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How can Changes in the Human-Flood Distance Mitigate Flood Fatalities and Displacements?

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Key Points:

- 53% of countries witnessed humans distancing themselves from floods between 2000 and 2018, especially those in the Middle East
- Humans distancing from the floods leads to a substantial reduction in both flood fatalities and flood displaced population
- Humans residing in regions with a high flood protection level tend not to move away from the flood

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Comprehending the correlation between alterations in human-flood distance and flood fatalities (as well as displacements) is pivotal for formulating effective human adaptive strategies in response to floods. However, this relationship remains inadequately explored in existing global analyses. To address this gap, we examine 910 flood events occurring from 2000 to 2018, resulting in significant numbers of fatalities and displacements. We find that in 53% of countries, humans tend to distance from floods, particularly in the Middle East. Such distancing greatly mitigates flood fatalities and displacements. Simultaneously, in areas with increased flood protection level (FPL), humans are less likely to move away from floods. Furthermore, FPL and human-flood distance have decreased in regions affected by ice jam- and hurricane-induced floods from 2000 to 2018. Notably, regions with human-flood distance slightly below the average for a given flood type experience more severe flood fatalities.

Plain Language Summary People have developed effective ways (i.e., distancing from flood and increasing flood protection level) to adapt and minimize the impact of catastrophic floods on exposed populations. However, the relationship between these behaviors and flood fatalities (as well as displacements) is not well understood on a global scale. To address this knowledge gap, we study 910 flood events that occurred between 2000 and 2018, leading to significant fatalities and displacements. We find that in 53% of countries, people tend to move away from flood-affected areas, especially in the Middle East. This distancing behavior greatly reduces the number of fatalities and displaced individuals caused by floods. Additionally, in areas with higher flood protection level, people are less likely to relocate away from floods. Over the studied period, both flood protection levels and the distance between humans and flood-prone areas have decreased in regions affected by ice jam- and hurricane-induced floods. Importantly, regions where the distance between humans and floods is slightly below the average for a given flood type experience more severe flood fatalities. These findings could help improve the efficiency of flood control management and the adoption of adaptive policies.

1. Introduction

Flooding is one of the most frequent and damaging natural hazards negatively affecting many regions of the world. In the last 20 years, the total fatalities and losses exceeded 105 thousand people and 651 billion US$, respectively (UNDRR, 2020). Global flood fatalities over the past decades have been attributed mainly to increasing exposure of people due to population growth in flood-prone areas (Bouwer, 2011; Jongman et al., 2015; Mård et al., 2018). The impact of floods on society mainly depends on the long-term adaptation and human response to flood events (Melvin et al., 2017; Quesnel & Ajami, 2017), as well as the flood risk management and the adoption of the control measures. However, the understanding of the relationship between human adaptive behaviors and flood fatalities and displacements remains vague in existing national to continental-scale flood risk assessments.

Humans either passively or actively engage in adaptive behaviors to mitigate the impact of the natural floods on the exposed socioeconomic elements, which are embodied in resettling further away from flood-prone areas, reinforcing structural flood defenses to improve the flood protection level, introducing quality early warning systems, investing in available health care and raising public awareness of risk aversion (Aerts et al., 2014; Di Baldassarre et al., 2010; Hino et al., 2017; Jongman et al., 2015). Some countries have even implemented managed retreat plans to discourage the human presence in the flood-prone areas as a means to mitigate future flood damages

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(Bronen & Chapin, 2013; Hino et al., 2017; Siders, 2019). However, these measures are likely to be more controversial due to society lacking a systematic understanding of the relationship between flood fatalities (as well as displacements) and the human resettlement behavior. Moreover, the dynamics of resettlement, as one of the representative human adaptive behaviors to flood, whether by managed retreat or spontaneous migration (Hino et al., 2017; Mård et al., 2018), has not been thoroughly described. Thus, a quantitative description of changes in human-flood distance and an understanding of its role in mitigating flood fatalities and displacements are needed in order to understand the interplay between human adaptive behaviors and flood fatalities, and ultimately the evolution of flood risk dynamics over time.

The research regarding the spatiotemporal relationship between human adaptive behaviors (i.e., changes in human-flood distance, flood protection level increase) and flood fatalities and displacements is currently accelerated by the emergence of remote-sensing big data circumventing the shortcomings of traditional census data (Collenteur et al., 2015). For example, Ceola et al. (2014, 2015) used nighttime light data to explore the spatial distribution of humans along the rivers for 1992–2013 and found a higher human concentration in the vicinity of the river network. Mård et al. (2018) found that societies with low protection levels tend to resettle further away from the river after experiencing damaging flood events while the ones with high protection level show no significant changes in resettling. Moreover, Mazzoleni et al. (2021) analyzed the interplay between the severity of flood losses and human presence in floodplain areas and found that in low-income countries population increased in floodplains even after experiencing a period of high flood fatalities. Most studies focus on the distance between people and rivers based on a fixed river network. However, this distance is often influenced by factors like water use rather than actual experience with flooding. We believe that looking at the area that gets flooded over time provides more detailed and reliable information for drawing conclusions. The flood-alleviating effects of cliffs, dams, and reservoirs remains conspicuously absent from extant explanatory analyses of flood-induced resettlement. Furthermore, the absence of a comprehensive assessment pertaining to the consequences of human-flood distance alterations on flood fatalities and displacements, along with the examination of the variability in human-flood distance across various flood types on a global scale, underscores a significant gap in existing research.

Here, we focus on the relationship between human-flood distance and flood fatalities and displacements on a global scale. To investigate changes in human-flood distance over a specified time period (2000–2018), we utilize spatiotemporal population data along with global flood inundation data (GFD, Tellman et al. (2021a)). These data sets are chosen based on their availability and coverage for the selected timeframe. The GFD specifically covers 910 significant flood events that resulted in 10 or more flood fatalities or affecting at least 100 people. This allows us, on the one hand, to precisely consider the protective influence of cliffs, dams, and reservoirs on individuals residing in flood-prone regions, and on the other hand, to focus more into areas that are flood-prone based on historical evidence. Moreover, we examine the correlation between human adaptive behaviors, as referenced by changes in human-flood distance and flood protection level, and flood fatalities (as well as displacements), and formulate a robust expression for this relationship explaining how certain adaptive behaviors mitigate flood fatalities. Furthermore, we investigate the heterogeneity of human-flood distance characteristics across different flood types.

2. Materials and Methods

2.1. Data and Processing

Six global data sets are used to explore the relationship between the human-flood distance and flood fatalities and displacements. The GFD data, which contains 910 large flood events documented by the Dartmouth Flood Observatory, is used to assess the dynamic changes of flood inundated areas for the period 2000–2018 at a spatial resolution of 250 m. The GFD is derived from a combination of the moderate-resolution imaging spectroradiometer (MODIS) satellite and global HydroSHEDS watersheds (Lehner & Grill, 2013), and has been reported to be a valuable data set for validating large flood inundated areas (Tellman et al., 2021b).

The spatiotemporal population data for the period 2000–2018 with a spatial resolution of 1 km is obtained from the Gridded Population of the WorldPop (POP, University of Southampton (2020)), which incorporates multiple spatial data sets into population mapping and has been widely used for describing the distribution of the population reliably (Lloyd et al., 2017; Ye et al., 2019). We employ Digital Elevation Model (DEM, Jarvis A.

et al. (2008)) and Global Reservoir and Dam (GranD, Lehner et al. (2011)) data sets to identify the areas around cliffs, dams and reservoirs, which are not susceptible to flooding (lower human proximity to flood). Otherwise, the human proximity to flood in these areas would be falsely higher.

Moreover, the national levels of structural flood protection (FPL, return period years) derived from Flood Protection Standards (FLOPROS) (Scussolini et al., 2016) is employed to reflect other human adaptive behaviors to flooding. Noted that we converted FLOPROS to a raster with a resolution of 1 km and counted the mean at the national and event scale as the FPL for each country and flood event. The flood fatalities and displacements data are retrieved from the Global Active Archive of Large Flood Events (GAALFE, Brakenridge (2021)) for the time frame spanning 2000 to 2018. The aforementioned data source additionally offers comprehensive information regarding the underlying factors contributing to each flood event. More details of the data sets are given in Table S1 in Supporting Information S1.

2.2. Human-Flood Distance

To provide a quantitative description of the human response to flooding over time, a method was developed to enhance the calculation of changes in human-flood distance for the period 2000–2018. Human-flood distance refers to the measurement of the separation between human settlements and the flood-inundated regions during each flood event. A greater numerical value signifies a reduced flood risk, resulting in fewer flood fatalities and displacements. Conversely, a smaller numerical value indicates a higher flood risk, potentially leading to an increase in flood fatalities and displacements. It's important to emphasize that we calculate the slope (km/year) of the human-flood distance over the specified time frame to characterize the change in human-flood distance. A positive slope indicates that human distanced from floods during the study period, signifying an increase in population in regions situated farther from floods. While a negative slope indicates they moved closer to floods, signifying an increase in population in regions located nearer to floods.

The method is built on the one proposed by Ceola et al. (2015) and differs in the following aspects: (a) We use the dynamically changing global flood inundated extent data, instead of the invariant river network, to represent the flood dynamics over time; (b) We use the annual-scale distribution of the population at a resolution of 1 km, instead of the nighttime light data, to enable the investigation of whether humans are moving closer to or farther from the flood, as evidenced by changes in human-flood distance; and (c) We explicitly incorporate the areas surrounding cliffs, dams, and reservoirs into our calculations to account for the tendency of individuals residing in these regions to experience reduced flood risks. Without this consideration, the method would inadvertently lead to an overestimation of the risks.

To identify spatiotemporal changes in human distribution to flood (see Figure S1 in Supporting Information S1), we buffer and divide the flood extent for each flood event, obtained from the GFD data, into 4 distinct distance-from-flood classes ranging from 0 to 4 km with a 1 km stepwise increase. All the global data sets used in identifying the human-flood distance are at a resolution of 1 km. Areas covered by flood inundated area are classified as class-0, areas adjacent to class-0 are defined as class-1, whereas the other 3 classes are defined from concentric zones. Similar to Ceola et al. (2015), the areas with a distance from the flood inundated extent greater than 4 km are excluded from the analysis, since these areas are less vulnerable to flood damage. Moreover, we use the DEM and GranD data sets to identify the areas where the cliffs (with a slope greater than 60°, Guzzetti et al. (2003)), dams and reservoirs are located and re-rank the classes greater than 0 into 4 along the vertical direction of these areas. First, we compute the absolute sum of populations within each distance class for every flood event and the weighted average of class abundance, where the weight is determined by the relative sum of populations. These calculations are then aggregated at the level of individual flood events (the detailed calculation methods can be found in Ceola et al. (2015)). It's noted that a subset of floods exhibits a transnational nature, constituting 13.5% of the selected flood events, with rare instances of spanning across continents. In terms of flood fatalities and displacements, these data are derived from the GAALFE at the flood event level, without division into national scales. Analyzing at the national level would introduce uncertainties in the allocation of flood fatalities and displacements. Hence, we employ the average distance value of each flood event that occurs within a particular year and continent as a representative measure to portray the attributes of human-flood distance within that specific continent. Second, we employ regression analysis to illustrate the potential of changes in human-flood distance in mitigating flood fatalities and displacements. We also investigate the heterogeneity of human-flood distance characteristics across diverse FPLs and flood types.

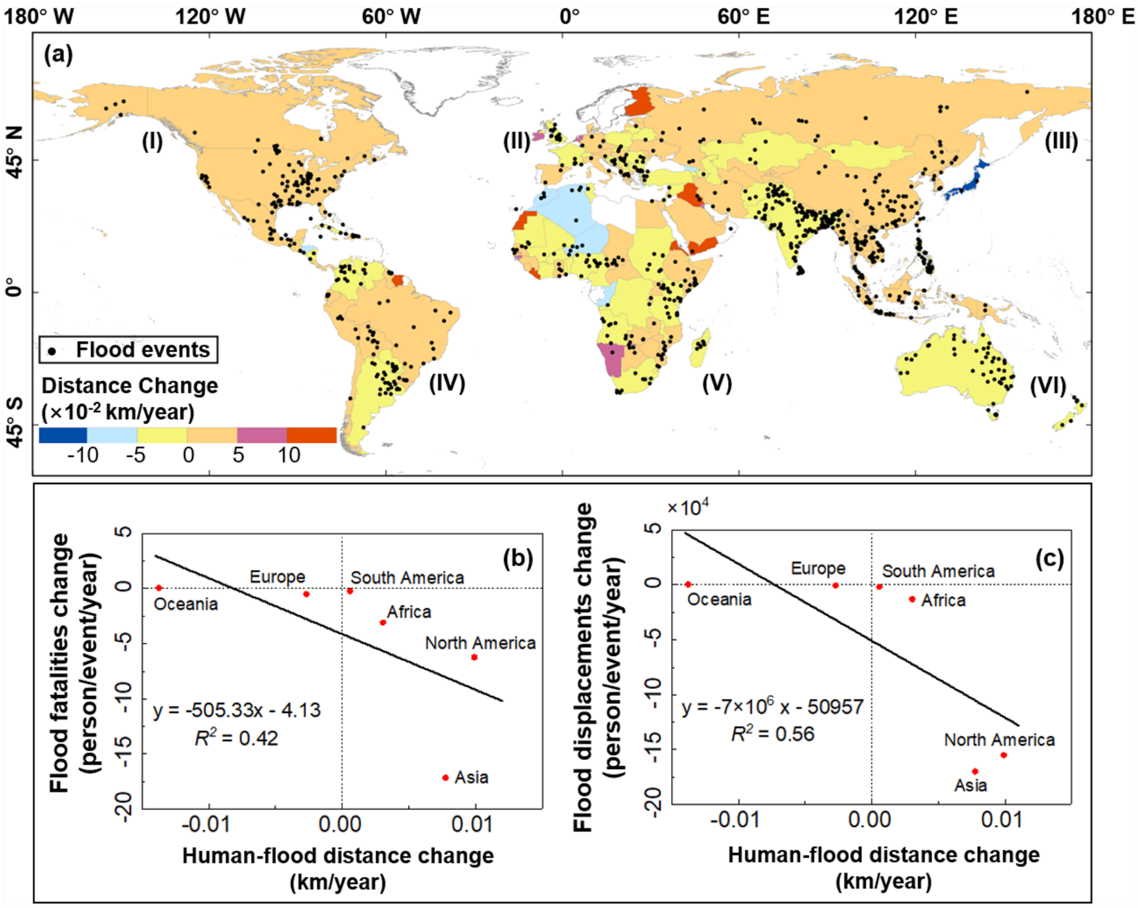

Figure 1. (a) Overview of the changes in human-flood distance (distance change, $\times 10^{-2}$ km/year) at a national level and the geographic locations of 910 selected flood events for the period 2000–2018. Positive values indicate that human distances from the floods, negative values indicate the opposite. Hollow values in some countries occur due to the absence of flood records in the global flood inundation data data set. The changes in human-flood distance, flood inundated area, as well as flood fatalities and displacements across six continents, labeled as (I) through (VI), for the period 2000–2018 are illustrated in Figure S2 in Supporting Information S1. The changes in flood fatalities (b) and displacements (c) are plotted as a function of human-flood distance change for the period 2000–2018 at a continental level. The black dash line is the reference line.

3. Results

3.1. Distancing From Flood Mitigates Flood Fatalities and Displacements Substantially

We calculate the changes in human-flood distance (distance change, see Section 2.2) which is represented by the regression slope obtained by a linear regression model at a national level for the period 2000–2018, as shown in Figure 1a. The global-scale analysis on distance changes shows variability for each country, with 53% of countries showing an increasing trend (distance change >0), indicating that in these countries humans tend to distance from floods over the period 2000–2018. Specifically, Middle East tends to get farther from flood than other regions, while Japan, most of Africa and Oceania tend to get closer to flood. In certain African regions, including Morocco, Algeria and Niger, that are characterized by low FPL, getting closer to flood may be attributed to limited resource availability. Analysis on continental average distance to flood (Figures S2I–S2VI in Supporting Information S1) shows that Africa was the one farthest from flood for the period 2000–2018, followed by North America, South America, Europe, Asia and Oceania. Global average distance to flood (conditioned on the range 0–4 km) is 2.62 km for the period 2000–2018.

The flood fatalities and displacements are directly related to the changes in human-flood distance (Di Baldassarre et al., 2013; López-Carr & Marter-Kenyon, 2015; Seebauer & Winkler, 2020) and flooded area (Bertilsson et al., 2019; Paprotny et al., 2018; Rozer et al., 2022). According to Figures 1b–1c, a discernible relationship can be observed, with an R^2 value of 0.42 (0.56). This relationship signifies that for every 10-m increase in distancing from floods, the

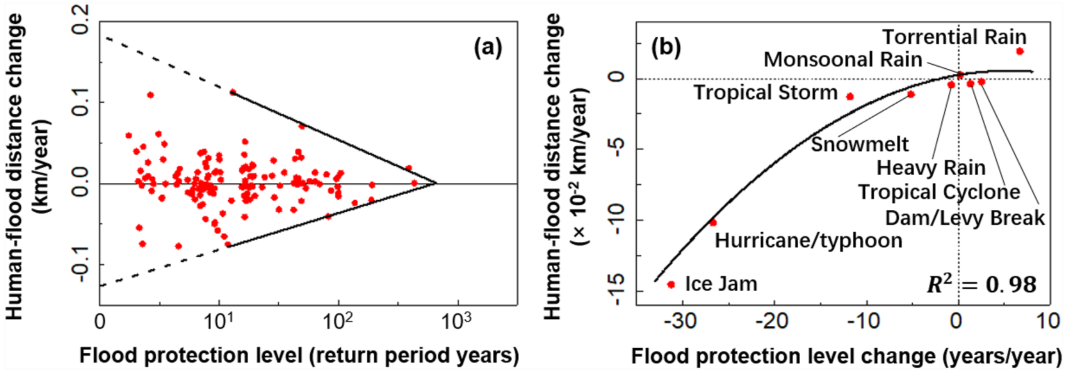

Figure 2. Relationships of human-flood distance change (in km/year) and (a) the average flood protection level (FPL, return period years) of flood events occurring within each country, (b) FPL change (in years per year) for the period 2000–2018. The solid/dash line in (a) is the reference boundary line. Distance change and FPL change across different flood types are associated by a curve with $R^2 = 0.98$. FPL changes for specific flood types are calculated by finding the yearly mean value and using a regression slope to show changes from 2000 to 2018.

estimated number of flood fatalities (displacements) is anticipated to decrease by nine (120,957) persons. This point indicates that an increase in the human-flood distance leads to a notable reduction in flood fatalities and displacements. Similarly, there exists a distinct relationship (Figure S3 in Supporting Information S1) highlighting that with each 1,000 km^2 increment in flooded area, the number of flood fatalities (displacements) is projected to increase by three (3,082) persons. These points support the notion that both distancing from floods and implementing effective flood control measures play integral and beneficial roles in mitigating the extent of flood fatalities and displacements.

3.2. The Effects of FPL on Human-Flood Distance Change

Building upon the results concerning changes in human-flood distance at the national level, as illustrated in Figure 1, we have conducted an investigation into how changes in human-flood distance are influenced by FPL. Specifically, we have examined the relationship between changes in human-flood distance and the average FPL of flood events occurring within each country, as depicted in Figure 2a. Furthermore, we have explored how changes in human-flood distance are shaped by FPL change for each flood type during the period spanning from 2000 to 2018, as shown in Figure 2b. Noted that FPL changes for specific flood types were computed by determining the mean value of these flood types for each specific year and subsequently employing a regression slope to represent the changes observed during the period from 2000 to 2018. We find human-flood distance changes convergence to 0 with FPL increasing (Figure 2a), indicating that humans exhibit a reduced tendency to relocate as the FPL improves. Humans in areas with low FPL show the full spectrum of possible behaviors, from keeping the same distance, to both increasing and decreasing thereof. It should be noted though that low FPL does not mean high flood fatalities and displacements, which explains why humans in some countries with low FPL may not change their distance. In areas with low FPL, people who tend to stay away from flood, help themselves mitigate flood fatalities. In contrast, those who tend to get closer to flood, seem willing to take more risk, seeking more of the usually limited resources.

An intriguing finding (Figure 2b) arises regarding the changes in human-flood distance and FPL across various flood types. It is observed that these changes remain minimal for floods predominantly caused by rain, such as torrential rain, monsoonal rain, and heavy rain, during the period from 2000 to 2018. In contrast, floods primarily triggered by hurricane, typhoon, and ice jam tend to occur in regions characterized by lower human-flood distance and FPL. Floods primarily triggered by ice jams, for example, exhibit the most significant changes in human-flood distance, with a decrease of 145 m per year, and in FPL, with a decrease of 31 years per year, during the period from 2000 to 2018. This finding highlights the necessity for attention and action concerning regions that are susceptible to ice jams. Strengthening efforts including resettlement initiatives and improving FPL in these regions can contribute significantly to mitigating the impact of ice jam-related flooding events.

3.3. Characteristics of Human-Flood Distance Across Different Flood Types

Distinct flood types manifest diverse characteristics in terms of human-flood distance and flood fatalities. The 910 flood events have been categorized into five groups based on their primary causes (Figure 3), allowing for a better

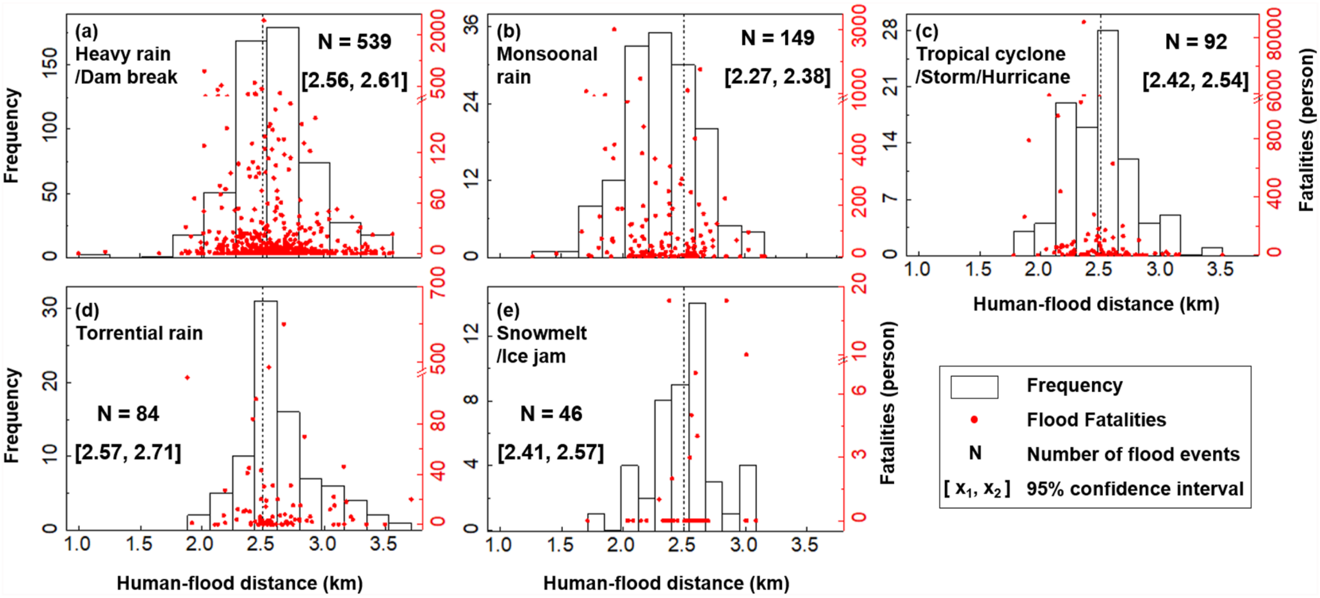

Figure 3. Characteristics of human-flood distance and associated flood fatalities across different flood types. The histograms (red points) represent the frequency (flood fatalities) related to the human-flood distance of the flood event. 95% confidence interval associated with each flood type is also presented in the figure. The dashed lines in the sub-figures represent the 2.5 km human-flood distance reference line.

understanding of the similarities and distinctions in the characteristics of human-flood distance and flood fatalities across each group. It should be noted that the grouping of flood events with similar main causes (a, c, e) is necessary due to the limited number of occurrences. For instance, floods triggered by dam break frequently exhibit concomitant heavy rain, we therefore consolidate flood events induced by heavy rain and dam break into a unified group, as depicted in Figure 3a. Floods induced by heavy rain exhibit the highest frequency of occurrence, accounting for 59% of the selected flood events. The histograms of all flood types demonstrate a close adherence to the normal distribution, with skewness less than 0.5 (Hair et al., 2019). The results of the 95% confidence internals indicate that the distance to floods induced by torrential rain is the greatest, followed by floods induced by heavy rain/dam break, snowmelt/ice jam, tropical cyclone/storm/hurricane, and monsoonal rain, for the period from 2000 to 2018. The majority of floods induced by monsoonal rainfall, particularly those occurring in South Asia (as depicted in Figure S4 in Supporting Information S1), are linked to high fatality rates. This correlation can potentially be attributed to the region's relatively high population density, resulting in close proximity to flood-prone areas. It highlights the importance of assessing the feasibility of resettlement initiatives and enhancing flood control measures in these areas. Except for the group related to snowmelt/ice jam, our analysis reveals that in each group, the flood events associated with the highest fatality rates have a human-flood distance below the average value. We also examined the characteristics of human-flood distance across various continents (Figure S5 in Supporting Information S1). Notably, the histograms of flood events in each continent display a notable conformity to the normal distribution. The 95% confidence intervals show that in Asia, the human-flood distance is concentrated within the range of 2.37–2.43 km from 2000 to 2018. Furthermore, severe floods associated with high fatality rates were more frequent in Asia, potentially due to the proximity of human settlements to flood-prone areas. This finding provides a new perspective that underscores the importance of prioritizing areas that are at a high risk of significant damage from various flood types before implementing managed retreat.

4. Discussions and Conclusions

Floods are among the most devastating natural disasters, inflicting widespread devastation on communities worldwide. With flood frequency and intensity predicted to escalate due to anthropogenic activities, comprehending the factors influencing flood-related harm is increasingly urgent. Among these factors, human-flood distance has gained substantial attention. This study investigates the relationship between changes in human-flood distance and flood fatalities and displacements, aiming to provide insights for informing flood risk mitigation strategies.

Our examination spans the years 2000–2018, using a dynamic approach that accounts for the evolving nature of floods. Conventionally, the study of human-flood distance relies on fixed river networks, a method that can overlook flood experiences due to other influences like water withdrawal. In contrast, we analyze flooded areas over time, yielding more detailed insights.

Our findings reveal intriguing patterns in human behavior in response to flood risk. Over the study period, we observed that 53% of countries tended to relocate away from flood inundated areas. This trend was particularly prominent in the Middle East, where populations displayed a strong inclination to distance themselves from floods. This behavior aligns with the idea that moving away from flood-prone regions is a rational response to reducing flood risk. Conversely, some regions, including Japan, parts of Africa, and Oceania, exhibited a propensity to get closer to flood-prone areas. This movement toward flood-prone regions is primarily driven by the advantages of resource accessibility, particularly water resources, which is also confirmed by Di Baldassarre et al. (2013).

However, it is crucial to acknowledge the complexities and uncertainties associated with measuring changes in human-flood distance at a resolution of meters per year. Additionally, variations in our findings compared to previous studies, such as those by Ceola et al. (2015), Mård et al. (2018), and Mazzoleni et al. (2021), may arise from differences in data sets used, and the enhanced methodology employed in this study. Nevertheless, our methodology offers a more realistic representation of changes in human-flood distance by incorporating dynamic flood event changes and geographical features such as cliffs, dams, and reservoirs. For example, we accounted for the presence of naturally protected areas and those safeguarded by infrastructure. This comprehensive approach captures the spatial complexities of human-flood distance more accurately, reflecting actual variations in human settlement patterns and their relationship with flood dynamics.

The impact of changes in human-flood distance on flood fatalities and displacements is a critical aspect of our study. We found that an increase in human-flood distance leads to a substantial reduction in both flood fatalities and displacements. This observation aligns with previous studies (López-Carr & Marter-Kenyon, 2015; Seebauer & Winkler, 2020; Siders, 2019) emphasizing that managed retreat from flood-prone regions can mitigate population exposure to flood hazards.

Moreover, various passive or active adaptive behaviors and socioeconomic processes contribute to mitigating flood fatalities and displacements (Paprotny et al., 2018). Communities adapt their behaviors and practices in response to flood vulnerability to minimize flood risks (Liu et al., 2022). These measures encompass the construction or enhancement of flood-resistant structures and the implementation of early warning systems. However, these behaviors and practices are influenced by various factors, including culture norms, historical events, policy interventions, and livelihood strategies (Alfieri et al., 2020; Haasnoot et al., 2013). Culture practices and historical events, such as the attachment to ancestral lands and cultural beliefs associated with floods, along with the impact of historical flood events, shape the settlement patterns of human populations in flood-prone areas. Additionally, policy interventions play a crucial role in shaping human settlement patterns and addressing flood vulnerability. These interventions encompass the provision of flood-resistant infrastructure, land-use planning, zoning regulations and insurance schemes. Moreover, livelihood strategies, which revolve around economic activities such as agriculture, fishing, or tourism, also influence human behaviors in managing flood risks. Furthermore, socioeconomic factors and technological innovations are crucial in mitigating flood fatalities and displacements through relocation (Hu et al., 2018; Kron et al., 2019). Socioeconomic factors, such as economic opportunities, infrastructure development and land availability, impact flood risk outcomes by shaping patterns of urbanization and rural-urban migration (Cutter et al., 2016). Technological innovations, such as remote sensing, early warning systems, flood forecasting models, and resilient infrastructure, enhance community resilience against floods.

Additionally, our study considers the impact of flood protection levels (FPL) on human-flood distance. Regions with a high FPL tend not to move away from floods. In contrast, regions with a low FPL exhibit a wide range of behaviors, including maintaining the same distance from flood events or increasing or decreasing proximity for various reasons, such as risk avoidance or resource-seeking. Examining variations in human-flood distance and FPL across different flood types, we find that changes in these factors remain minimal for floods primarily triggered by rainfall. However, significant variations are observed for floods caused by hurricane/typhoon and ice jam. Importantly, flood events associated with higher fatality rates tend to have human-flood distance values below the average.

In conclusion, the scientific evidence presented in this study carries significant implications for the prioritization and design of flood mitigation strategies and projects. Stakeholders involved in regional flood management can make informed decisions aimed at reducing flood fatalities and displacements while enhancing overall flood management practices. Nonetheless, it is vital to acknowledge the limitations of this study and the potential impacts of the assumptions made. Major sources of uncertainty in the analyses include the spatial resolution of measurements, variations in data sets, and the complexity of human behaviors and adaptive strategies. Therefore, further research and data collection efforts are needed to refine our understanding of these dynamics.

Data Availability Statement

The global flood database is accessed through Tellman et al. (2021a). Flood fatalities and displacements data is available at Brakenridge (2021). Gridded population data is available at University of Southampton (2020). Global Reservoir and Dam and DEM are obtained from Lehner et al. (2011) and Jarvis A. et al. (2008), respectively. Flood protection level data is acquired from Scussolini et al. (2016).

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