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Intensive Versus Extensive Events? Insights from Cumulative Flood-Induced Mortality Over the Globe, 1976–2016

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Abstract More attention has been paid to the cost of intensive but sporadic floods than the cost of extensive but frequent events. To examine the impacts of intensive versus extensive events, we investigated the loss structure of global flood-induced mortality by using the cumulative loss ratio, marginal benefit chart, and cumulative loss plot. Drawing on the flood-induced mortality data for four decades (1976–2016) from the international disaster database EM-DAT, we defined the levels of flood loss according to the frequency of flood-induced deaths, and calculated the cumulative mortality and the marginal benefits of flood loss prevention practices at different levels. Our analysis showed that for the world's leading 30 countries with large flood-induced mortality and different levels of development: (1) 70% of them have the cumulative deaths from extensive floods exceeding half of those caused by intensive floods in the study's four data decades; and (2) 80% of them tend to gain less marginal benefit with increasing levels of flood prevention, with their marginal benefits peaking at loss prevention levels of 2-year or 5-year flood-induced mortality. These results indicate that, in the long run, the cumulative deaths of extensive floods are comparable to that of intensive events, and prevention

of loss from extensive events can be an efficient way to reduce the total loss. For flood risk management under conditions of climate change, extensive loss events deserve more consideration.

Keywords Cumulative loss · Extensive flood · Flood-induced mortality · Intensive flood · Marginal benefit

1 Introduction

Across the globe, floods have been proved to be (Jonkman and Vrijling 2008; Kundzewicz et al. 2012; Stevens et al. 2014; Kousky and Michel-Kerjan 2017) or are projected to be (Hallegatte et al. 2013; Hirabayashi et al. 2013; Jongman et al. 2014) among the top-ranking destructive natural hazards in terms of economic losses and people affected. The pressing need for effective flood risk management and adaptation interventions requires complete information on flood impact. However, more attention has been paid to the losses of individual extreme events, rather than the long-term cumulative impacts of extreme and minor events.

Floods are usually categorized into extreme, major, medium, and minor events in a relative sense, typically according to their hazard intensity such as return period (Moftakhari et al. 2017) and magnitude, for example, water depth (Burgos et al. 2018; Moftakhari et al. 2018). Some governmental agencies, the insurance industry, and some researchers categorize floods based on the severity of their impacts, including but not limited to areas affected and fatalities caused. The National Weather Service (NWS 2019) of the United States describes the severity of flood impacts using four categories: minor, moderate, major, and record flooding. FEMA (2015) interpreted repetitive loss structure as a National Flood Insurance Program (NFIP)-

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insured structure that has had at least two paid flood losses of more than USD 1000 each in any 10-year period since 1978. The insurance industry uses historical disaster loss data to build loss exceedance curves for risk assessment (Kunreuther and Pauly 2004; Velásquez et al. 2014). Haigh (2017) categorized events into six groups based on the severity of their impacts in the improved version of the SurgeWatch v1.0 database, which systematically documents the consequences of historical coastal flood events around the UK. The United Nations Office for Disaster Risk Reduction (UNISDR 2015) refers the term “intensive disasters” to those disasters associated with high severity and medium to low frequency, and the term “extensive disasters” to those associated with low severity and high frequency. We follow these UNISDR terms hereafter in this work.

The total flood loss of a region over a long-term period (for example, 40 years) depends not only on the single-event impact but also on the numbers of their occurrence. From the perspective of historical flood losses, past studies have focused more on sporadic intensive floods (Perry 2000; Kundzewicz et al. 2012; Kousky and Michel-Kerjan 2017), which usually affect large areas and lead to high per-event cost. However, extensive flood events, despite of their local impact and small per-event loss, occur more frequently. The emphasis on intensive floods, therefore, offers an incomplete picture of the long-term flood impact of a region. Investigating the accumulated impacts of extensive but frequent floods and those of intensive but infrequent events provides a closer insight about flood risks (Velásquez et al. 2014). Some regional studies have shown that over time, the accumulated historical impact of small disasters can be remarkable when compared to that of large disasters. A few examples are found in the evaluations of Marulanda et al. (2010) in Columbia, which use the DesInventar method, and the work of the General Accounting Office (2004) of the United States, which employs flood insurance claims. Similarly, extensive studies that focus on future flood risk under climate change have concentrated on intensive events, which consistently suggested that the population (Hirabayashi et al. 2013; Lim et al. 2018) and wealth (Hallegatte et al. 2013; Jongman et al. 2014; Lim et al. 2018) would face increasing stress; few evaluated the future flood risk caused by extensive floods. By categorizing floods into minor, major, and extreme events based on water levels with respective probabilities, Moftakhari et al. (2017) estimated and compared the cumulative exposures to each category for the coastal United States. They further proposed the cumulative hazard index (CHI) as an indicator of relative cumulative exposure to extensive versus intensive events. They found that, over time, extensive flooding could generate property value exposure of the same order, or larger than,

that of intensive events. With climate change, extensive floods have also been observed and projected to be more frequent in the future (Sweet and Park 2014; Burgos et al. 2018; Moftakhari et al. 2018). Their cumulative impact, therefore, merits further investigation.

Overall, existing characterization of the relative importance of cumulative impacts of extensive but frequent floods versus intensive but sporadic events is limited. Complementary to regional studies using historical data (General Accounting Office 2004; Marulanda et al. 2010) and risk analysis (Moftakhari et al. 2017), we seek to reduce this knowledge gap by analyzing the flood loss data across the globe in the four decades between 1976 and 2016. We investigated the cumulative loss of human lives recorded in EM-DAT to explore (1) the relative importance of the cumulative flood-induced mortalities of extensive events to that of intensive events; and (2) the marginal benefits of different levels of loss prevention, so as to provide insights into the decision making of preventive strategies. In this work, we categorized floods based on the number of mortalities they caused (that is, flood impacts).

2 Data and Method

Using the flood-induced mortality data for four decades (1976–2016) from the international Emergency Events Database (EM-DAT),¹ we defined the levels of flood loss according to the frequency of flood-induced deaths, and calculated the cumulative loss ratio and the marginal benefits of flood loss prevention practices at different levels.

2.1 Data of Flood-Induced Loss Across the Globe

The EM-DAT, maintained by the Centre for Research on the Epidemiology of Disasters (CRED) in Brussels, is a widely used disaster database for scientific research of disaster reduction (Jonkman 2005; Doocy et al. 2013; Lesk et al. 2016; Hu et al. 2018). EM-DAT archives any disaster if at least 10 persons died, 100 or more persons were affected, a state of emergency was declared, or international assistance was required. Flood events with relatively small losses in developing countries might not be included in the database. The flood data consist of national- and international-level total deaths, number of affected people, the total affected area, economic damage, flood subtype, date, and disaster record number across the globe back to 1900. Floods in the EM-DAT archive are categorized into subtypes: flash floods, riverine floods, coastal floods, and others. Since the number of records has markedly increased

¹ <http://www.emdat.be/database>.

since 1975, in this study we used mainly the flood-induced mortality data over the period from 1976 to 2016. It is acknowledged that many small flood events are not included in the EM-DAT (Marulanda et al. 2010). Nevertheless, in the relative sense, the EM-DAT contains both intensive and small events. Among the total of 4315 flood events extracted, 82% (3547) of them affected more than 100 persons. About 40% of these 3547 events led to a death toll of less than three. These statistics indicate that a notable number of flood events with extensive loss were included, allowing for our investigation of cumulative mortality of extensive events.

2.2 Selection of Annual Exceedance Series of Flood-Induced Loss

The availability of 40 years of flood records in the EM-DAT database allows frequency analysis of the flood loss across countries and over the globe. We extracted the annual exceedance series (Chow et al. 1988) from all the records of flood-induced losses of each country by selecting data with their magnitude greater than a base value. The base value was chosen such that the number of values in the series is the same as the number of years of the record. We preferred these exceedance series over annual maximum series to account for the second-largest values in some years that are larger than the annual maximum values of other years. Exceedance series sometimes allows more accurate estimates of the probabilities in flood risk analysis (see Bezak et al. 2013 for more details).

2.3 Definition of Cumulative Loss Ratio

We defined the cumulative loss ratio, CLR , as the quotient of cumulative loss over a period due to extensive events divided by that due to intensive events:

$$CLR = \frac{CL_{\text{extensive}}}{CL_{\text{intensive}}} \quad (1)$$

where $CL_{\text{extensive}}$ and $CL_{\text{intensive}}$ are the cumulative losses over the same period due to extensive and intensive events, respectively. In this work, extensive and intensive events are defined according to the magnitude of flood-induced loss rather than flood hazard. The loss exceedance probability, which shows the relation between a given loss and the annual frequency of occurrence of that loss or a larger one, has been adopted to characterize the size of losses (Velásquez et al. 2014; Haigh 2017). Extensive and intensive flood events in this study are defined as those with exceedance probabilities of loss greater than 0.50 (that is, a return period of 2 years) and less than 0.05 (that is, a return period of 20 years), respectively. These thresholding probabilities were selected similarly to the work of

Moftakhari et al. (2017). In our study, we applied the distribution-free plotting position method and the Weibull formula to determine the exceedance probability (for example, $L_{2\text{-year}}$ and $L_{20\text{-year}}$) of flood-induced loss. Taking the flood-induced loss of human life as an example, annual exceedance series of death for a country over N years were firstly selected and ordered by descending magnitude as, $\{D_1, D_2, D_3, \dots, D_N\}$, the exceedance probability of the m^{th} largest death, D_m , can then be expressed by the Weibull formula as:

$$P(D \geq D_m) = \frac{m}{N+1} \quad (2)$$

Although many other plotting formulas and numerical methods have been suggested in the past century, Makkonen (2008) proved that Eq. (2) should be the correct one to apply.

After the exceedance probabilities of $L_{2\text{-year}}$ and $L_{20\text{-year}}$ are determined, the cumulative losses due to extensive and intensive events— $CL_{\text{extensive}}$ and $CL_{\text{intensive}}$ —can be calculated using the following equations, which are, in continuous form

$$CL_{\text{extensive}} = N \int_0^{L_{2\text{-yr}}} L \times p(L) \times dL, \text{ and} \quad (3a)$$

$$CL_{\text{intensive}} = N \int_{L_{20\text{-yr}}}^{\infty} L \times p(L) \times dL$$

or in discrete form

$$CL_{\text{extensive}} = \sum L, \text{ where } L \leq L_{2\text{-yr}}, \text{ and} \quad (3b)$$

$$CL_{\text{intensive}} = \sum L, \text{ where } L \geq L_{20\text{-yr}}$$

where N is the number of flood events, L is the loss of a flood event, $p(L)$ is the probability density function of loss, and $L_{2\text{-year}}$ and $L_{20\text{-year}}$ are the magnitudes of loss with return periods of 2 year and 20 year, respectively. The larger the CLR is, the more relatively important the loss due to extensive flood events is.

Since fitting a distribution itself can be a major source of error in risk analysis, we used the discrete form in this study and limited our analyses to the flood-induced losses with return periods of 2, 5, 10, and 20 years, instead of fitting a distribution to the observed data and extrapolating into losses associated with long return periods.

2.4 Marginal Benefit for Loss Prevention Levels

We propose to use a marginal benefit chart to offer tabulated information about the potential incremental gain from raising the loss prevention level. In this study, we define protection benefit (or utility) as the gain from loss

prevention practices, which can be mathematically determined as the cumulative loss smaller than a certain level of loss. For example, if all the flood losses smaller than the 2-year loss were avoided by regional flood mitigation practices, their summation is the protection benefit of promoting the flood protection level to avoid a 2-year loss. In reality, flood mitigation agencies may not pursue as high standards as would be ideal to maximize flood protection benefits. Marginal benefits (Barro 2015) for loss prevention practices are, therefore, hypothetical. Nevertheless, along the avenue of managing flood risks incrementally (Jha et al. 2012), maximizing the marginal benefits may provide insights into flood loss prevention planning (Lewis and Nickerson 1989). To obtain the marginal benefits of promoting flood protection levels gradually, we first calculated the cumulative losses below the magnitude associated with each of the typical return periods in ascending order (that is, protection benefits), then took the differences between consecutive cumulative losses. For each country, we also divided the marginal benefits by its cumulative sum of the loss below the 20-year loss to obtain normalized marginal benefits for cross-country comparison. Normalized marginal benefits take values between zero and unity, and they sum to one.

3 Results

In this section, we present first data analysis results for China and then the results of the world. There are two reasons for this. First, we want to provide details about the analysis for clarity; second, China, as one of the most flood-prone countries in the world, has invested remarkably in flood management over the study period (Cheng 2006; Han and Kaspersen 2011; Moore 2018).

3.1 Cumulative Loss Due to Floods in China

We use the cumulative loss ratio and marginal benefit chart to show the cumulative loss due to extensive floods in China.

3.1.1 Cumulative Loss Ratio of China

Floods have caused serious loss of human lives in China. Figure 1 illustrates the distribution of flood-induced deaths in China from 1976 to 2016. The EM-DAT archive recorded 282 flood events in China over this period, with 252 events causing a total of 43,537 deaths and 30 events causing zero death. Our quantile analysis showed that the flood-induced deaths of events with 2- and 20-year return periods are 425 and 3475 persons, respectively. This means that, in the four decades from 1976 to 2016, there were 20

Fig. 1 Cumulative loss plot showing the distribution of flood-induced deaths of China. Data are from the EM-DAT archive, over the period from 1976 to 2016. The histogram has a bin width of 5 persons and log-scale horizontal axis. The orange bars indicate deaths due to flood events with a return period below 2 years, the red bars are deaths due to flood events with a return period over 20 years, and the black bars with an in-between return period. The orange-black-red curve and the right vertical axis depict the cumulative flood-induced deaths. CLR represents cumulative loss ratio

events (black and red bars in Fig. 1) with flood-induced deaths of more than 425 persons and two events (red bars) with deaths of more than 3475 persons. The two intensive events are the 1980 flood, which caused 6200 deaths, and the 1998 flood, which caused 3656 deaths.

The cumulative loss ratio of flood-induced deaths in China over the period from 1976 to 2016 is 1.44, indicating that the cumulative deaths over the past 40 years due to small and frequent flood events are about 1.4 times greater than that due to intensive and sporadic flood events. The 232 events with deaths less than 425 persons (2-year return period) are represented by the orange bars in Fig. 1, which caused a total of 14,359 deaths. The two events (red bars) with return periods longer than 20 years resulted in 9856 deaths. These numbers show that, in the long run, the cumulative death due to extensive floods is larger than that due to intensive floods in China.

3.1.2 Marginal Benefit Chart for Loss Prevention of China

The marginal benefits for China peak at loss prevention levels of 2-year (for deaths and economic damage) or 5-year (for affected population) losses (Table 1), and they generally diminish with increasing levels of flood loss prevention. Table 1 illustrates that, when consecutively promoting the levels of death prevention to avoiding 2-, 5-, 10-, and 20-year flood-induced mortality, while the total benefits (that is, the cumulative loss) would increase from 14,359 to 22,738, 28,906, and 33,681 persons, the marginal benefits decrease gradually from 14,359 to 8379, 6168, and 4775 persons. The normalized marginal benefits also

Table 1 Marginal benefit chart for loss prevention levels of China

	Return period (years)	Loss magnitude	Cumulative loss	Marginal benefit	Normalized marginal benefit
Deaths (persons)	2	425	14,359	14,359	0.43
	5	1245	22,738	8379	0.25
	10	1910	28,906	6168	0.18
	20	3475	33,681	4775	0.14
Affected Population (million persons)	2	17	228	228	0.14
	5	100	825	596	0.38
	10	145	1279	454	0.29
	20	199	1584	305	0.19
Damage (billion USD, 2017 USD)	2	3.65	86.22	86.22	0.35
	5	9.23	164.28	78.06	0.32
	10	15.55	208.44	44.16	0.18
	20	21.55	243.86	35.42	0.15

decrease as the levels of flood-induced death prevention would increase. Similar climbing total benefits and declining marginal benefits are also observed for the loss types of flood-affected population and economic damage (Table 1).

3.2 Cumulative Loss Due to Flood Across the Globe

The analysis described above signifies the relative importance of the cumulative losses from extensive events to those from intensive events in China. To examine whether this phenomenon holds generally, we analyzed the flood-induced deaths over the globe and across 30 countries.

3.2.1 Cumulative Loss Ratio Across Countries

The loss of human lives caused by floods is also quite serious globally (Fig. 2). The EM-DAT recorded 4315 flood events over the globe from 1976 to 2016, with 70% of these events causing a total of 251,058 deaths and the remaining events causing zero death. Our quantile analysis showed that, in the four decades (1976–2016) covered by our study, there were 21 events (shown as black and red bars in Fig. 2) with flood-induced deaths of more than 1395 persons (2-year return period loss) and two events (red bars in Fig. 2) with deaths greater than 6170 persons (20-year return period loss). The two deadliest events are the 1999 flood in Venezuela, which caused 30,000 deaths, and the 1980 flood in China, which caused 6200 deaths. Among the total of 251,058 deaths, about 87% occurred in the 30 countries shown in Fig. 3, most of which are developing countries. The top five countries colored in dark red—India (~ 55,000 deaths), China (~ 43,000 deaths), Venezuela

Fig. 2 Cumulative loss plot showing the distribution of global flood-induced deaths for the period 1976–2016 (based on the EM-DAT data). Explanations for Fig. 2 categories are similar to those found in Fig. 1

(~ 30,000 deaths), Bangladesh (~ 13,000 deaths), and Pakistan (~ 13,000 deaths)—account for 62% of the total mortality.

The cumulative loss ratios of flood-induced deaths over the globe (Fig. 2) and across 30 countries (Fig. 3) during the period from 1976 to 2016 both signify that, in the long run, cumulative deaths due to extensive floods are remarkable when compared to those due to intensive floods. The cumulative loss ratio over the globe is 4.71 (Fig. 2), indicating that the cumulative deaths over the past 40 years due to small and frequent floods (2-year return period) are 4.71 times greater than those due to intensive and infrequent floods (20-year return period). Among the 30 countries shown in Fig. 3, 22 of them have a cumulative loss ratio greater than 0.5, indicating that their cumulative loss of human lives due to small events is greater than 50%

Fig. 3 Cumulative loss ratios of flood-induced deaths across countries in the four decades (1976 to 2016) based on the EM-DAT data. Colors and lengths of bars represent the total deaths and cumulative loss ratios due to floods, respectively

of the loss due to intensive events. Thirteen countries have a cumulative loss ratio greater than unity, that is, they have more cumulative loss of human lives due to extensive events than that due to intensive events in the past 40 years.

The cumulative loss ratio tends to be independent of the total loss. As shown in Fig. 3, countries with a small total loss of human lives (colored in green) could have high cumulative loss ratios, such as the United States, Malaysia, and France, or low cumulative loss ratios, such as Spain and Nigeria. Meanwhile, countries with a large total loss of human lives (colored in red) could also have high cumulative loss ratios, such as India and China, or low cumulative loss ratios, such as Bangladesh and Venezuela. Linear regression of cumulative loss ratios against total flood-induced deaths of these 30 countries gives a coefficient of determination of 0.02 and a p value of 0.40, indicating their lack of association.

3.2.2 Marginal Benefit for Loss Prevention Across Countries

The marginal benefits tend to peak at loss prevention levels of 2-year or 5-year flood-induced mortality across countries in the decades between 1976 and 2016. Figure 4 shows the marginal benefits of four levels of loss prevention for the 30 countries with the highest flood-induced mortality. When consecutively promoting the levels of death prevention to avoid 2-, 5-, 10-, and 20-year flood-induced mortality, the normalized marginal benefits for 80% of these 30 countries reach their maximum values at the loss

prevention levels of 2-year or 5-year flood-induced deaths. The normalized marginal benefits for these 24 countries generally decrease with increasing levels of flood loss prevention. For the remaining six countries, South Africa, Mozambique, Ethiopia, Iran, and Afghanistan have their normalized marginal benefits maximized at the loss prevention level of 20-year mortality, while Bangladesh's normalized marginal benefit peaks at the prevention level of the 10-year flood-induced mortality. Overall, these statistics indicate that most of the countries analyzed would not receive incremental gain when adopting higher flood loss prevention levels.

4 Discussion

The composition of disaster loss for a region over some time period is essential for decision making in effective flood risk management and adaptation interventions. Flood loss structure is the composition of loss for a given region over some period, which is broken down into categories based on the severity of flood consequences. In this study, we present the flood loss structure with the cumulative distribution plot and its derivatives, including cumulative loss ratio and marginal benefit table. Cumulative loss plot (for example, Fig. 1) and marginal benefit table (for example, Table 1) show the breakdown of loss on a local, regional, national, or global scale based on quantiles of loss. These illustrations are useful for characterizing loss patterns and providing insights for flood risk management.

Fig. 4 Country-wise normalized marginal benefits for four flood loss prevention levels based on the EM-DAT data (1976–2016)

4.1 The Relative Importance of the Cumulative Losses of Extensive and Intensive Events

Tremendous efforts have been devoted to flood management worldwide (Cheng 2006; Han and Kaspersen 2011; Morrison et al. 2018). What are the achievements and what can we learn? The 40-year time series of flood records from the EM-DAT database enable investigation into these queries from the perspective of comparing the relative importance of the cumulative losses of extensive and intensive floods. In this study, we analyzed the overall occurrence, temporal changes, and spatial (country-wise) variations of simple statistics of floods below fixed loss thresholds from 1976 to 2016.

The results of data analysis presented in Sect. 3 show that, over the period from 1976 to 2016, extensive events over the globe have accounted for about 70% of the total deaths caused by floods, despite their average per-event deaths (40 persons) being only 0.65% of that of the intensive events (6200 persons). In terms of cumulative loss ratio (extensive to intensive) proposed in this work, the value is 4.71 at the global scale (Fig. 2). This is generally consistent with the conclusions reported by Jonkman (2005) and Hu et al. (2018) to the effect that flash floods, which often affect small areas and are analogous to extensive floods defined in this study, contributed much to the total number killed by floods. Similarly, at the country scale, the findings of comparable cumulative losses of minor and extreme disasters in Columbia (Marulanda et al. 2010) and the United States (General Accounting Office 2004) coincide with our calculated cumulative loss ratios of about 0.7 and 2.5 (Fig. 3) for these two countries,

respectively. Overall, our study indicates that, for most countries with large flood-induced mortality, their cumulative deaths due to extensive floods are on the same order or even larger than that due to intensive events in the decades between 1976 and 2016.

Will this overall relative importance of the cumulative loss of extensive floods persist in the future? Examining its historical trend may provide insights into the future. Using the threshold of flood-induced mortality whose return period is 2-year, Fig. 5 illustrates some facts of extensive floods in China and the world in each five-year period since 1976. Unfortunately, the series of total number of deaths caused by all flood events tend to show overall non-negative trends (Fig. 5a), even though flood risk awareness has probably been increased worldwide. Similar findings were reported by Hu et al. (2018). Additionally, there is a slight increasing trend in the number of deaths due to extensive floods in China and the world over the 1976 to 2016 decades (Fig. 5b). Comparison between these trends in Fig. 5a, b indicates that either the benefits of our management practices targeting intensive floods could not be seen due to the “short” observation period, or our efforts have turned some potential “intensive” loss events to extensive ones. Interestingly, the four intensive floods in China and the world, as reported in Sects. 3.1.1 and 3.2.1, all occurred before the millennium, which may indicate that the world has possibly made good progress in managing intensive flood events, at least from the perspective of reducing the loss of human lives. Nevertheless, these hypotheses merit a future combined investigation into flood hazards and impacts. Figure 5c displays that the percentages of total flood-induced deaths due to extensive

Fig. 5 Time series of (a) the number of total deaths from all floods; b the number of deaths from extensive floods; c the percentage of the total deaths from extensive flood loss events (that is, a return period of 2-years or shorter); d the average deaths per event from extensive floods; and e the number of extensive floods in China (solid dots) and across the globe (triangles) from the EM-DAT database (1976 to 2016). The lines connecting successive data points are for visual comparison and do not imply the full time series of variables

events remained high, and almost the same in the world, and increased notably to about 85% in China, again signifying the importance of the cumulative losses from extensive floods. The mild increasing numbers of deaths due to extensive floods in both China and the world (Fig. 5b) can be explained by the facts that, although the average per-event deaths of extensive floods have been reduced by about 75% over the period 1976–2016 (Fig. 5d), their occurrence frequency have quintupled in the same time. Given the fact that the series of data was built from media-based information, which has possibly increased in coverage over time and varied across countries, caution is needed when interpreting the analysis result. However, the relative importance of the cumulative impact of extensive floods over long-term periods is still apparent.

Indication of the relative importance of the cumulative loss of extensive floods into the future can also be obtained by comparing data from countries with varying levels of development. Our analyses of the cumulative loss ratios

across countries (Fig. 3) showed that developed countries appear to have less flood-induced mortality. This supports the hypothesis, which is still under debate, that the total deaths caused by natural hazards seem to decrease with the level of socioeconomic development (Schumacher and Strobl 2011; Hu et al. 2018). However, Fig. 3 also shows that the relative importance of extensive floods can be remarkable too in developed countries, such as the United States and France. Meanwhile, countries with great investment in flood mitigation, such as China (Cheng 2006; Han and Kaspersen 2011), still have high cumulative loss ratios (Fig. 5c). These three countries have one thing in common—they all suffer from flash floods frequently in their mountainous regions (Jonkman and Vrijling 2008; Hu et al. 2018). These analyses imply that the relative importance of extensive floods could remain high in regions with inherently high levels of flood risk due to geophysical characteristics, regardless of their levels of development.

4.2 The Marginal Benefits of Different Levels of Loss Prevention

Although the emphasis on intensive floods (Perry 2000; Kundzewicz et al. 2012; Kousky and Michel-Kerjan 2017) provides partial information about the long-term flood impact over a region, the cumulative loss ratio proposed in this work, which compares the relative importance of the cumulative losses due to extensive and intensive floods, may help to call for more attention towards extensive floods. But the cumulative loss ratio merely provides information about both ends of the loss distribution. By breaking down the loss distribution into categories based on the severity of flood consequences, the marginal benefit chart provides further information, that is, the marginal gain of avoiding different levels of loss. Our data analysis (Fig. 4) shows that, for 80% of the 30 countries with the highest flood-induced mortality, their marginal benefits peak at loss prevention levels of 2-year or 5-year flood-induced deaths and generally decrease with increasing levels of flood loss prevention. This indicates that, for these countries, it would be more effective if the effort had been made to reduce the flood-induced mortality of extensive events. For the remaining 20% of countries, preventing intensive losses merits higher priority. The example herein illustrates that marginal benefit analysis can help to pursue the “optimal” investment in terms of maximizing the utility of the limited resources available for disaster mitigation. Marginal benefit analysis, to some extent, can be used as a tool to facilitate applying the guidelines of managing flood risks incrementally (Jha et al. 2012).

4.3 Implications for Flood Risk Management

Complementary to focusing on intensive flood loss events, additional attention paid to the extensive loss events could probably become an effective strategy to reduce future flood risk. Some regional studies documented that the cumulative historical impacts of small disasters can be comparable to or even greater than that of large disasters (General Accounting Office 2004; Marulanda 2008). Recent studies went one step further to report that, in the future, the frequency and potential socioeconomic impacts of nuisance floods will continuously increase under climate change (Sweet and Park 2014; Moftakhari et al. 2017; Burgos et al. 2018). Terming extensive floods sometimes interchangeably as nuisance floods, these studies reported them to represent a considerable burden for future communities (Moftakhari et al. 2018). Although uncertainties about the indications from these regional and risk-assessment based studies could be of concern, one can inspect them by analyzing comprehensive disaster loss data covering a large area and a long period. Our analysis of 40-year flood loss records across the globe shows that: (1) cumulative flood loss, in terms of mortality, due to extensive loss events is comparable to or greater than that due to intensive events in the recent four-decade period from 1976 to 2016; and (2) the total loss and, especially, the frequency of extensive loss events tend to increase with time. Our further analysis suggests that for most countries, the marginal benefits generally decrease with increasing levels of flood loss prevention. Overall, these studies suggest that extensive floods merit additional attention in the future due to their notable cumulative impacts.

Many strategies for managing intensive floods can be adapted to dealing with risk from extensive floods. The number of small streams is tenfold that of larger rivers. Intensive floods, which generally occur along large rivers, therefore, tend to be more spatially concentrated, while extensive floods, which normally happen at headwaters of the river network, are more widely distributed in space. This characteristic makes structural measures (for example, building flood control dams or levees), which is a norm for managing intensive floods, extremely expensive and infeasible for managing extensive floods. However, other community resilience enhancing actions, including but not limited to flood education, flood forecasting, and flood monitoring, have the potential to reduce future impacts from extensive floods.

4.4 Limitations

Although the quality of flood-induced loss data deserves further examination, and it is difficult to determine the exact threshold by which to categorize intensive and

extensive floods, our findings generally hold. As the major source of data for our analysis, the flood records in the EM-DAT archive are certainly incomplete. Since the EM-DAT mainly relies on public information sources, the infrequent, spectacularly impactful events could always get noticed, while the extensive, unnoticed flood events are less likely to be picked up (Jonkman and Vrijling 2008; Marulanda et al. 2010; Hu et al. 2018). The missing loss information about extensive floods would, therefore, underestimate the cumulative loss ratio and the marginal benefit of promoting flood loss prevention level to the 2-year flood loss. Including more data on extensive floods will likely increase the relative importance of extensive floods, and further enhance our finding.

The definition of extensive and intensive flood events is not straightforward (Marulanda et al. 2010; Moftakhari et al. 2018). Generally, both magnitudes of hazards and costs of flood events decrease with their occurrence frequencies. Analogically (Bell and Tobin 2007; Bezak et al. 2013; NWS 2019) and similarly (Velásquez et al. 2014; Haigh 2017), we used exceedance probability to describe the relative importance of flood impacts. Although a 20-year event may not seem to be “intensive,” it is still reasonable given the fact that we used only 40-year data and did not fit distributions and extrapolate them to long return periods. Furthermore, the cumulative loss ratio will be greater than the current result if we use a larger return period, for example, 40-year as threshold for intensive flood events.

5 Conclusion

Using the cumulative loss ratio and marginal benefit chart, we analyzed the structure of flood-induced mortality across the globe over the period from 1976 to 2016. While recognizing the deficiency of the EM-DAT database and the relative nature of the extensive and intensive flood division, our results suggest that: (1) Across the globe as a whole, or the top 30 countries with high flood-induced mortality, the long-term cumulative deaths due to extensive floods are remarkable when compared to that due to intensive floods; (2) Although the average per-event deaths of extensive floods have reduced by about 75% over the study period in the world, their occurrence frequency has more than quintupled, leading to the slightly increased number of deaths due to extensive floods and the high contribution to the world's total death from all floods; and (3) Across the top 30 countries with a large number of flood-induced mortalities, their marginal benefits tend to peak at loss prevention levels of 2-year or 5-year flood-induced mortality and diminish with increasing levels of flood loss prevention. Studies have projected that the frequency and

potential socioeconomic impacts of extensive floods will continuously increase under climate change (Sweet and Park 2014; Moftakhari et al. 2017; Burgos et al. 2018). Our analysis of historical records and these projections suggest that extensive floods merit additional attention in the future due to their notable cumulative impacts.

Climate change alters flood regimes, making flood risk management more challenging. Abstracted yet sufficiently detailed information on the composite of flood impact is essential for policymakers. Such information could be provided with increasing abundance by adopting the cumulative loss ratio, the marginal benefit chart, and the cumulative loss plot proposed in this work. It would be interesting to test the applicability of these tools to the observed or simulated data for different types of disasters and impacts over regions of various scales.

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