Floodplains in the Anthropocene: A global analysis of the interplay between human population, built environment and flood severity

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Key Points:

- We analyzed the interplay between the severity of flood losses and human presence in floodplains using freely available global datasets.
- Despite the frequent flood losses in the period 1990-2000, human presence and built-up areas in the floodplains increased between 2000 and 2015.
- In low-income countries, population in floodplains increased after a period of high flood fatalities.
- In high-income countries, built-up areas increased after a period of frequent economic losses.

Keywords: Global dataset; Flood fatalities; Economic flood losses; Population in floodplains; Built-up areas in floodplains

Abstract

This study presents a global explanatory analysis of the interplay between the severity of flood losses and human presence in floodplain areas. In particular, we relate economic losses and fatalities caused by floods during 1990-2000, with changes in human population and built-up areas in floodplains during 2000-2015 by exploiting global archives. We found that population and built-up areas in floodplains increased in the period 2000-2015 for the majority of the analysed countries, albeit frequent flood losses in the previous period 1990-2000. In some countries, however, population in floodplains decreased in the period 2000-2015, following more severe floods losses that occurred in the period 1975-2000. Our analysis shows that: i) in low-income countries, population in floodplains increased after a period of high flood fatalities; while ii) in upper-middle and high-income countries, built-up areas increased after a period of frequent economic losses. In this study, we also provide a general framework to advance knowledge of human-flood interactions and support the development of sustainable policies and measures for flood risk management and disaster risk reduction.

1 Introduction

Floodplains offer favorable conditions for socio-economic growth, cultural organization, fishing, and agricultural production (de Moel et al., 2011; Di Baldassarre et al., 2010; Leauthaud et al., 2013; Vis et al., 2003). Over the past decades, human presence in floodplains has substantially increased in many parts of the world (Früh-Müller et al., 2015; Han et al., 2020). To illustrate, recent estimates indicate that in 2015, 33% of the Chinese population lived in floodplains, with a population density that was 3.6 times higher than in the areas outside (Fang et al., 2018). In the contiguous United States, 13.3% of the population lives in floodplains that are exposed to a 1 in 100-year flood (Wing et al., 2018).

Increasing population in floodplains (Di Baldassarre et al., 2013; Hu et al., 2018), along with climatic alteration of the magnitude and timing of floods (Blöschl et al., 2019, 2017; Ji et al., 2015), might increase flood risk in many places around the world (Bouwer et al., 2010; Jongman et al., 2012; Jongman et al., 2014; Swain et al., 2020). One strategy to reduce flood risk consists of reducing human presence in flood-prone areas or relocate further away from the river or to upland areas (Hino et al., 2017; Penning-Rowsell et al., 2013). Some countries have implemented (at times controversial) retreat programs as a response to floods through the buyout of properties located in more exposed areas in the floodplains (Binder et al., 2020; Siders, 2019; Sipe and Vella, 2014; Thaler and Fuchs, 2019). Alternatively, countries rely on structural protective measures, such as levees, to reduce the frequency of flooding (Takahasi and Uitto, 2004; Mazzoleni et al., 2014; Collenteur et al., 2015; Mård et al., 2018; D'Oria et al., 2019). However, these measures may lead to the unintended effects of enabling intense urbanization of flood prone areas and the subsequent reduction of flood risk awareness, often referred to as the safe development paradox (White, 1945; Kates et al., 2006; Di Baldassarre et al., 2019; Hutton et al., 2019; Haer et al., 2020). Other flood mitigation strategies entail the use of non-structural measures such as early warning systems, land use planning, and insurance to reduce flood vulnerability (Bubeck et al., 2013; Dawson et al., 2011; Pappenberger et al., 2015).

Güneralp et al. (2015) developed global estimates of changing exposure to floods and droughts due to urban expansion from 2000 to 2030. The study suggested that, even without climate change, urban areas exposed to flood and drought hazards would grow considerably due to socio-economic factors (e.g. cheaper land in floodplains). Similarly, using USEPA population and land-use projections data, Wing et al. (2018) reported that in the US exposure nearly doubled in the 21st century. However, reduced vulnerability to river floods has been observed in low- and high-income countries (Jongman et al., 2015; Tanoue et al. 2016). Formetta and Feyen (2019) quantified fatalities and economic losses due to climate-related hazards, demonstrating that vulnerability decreased globally and the difference in vulnerability between low- and high-income countries reduced over the period 1980-2016. As an example, despite the increase in annually inundated areas, continuous urbanization growth, and number of affected people in Europe since 1870, a decline in fatalities and financial losses was observed (Paprotny et al., 2018). Similarly, decreasing mortality rates caused by storm surges and heat waves was reported by both Bouwer and Jonkman (2018) and Sheridan and Allen (2018).

Other studies have revealed that exposure to repeated hazard events (such as floods) may consequently shape the human presence in floodplains (e.g. Di Baldassarre et al., 2015; Kreibich et al., 2017; Mård et al. 2018; Barendrecht et al., 2019; Michaelis et al., 2020). However, only a few empirical studies have investigated the relationship between flooding and consequent population growth in flood-prone areas. For example, Stal (2011) showed that after the 2007 flood event in Mozambique, people resettled far from the river due to the loss of their homes and livelihoods. Collenteur et al. (2015) analyzed population growth in St Louis, US, following the catastrophic Mississippi flood in 1993, and found that in the period 1990-2000 population growth in flood-affected areas was 50-80% lower than the one in non-flooded areas. However, this drastically changed in the following decade when levees were repaired and the population in floodplains increased by 300%. Deryugina et al. (2018) examined the relationship between the widespread flooding caused by Hurricane Katrina in New Orleans and human presence in the floodplains (2005). The study found that following Katrina, over one-fourth of the population was displaced and more than one third had not returned as of 2013. In a global study, Mård et al. (2018) found that societies that experience damaging flood events tend to relocate further away from the river towards flood safe areas. However, this tendency was only observed in societies with low structural flood protection levels, as Lower Limpopo River in Mozambique, and Lower Mekong River. Societies with high protection levels showed no significant changes in human presence following floods, instead, they tend to reinforce flood protection and resettle in floodplains.

Despite this emerging body of literature, changes in human presence in floodplains following the occurrence of severe flood losses remains largely unexplored at global scale. Here we aim to advance the understanding of human-flood interactions by exploring, globally, how the severity of floods losses relates to human presence in floodplains. In our analysis, we examine the correlation between the severity of flood fatalities with changes in population in floodplain, and between the severity of economic damages caused by floods with changes in built-up areas.

2 Material

2.1 Datasets

Three global datasets are used to explore the interplay between human presence in floodplains and severity of flood losses. The spatial distribution of human presence is assessed using the Global Human Settlement Layer (GHSL, Pesaresi et al., 2013) for the years 1975, 1990, 2000, and 2015. The GHSL is derived from 40 years of Landsat satellite imagery, processed using a supervised classification paradigm developed for big remote sensing data scenarios to estimate a multi-temporal classification grid at 38 m resolution. The dataset is also available at coarser resolutions of 250 m and 1 km (Pesaresi et al., 2013). The GHSL consists of three different information layers: the built-up area density layer, the population layer, and the grid cell classification into one of the settlement model classes, which can be considered as a degree of urbanization (Melchiorri et al., 2018). In this study, we used both the built-up and the population layer at 38 m and 250 m spatial resolution, respectively, as a proxy of human presence at global scale (Klotz et al., 2016; Leyk et al., 2018).

The built-up area layer is derived from multi-temporal information based on Landsat satellite imagery for different periods at global scale. The population layer is calculated for the built-up area layer and the multi-temporal census data from the Gridded Population of the World-GPW (CIESIN, 2016). As both built-up and population layers are calculated as differential values between two different years (e.g. from 1975 to 1990), their cumulative value is calculated and used instead. Results of previous studies have suggested that GHSL is one of the most reliable global, open and available datasets for mapping population distribution since it has been validated using independent reference data (Melchiorri et al., 2018). Moreover, temporary and informal human settlements are also included in the GHSL dataset (Pesaresi et al., 2012).

The proper delineation of floodplains is fundamental to assess the exposed population to possible river floods and consequent losses. There are two main approaches to map flooding: *hydrological* and *hydrogeomorphic* (Di Baldassarre et al., 2020). In the hydrological approach, mapping is based on the use of hydrological and hydrodynamic models forced with synthetic flood events of a given probability of occurrence or return period (Pappenberger et al., 2013; Sampson et al., 2015; Ward et al., 2015; Dottori et al., 2016). In the hydrogeomorphic approach, floodplains are identified directly from the topography as unique morphological entities primarily shaped by the accumulated effects of geomorphic and hydrologic processes (Jafarzadegan and Merwade, 2017; Nardi et al., 2006). Both approaches are based on consolidated theories and they have different pros and cons (Di Baldassarre et al., 2020). In this study, we used the global floodplains dataset (GFPLAIN250m), derived with a hydrogeomorphic approach (Nardi et al., 2019). This is consistent with the goal of our study as hydrogeomorphic maps identify floodplains regardless of the presence or lack of flood protection structures. We complemented our study with an additional comparison of the human presence from GHSL with floodplains delineation from both hydrogeomorphic (GFPLAIN250m) and hydrological (Dottori et al., 2016) approaches. The results are presented in the Supplementary document (Figure S1).

Natural hazard impact data are retrieved from the International Disaster Database (EM-DAT global dataset, CRED, 2018) for the period 1975-2015. EM-DAT contains global data of the occurrence and effects of over 22,000 disasters from 1900 to present day that are related to natural and technological hazards. Flood losses are estimated from fatalities (sum of casualties and missing people due to a hazard event) and economic damage (e.g., damage to property, crops, and livestock) reported in EM-DAT. It should be noted that EM-DAT only includes hazard events with one or more of the following criteria: causing at least 10 fatalities, 100 affected people, a call for international humanitarian assistance, or a declaration of a state of emergency (Andrewin et al., 2015; Pascal Peduzzi et al., 2012; Peduzzi and Herold, 2005). Thus, the reported number of hazard events and their impacts may be underestimated.

2.2 Method

The methodology adopted in this study is structured in 4 main steps: i) estimation of the indexes of flood losses; ii) estimation of the severity of flood losses; iii) estimation of human presence changes in floodplains after a period of flood losses; and iv) statistical analyses.

Indexes of flood losses: The frequency and intensity of hazardous events can differently shape risk perception and the consequent human presence in floodplains. An event responsible for many fatalities may generate small social disturbances if it occurs in a well-understood and experienced system (e.g. train wreck), while an unexpected event (e.g. plane crash or nuclear reactor accidents) can have huge social consequences (Slovic, 1987). In the case of flooding, Baan and Klijn (2004) found that the populations living close to the levee system of the Meuse river were not aware of any flood risk and did not feel they were in danger. However, after the major unexpected flood of 1993, the perception of risk changed for the majority of the people, with some of them experiencing high-stress levels unable to go to work. Similar conditions were found after the 1998 flood events in the UK (Tapsell & Tunstall, 2000). One of the main innovations of this study is the estimation of flood losses indexes, which is not only based on flood intensity but also on the frequency of floods to better identify experienced and unexpected events. For this reason, we assessed flood losses, at country level, as number of fatalities and economic losses caused by floods averaged per year and by the number of occurring events. The assumption is that a higher annual average flood losses leads to a more flood experienced society, while a higher average per event of flood losses indicates a less flood experienced society, in line with the perception of risk described by Slovic (1987).

Severity of flood losses: Another main innovation of this study is the new normalization approach used to assess changes of flood losses and human presence in floodplains for different periods, i.e., a flood losses period followed by a human presence change period, instead of a standard trend analysis framework. We divided the analysis time period into 3 parts (based on the time steps for the GHSL data), a baseline from 1975 to 2000, a flood exposure period between 1990 and 2000, and a human presence change period from 2000 to 2015 (Figure 1). We then calculated the annual average and the average per event of flood losses in each of those periods. Using a decade-long timescale is justified by previous empirical and theoretical social, behavioural, and psychological studies (Squire 1989; Ellis et al. 1998; Hanak, 2011; Hirst et al. 2015; Fanta et al. 2019; Mondino et al. 2020a,b).

The severity of flood losses index (ϕ) is estimated as the ratio between the average flood losses in the period from 1990 to 2000, and the average flood losses in the baseline period (1975-

2000). In particular, the severity index for both flood fatalities (ϕ_F^E) and economic flood losses (ϕ_L^E) are first calculated as the average per event:

$$\phi^E = \frac{\frac{1}{N}\sum_{i=1}^{N} L_i^{1990-2000}}{\frac{1}{B}\sum_{i=1}^{B} L_i^{1975-2000}} \tag{1}$$

Where L is the flood losses expressed as flood fatalities and economic flood losses, N is the number of events in the flood exposure period, while B is the number of events in the baseline period that is the sum of the events occurring between 1975 and 1990 and the exposure period (1990-2000). This index is affected by both the intensity and frequency of flood losses. The severity of flood losses index per year is estimated as:

$$\phi^Y = \frac{\frac{1}{10}\sum_{i=1}^{N} L_i^{1990-2000}}{\frac{1}{25}\sum_{i=1}^{M} L_i^{1975-2000}} \tag{2}$$

Based on the different values of ϕ^Y and ϕ^E we can identify different scenarios that characterize flood losses (Figure 2). For example, values higher than 1 of both ϕ^Y and ϕ^E is indicative of more intense severity of flood losses in the period between 1990 and 2000 than in the long-term baseline period (1975-2000). Cases where $\phi^Y > \phi^E$ would be indicative of more frequent flood losses between 1990 and 2000, while countries with less frequent flood losses are characterized by $\phi^E > \phi^Y$, as visualized in Figure 2. We implemented this method as the standard approach to normalize country-level economic flood losses over the gross domestic product could not capture the exceptionality of the flood events to the long-term flood losses averages. With this method, we explicitly recognize that the severity of events is relative to the historical experience of each country. It is worth noting that economic flood losses are inflation-adjusted to the year 2000 to properly compare losses through time. We did not adjust flood losses for population density as we assumed that community-wide mortality and economic loss is what drives floodplains human presence change and risk management decisions rather than per-capita perceived risk to each individual or economic asset (Dottori et al., 2018).

Human presence change: The values of population and built-up area in floodplains at country level are estimated as the sum of the pixel values and area, respectively, of the GHSL dataset within the floodplains identified in the GFPLAIN250m dataset. We calculated the human presence change index (η) as the ratio between the observed values of normalized population and built-up area in 2015 and their extrapolated values in 2015 using the time series of the baseline period as observed values. This index provides a quantitative indication of changes in human presence in floodplains, as a response to flood losses, between 2000 and 2015 compared to the baseline (1975-2000). In this way, a value of η higher than 1 indicates that human presence in floodplains is increasing more than expected from the historical observations. Due to the geographical extent of the GFPLAIN250m dataset (only available up to 60°N), 153 countries are included in the analysis.

The main country sample is generated by selecting those countries for which fatalities and economic losses were available for at least 1 severe flooding during the flood exposure period (1990-2000) according to the EM-DAT dataset. This led to a main sample of 75 countries for comparison of flood fatalities and population in floodplains, and a subsequent sample of 55 countries for comparison of economic losses and built-up areas in floodplains. The resulting countries, number of events, and the distribution between the number of events and the number of countries in each time-period are displayed in Figure 3. Country sample sizes when using other minimum values of recorded flood events are reported in Figure S2. The difference in selected countries is due to underreported fatalities or economic losses in the EM-DAT database.

It should be noted that the spatial resolution of the GHSL dataset may influence the results, as it can misrepresent the real population distribution at small scale. Recently, Smith et al. (2019) demonstrated that high resolution (about 30m) population and flood hazard datasets show a tendency of humans to make more rational decisions about flood risk and seems to be more risk-averse than current demographic data suggest. To assess the influence of the spatial resolution on the results, we first compared the country population estimated with the GHSL and High Resolution Settlement Layer (HRSL; CIESIN 2018) datasets against WorldBank data (WorldBank, 2020), and then compared the population in floodplains estimated with the GHSL and HRSL datasets for 20 countries in 2000 and 2015. As shown in Table S1, similar countries population are found with WorldBank data, GHSL, and HRSL datasets. However, more variable results are obtained when calculating the population in floodplains with the two spatially distributed population datasets, with GHSL showing higher values than HRSL. Similar results are reported in Smith et al. (2019). Because of the normalization approach used to calculate the severity of flood losses and human presence changes, we assume that the spatial resolution issue may not influence the results of our study. We tested this hypothesis by calculating the ratio between population in floodplains in 2015 with 2000 in the same countries reported in Table S1 using the GHSL and WorldPop (100m spatial resolution, Tatem, 2017) datasets. The results (Table S2) show that despite the high difference in the single years, their ratios are similar in both datasets in most of the analyzed countries.

Statistical analysis: Given the exploratory value of this study, a Mann-Kendall non-parametric statistical trend test (Mann, 1945, Kendall, 1975), widely adopted in hydrological and hydroclimatic analyses, is used to assess Kendall's tau and detect significant monotonic trends at the 0.05 significance level. Being the Mann–Kendall trend test a rank-based significance test, it is not affected by the distribution of the data, unlike other parametric statistical tests, and is less sensitive to outliers (Hamed, 2008). We also used the Theil–Sen slope estimator and the p-values to assess the magnitude of the statistical trends between severity of flood losses and human presence change index.

The proper selection of the minimum number of reported flood events in the exposure period can significantly affect the corresponding number of countries included in the analysis (see Figure S2 in the supporting information). For this reason, in order to assess the robustness of our findings, we used a range of minimum values of flood events in the period between 1 and 6 for filtering the countries for the statistical analysis. The former (i.e. 1) is selected because, while flooding can be a local phenomenon, the effect of a severe event can indirectly influence floodplains development for a larger area. The 2005 flooding in New Orleans, for example, triggered a discussion about the urbanization of floodplains in the U.S. and beyond. To illustrate, De Wit et al. report that "triggered by the flooding disaster in New Orleans (Katrina), the Dutch government has launched a campaign to better prepare for the situation that a flood actually does occur". The latter minimum values of flood events (i.e. 6) is selected as higher thresholds would make the number of countries too small for a robust analysis (see Figure S2).

The countries are further classified by income-levels to account for possible wealth effects. The classification of income is performed following the 2015 income division as used by the World Bank (https://datahelpdesk.worldbank.org/knowledgebase/articles/378834-how-does-the-world-bank-classify-countries).

3 Results

3.1 Historical analysis of severity of flood losses

This section shows the findings of the severity of flood losses analysis, independently from the human changes in floodplains, using 1 flood event in the exposure period as threshold. The results show that the majority of the countries have experienced more annual average flood fatalities and economic losses in the period 1990-2000 compared to the baseline period (Figure 4.a and Figure 4.c). Some countries, e.g., China, Australia, Italy, Japan, Indonesia, and Peru, show that the severity of economic losses is increasing, in contrast to decreasing severity of flood fatalities. Other countries, such as Malaysia, Afghanistan, and Paraguay, have more population exposed to floods and suffer higher flood fatalities, but have lower economic losses than the baseline.

The majority of the countries experience more frequent flood losses between 1990 and 2000 as $\phi^{Y} > \phi^{E}$. This could be due to an increasing number of events, but also due to a better reporting of flood events and their impacts in the exposure period than in the baseline. High severity of flood losses values, calculated as annual average, corresponds to low severity, estimated using average per event, as more frequent losses occurred in the exposure period (Figure 4.b and Figure 4.d). Moreover, the majority of the countries experienced less severe flood fatalities calculated as average per event between 1990 and 2000 than in the baseline period (ϕ^{E} <1 in Figure 4.b). However, the opposite situation is found with respect to economic flood losses (Figure 4.d). As a consequence, the percentage of countries experiencing both more severity, calculated as average per event, of flood fatalities and economic losses than baseline dropped to 14%. Overall, the severity of economic flood losses is higher than the severity of flood fatalities in 59% and 55% of the analysed countries, estimated as annual average and average per event, respectively.

A spatial distribution of the difference between ϕ^{Y} and ϕ^{E} is shown in Figure S3. It can be observed that more frequent flood fatalities in 1990-2000 are found overall in Africa, North America, and East Europe. On the other hand, Asia, Oceania, and South America experienced more frequent flood fatalities throughout the entire baseline period. When focusing on the economic flood losses, a higher difference between ϕ^{Y} and ϕ^{E} are found in North America, Europe, and Asia. This shows that countries that experienced frequent flood fatalities in the entire baseline period (small difference between ϕ^{Y} and ϕ^{E}), may have experienced frequent economic flood losses only in the period between 1990 and 2000 (high difference between ϕ^Y and ϕ^E) as in case of U.S., China, and part of Europe. Few countries (e.g. India) showed opposite outcomes.

3.2 Increasing human presence in river floodplains

With respect to the human presence change index, it is estimated that around 64% and 80% of the analysed countries show increasing trends in population and built-up area in floodplains changes between 2000 and 2015, respectively (Figure 5). Furthermore, about 70% of the countries show a higher change in built-up area in floodplains than population change. However, countries that experienced increasing population change do not always show a similar trend in built-up area change. In fact, such a positive correlation occurs only in 55% of the countries. Situations in which population is growing and built-up area is declining can be associated with unplanned development (Jha et al., 2012), higher household density, or vertical urbanization in the floodplains. This can be observed in 9% of the countries displayed in Figure 5, e.g. Peru and Benin. On the other hand, decreasing population and increasing built-up area (25% of the analysed countries) can be observed together with relocation policies (Fang et al., 2018) or in situations in which population leave the floodplains to give more space to industry or other types of sectors (Pinter, 2005). The remaining 11% of the countries are characterized by negative changes in both built-up areas and population in floodplains. Similar outcomes are reported in Figure S4 when using flood hazard maps for a 200-year return period from JRC as floodplains delineation.

3.3 Human presence change and relationships with flood losses

There are several socioeconomic and hydroclimatic factors that determine human mobility in floodplains. Here, we explore worldwide changes in human presence in floodplains after 25 years of severe flood losses. As previously mentioned, we used 1 and 6 as minimum values of flood events recorded in the exposure period (1990-2000) for selecting the sub-sample of countries to include in the statistical analysis. The results of Figure 6 and Figure 7 refer to the country sub-sample that is generated considering at least 3 flood events in the flood exposure period, resulting in 63 and 35 analyzed countries for flood fatalities and economic flood losses, respectively. As the results show, there is no clear statistical correlation or trend of human presence changes after extreme flood events (Figure 6). However, we observe that the built-up area is expanding in floodplains after high annual average values of the severity of economic flood losses (ϕ^Y>1), with a significant correlation with p-value of 0.04 and Theil-Sen's regression slope of 0.17. Similar, but not significant, results are also observed for the severity of economic losses calculated as average per event (Figure 6.d). Analogous findings can be observed in Figure S5 when using flood hazard maps for a 200-year return period from JRC as floodplains delineation.

Human population dynamics in floodplains are not only influenced by the occurrence of frequent flood events, but also by the prolonged exposure of population to frequent and intense flood losses. To analyze such an effect, we considered the difference between the severity of flood losses calculated as annual average (ϕ^Y) and average per event (ϕ^E) as a proxy for human experience of previous flood losses. We focused on the cases in which $\phi^Y > \phi^E$ as they represent

90% of the analysed countries. Under this assumption, high differences (length of the arrows in Figure 7) between ϕ^Y and ϕ^E represent more frequent flood losses in the exposure period than in the period 1975-1990 and the entire baseline period. On the other hand, smaller differences characterize periods in which the population in floodplains experienced more frequent flood losses in the baseline period (1975-2000). Based on this formulation, negative values of the difference between ϕ^Y and ϕ^E indicate less frequent flood losses in the exposure period than in the baseline period.

We then investigated possible patterns when correlating population and built-up area changes to different scenarios of the severity of flood losses: 1) More frequent flood losses in the period between 1990 and 2000 ($\phi^Y > \phi^E$, Figure 2.a); 2) More intense (and frequent) flood losses than in the baseline period ($\phi^Y>1$ and $\phi^E>1$, Figure 2.a); 3) Less intense but more frequent losses in the exposure period and more intense losses in the baseline period ($\phi^Y>1$ and $\phi^E<1$, Figure 2.a); and 4) More frequent flood losses in the exposure period but more intense flood losses in the baseline period ($\phi^Y<1$ and $\phi^E<1$, Figure 2.a).

Our exploratory analysis (Figure 8) recognizes that an average high and positive correlation, with low p-values, between the difference ϕ^Y - ϕ^E and population changes can be observed with more frequent expected annual flood fatalities than in the baseline period ($\phi^Y>1$), and more intense flood fatalities occurred between 1975 and 1990 ($\phi^E<1$, as represented in Figure 2.a). We also found an average small positive correlation (Theil-Sen's regression slope of 0.17 and p-value of 0.36 as showed in Figure 8) between the difference ϕ^Y - ϕ^E and changes in built-up areas in floodplains when there are more economic flood losses occurring in the flood exposure period ($\phi^Y > \phi^E$), considering six different minimum values of recorded events in the exposure period.

The results of Figure 7 indicate an increment of both population and built-up areas after frequent economic flood losses in the exposure period (1990-2000). However, the population in floodplains is reducing between 2000 and 2015 if more frequent and intense flood fatalities occur between 1975 and 1990. In a similar way, built-up areas increase slightly in floodplains when humans are exposed to long periods of frequent economic flood losses, i.e. growth in both frequency and/or intensity also in the baseline period (leading to higher values of ϕ^E and consequent reduction of the arrow's length). These results demonstrate, one more time, how experiencing flood losses can shape human population and built-up areas dynamics in floodplains. The results obtained using flood hazard maps for a 200-year return period from the JRC dataset to delineate floodplains are shown in Figure S6 and reported in the supporting information.

3.4 Influence of income levels

The risk perception and vulnerability of humans living in floodplains are related to many factors such as past experience of floods (Scolobig et al., 2012), personal factors (e.g. age, education, occupation) (Wachinger et al., 2013), and contextual factors (Lechowska, 2018). Among the latter, class, economic factors, and level of development of a specific country play an important role in flood risk adaptation and consequent human dynamics in floodplains (Ferreira et al., 2011).

Interesting results are obtained when focusing on specific categories of country income levels (Figure 9 in case of 3 minimum-recorded flood events in the exposure period). The higher the country income level the lower the severity of flood fatalities with both ϕ^Y and ϕ^E (Figure 9.a). Values of severity of flood fatalities, estimated as average per event, are on average lower than 1 for low, lower-middle, higher-middle, and high-income level countries (Figure 9.a). This means that more intense and less frequent flood fatalities are experienced in the baseline period than in the exposure period. Between 2000 and 2015, increment in population in floodplains population is found in low-income countries, while for higher income levels we can observe limited change. Similar results are also found when using the 200-year flood hazard map from the JRC dataset (Dottori et al. 2016) for floodplains delineation (Figure S7 in the supporting information). A positive correlation between the decreasing severity of flood fatalities and a slight decrease in population in floodplains is found with increasing income-level classes. In particular, the increase of population in floodplains in low-income countries after an exposure period (1990-2000) of high and variable severity of flood fatalities may be due to a lack of adaptation strategies, unplanned development in floodplains (Jha et al., 2012), and lower preparedness levels and responses by the authorities (Egbinola et al., 2017).

On the other hand, higher severity of economic flood losses is found with higher income classes at country level (Figure 7.b). This can be due to a higher exposure of valuable assets (Jongman et al., 2015) or to flood prevention measures aimed at reducing flood fatalities during extreme flood events (e.g. flood forecasting, and early warning systems) (Merz et al., 2010). Changes in built-up areas in floodplains are higher with higher-income level countries, similarly to high severity of economic flood losses. As described before, the majority of annual average economic flood losses are higher in the exposure period than in the baseline period. The high values of increasing built-up areas in floodplains in upper-middle and high-income countries can be due to the tendency of those countries implementing flood protection measures (e.g. levee system) to live in floodplains and closer to the river (safe development paradox; White, 1945). On the other hand, decreasing built-up area values may be due to the choice of lower-income countries to settle far away from the river after a damaging flood event (Mård et al., 2018).

4 Discussion and conclusions

We explored the change in floodplains human presence after severe flood losses with respect to countries income level globally. We found that the majority of the countries have experienced more frequent and intense flood fatalities and economic losses in the period 1990-2000 compared to the baseline period (1975-2000). Despite the increment of frequent flood losses, an increase in both population and built-up areas in floodplains is recorded at a global level in the following period (2000-2015). The increase of frequent flood losses could be due to a combination of an increased number of events and an increased reporting of flood events in the EM-DAT dataset during the exposure period than the baseline, particularly in lower-income countries. Furthermore, we determined that the increase of built-up areas in floodplains is larger than the population growth in more than 50% of the countries. In the period following increased frequency in economic losses, the degree of built-up areas in floodplains has grown at a lower rate. Similarly, when flood fatalities increase in frequency in the period 1975-2000 and in intensity between 1975 and 1990, population in floodplains tends to reduce in the following period.

With respect to socio-economic factors, lower income countries experienced more severe flood fatalities, followed by a period where the population change in floodplains increased more compared to upper-middle and high-income level countries. On the contrary, higher economic flood losses are found in higher-income level countries, presumably due to a higher exposure of valuable assets in those countries. However, despite the growing amount of economic flood losses, a similar increase in the degree of built-up areas in floodplains is recorded in upper-middle and high-income level countries. This might be explained by the recent implementation of flood protection measures, allowing for new development within floodplains (Mård et al., 2018). It is worth mentioning that the results might have been different if we would have analyzed human presence of different societal groups within a country. For example, more in-depth analyses focusing on the vulnerability within high-income countries and within cities are needed to better understand the social processes and trends at different scales after intense flood events.

We analyzed flood losses in absolute terms, which may obfuscate the spatial distribution of flood risk and impact across income levels. The relative burden of flood impacts generally falls heavier on low-income countries, even though the absolute economic losses are higher in richer countries (UNISDR, 2018). Studies comparing flood risk across income groups, therefore, often normalize impact data, typically using mortality rate (fatalities normalized to exposed population) and economic loss rate (damages normalized to gross domestic product) (Formetta and Feyen, 2019; Jongman et al., 2015; Tanoue et al., 2016). Looking at relative losses, previous studies have found an overall negative global trend for flood vulnerability, in terms of both mortality and economic loss rate (Formetta and Feyen, 2019; Jongman et al., 2015; Tanoue et al., 2016). Tanoue et al. (2016), however, reported that upper-middle income countries showed a long-term positive trend in economic loss rate. There have also been findings of convergence between low- and high-income countries, where the mortality and loss rates have been shown to decline faster in high-income countries compared to low-income countries, even though the vulnerability gap across income levels remains substantial (Jongman et al., 2015; UNISDR, 2018). Our results show that low-income countries exhibit higher flood fatalities, which corresponds to previous literature reporting a negative relation between country wealth and flood vulnerability, meaning that the mortality rates and relative economic flood losses generally decrease as countries get richer (Formetta and Feyen, 2019; Jongman et al., 2015; Kahn, 2005; Lim and Skidmore, 2019; Strömberg, 2007; Toya and Skidmore, 2007). The relationship between relative disaster damages and country wealth is not necessarily linear, however, some studies point to non-linear U-shape trends, revealing the intricate balance of economic development and flood protection measures (Kellenberg and Mobarak, 2008; Tanoue et al., 2016; Zhou et al., 2014).

This study comes with some caveats. One caveat is that the EM-DAT data are constrained by known inconsistencies in data-collection due to exclusion of small-scale events, missing data, improved losses reporting, spatial discrepancies resulting from changes of political boundaries, and observational bias due to the increased observational capacity for natural disasters over time, particularly for low-damage events. A possible way to overcome these limitations is to exploit other global disaster databases like NatCatSERVICE provided by Munich Re and with flood specific dataset as the Global Runoff Database. Another limitation of this study is that the Landsat imagery used to derive the GHSL dataset may fail to capture temporary housing built following past flood severity. Future analysis using available ground truth data could help in reducing the correlation between observational errors in the satellite-derived human presence products and past flood severity. Moreover, due to the spatial extent of the GFPLAIN250m dataset up to 60°N, some countries are not included in the analysis of this study. Finally, changes in human presence within floodplains have been related only to severity of flood losses. However, many socio-economic and political factors (e.g., political economy of natural resources, socio-economic status, flood insurances) play crucial roles in explaining human population dynamics in floodplains. As such, there might be other confounding variables potentially obfuscating the results. These should be considered in future studies by means of causal inference methods, and more detailed analyses of local data and case studies identified as specific hotspots using the findings of our study.

The analyses and interpretations provided in this paper can be advanced by integrating examinations of how politics, power, culture and policy visions shape the interplay between flood events, economic losses and urbanization in floodplains (Di Baldassarre et al., 2019; Graham and Shelton, 2013; Kitchin, 2013; Rusca and Di Baldassarre, 2019). This entails empirical examinations of multiple factors, such as the relationship between uneven urban development and distribution of flood risks across different societal groups (Parthasarathy, 2018; Porio, 2011; Thaler and Hartmann, 2016; Verchick, 2012; Williamson, 2018; Zwarteveen et al., 2017), or the effectiveness and social disruptions of managed retreat programs from floodplains (Binder et al., 2020; Siders, 2019). Other factors include long term impacts of flood resilience strategies such as 'room for the river' (Rijke et al., 2012) and other hybrid approaches (Aerts et al., 2013), as well as of the role of flood mapping in (re)distributing risk and reshaping building codes and, in turn, urbanization in floodplains (Pralle, 2019).

As such, the global trends discussed in this paper are also shaped by complex relationships between the implementation of structural flood protection and the resulting changes in the economic value of properties, guiding principles on liability for flood damage, and social welfare measures concerning flood risk mitigation and recovery processes (Barraqué, 2017; Thaler and Hartmann, 2016). A closer examination of these interconnected processes may further explain how global trends are produced and materialized in different contexts.

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The datasets of floodplains delineation, global human settlements, and flood losses used in this study are available through Nardi et al. (2019), Pesaresi et al. (2013), and CRED (2018) respectively. In particular, the GFPLAIN250m dataset can be found at https://www.nature.com/articles/sdata2018309#Sec6, the GHSL dataset can be downloaded at https://ghsl.jrc.ec.europa.eu/datasets.php, while the EM-DAT dataset is available at https://www.emdat.be/database.

Author contribution

Conceptualization: MM, GDB; Methodology: MM, JM, MR, VO, SL, GDB; Software: MM; Validation: MM; Formal analysis: MM; Investigation: MM, JM, GDB; Data curation: MM; Writing – original draft: MM; Writing – review & editing: MM, JM, MR, VO, SL, GDB; Visualization: MM; Funding acquisition: GDB;

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Figures

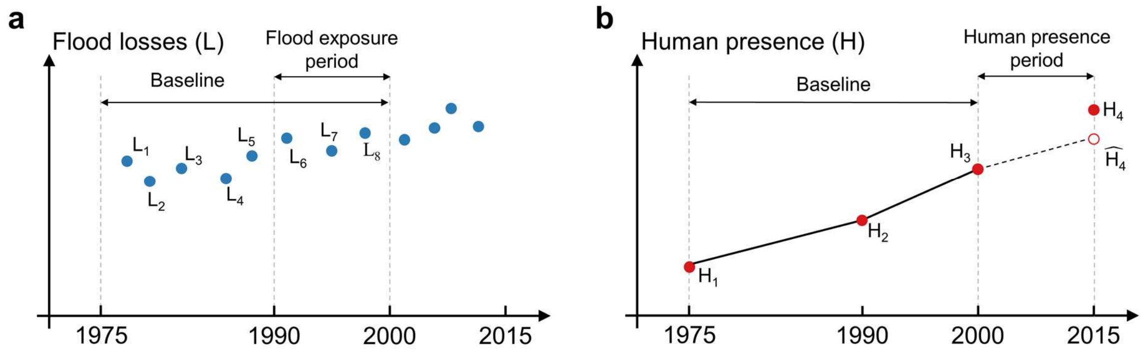


Figure 1. Representation of the 3 periods used to assess the severity of flood losses (a) and changes in human presence in floodplains (b). Each blue dot on the left side represents a given flood event generating flood fatalities and economic flood losses. On the right side, the filled red dots represent the observed population in 1975, 1990, 2000, and 2015, while the empty red dot is the expected population in 2015 calculated as linear extrapolation (Bongaarts, 2009) based on the population in 1975, 1990, and 2000.

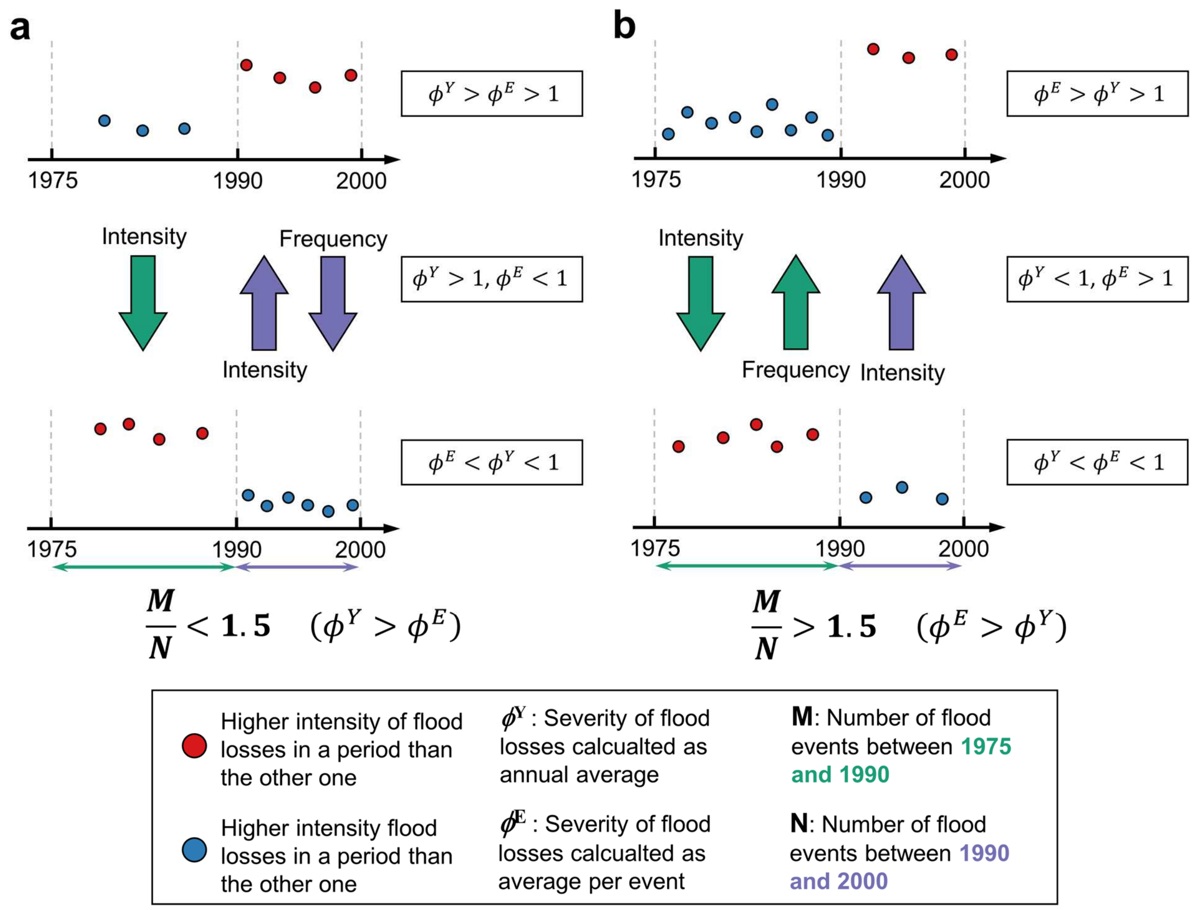


Figure 2. Summary of the possible scenarios of the severity of flood losses (ϕ^Y and ϕ^E) based on the frequency and intensity of the flood events occurring in the period 1975-1990 (represented with green color) and 1990-2000 (represented with purple color). Two possible situations in which $\phi^Y > \phi^E$ (left side) and $\phi^E > \phi^Y$ (right side) are illustrated.

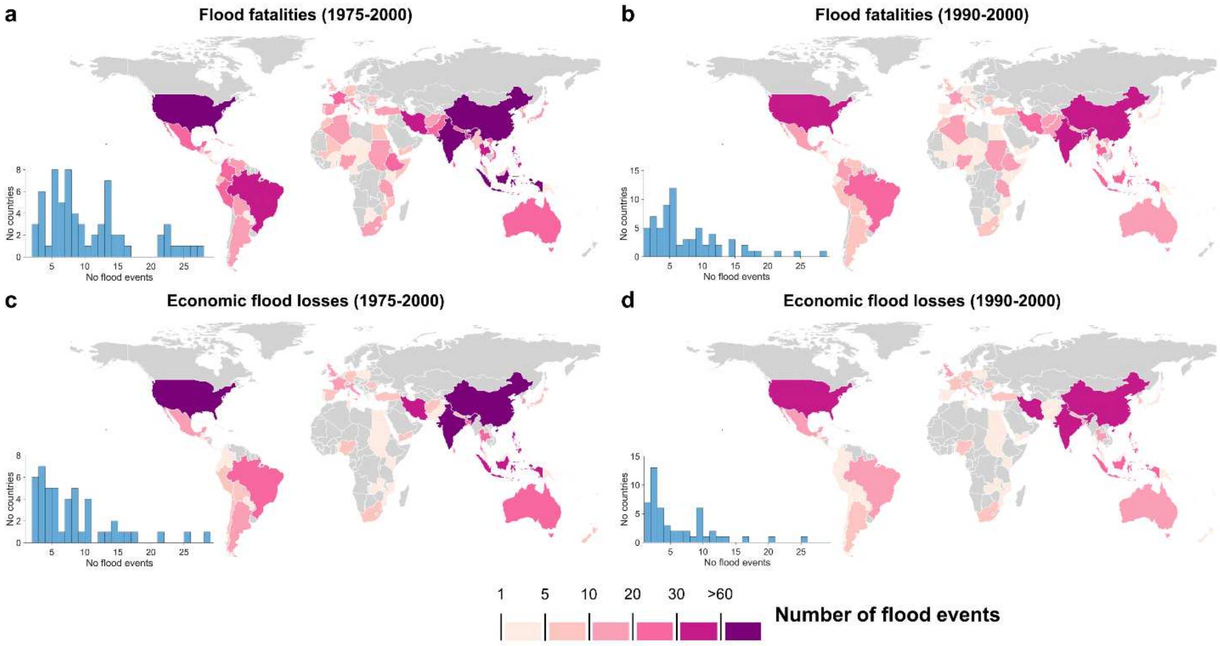


Figure 3. Spatial distribution at global scale of the number of events of flood fatalities (a-b) and economic flood losses (c-d). The distribution between the number of events and the number of countries is reported for each period. Grey colors indicate countries in which either no floodplain data or recorded flood events are available.

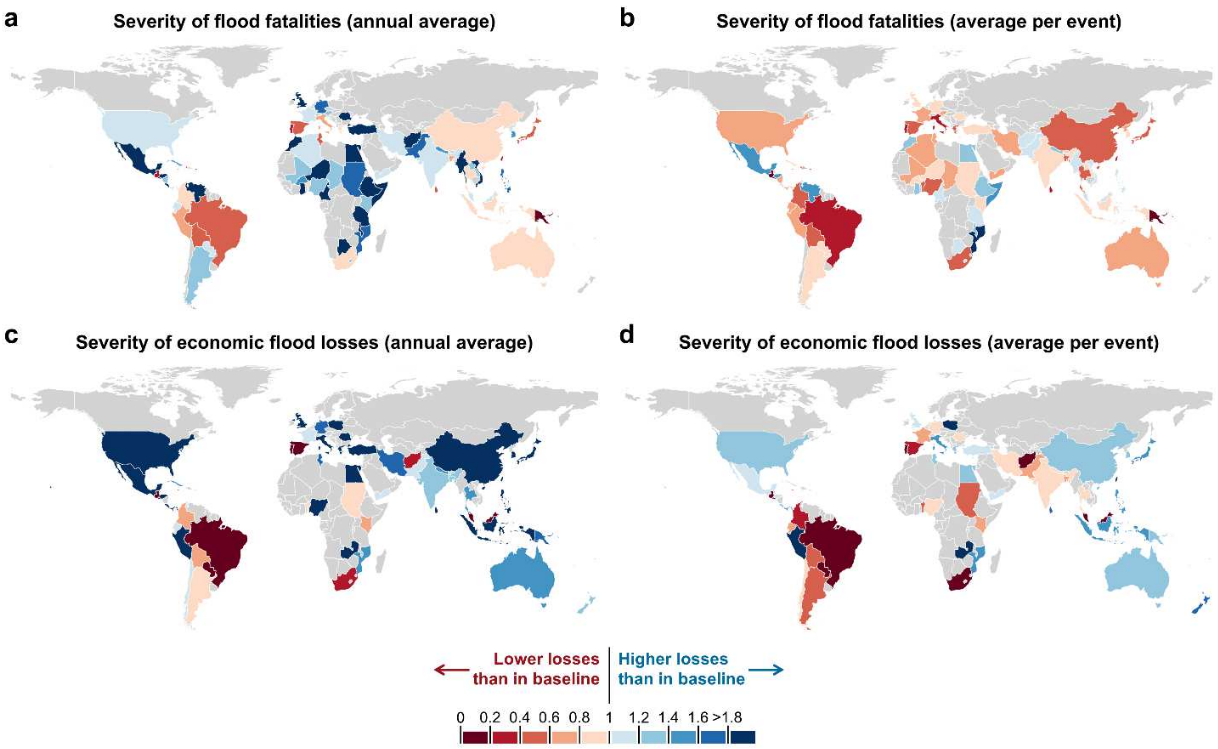


Figure 4. Spatial distribution at global scale of severity of flood fatalities (a-b) and economic flood losses (c-d) estimated (at country level) as annual average (a-c) and average per event (b-d) considering the baseline period 1975-2000 and the exposure period 1990-2000. Grey colors indicate countries in which either no floodplain data or recorded flood events are available. Increasing flood losses (severity of flood exposure higher than 1) are represented with a scale of blue color, while decreasing values (severity of flood exposure lower than 1) are represented with a scale of red color.

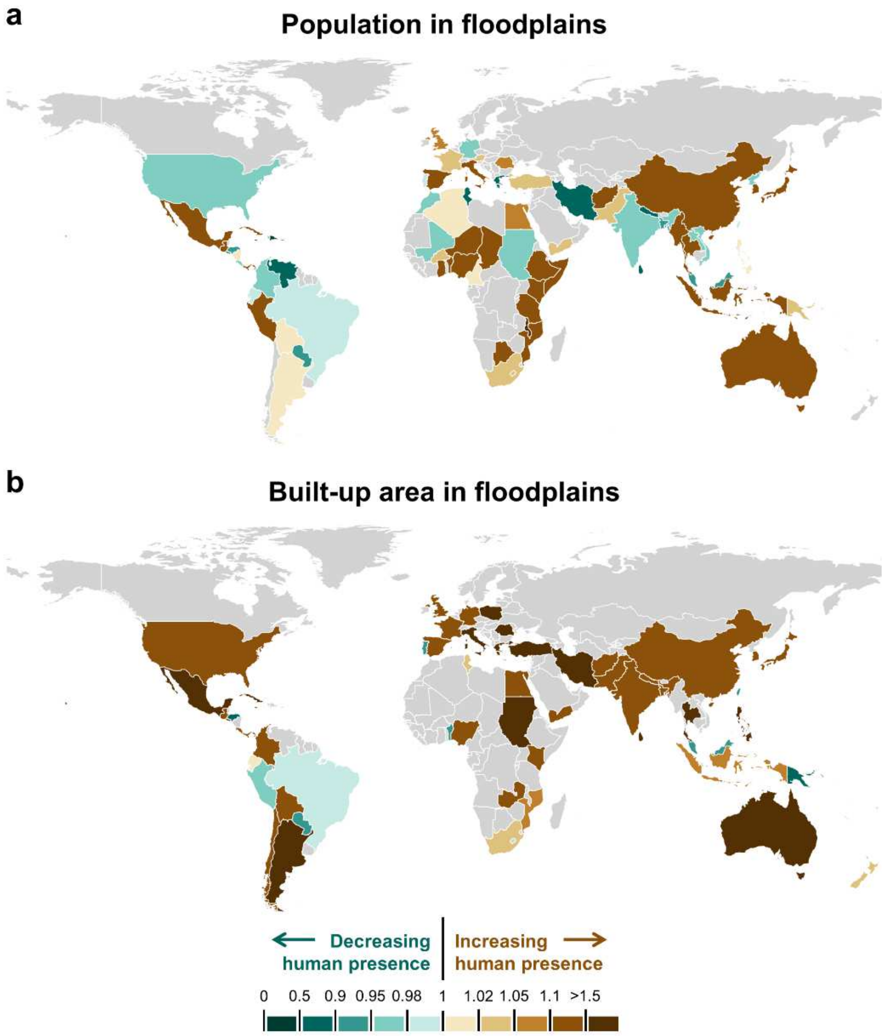


Figure 5. Spatial distribution at global scale of human presence change index between 2000 and 2015. Grey colors indicate countries in which either no floodplain data or recorded flood events are available. Increasing human presence (human presence change index higher than 1) are represented with a scale of brown color, while decreasing values (human presence change index lower than 1) are represented with a scale of brown color.

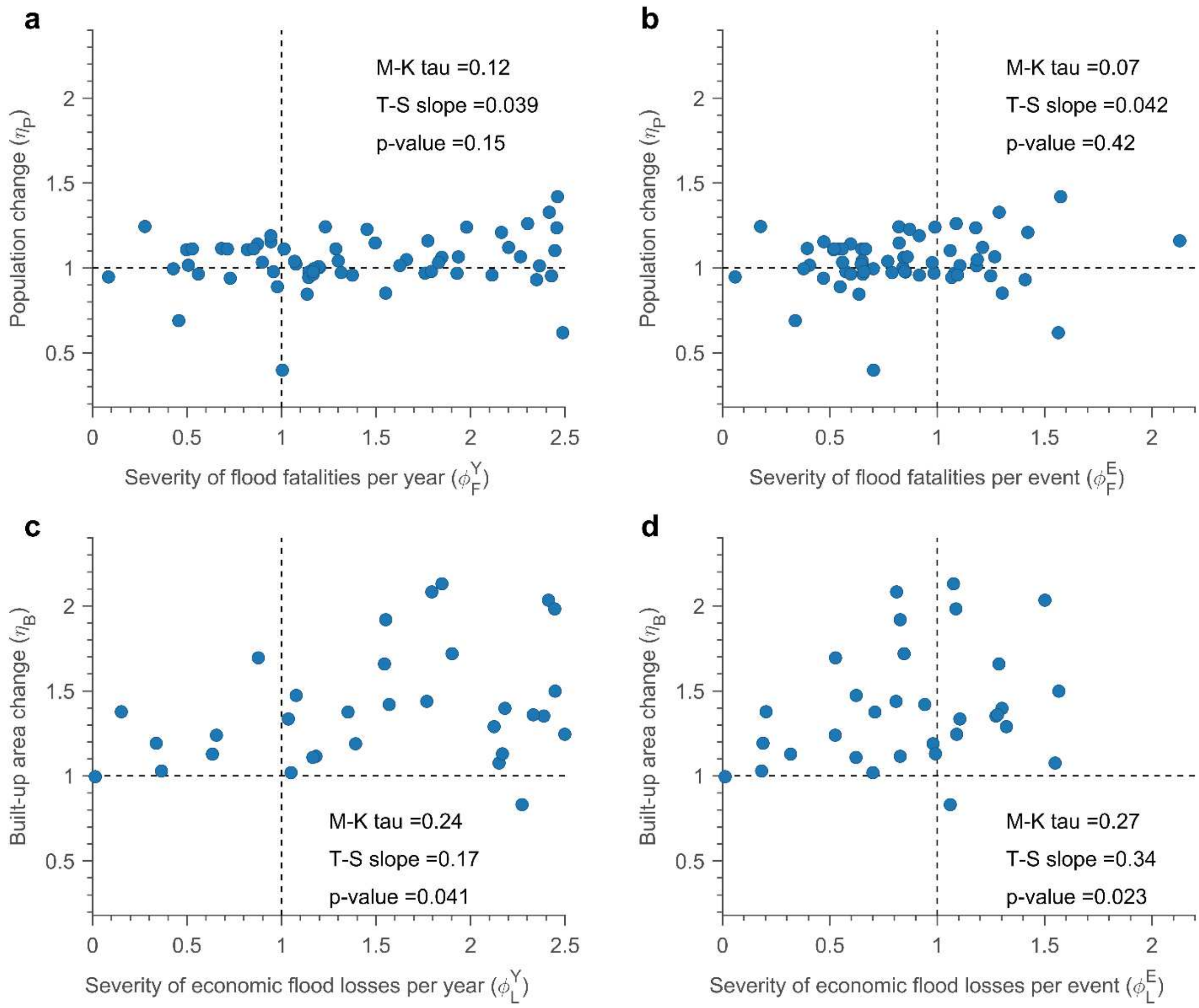


Figure 6. Change in population in floodplains in relation to the severity of flood fatalities (a-b), and built-up areas in relation to economic flood losses (c-d), estimated as annual average (a-c) and average per event (b-d) in case of 3 minimum recorded flood event in the exposure period. Thiel-Sen regression slope (T-S slope) and p-value are also calculated and showed in each scatter sub-plot.

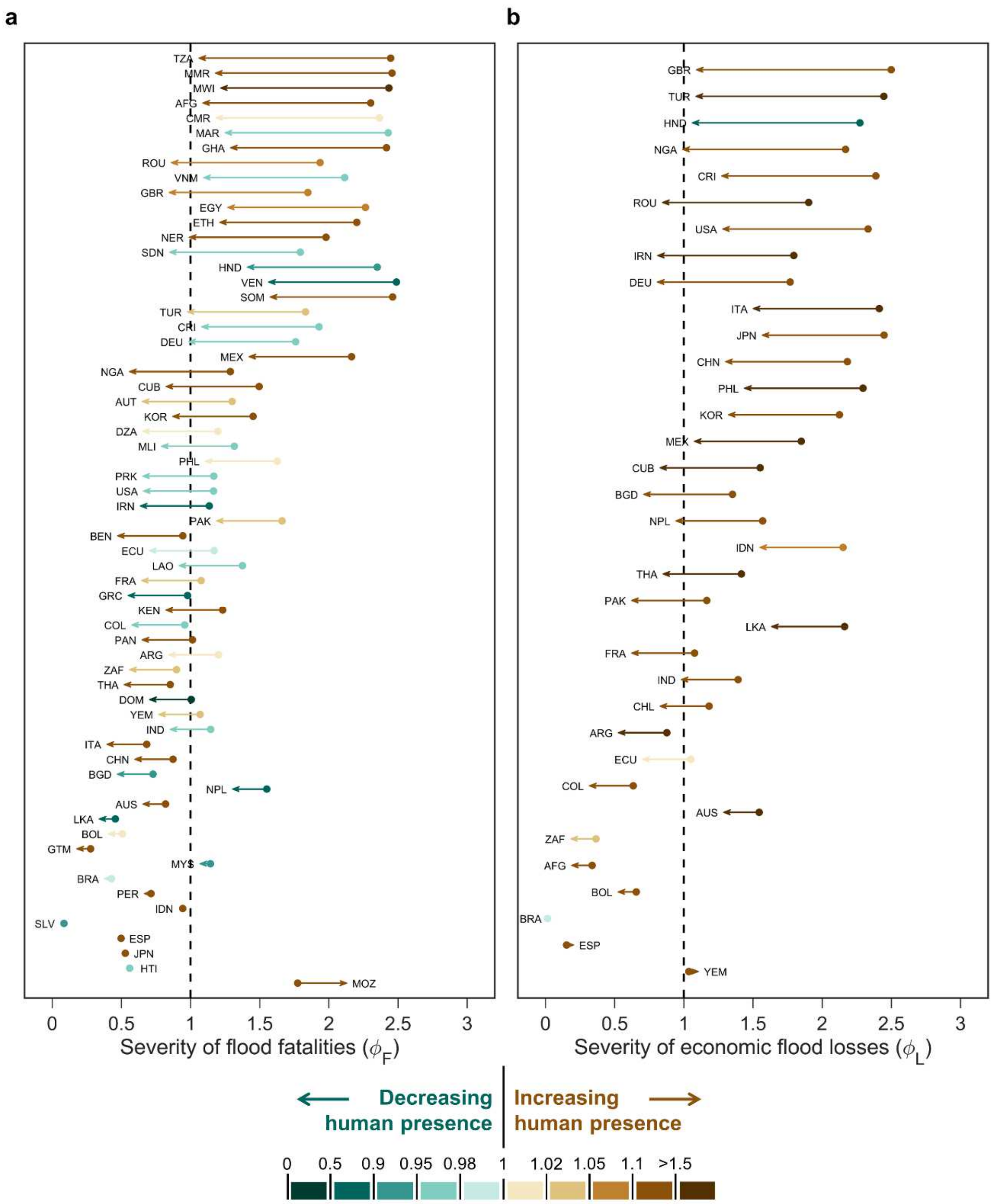


Figure 7. Comparative analysis between severity of flood fatalities (a) and severity of economic flood losses (b) with changing in floodplain human presence at country level in case of 3 minimum recorded flood events in the exposure period. For each country (displayed using an alpha-3 ISO country code), the dot corresponds to the severity of flood exposure calculated as annual average (ϕ^Y), while the ending point of the arrow corresponds to the severity of flood exposure estimated as average per event (ϕ^E). Countries are ordered from top to bottom by decreasing difference between ϕ^Y and ϕ^E.

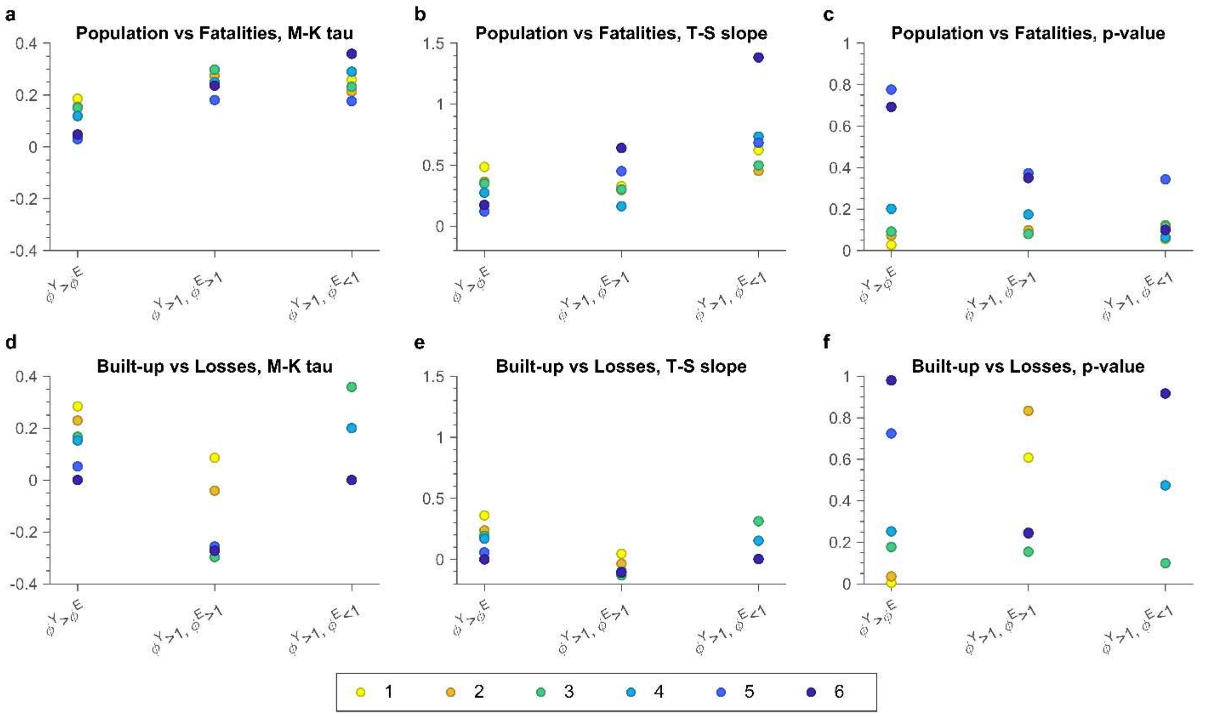


Figure 8. Results of the sensitivity analysis showing the Kendall's tau (a and d) Theil-Sen's (T-S) regression slope values (panels b and e) and p-values (panels c and f) for the different scenarios of severity of flood losses (flood fatalities and economic flood losses) calculated as annual average (ϕ^Y) and average per event (ϕ^E), compared with population and built-up area changes in the period 2000-2015 in floodplains for different minimum values of flood events in the exposure period.

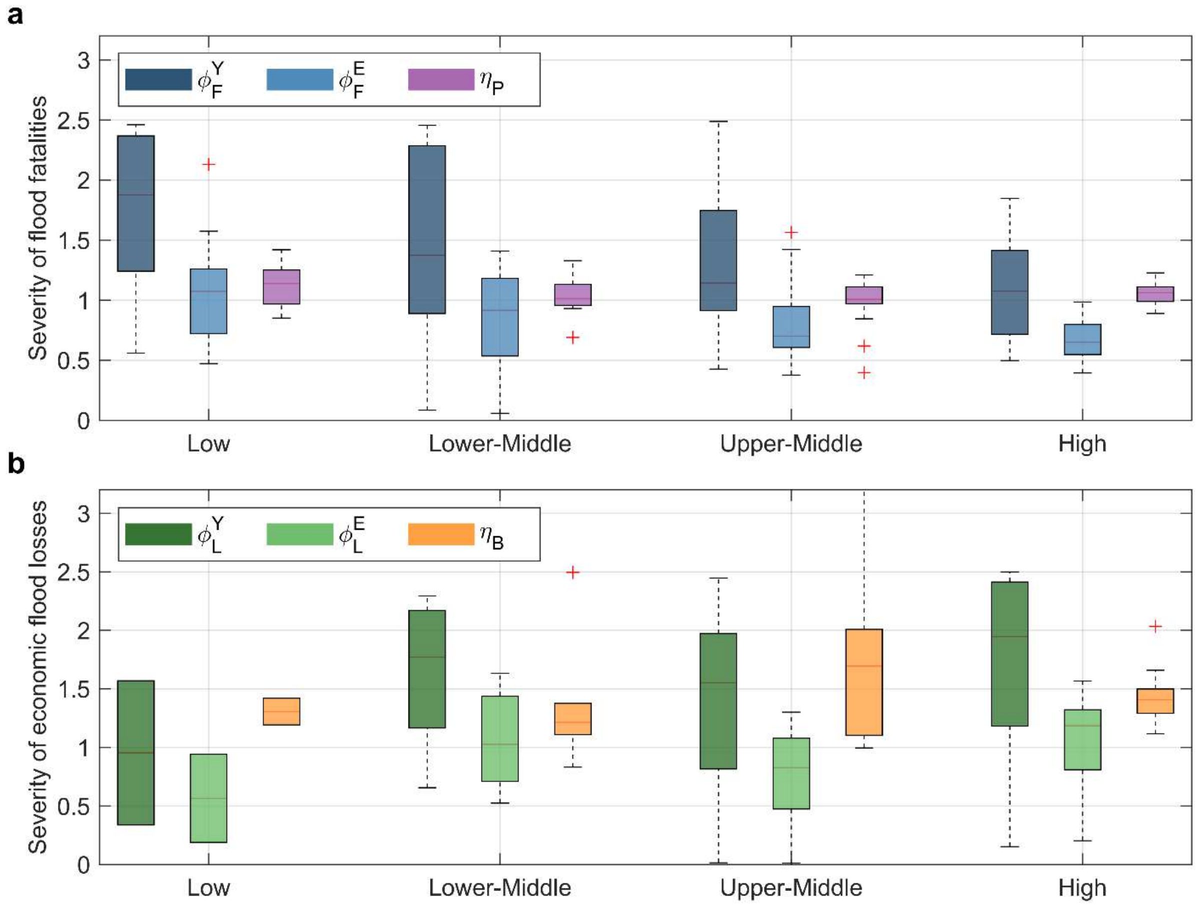
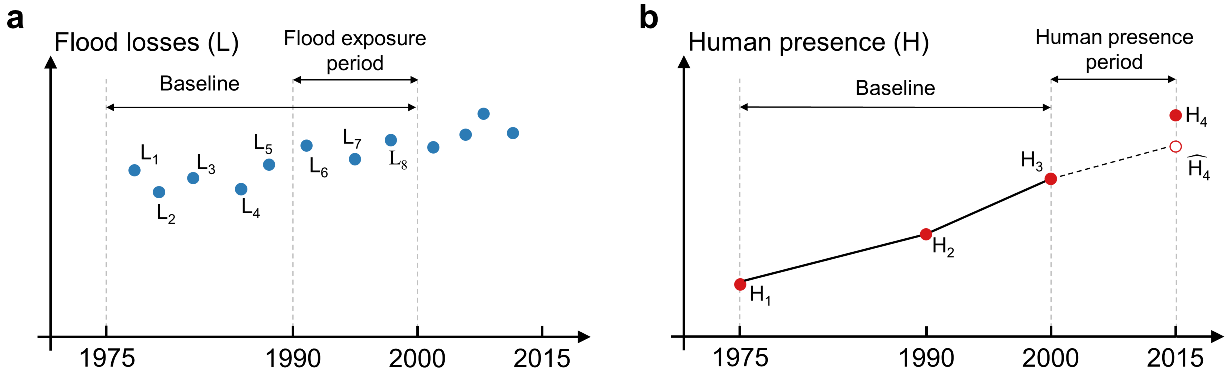
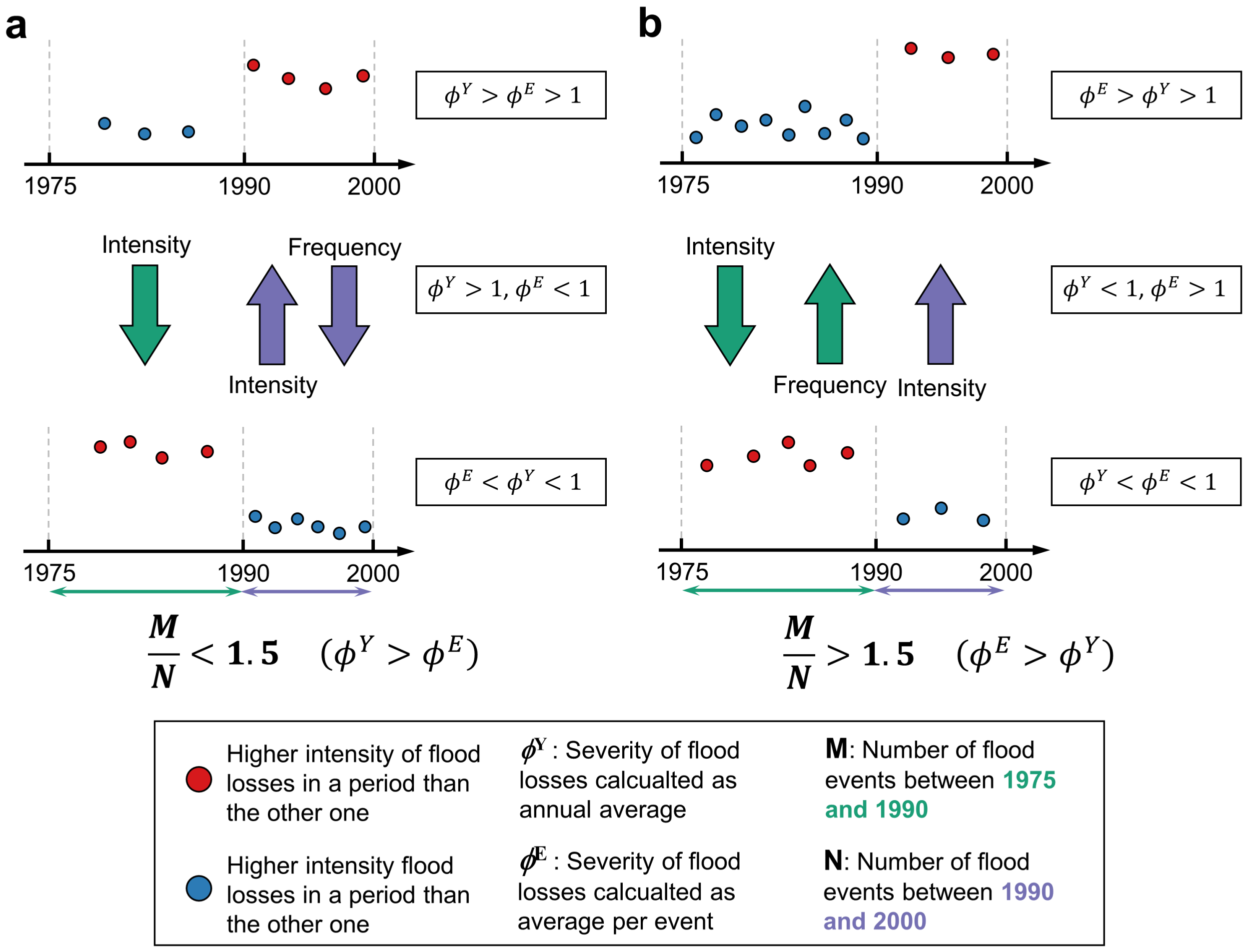
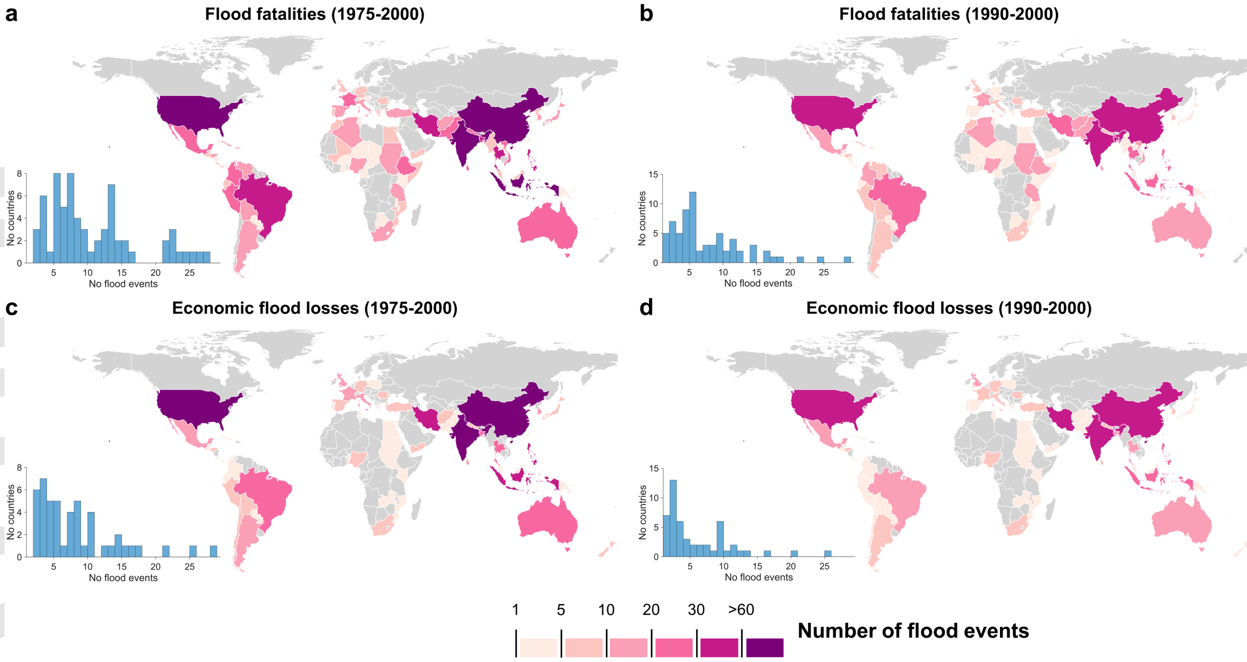
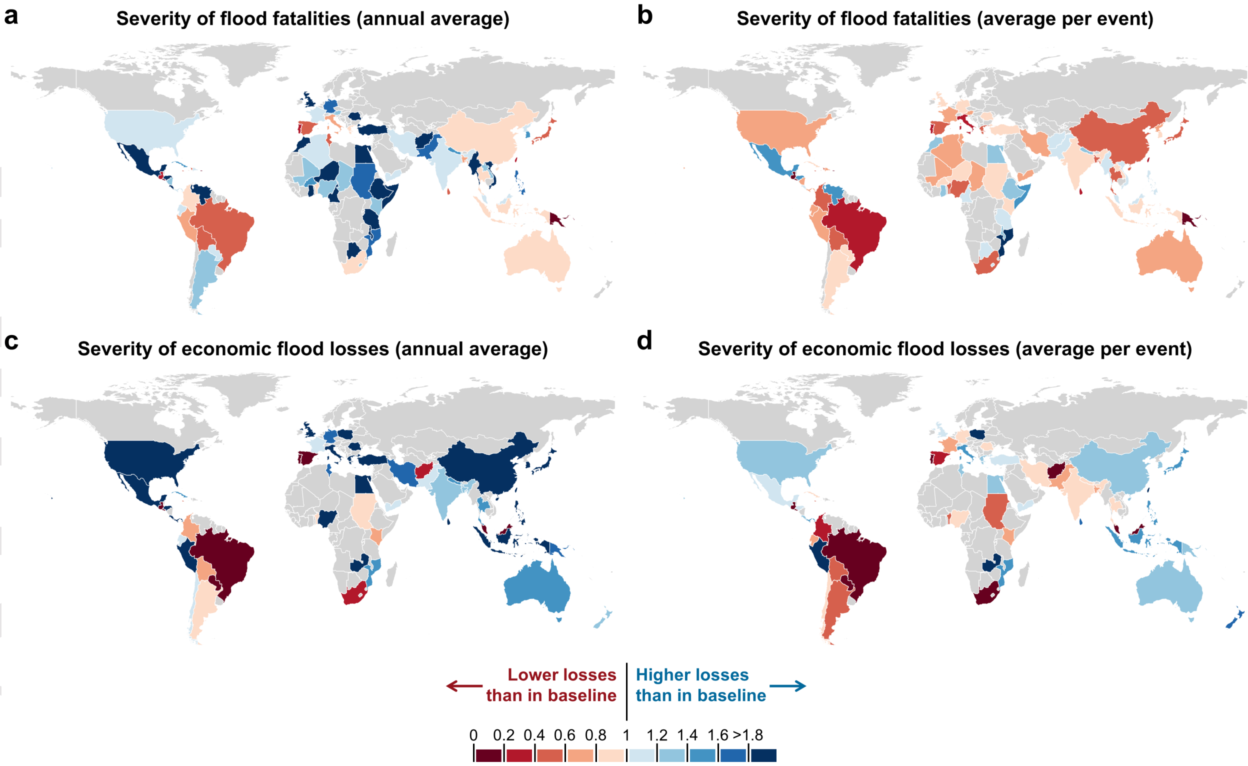


Figure 9. Variation of the severity of flood fatalities (a) and severity of economic flood losses (b) calculated as annual average (ϕ^Y) and average per event (ϕ^E) for the different country income level (low, lower-middle, upper-middle, and high) in case of 3 minimum recorded flood events in the exposure period. Change in population (a) and built-up area (b) in floodplains are also visualized for the different country income levels.

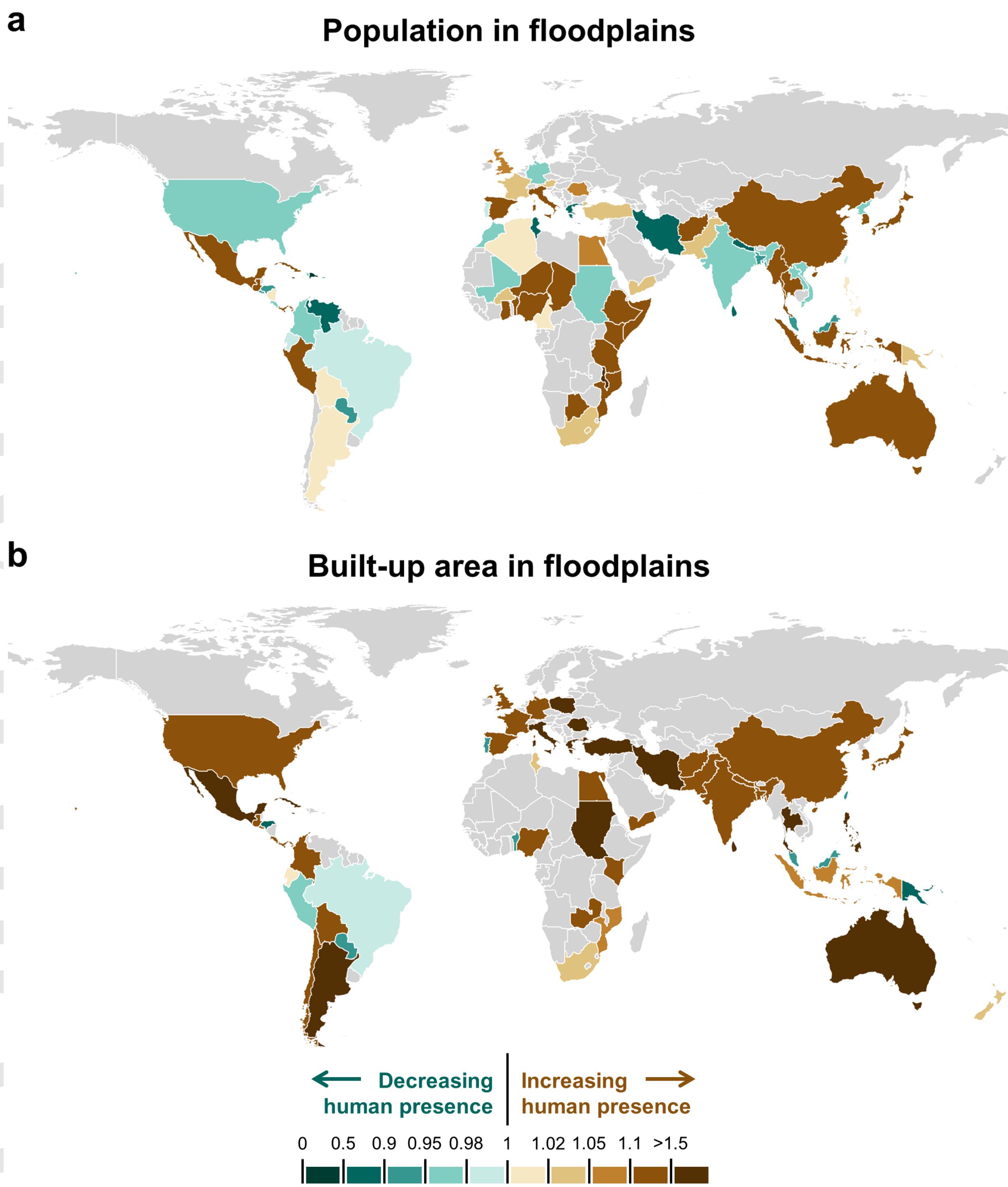

a
Flood losses (L)
Flood exposure period
Baseline
L1
L2
L3
L4
L5
L6
L7
L8
1975
1990
2000
2015
b
Human presence (H)
Human presence period
Baseline
H1
H2
H3
H4
1975
1990
2000
2015

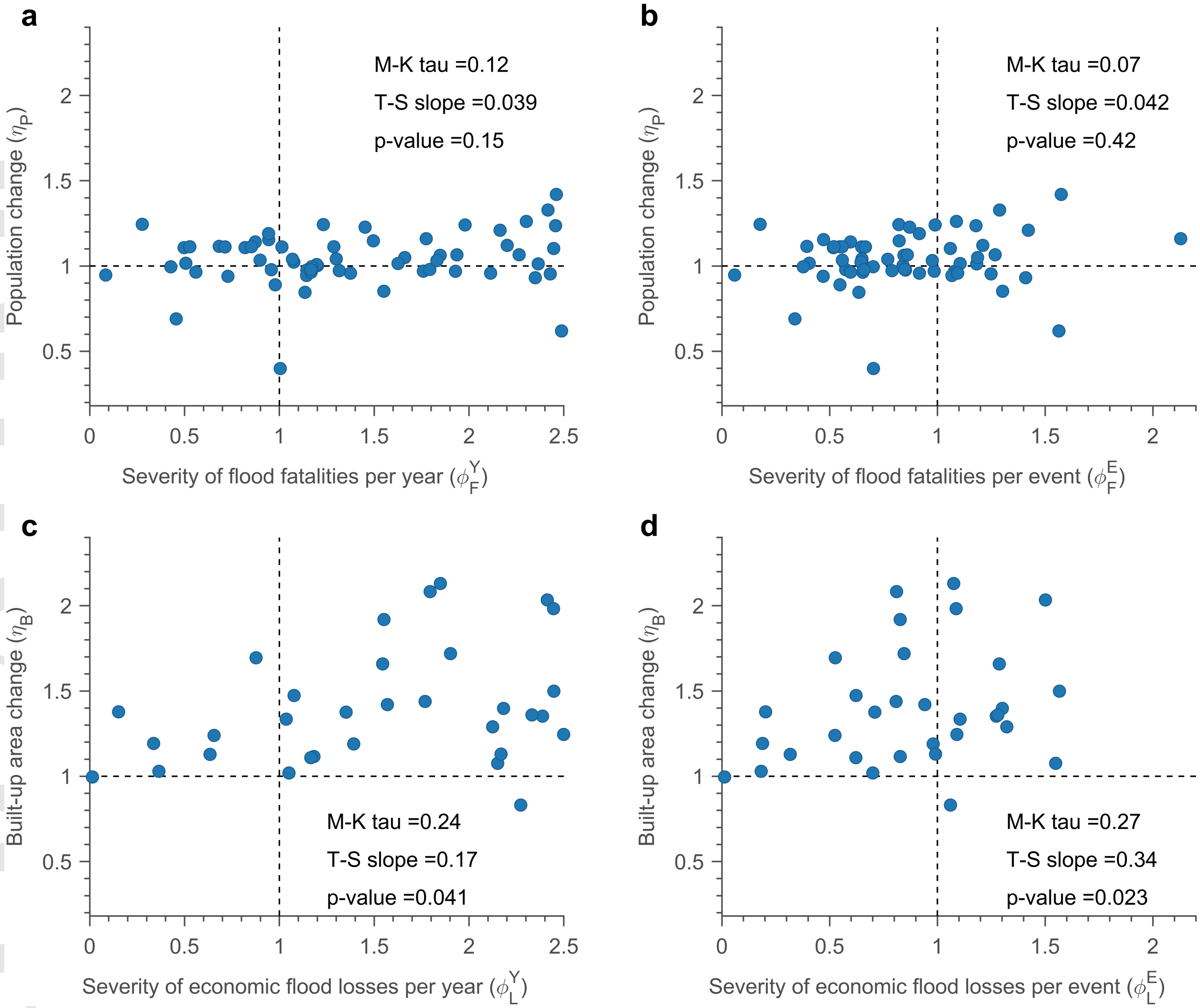

a
1975
1990
2000
$\phi^Y > \phi^E > 1$
Intensity
Frequency
Intensity
$\phi^Y > 1, \phi^E < 1$
$\phi^E < \phi^Y < 1$
$\frac{M}{N} < 1.5 \quad (\phi^Y > \phi^E)$
b
$\phi^E > \phi^Y > 1$
Intensity
Frequency
Intensity
$\phi^Y < 1, \phi^E > 1$
$\phi^Y < \phi^E < 1$
$\frac{M}{N} > 1.5 \quad (\phi^E > \phi^Y)$
Higher intensity of flood losses in a period than the other one
Higher intensity flood losses in a period than the other one
ϕ^Y : Severity of flood losses calcualted as annual average
ϕ^E : Severity of flood losses calcualted as average per event
M: Number of flood events between 1975 and 1990
N: Number of flood events between 1990 and 2000

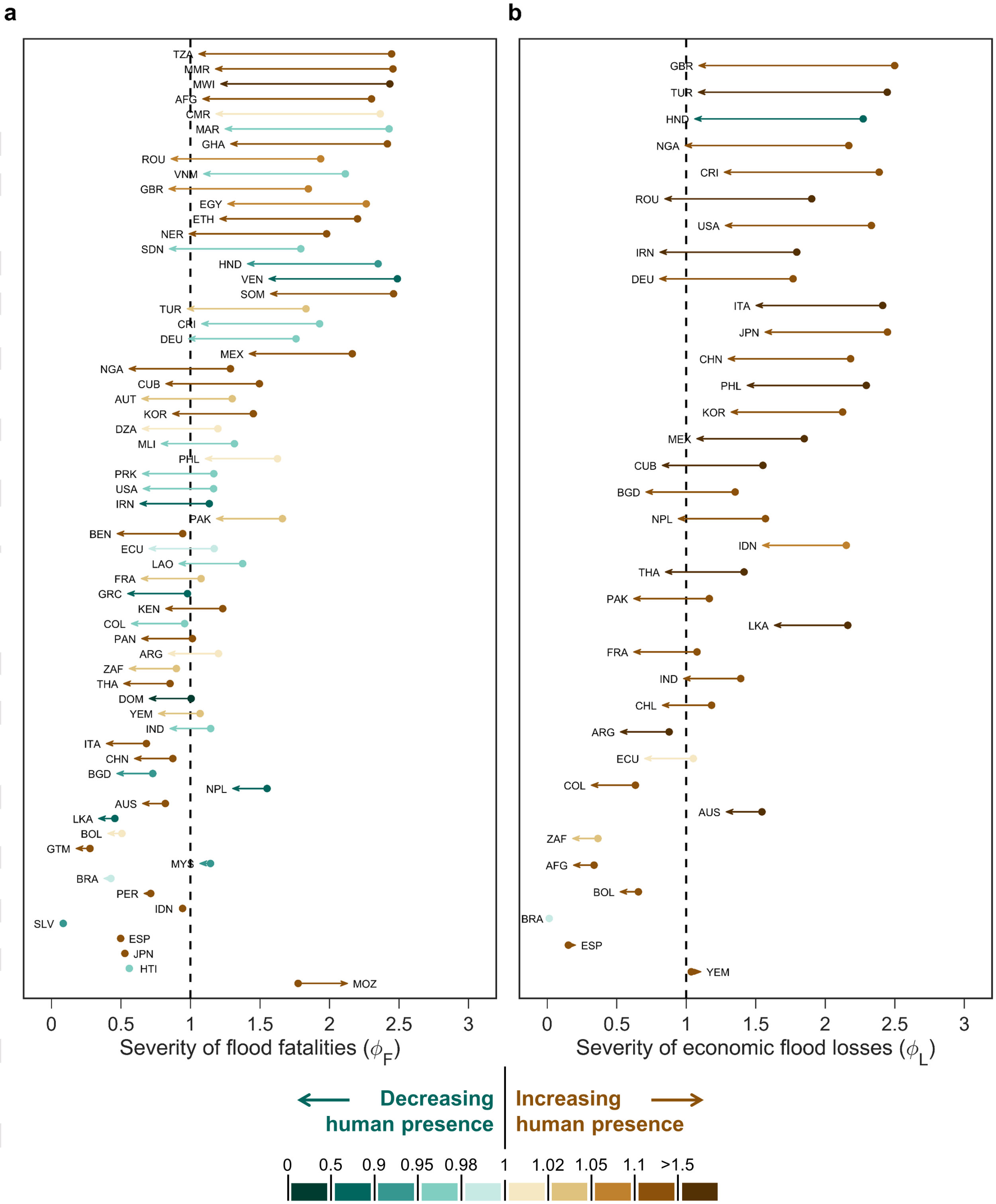

a
Flood fatalities (1975-2000)
b
Flood fatalities (1990-2000)
c
Economic flood losses (1975-2000)
d
Economic flood losses (1990-2000)
No countries
No flood events
1
5
10
20
30
>60
Number of flood events

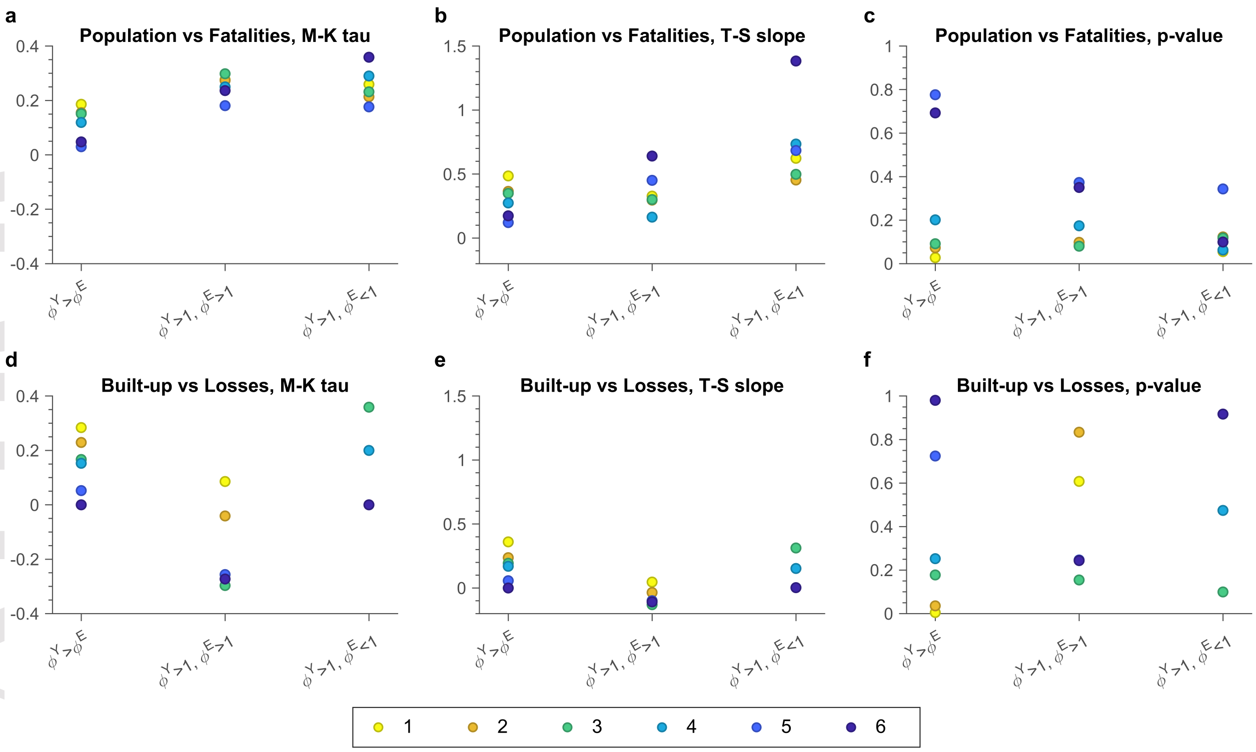


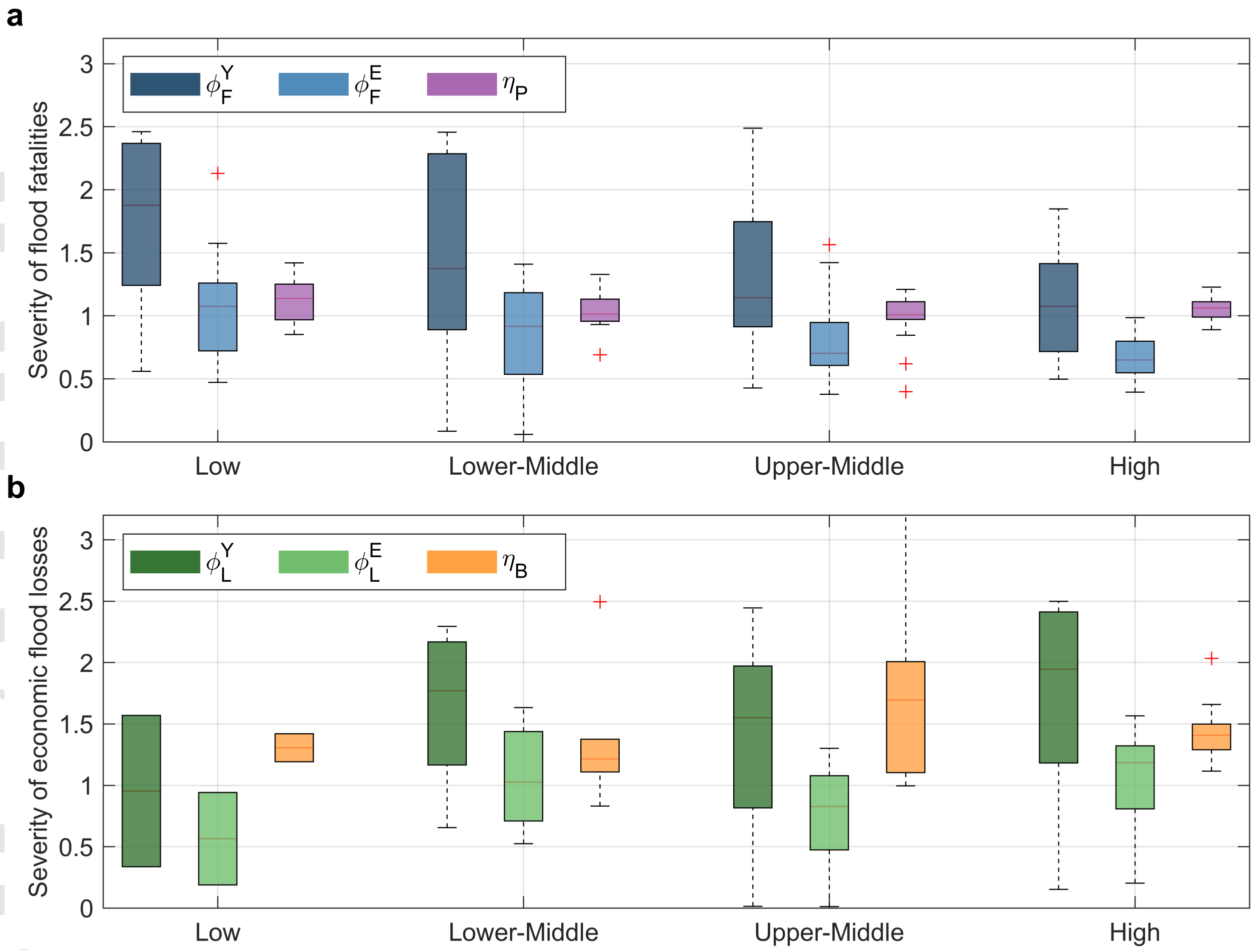
a
Severity of flood fatalities (annual average)
b
Severity of flood fatalities (average per event)
c
Severity of economic flood losses (annual average)
d
Severity of economic flood losses (average per event)
Lower losses than in baseline
Higher losses than in baseline
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 >1.8


a
Population in floodplains
b
Built-up area in floodplains
Decreasing
human presence
Increasing
human presence
0
0.5
0.9
0.95
0.98
1
1.02
1.05
1.1
>1.5


a
M-K tau =0.12
T-S slope =0.039
p-value =0.15
Population change (η_P)
Severity of flood fatalities per year (ϕ_F^Y)
b
M-K tau =0.07
T-S slope =0.042
p-value =0.42
Population change (η_P)
Severity of flood fatalities per event (ϕ_F^E)
c
M-K tau =0.24
T-S slope =0.17
p-value =0.041
Built-up area change (η_B)
Severity of economic flood losses per year (ϕ_L^Y)
d
M-K tau =0.27
T-S slope =0.34
p-value =0.023
Built-up area change (η_B)
Severity of economic flood losses per event (ϕ_L^E)


a
b
TZA
MMR
MWI
AFG
CMR
MAR
GHA
ROU
VNM
GBR
EGY
ETH
NER
SDN
HND
VEN
SOM
TUR
CRI
DEU
MEX
NGA
CUB
AUT
KOR
DZA
MLI
PHL
PRK
USA
IRN
PAK
BEN
ECU
LAO
FRA
GRC
KEN
COL
PAN
ARG
ZAF
THA
DOM
YEM
IND
ITA
CHN
BGD
NPL
AUS
LKA
BOL
GTM
MYS
BRA
PER
IDN
SLV
ESP
JPN
HTI
MOZ
0 0.5 1 1.5 2 2.5 3
Severity of flood fatalities (ϕ_F)
GBR
TUR
HND
NGA
CRI
ROU
USA
IRN
DEU
ITA
JPN
CHN
PHL
KOR
MEX
CUB
BGD
NPL
IDN
THA
PAK
LKA
FRA
IND
CHL
ARG
ECU
COL
AUS
ZAF
AFG
BOL
BRA
ESP
YEM
0 0.5 1 1.5 2 2.5 3
Severity of economic flood losses (ϕ_L)
Decreasing human presence
Increasing human presence
0 0.5 0.9 0.95 0.98 1 1.02 1.05 1.1 >1.5


a
Population vs Fatalities, M-K tau
b
Population vs Fatalities, T-S slope
c
Population vs Fatalities, p-value
d
Built-up vs Losses, M-K tau
e
Built-up vs Losses, T-S slope
f
Built-up vs Losses, p-value
1
2
3
4
5
6


a
Severity of flood fatalities
ϕ_F^Y
ϕ_F^E
η_P
0
0.5
1
1.5
2
2.5
3
Low
Lower-Middle
Upper-Middle
High
b
Severity of economic flood losses
ϕ_L^Y
ϕ_L^E
η_B
0
0.5
1
1.5
2
2.5
3
Low
Lower-Middle
Upper-Middle
High