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Spatiotemporal variations of riverine flood fatalities: 70 years global to regional perspective

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Abstract

Floods are among the most devastating natural hazards worldwide. While rainfall is the primary trigger of floods, human activities and climate change can exacerbate the impacts of floods and lead to more significant economic and social consequences. In this research, fluvial flood fatalities in the 1951–2020 period have been studied, analyzing the information reported in the Emergency Database (EM-DAT). The EM-DAT data were classified into five categories in terms of the number of events and fatalities connected with riverine floods, considering only events that caused more than 10 fatalities. The results show that the severity of flood-related fatalities is not equally distributed worldwide, but presents specific geographical patterns. The flood fatality coefficient, which represents the ratio between the total number of fatalities and the number of flood events, calculated for different countries, identified that the Southern, Eastern, and South-Eastern regions of Asia have the deadliest floods in the world. The number of flood events has been increasing since 1951 and peaked in 2007, following a relative decline since then. Though, the resulting fatalities do not follow a statistically significant trend. An analysis of the number of flood events in different decades shows that the 2001–2010 decade saw the highest number of events, which corresponds to the largest precipitation anomaly in the world. The lethality of riverine floods decreased over time, from 412 per flood in 1951–1960 to 67 in the 2011–2020 decade. This declining trend is probably a consequence of a more resilient environment and better risk reduction strategies. Based on the presented data and using regression analysis, relationships between flood fatalities and the number of flood events with population density and gross domestic product are developed and discussed.

KEYWORDS

disaster, food fatality, global scale, natural hazards, river flood

1 | INTRODUCTION

Worldwide, fluvial, coastal, and pluvial flooding events have caused millions of fatalities in the last century. Only in the past decade, the global average annual loss due to riverine floods was estimated at around USD 651 billion (United Nations Office for Disaster Risk Reduction [UNDRR], 2020).

Major floods happened in the past (Berz, 1988), but following changes in climate, land use, infrastructure, and population demographics, even more extreme and frequent events should be expected in the next years (Brunner et al., 2021). Indeed, exposure to floods is forecasted to grow by a factor of three by 2050, owing to a surge in population and economic assets in flood-prone areas (Jongman et al., 2012). Depending on the socioeconomic scenario and assuming a temperature increase of 1.5°C, human losses from flooding are projected to rise by 70%–83% and direct flood damage by 160%–240% relative to the 1976–2005 period (Dottori et al., 2018). To adequately address such scenarios and develop suitable risk reduction strategies, improving the understanding of river flooding processes and their multiscale impacts is critical, especially in light of global warming (Nones & Pescaroli, 2016; Tellman et al., 2021; Wasko et al., 2021).

Floods in river valleys occur mostly on floodplains or washlands, as a result of flow exceeding the volumetric capacity of the stream channels and spilling over their natural banks or artificial embankments (World Meteorological Organization, 2011), inundating adjacent areas and potentially causing bank failures. The potential adverse consequences of flooding to human life, health, livelihoods, assets, and the environment (UNDRR, 2017), often termed flood risk, results from the superposition of three components (e.g., Barendrecht et al., 2017; Kron, 2005; Zhou et al., 2017), driven by multiple processes (Merz et al., 2021): "hazard," meaning the process frequency and magnitude; "exposure," which accounts for the elements at risk, such as population, ecosystems, and infrastructure; and "vulnerability," that is, the susceptibility of the elements at risk, like lives, livelihoods, and other aspects of well-being that are adversely affected by flooding events (Turner et al., 2003; UNDRR, 2019). Generally, the riverine flood hazard is a consequence of high-rainfall processes starting in the atmosphere, run-off generation in the catchment, and flood waves traveling through the river network. The exposure depends on anthropogenic aspects, such as the use of floodplains, population density, and economic development (Adhikari et al., 2010), while the vulnerability is shaped by human adaptive influences, such as private precautions, education level, presence of early warning systems or crisis management strategies, as well as adaptive plans. Previous experience with floods could also play a major role: as pointed out by Ross and Chang (2020) in their review, there are many examples in the literature showing that the memory of people is an important factor when dealing with flood damage.

It is well known that human activities interfere with flood processes broadly (Chen et al., 2012; Ross & Chang, 2020). Indeed, the alteration of land use land cover at the watershed scale is transforming run-off generation and transport processes, and human-driven climate change can enhance heavy precipitations and affect snow-melt or catchment wetness, thus influencing the hazard component and, therefore, flood risk (Blöschl et al., 2015). Levees, flood retention infrastructures like check dams, and early warning systems are potentially effective in reducing risk, but can also fail unexpectedly, thereby surprising affected communities and amplifying the damage (e.g., Liu et al., 2019; Manfreda et al., 2021; Nones, 2019).

Various methods have been proposed to reduce the damage and severity of floods, which yet require a deeper understanding of vulnerability both at the global and local scale to effectively implement proper management, as well as an accurate and fair distribution of facilities. Indeed, uncertainties and complexities are intrinsically present in flood-related issues (Altez & Revet, 2005; Petrucci, 2022), propagating in flood prediction modeling. New insights on the effects of past floods and society's response can be acquired through the available comprehensive and up-to-date databases of flooding events (e.g., EM-DAT, Global Flood Monitor, Global Flood Database). The recent development of these databases is also taking advantage of social media, where a rapid flow of data occurs almost in real-time during the flood event, as users act as sensors (e.g., through smartphones, wearable devices, etc.), with the main disadvantage of large biases such as language and geographical distribution of social networks (de Bruijn et al., 2019).

Apart from the EM-DAT, there are currently several databases on the details or consequences of natural hazards providing some information on a local or a global scale. For example, the Global Flood Database provides useful statistics on the population exposed to floods, but it presents some shortcomings in the investigation of small but dangerous floods, events impacting urban areas, and the number of fatalities caused by compound events (Tellman et al., 2021). Databases with a national focus: SICI is a source of information on landslide and flood hazards and risks in Italy (Guzzetti & Tonelli, 2004), while DISASTER summarizes disastrous floods and landslides data for Portugal (Zêzere et al., 2014). Also, NATHAN is a database of significant natural-hazard economic losses (available at www.munichre.com), and GLOFRIS provides flood risk maps, but its applicability is limited to areas with low protection standards (Winsemius et al., 2013). Beyond the local scale, Pereira et al. (2017) merged the DISASTER database for Portugal and the national Greek database to form a common flood fatalities database covering the period 1960–2010. With the same goal, Petrucci, Papagiannaki, et al. (2019) developed the MEFF database to study flood fatalities in five Mediterranean areas and Saharia et al. (2021) created the India Flood Inventory (IFI) for disaster modeling and analysis. In 2010, Adhikari et al. compiled a digitized Global Flood Inventory (GFI) for the period 1998–2008, and derives seasonal patterns in flooding, showing that the number of events generally increased in May and peaked from July to August. Papagiannaki et al. (2022) have recently presented the FFEM-DB, a novel database that compiles information on Flood Fatalities across the Euro-Mediterranean region. This database contains data from 1980 to 2020 and covers 12 different territories within Europe and the broader Mediterranean region.

Although the Emergency Database (EM-DAT) is a multihazard database with some uncertainties correlated to the data sources and the reported information (Jonkman & Kelman, 2005; Panwar & Sen, 2020; Petrucci, Aceto, et al., 2019; Petrucci, Papagiannaki, et al., 2019; Saharia et al., 2021; Zêzere et al., 2014), it has been selected for the present study because of its global focus and long-lasting record of flood events, as well as its widespread use among researchers and practitioners. It should be noted that, despite the existing shortcomings, the EM-DAT database has been used as the main source of information by several researchers (e.g., Barredo, 2007, 2009; Chen et al., 2020;

Doocy et al., 2013; Guoqiang & Seong, 2019; Hu et al., 2018; Jonkman, 2005; Lesk et al., 2016; Peduzzi & Herold, 2005) and as a tool for validation of some other models (Hohmann et al., 2021; Winsemius et al., 2013). For example, Li et al. (2016) employed the EM-DAT database to investigate the correlation between flood disaster occurrence with runoff, forest coverage rate, gross domestic product (GDP) per capita, population, and urbanization rates in Africa from 1990 to 2014. They concluded that, due to climate change and global anomalies, the annual frequency of floods may intensify, leading to increased exposure to these risks. In its work, Alfieri et al. (2020) investigated monthly trends in population exposure and river flood fatality over the period 1980–2018 using both the EM-DAT and Munich-RE databases, pointing out that around 54 million people worldwide are exposed to river flooding annually.

The present study, stepping on a parallel track, looks at understanding possible relationships between the number of flood fatalities, the GDP of different countries, and the historical population statistics. Here, flood-related fatalities are analyzed at a global scale using quantitative data. It should be mentioned that in the present study, only riverine floods are considered and other kinds of events, such as coastal floods or damages caused by cyclones and hurricanes, were excluded. As floods are likely to increase in different countries around the world for manifold reasons, efforts supporting decision-makers in making informed choices of policies and priorities and adequate allocation of resources are necessary to reduce flood fatalities. More than 10,000 flooding events were identified in the 1951–2020 period in the EM-DAT database (www.emdat.be). While there are some other studies available in the literature dealing with flood fatalities analysis using the same source of data (e.g., Alfieri et al., 2020; Li et al., 2016), we extended the study period to 70 years for a more comprehensive understanding of the spatiotemporal variations and the relationships between the flood fatalities and the socioeconomic variables acting at different spatial scales. Section 2 outlines the process of data gathering and analysis, while the findings are presented in Section 3. Section 4 provides an overview of the factors that have an impact on the problem under investigation, and Section 5 delves into a discussion of the results.

2 | DATA AND METHODS

2.1 | Data gathering and analysis

In this work, flood events collected in EM-DAT were analyzed. This database contains basic data on the occurrence and effects of more than 22,000 disasters in the world from 1900 to the present day. The database is based on various sources, including United Nations (UN) agencies, nongovernmental organizations, insurance companies, research institutes, and media agencies, and adopts a recognized ranking method to select sources for flood disaster statistics (De Groeve et al., 2013).

For a disaster to be entered into the database, at least one of the following criteria must be fulfilled (Djalante & Garschagen, 2017; EM-DAT, 2016):

- Ten or more people reported fatalities.
- Hundred or more people reported being affected.
- Declaration of a state of emergency.
- Call for international assistance.

For the present study, data referring to the last 70 years (period 1951–2020) were downloaded from the database and postprocessed, as described in the following. It should be noted that the EM-DAT data is available since 1900, and one of the important sources of data collection in this database is the UN agencies. Since there are gaps for some countries and the UN was established in 1945, earlier data were not considered and only data from the 1950s onwards have been examined in the present study to ensure proper global-scale analysis.

To extract flood data from EM-DAT, the website was accessed, and the search criteria were set to "Natural Disasters" and "Flood." The period and location were specified, and relevant floods were selected from the results list. Specific information about each event was accessed, including the date, location, and number of people affected.

The EM-DAT data were classified in terms of the number of events and fatalities. Five categories were considered: less than 10, 10–99, 100–999, 1000–9999, and more than 10,000 fatalities. The frequency of occurrences as well as the number of fatalities during the period of 1951–2020 is shown in Figure 1. According to Figure 1a, it can be seen that the highest frequency (about 51%) belongs to the category of 10–99 fatalities, while the lowest frequency (about 0.15%) belongs to events with more than 10,000 fatalities. On the other hand, Figure 1b shows that the category of less than 10 fatalities includes a small part (less than 0.2%) of total death connected with riverine floods, and therefore, in the present study, this category of data was not considered. This corroborates the research assumption to focus only on relatively frequent events causing more than 10 fatalities. In summary, only river flooding events causing between 10 and 9999 fatalities have been included in the present study.

While it is true that flood fatalities depend on several parameters, the specific contribution of each parameter is not yet clear. For example, a previous study has shown that fatalities vary by geographical region, but the assumption that floods in areas with lower living standards will cause higher mortality is not supported by evidence (Jonkman, 2005). We investigated the variation in flood fatalities over the last 70 years as a function of two socioeconomic indicators: total population and per capita GDP. Although we acknowledge that the population of each country grows with time, for sake of simplicity, we assumed it as a constant and used 2020 as the reference year, looking at the cumulative number of fatalities and the population of

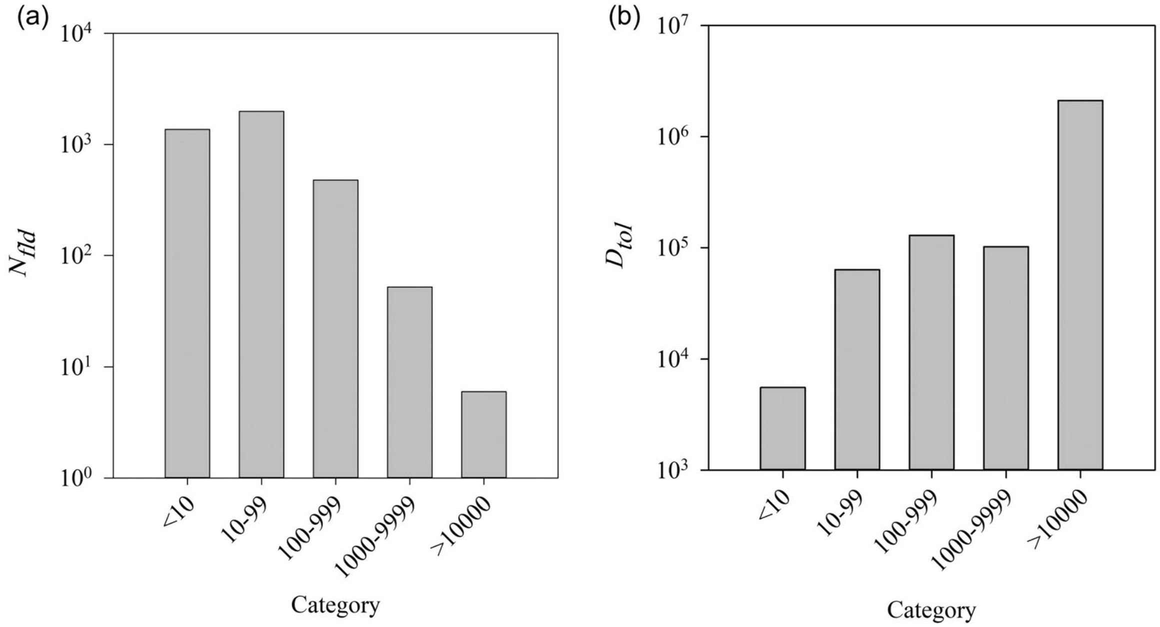

FIGURE 1 Classification of Emergency Database data according to (a) number of flood events N_{fld}; (b) number of total flood fatalities D_{tol}.

each country at the end of the study period. While the focus of this study is a global to regional overview of flood fatalities, investigating changes in the number of fatalities and events in each country individually was also investigated and is briefly addressed here. Finally, using regression analyses, predictive models are presented to estimate the flood fatalities and the number of flood events based on selected physical and socio-economic factors.

2.2 | Major flooding events

Since the number of events with more than 10,000 fatalities is small (six cases), and the fatalities number mentioned in the sources is mainly mixed with fatalities due to compound and cascading events, this category has been investigated on a case-by-case basis, as briefly reported in the following, and not considered in the overall analysis reported in the next sections. It should be noted that while coastal and flash floods are very catastrophic and cause the most deaths worldwide, river floods have the highest frequency among all types of floods and have the greatest impact on human society in terms of loss of life and economic damage (Hu et al., 2018).

2.2.1 | China 1954 flood

In the summer of 1954, following heavy and continuous rains in the Yangtze River Basin, a huge flood occurred, causing the most damage in the Hubei Province. Even if the 1931 event was even more disastrous (Wang & Plate, 2002), official agencies reported more than 33,200 fatalities were caused by the 1954 flood (Zong & Chen, 2000). It was estimated that a total of more than 20.7 million people were affected by this event.

2.2.2 | Bangladesh (East Pakistan) 1960 flood

Despite its relatively small area, Bangladesh is one of the most populated regions in the world, as well as one of the poorest (Dasgupta, 2007). This country is very disaster-prone, for its peculiar geographical position, with floods being the second most frequent occurrence after wind storms.

The flood of 1960 is a clear example of disastrous events that happened in the region, as very intense precipitations caused the inundation of about 20% of the country. As a result, more than 10,000 people lost their lives, while many others were displaced.

2.2.3 | Bangladesh 1974 flood

Heavy rains in Bangladesh in the late spring of 1974 caused very severe flooding in the area around the Brahmaputra, Ganges, and Meghna rivers, killing at least 28,700 people and affecting more than 50% of the entire population of the country (Paul & Mahmoud, 2016). Following this flood, other disasters took place in this country, including a severe famine (Clay, 1985). The number of fatalities is likely much higher than the one reported by official sources, as the affected areas were very poor and a full record of fatalities lacks.

2.2.4 | China 1975 flood

In August 1975, central China was impacted by very high rainfall events, with statistics reporting 830 mm of precipitation in 6 h, and about 1000 mm cumulatively in 3 days (Yang et al., 2017). Triggered by such extreme rainfall, a massive flood occurred, killing more than 20,000 people, and dislocating more than 10 million people. During the event, several dams on the flood path failed, leading to an increase in fatalities, not officially reported. Among other infrastructures, the flood impacted the Banqiao Dam, a reservoir 118 meters high and with a volume of 492 million m^3, causing a wave that reached 10 meters and moved downstream at a velocity of 50 km/h (Liu et al., 2019).

2.2.5 | Venezuela 1999 flood

In December 1999, heavy rains caused a severe flood in Venezuela. About 200 mm of rainfall was registered in 2 days in the Vargas area, triggering floods, landslides, and debris flow, killing about 30,000 people. However, Altez and Revet (2005) showed that this event would have triggered about 3000 deaths, 10 times less than the human losses mentioned by EM-DAT. It is worth also mentioning that most of the hazard-related victims in Venezuela in 1999 died due to landslides and not because of the direct impact of riverine floods.

During this event, about 20 million m^3 of sediments were transported downstream from the 24 watersheds upstream of Vargas Beach and spread over an area of about 200 km^2 (Larsen et al., 2006). Subsequent estimates showed that debris flows with a velocity greater than 10 m/s were the main causes of high fatalities (Takahashi et al., 2001; Wieczorek et al., 2001).

3 | SPATIOTEMPORAL VARIATION OF FLOOD FATALITIES

3.1 | Spatial analysis

The spatial distribution of the number of flood events and fatalities is shown in Figure 2a and b, respectively. Large differences between the upper and lower bounds of data in terms of statistics are present: the average number of flood events with more than 10 fatalities N_{fld}, and the number of fatalities D_{tol}, are 18.4 and 21.8, respectively, with standard deviations of 35.9 and 8070.7. Therefore, to better represent the differences between countries, a logarithmic scale (i.e., $log_{10}(N_{\text{fld}})$ and $log_{10}(D_{\text{tol}})$) is chosen for reporting. According to Figure 2, the maximum number of flood events corresponds to India, China, Indonesia, Pakistan, Brazil, and Vietnam, with values corresponding to N_{fld} of 270, 247, 118, 98, 92, and 76 events, respectively. However, the highest fatalities correlated to flooding events were reported in India, China, Pakistan, Bangladesh, Japan, and Iran, with values corresponding to D_{tol} of 75,355, 53,966, 15,192, 14,238, 8033, and 7883 fatalities, respectively.

Only three countries appear in both lists: India, China, and Pakistan, which are in the top 5% of the data range, meaning that some countries are more vulnerable to floods than others. For example, Bangladesh, Iran, and Japan, although ranked 9th, 10th, and 18th in terms of the number of floods, are ranked 4th, 5th, and 6th, respectively, in terms of the total number of fatalities. On the other hand, Indonesia, Brazil, and Vietnam, which are ranked 3rd, 5th, and 6th among the countries with the highest number of flooding events, respectively, are also 9th, 8th, and 10th in terms of the total number of fatalities.

To compare the human losses caused in different countries, the flood fatality coefficient is calculated by dividing the total number of fatalities by the number of events for each country, and its spatial distribution is shown in Figure 3.

To better represent the differences at the global level, a log scale is used in Figure 3, as already made in Figure 2 (Equation 1).

$$C_{\text{fat}} = log_{10}\left(\frac{D_{\text{tol}}}{N_{\text{fld}}}\right), \tag{1}$$

where C_{fat} is the fatality coefficient of floods for each country.

As can be seen, the Netherlands, Lebanon, Yemen, Hungary, India, and Somalia have the highest fatality coefficient in the world (top 5%). It should be noted that, for Netherlands, Lebanon, and Hungary, only one flood event was recorded during the studied period, which occurred in 1953, 1955, and 1970, respectively, and no other floods with more than 10 fatalities have been recorded in these countries since then. The countries of Liberia, Canada, Albania, Azerbaijan, Belgium, Mauritius, Serbia, Montenegro, Swaziland (Eswatini), and Sweden, for which also only one flood event was recorded during the last 70 years, are at the bottom of this list (bottom 5%).

From the analysis, it is possible to note that countries in Southern, South-Eastern, and Eastern Asia have the highest number of floods worldwide, with 651, 367, and 349 events, respectively. On the contrary, Northern Europe, Russia, Australia, and New Zealand, respectively, with 2, 3, 6, and 8 events, have the lowest number of recorded events worldwide. In terms of flood fatalities, Southern Asia, Eastern Asia, and South-East Asia regions, with 127,738, 69,381, and 23,930 flood fatalities, are the most impacted, while Northern Europe, Russia, and Melanesia regions, with 45, 141, and 187, have the lowest number of fatalities during the studied period.

As an example of geographical disparities, one can observe that flooding that occurred in the Asian continent led to higher average human losses, which could be due to the presence of monsoons, but also to the very high population density (more than four times that of Europe and more than 40 times that of Oceania, following the

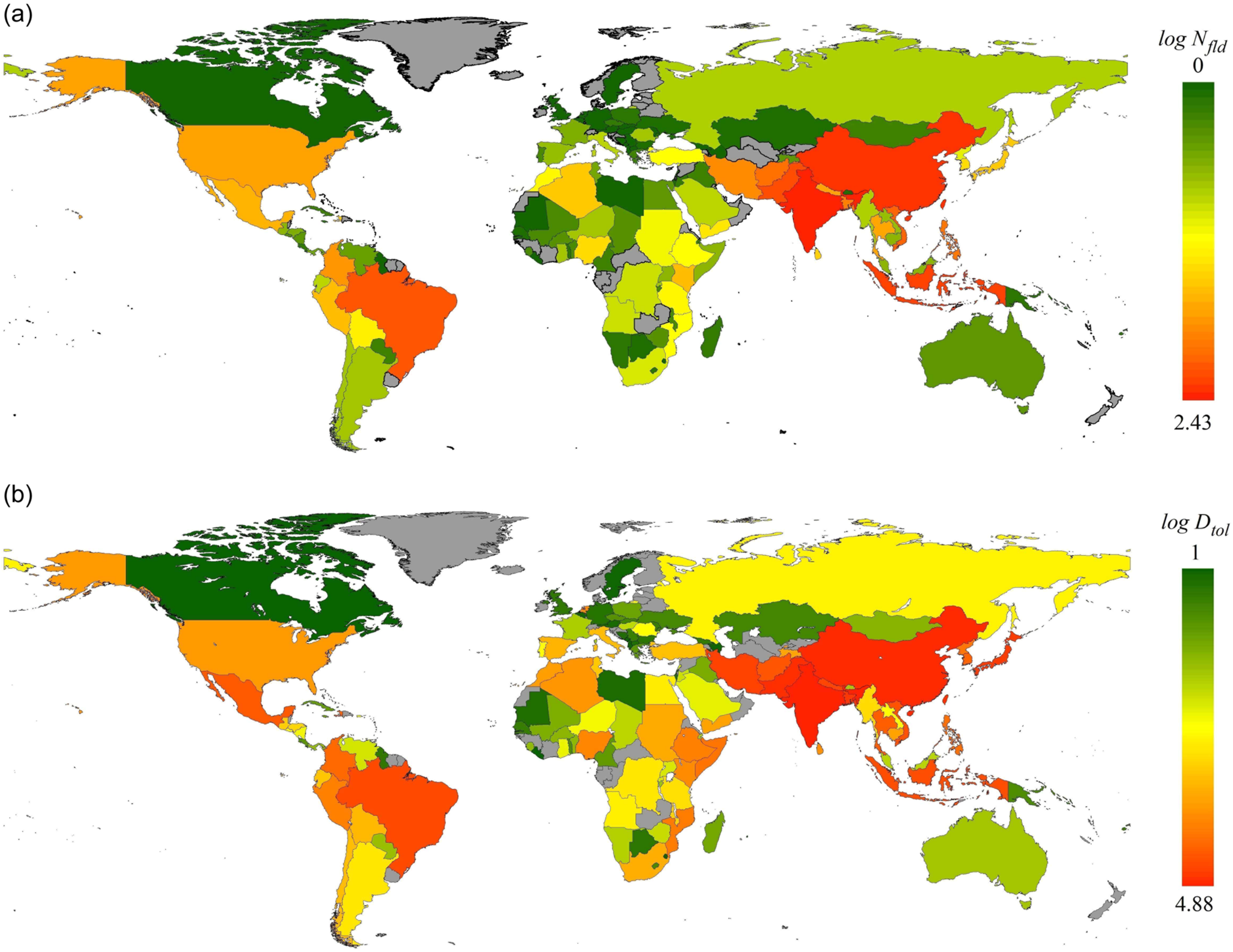

FIGURE 2 Global distribution of (a) number of flood events N_{fld}; (b) number of flood fatalities D_{tol}. The areas in gray are those countries having less than 10 flood fatalities per event during the study period.

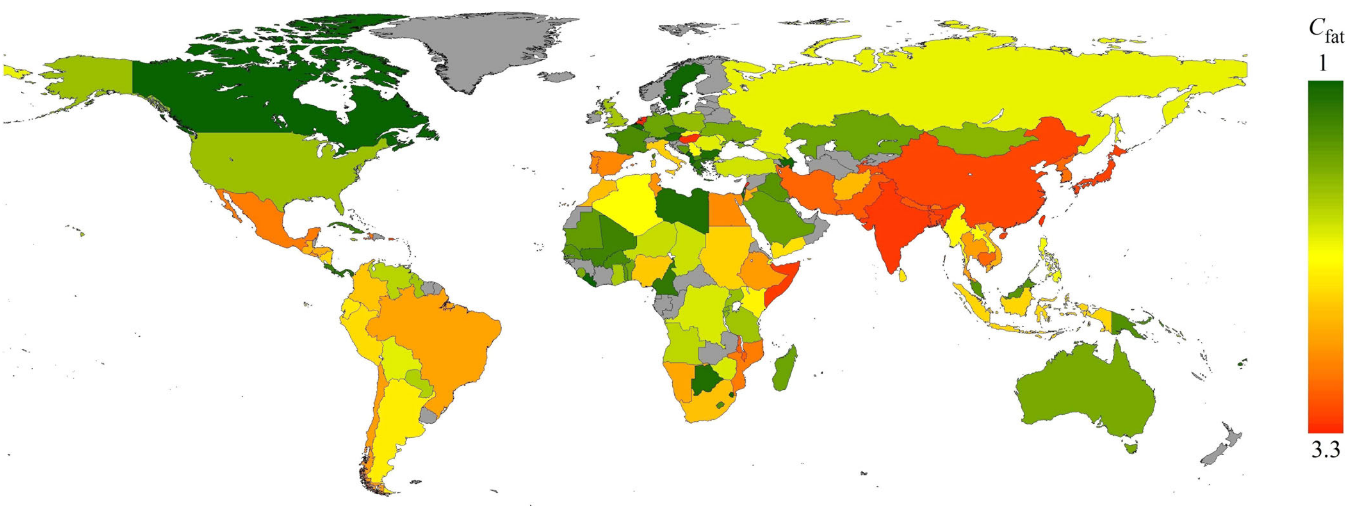

FIGURE 3 Global distribution of the flood fatality coefficient C_{fat}. The areas in gray are those countries having less than 10 flood fatalities per event during the study period.

www.worldpopulationreview.com data), as well as to the poverty of some of the major impacted countries. A further discussion about the effects of socioeconomic conditions on flood-related fatalities is reported in the following section.

To provide a global overview of flood-related hazards, Figure 4 shows the spatial distribution of the number of flooding events and the number of fatalities for different continents. As can be seen, Asia has 76.9% of fatalities with 57.9% of events. In contrast, about 11.2% of the total fatalities due to floods were reported in the Americas, characterized by 18.7% of events, about 9.2% in the African continent with 18.3% of fatalities, about 2.6% in the European continent with 4.5% of flood events, and finally, Oceania accounts for 0.7% of all fatalities with 0.7% of flood events.

3.2 | Temporal analysis

Figure 5 shows the temporal variations of flooding events and flood fatalities during the 1951–2020 period. From 1951 to 2007, the number of flood events had an increasing trend, and then followed a decreasing path. However, the number of fatalities does not present a statistically significant trend, as there are many fluctuations during the studied period. Figure 5c,d show the 5-year moving average of flood events and fatalities, respectively, normalized by their average values.

While clear increasing and decreasing trends can be observed for the normalized number of flood events over time before and after 2007, respectively, the moving average (Figure 5d) does not present a clear temporal trend. Instead, periods of normalized fatalities lower and greater than unity can be observed before and after 1980, respectively. Nevertheless, during the last 3 years of the study period, the normalized flood fatalities are below the long-time average losses.

To evaluate the long-term trends, in Figure 6, these variations are depicted over different decades.

As can be seen, the highest number of flood events, with 735 cases, is related to the decade 2000–2010. Such a high number can be related to the most positive annual rainfall anomaly (about +27.5 mm, Figure 6b) in the world during the study period. In the last decade (2010–2020), the number of flood events has dropped to 694. Although this decrease can seem promising, it should be noted that the average number of flood events in the period 2000–2020 is about three times higher than the corresponding average in the period 1951–2000. On the other hand, the number of flood fatalities, after an increasing trend from the beginning of the period, reached its peak in the 1990–2000 period and has decreased since then.

To have a clearer picture of the temporal variations of flood loss intensity, the fatality coefficient variation for each decade is given in Figure 6d. As can be seen, despite the increase in the number of flood events (Figure 6a) and fatalities (Figure 6c) in recent decades, the number of flood fatalities per event shows a decreasing trend that could be due to increased early warning measures and safety levels. There have been several studies that suggest that improved early warning systems and safety measures have contributed to a decrease in flood fatalities. For example, a study by the UN Office for Disaster Risk Reduction found that investments in early warning systems and preparedness measures have led to a decrease in the number of deaths caused by floods and other natural disasters (UNDRR, 2019). Similarly, a study by the European Commission's Joint Research Centre found that early warning systems have been effective in reducing flood risk and improving public safety (Pappenberger et al., 2015). However, it is important to note that there may be other factors that have contributed to the decrease in flood fatalities. For example, changes in land use, urbanization, and infrastructure development may have reduced exposure and vulnerability to floods (Cutter et al., 2008). Additionally, improvements in emergency response and rescue operations may have also played a role in reducing flood fatalities (Pappenberger et al., 2015). Therefore, while improved early warning systems and safety measures have been shown to be effective, a combination of different approaches may be needed to effectively address flood risk and reduce fatalities. It should be noted that, while the increase in flood events

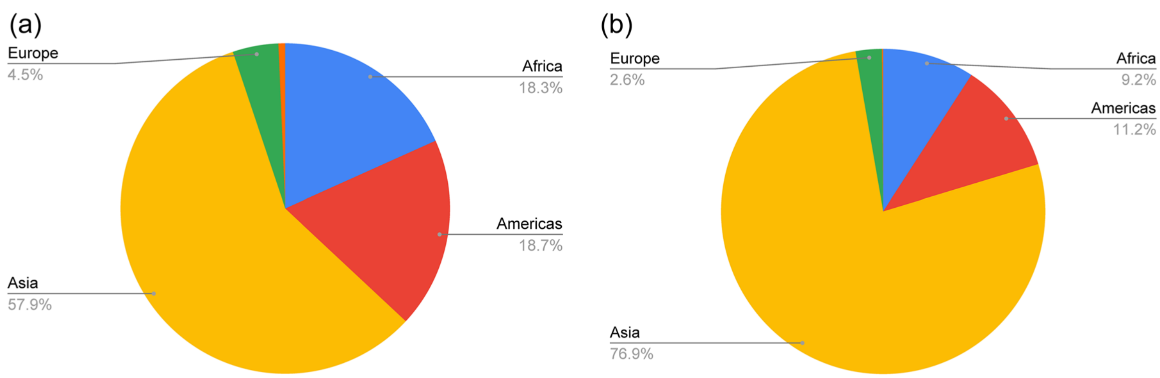

FIGURE 4 Percentage distribution of (a) total flood events N_{fld} and (b) total flood fatalities D_{tol} in the different continents.

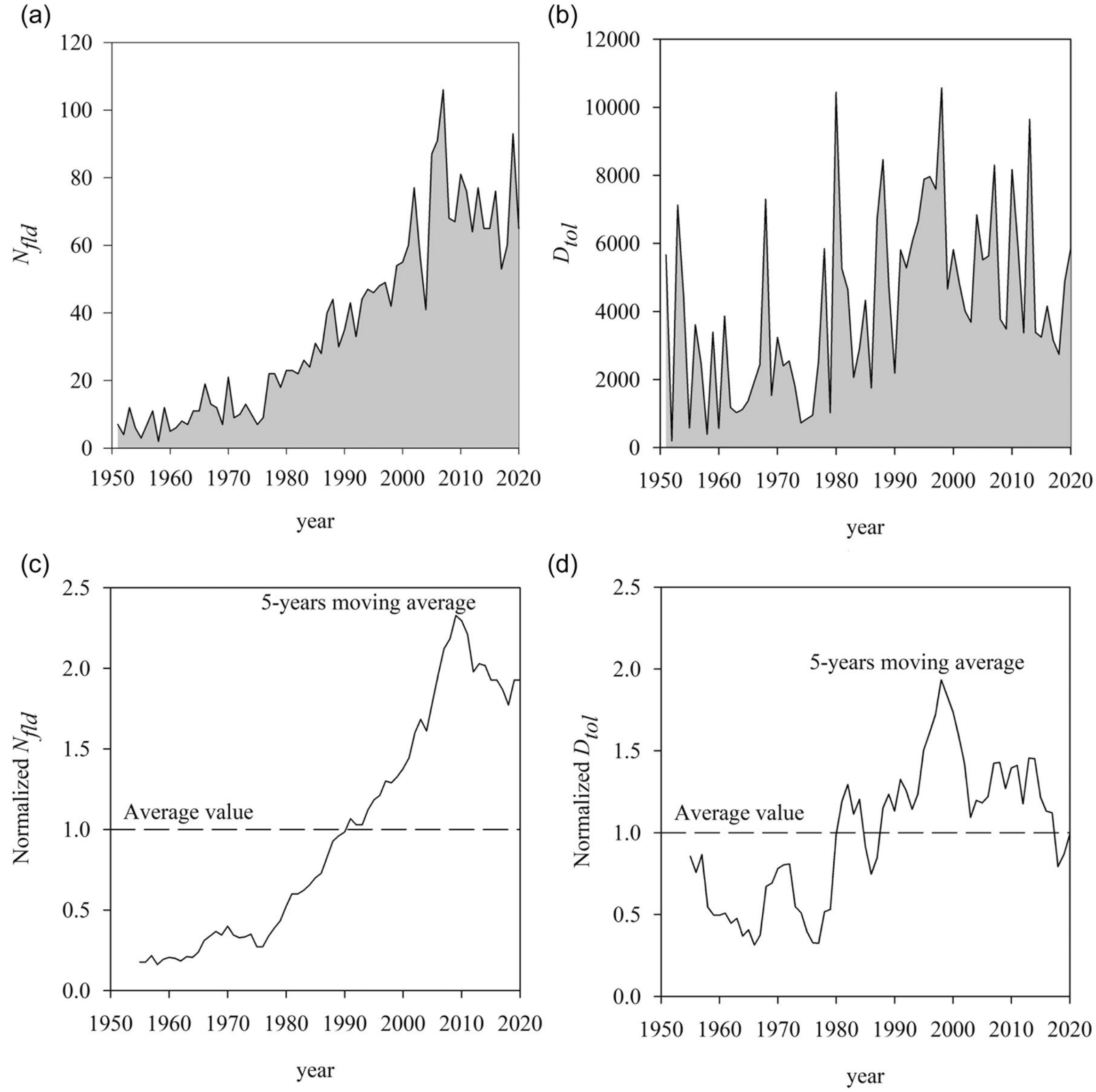

FIGURE 5 Temporal variations in (a) number of flood events N_{fld}; (b) number of flood fatalities D_{tol}; (c) 5-year moving average of flood events; (d) 5-year moving average of flood fatalities.

and fatalities observed in the present study is a concerning trend, it is important to take into account the limitations of the data and, therefore, consider additional analyses and sources to provide a more comprehensive understanding of the observed trend and its drivers.

4 | DRIVERS OF FLOOD FATALITIES

To evaluate the role that anthropic pressure can have on flood fatalities, we examined the relationships between the number of flood events, flood fatalities, and world population P_{W} (Figure 7). Figure 7a,b show the variations in the number of flooding events and fatalities against the total world population, respectively, considering different decades.

There is a direct correlation between the number of flood events and the number of fatalities with the world's population. In other terms, as expected, an increase in population corresponds to a higher number of fatalities. This reflects the role of anthropogenic activities and increasing population on natural processes such as floods (e.g., Kiss & Blanka, 2012; Stuart-Smith et al., 2021; Tellman et al., 2021; Yin & Li, 2001). In a study on the relationship between flood fatalities and the African population, carried out by Di Baldassarre et al. (2010), it was concluded that the increase in the population living in floodplains is the main reason for more flood fatalities. It should be noted that, in the present investigation, the direct relationship between population and flood deaths has been researched separately for each country. When flood-related deaths are analyzed in proportion to population, as shown in Figures 6c and 7c, it is observed that, while the global

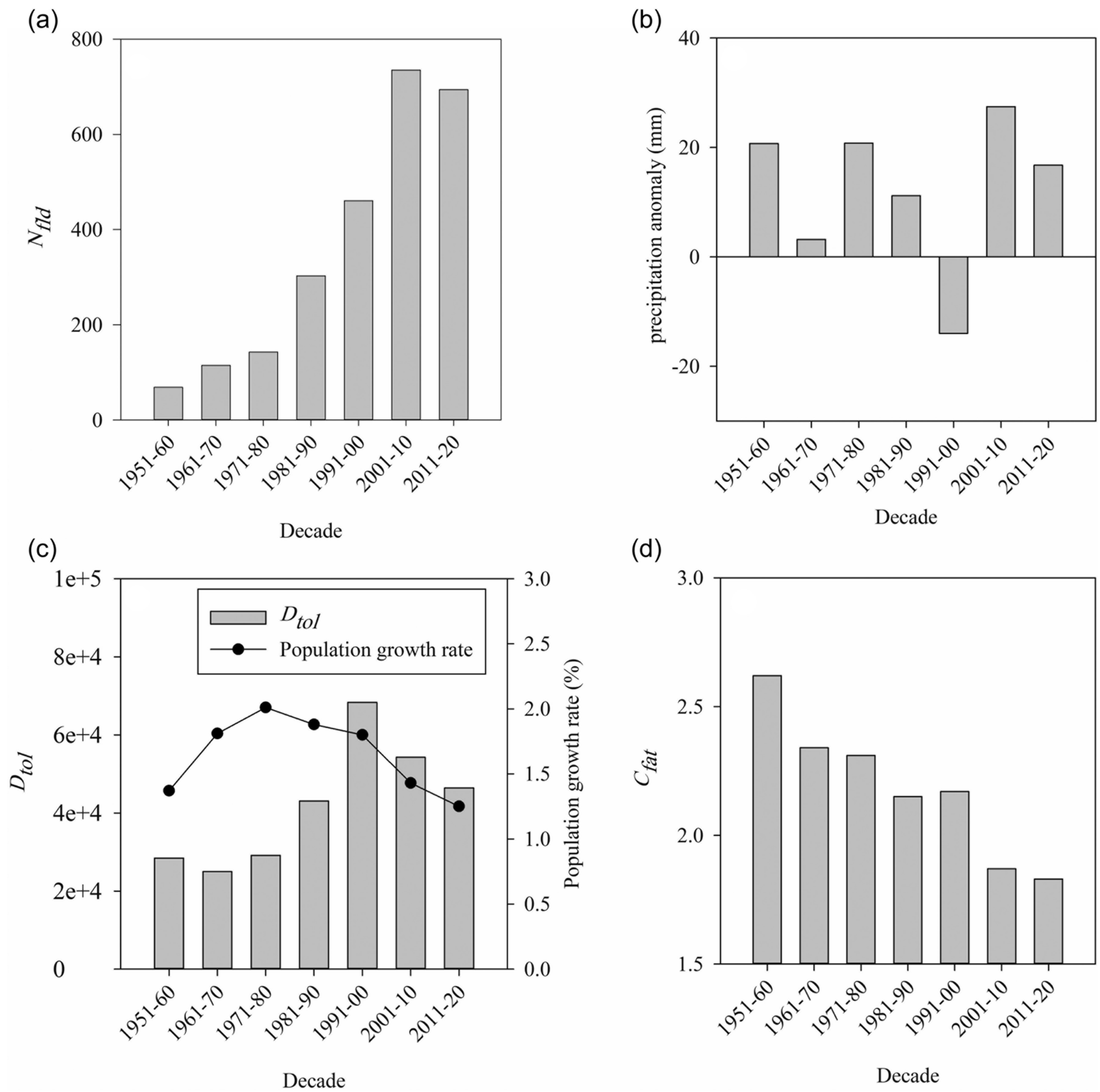

FIGURE 6 Decadal variations of (a) number of flood events N_{fld}; (b) anomaly of global precipitation; (c) total flood fatalities D_{tol}; (d) flood fatality coefficient C_{fat}.

population has grown continuously, the number of fatalities has dropped from 1991 to 2000 and has now reached its lowest level during the study period.

It is worth noting that the interactions between humans and nature, as well as the potential effects of anthropogenic alterations in many river corridors worldwide, were the focus of several studies. For example, artificial channelization has changed the stage-discharge relationship and accelerated the rate of land loss in the Mississippi River delta, and consequently has shown the need for more investment to deal with floods in the region and reduce related fatalities (Criss & Shock, 2001; Munoz et al., 2018; Pinter et al., 2008). Another example is the increased flow velocity and flood level for a given discharge due to the construction of narrow levees along the American Wisconsin River, which caused significant damages, especially during larger magnitude events (Gergel et al., 2002), driving an increase in potential human losses in case of flooding events.

Climate change is further stressing the need for addressing flood risk by combining anthropogenic and natural drivers (Albright & Crow, 2019; Bronstert, 2003). A direct correlation has been proved between global warming and increasing flood risk (e.g., Hirabayashi et al., 2013; Intergovernmental Panel on Climate Change [IPCC], 2021; Yang et al., 2012). Moreover, the impact of socioeconomic development on the increase in flood fatalities cannot be ignored (Barredo, 2009; Tanoue et al., 2016). For example, Tellman et al. (2021) used satellite imagery to estimate flood extent and population exposure for 913 large flood events from 2000 to 2018 and concluded that, as population density increases in areas at high risk of flooding, the number of flood fatalities is also expected to increase over time.

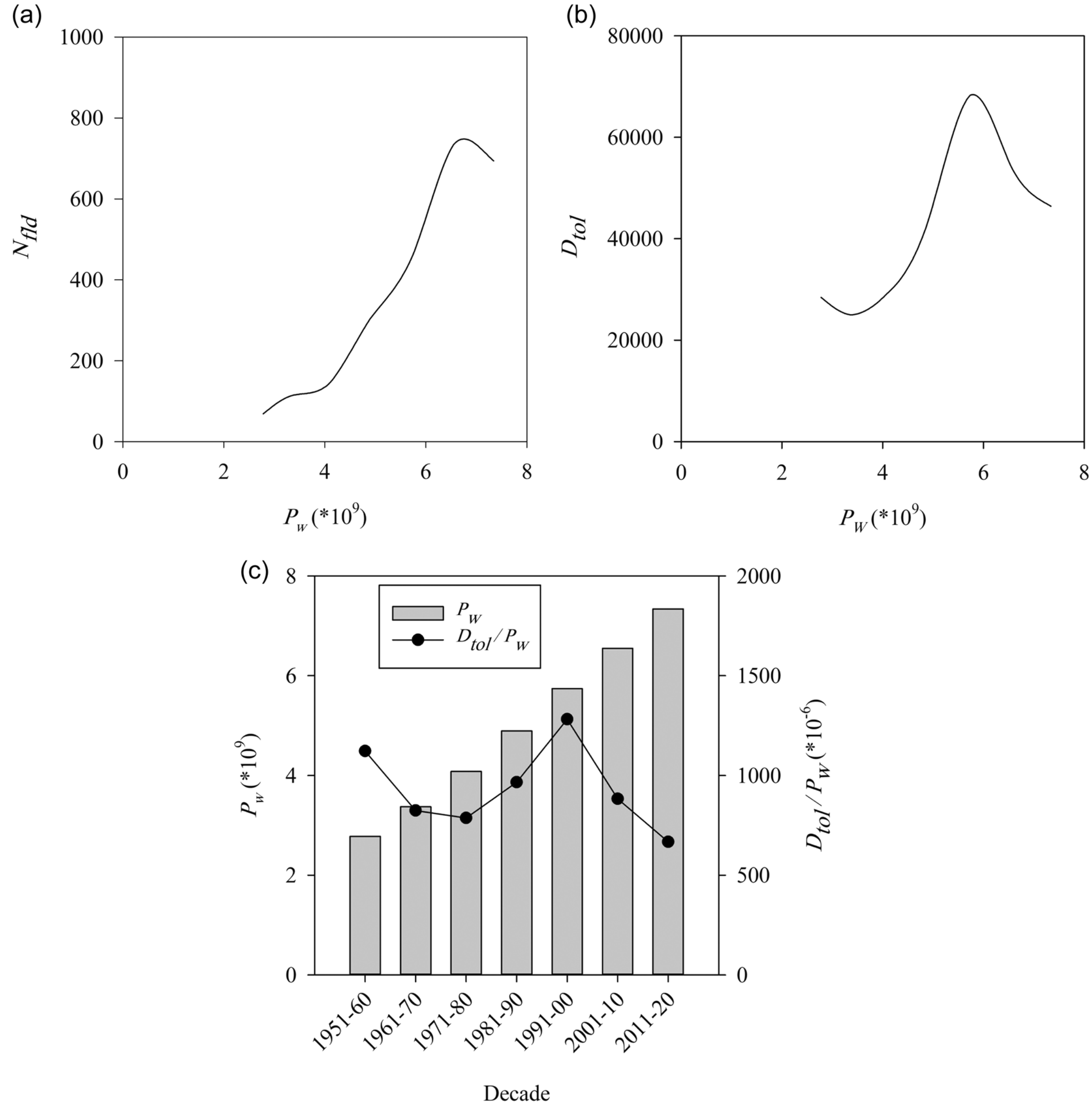

FIGURE 7 Variations of (a) number of flood events N_{fld} and (b) total flood fatalities D_{tol} against world population P_{w}. (c) Decadal variations in world population P_{w} and flood fatalities D_{tol}.

5 | DISCUSSION

It must be stressed that a more connected world is driving abundant and faster access to information and data, which play a major role in detecting trends of flood events and related damages (de Bruijn et al., 2019; Tanoue et al., 2016). However, such a growing availability of data does not mean, per se, more scientifically sound information. Indeed, as pointed out by Altez and Revet (2005), there could be cases where official reports are very uncertain in terms of the number of fatalities, especially in hardly accessible areas.

Figure 8a shows the relationship between the number of fatalities (D_{tol}) versus the number of flood events (N_{fld}) for the period 1951–2020.

As can be seen, the number of fatalities increases with the number of flood events, following Equation (2) with a correlation coefficient R^2 of 0.92:

$$D_{\text{tol}} = 25.45(N_{\text{fld}})^{1.30}. \tag{2}$$

This shows that, potentially, if the number of flood events can be reduced, the number of fatalities reduces as well. At present, concrete strategies were proposed to reduce flood risks, among which planting more trees and hedges to increase water absorption, dredging rivers, establishing retention basins, creating sponge cities with green roofs and permeable pavements, restoring rivers to their natural courses, locally using water butts to collect rainfall, desynchronizing peak flows from tributaries.

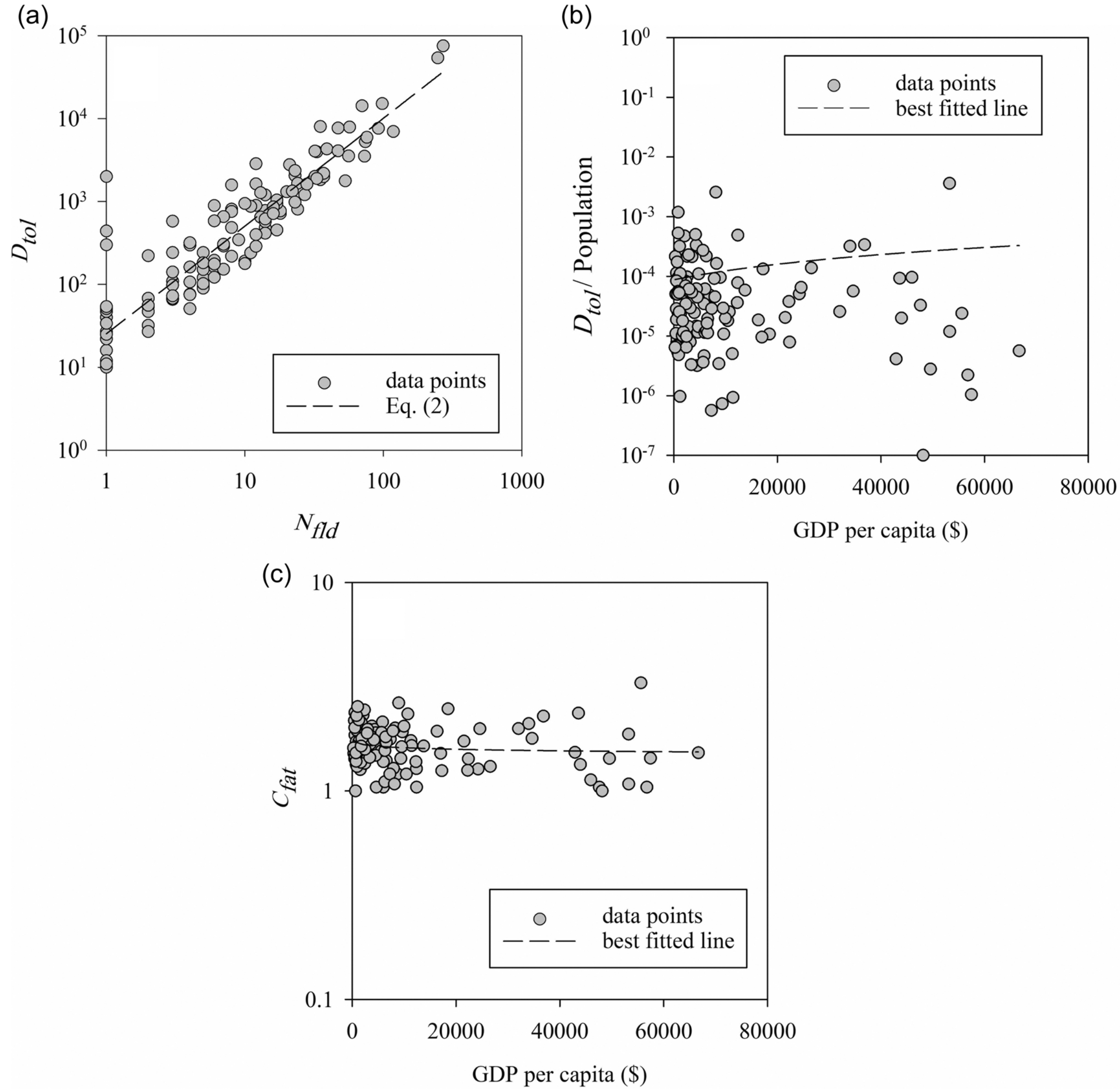

FIGURE 8 Variations of (a) total flood fatalities D_{tol} against the number of flood events N_{fld}; (b) number of flood fatalities D_{tol} per population against gross domestic product (GDP) per capita; (c) fatality coefficient C_{fat} against GDP per capita.

Physical interventions should be supported by communications strategies aiming to reduce the occurrence of flood hazards and increase public awareness, preparedness, and emergency response. Past studies demonstrated that there is a critical need of increasing community knowledge about river floods and their physical and socioeconomic consequences before each flood season, particularly in countries with no effective early warning systems (Alfieri et al., 2020).

To determine the variations in the number of events and fatalities, as well as the relationship with the economy in different countries, the changes in the number of fatalities per population and the fatality coefficient against GDP per capita are shown in Figure 8b and c, respectively. As can be seen, there is a direct link between the number of fatalities and the GDP per capita for different countries. This may be because, for many countries, GDP growth is the main priority, and other changes are left unregulated, such as increased flooding due to land use change, deforestation, and rapid rate (Nzunda & Midtgaard, 2017; Trinh & Quoc, 2017), as well as the increased population density in the adjacent areas of rivers. Therefore, contradictions in increasing GDP at the regional scale and side effects such as increased floods should be considered by decision-makers. Findings similar to the ones presented here were reported by Mazzoleni et al. (2021) that used the Global Human Settlement Layer (GHSL) for the years 1975, 1990, 2000, and 2015, finding that lower-income countries had more severe flood fatalities, which followed by a period in which the population located in floodplains grew more than in upper-middle and high-income countries. Other studies have shown that the amount invested in protective measures against natural hazards, early warning systems, and disaster risk management strategies increases with the country's level of development (Formetta & Feyen, 2019).

Although almost every country in the world, except for regions located at latitudes greater than approximately 60°, is susceptible to flooding (Adhikari et al., 2010), a higher level of safety measures is expected in countries with higher GDP per capita (Hu et al., 2018; Okazawa et al., 2011; Wang et al., 2021). However, exploring the variations in the fatality coefficient against the per capita GDP shows that the fatality coefficient is not strongly correlated with the GDP per capita and follows an almost constant trend with an average value of 1.68 (Figure 8c). Those global-scale results are somehow counter-intuitive, as a few previous pieces of research, focussing on specific case studies, shown that flood-induced death rates (fatalities per million people) and flood-affected rates decreased with GDP growth per capita (Hu et al., 2018; Lee & Vink, 2015). Low-level of education can be considered an intrinsic risk factor for flood mortality (Yari et al., 2020) as well. Kahn (2005) studied flood fatalities from floods and other disasters in 73 countries from 1980 to 2002, pointing out that fewer people in rich countries die from floods compared to poor countries. Also, a country-year panel data set proposed by Kellenberg and Mobarak (2008) showed that disaster risk associated with flooding increases with income up to GDP per capita of US$ 5044 per year and decreases thereafter. Similarly, Liu et al. (2022) found that flood fatalities first increased with GDP per capita and then declined as more investments could be placed in flood prevention measures. It should be noted that social vulnerability is highly heterogeneous at a scale much smaller than GDP. Moreover, it should be considered that the total number of floods is likely related to the size of the country. Based on these, in future works, the total number of floods and the country-level GDP will be normalized by considering additional datasets and available literature to capture and understand the key drivers behind this trend. It is crucial to take into account the changes in per capita GDP over time when examining the trend. Relying solely on static data from 2020 may not present a comprehensive picture of the trend. To address this concern, collecting data on per capita GDP for each year between 1951 and 2020 would help in analyzing the trend of flood fatalities over time. This approach would allow for an examination of the correlation between changes in population and per capita GDP with changes in flood fatalities. However, due to the high level of uncertainty in GDP data for different countries during the period of 1951–2020, only GDP values referring to 2022 were used in the present study as a reference. In future research, the effects of time-varying GDP on flood fatalities will be investigated.

Figure 9 shows the ratio of flood-related fatalities to the population of different countries. As can be seen, Haiti, Bhutan, Nepal, Djibouti, Puerto Rico, Somalia, Tajikistan, Afghanistan, the Netherlands, Saint Vincent, and the Grenadines have the highest mortality rates. All of these countries, except for the Netherlands and Puerto Rico, have a GDP per capita of less than US$ 10,000 and can be classified among the poorest countries in the world.

Providing relationships between different parameters can be effective in models for predicting and estimating flood-related human and economic losses (Ward et al., 2013). Therefore, in this study, an attempt was made to establish relationships between the number of flood events, flood fatalities, number of events per unit area, fatality coefficient, and population.

Figure 10a–c report the variations in the number of flood events (Figure 10a), the number of fatalities (Figure 10b), and the fatality coefficient (Figure 10c) against the population of each country.

As can be seen in this figure, power relations (Equations 3, 4, 5) can be fitted between these parameters with R^2 of 0.85, 0.89, and 0.15, respectively. The increase in the number of flood events with population can be attributed to the increase in the number of Level II and Level III floods as reported by Liu et al. (2022), who

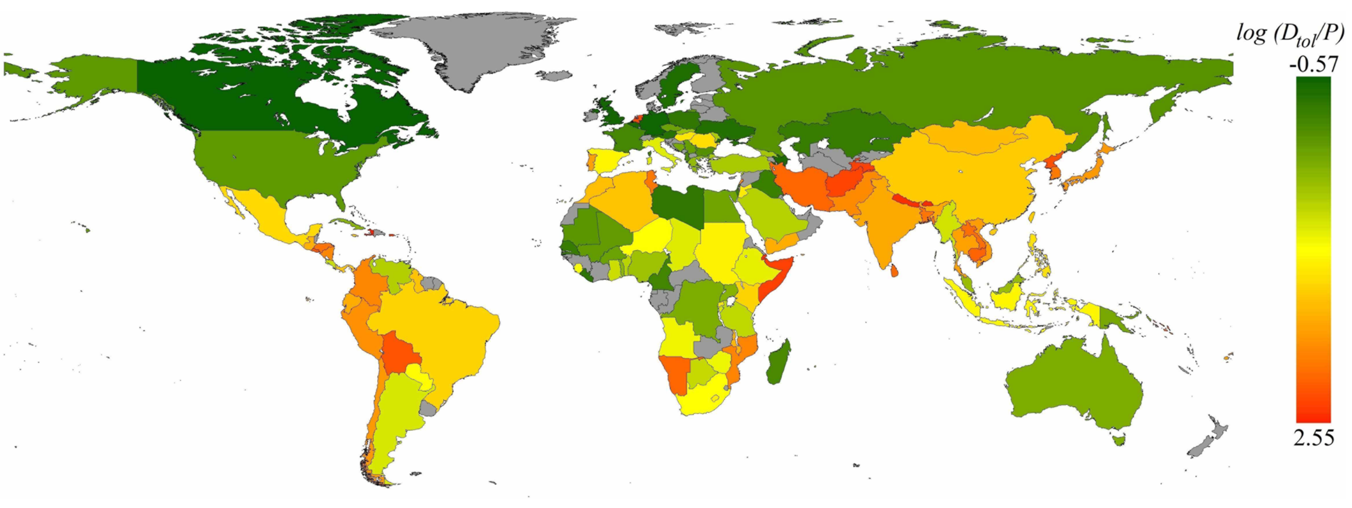

FIGURE 9 Distribution of the ratio of total flood fatalities D_{tol} to country population P. The areas in gray are those countries having less than 10 flood fatalities per event during the study period.

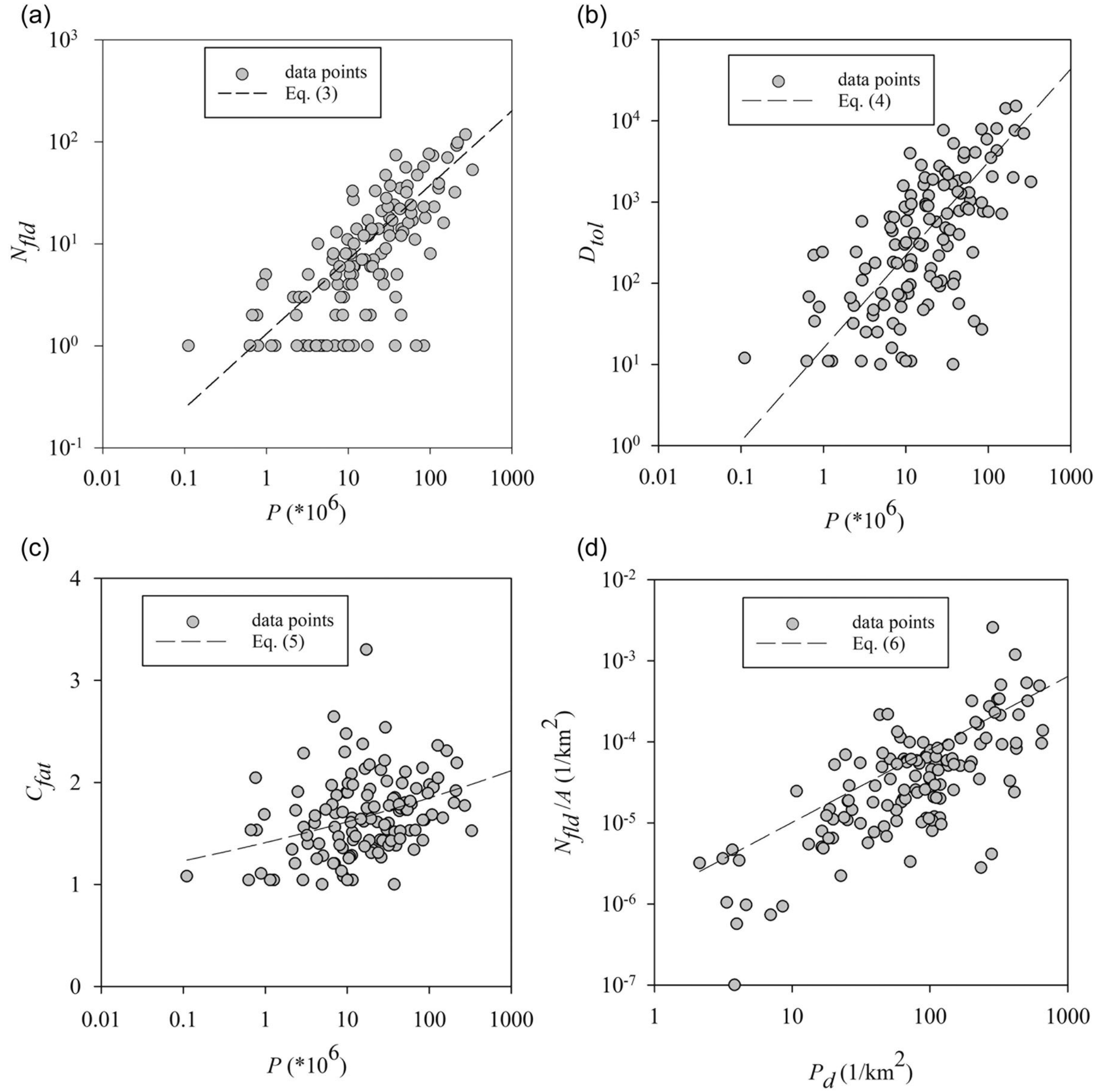

FIGURE 10 Variations of (a) number of flood events N_{fld}; (b) total flood fatalities D_{tol}; (c) fatality coefficient C_{fat} against country population P; (d) number of flood events per unit area against population density P_{d}.

classified flood events into three categories: Level I (affected area < $2 \times 10^4\,\text{km}^2$), Level II ($2 \times 10^4\,\text{km}^2$ < affected area < $10 \times 10^4\,\text{km}^2$), and Level III (affected area > $10 \times 10^4\,\text{km}^2$). Figure 10d shows the variations in the number of flooding events per unit area versus the population density for each country. Using the data plotted in this figure, a power relationship (Equation 6) can be fitted between the number of events per unit area and the population density, with a correlation coefficient R^2 of 0.65.

$$N_{\text{fld}} = 1.32P^{0.73}, \tag{3}$$

$$D_{\text{tol}} = 15.79P^{1.15}, \tag{4}$$

$$C_{\text{fat}} = 1.41P^{0.06}, \tag{5}$$

$$N_{\text{fld}}/A = 1.28 \times 10^{-6}(P_{\text{d}})^{0.90}. \tag{6}$$

In the above equations, P and A are the populations (in 10^6 persons) and area (in km^2) of each country, respectively. Also, P_{d} is the population density, that is, population per unit area (in person per km^2).

With a growing population or population density, the number of events, fatalities, events per unit area, and the fatality coefficient tends to increase. Despite the results reported in the present study, the findings of another study by Vinet et al. (2022) suggest that flood-related mortality in the French Mediterranean region has been relatively low over the past 40 years. Also, Diakakis and Deligiannakis (2013) reported that flood-related mortality in Greece has decreased significantly over the past 50 years. Their study reveals that the number of flood-related deaths has decreased from an average of 11.6 deaths per year during the period from 1961 to 1980 to an average of 2.2 deaths per year during the period from 2001 to 2010. Similarly, Diakakis and Deligiannakis (2017) analyzed flood fatalities in Greece from 1970 to 2010. Their results indicated that the highest number of fatalities occurred in the 1980s and 1990s, while the number of deaths decreased in the 2000s. Also, according to a study by Haynes et al. (2017), the most severe flood events in Australia occurred in the 1950s and 1970s. Besides, the finding that the impact of floods on the loss of life is likely to increase in the future reported by Vinet (2017) highlights the urgency of taking action to address the risks associated with floods, including the need to reduce greenhouse gas emissions and to adapt to the impacts of climate change. Also, Vinet et al. (2019) declared that while there has been a slight decrease in the long-term trends of flood-related mortality, recent events in France, Greece, and the Balearic Islands serve as a reminder that future drivers, such as global warming, population increase, lack of prevention measures, and an aging population, could result in a surge in mortality.

Due to the nature of the fitted relationships, it can be seen that the rate of increase of these parameters is more severe at first, that is, for lower values of population, and decreases with increasing population or population density. These relationships can be used as a preliminary approximation in models for predicting and estimating flood-related human losses. On the other part, it is worth to note there that only the more recent values of population density and GDP were considered in the present study, mainly aiming to reduce uncertainty in data collection as some countries do not have historic statistics. To address this issue, future investigations will consider multiple periods of observations, aiming to correlate time-variant relations between flood fatalities and socioeconomic factors.

While the EM DAT database is a valuable resource for analyzing the trends and impacts of floods on the loss of life, it is important to exercise caution when interpreting the data and to take into account the potential limitations and uncertainties. Future research could explore ways to improve the accuracy and completeness of reporting flood-related events to enhance the reliability of the data.

6 | CONCLUSIONS

In this study, floods that occurred in the 1951–2020 period and caused between 10 and 9999 fatalities were investigated, using the EM-DAT database as the main source of information.

The results showed that there is a large difference among the countries in terms of the number of flood events and fatalities. Most floods occur in India, China, Indonesia, Pakistan, Brazil, and Vietnam, while India, China, Pakistan, Bangladesh, Japan, and Iran have the highest flood fatalities. To compare the most vulnerable countries in terms of human fatalities against floods, the flood fatality coefficient was calculated by dividing the number of fatalities by the number of flood events. Accordingly, the Netherlands, Lebanon, Yemen, Hungary, India, and Somalia have the highest fatality coefficient. Also, in general, the South, East, and South-East Asia regions are the most vulnerable regions to floods. The study of the temporal changes of floods showed that the number of events has been increasing since the beginning of the period and reached its peak in the 2001–2011 decade, which corresponded to the largest precipitation anomaly in the world. Furthermore, the 1991–2000 decade shows the largest number of fatalities during the last 60 years. Finally, it was found that the number of fatalities per flood event is currently declining, thus indicating the effectiveness of flood control methods, including flood awareness, early warning, and advances in data availability and information gathering which can play an important role in reducing fatalities. A direct correlation was found between the number of flood events and the number of fatalities with the world population, while a relationship was found between some socioeconomic factors and the number of flood fatalities.

Of course, since the EM-DAT database is based on information collected from various sources, including the Internet, the impact of the development of information technology and media on the increase in the number of flood events cannot be ignored and should be included in future investigations. It is, therefore, worth noting that the presented conclusions derive from a single database and are, therefore, influenced by the data availability and the uncertainty of the collected information (e.g., de Bruijn et al., 2019; Tanoue et al., 2016). Future studies will concentrate on integrating information coming from multiple databases, aiming to obtain more structured and event-based outcomes and to gain additional insights into the data uncertainty (namely, differences between the datasets) and its sources.

As drivers such as population density and GDP vary in time, future investigations will consider those variations, aiming to provide additional insights on correlations between socioeconomic factors and flood fatalities.

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DATA AVAILABILITY STATEMENT

The data used in the research are available in the EM-DAT database www.emdat.be. Additional data are available online in Hamidifar (2023).

ETHICS STATEMENT

None declared.

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