The database contains information on 192 countries. The direct losses were originally available in nominal US dollars and were deflated and converted to US dollars at PPP values (base year 2010) for the sake of spatiotemporal comparison. This was done on the basis of inflation and PPP data from the Penn World Tables (62). For each country and year, the mortality and loss rates were then computed as the ratio of reported fatalities and losses over

modeled exposed population and GDP. The resulting mortality and loss rates are presented by income group (low-, lower middle-, upper middle-, and higher-income groups). We assessed the significance of the differences between these income groups by bootstrapping the results for the period 2006–2010 (1,000 repetitions for each of the years), the results of which are presented in Fig. 5 A and B.

Flood Risk Projections. Projections of changes in flood hazard and exposure were produced by first forcing the model cascade with bias-corrected baseline GCM simulation data over (i) the same baseline period as the EU-WATCH run (1960–1999); and (ii) for two 40-y future time slices (2010–2049, named “2030” in Fig. 6; and 2060–2099, labeled “2080” in Fig. 6). Second, the resulting flood hazard maps were combined with exposure maps based on the SSPs for those time slices. This was done with all four AR5 RCP emission scenarios (63) and with five different bias-corrected GCM outputs from the ISI-MIP project (64). The changes were imposed as a multiplier on the baseline projection, which was based on a run with the EU-WATCH forcing data (1960–1999). The baseline projections of fatalities and losses were produced by multiplying the average vulnerability rates per income region to the projected exposure levels, using a linear interpolation for the individual years between the current situation and the two time slices (2030 and 2080). In addition, two vulnerability scenarios were developed (see *Future Projections of Global Flood Fatalities and Losses*). Note that the future population and GDP projections therefore assume a constant spatial distribution of population within each country. Because previous research has shown that historical population growth is generally higher in flood-prone areas than outside of flood-prone areas (36), this may lead to a small underestimation of real future exposure and risk.

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