Mapping Global Risk of River Flood Mortality

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1 Background

Globally, river flooding induced by heavy rainfall frequently causes fatalities every year (Jongman et al. 2015; CRED and UNISDR 2018; CRED 2019). Particularly, heavy rainfall will increase in the future with climate warming (Liao et al. 2019). This could lead to greater rain-induced local flooding in some watersheds or regions (IPCC 2012). Besides, exposed populations to floods are increasing with the socioeconomic development (Jongman et al. 2015; Winsemius et al. 2018; Liao et al. 2019).

Generally, river flooding risk assessment has two steps. The first is to simulate river flooding hazard using hydrological or hydrodynamic model and inundation model, and the second is to calculate affected populations by overlaying the population data and flood hazard maps, and the results are used to assess the risk of affected population by floods (Arnell and Gosling 2016; Lim et al. 2018). Projected future precipitation and social-economic datasets provide a basis for these studies. However, when assessing risks in the population, most studies are concerned with the affected population (Alfieri et al. 2015; Dottori et al. 2016; Wing et al. 2018) and few studies concern mortality risks. Shi and Kaspersen (2015) and Jongman et al. (2015) assessed the mortality risk using baseline mortality rate. Kinoshita et al. (2018) simulated changing mortality vulnerability with time

to assess risks, but the vulnerability is measured by an index rather than vulnerability functions that involve certain physical processes. The difficulty of mortality risk research is lacking proven vulnerability functions. In addition, many studies focus on the risk at the country and regional levels, lacking grid level high spatial resolution results.

In order to address the issues, this study assessed the global mortality risks from floods by two main steps. The first was to develop mortality vulnerability functions for all countries by revising an existing vulnerability function. Then future potential death tolls of the 2030s and the 2050s were estimated at the 2.5' grid level under the Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathway (SSP) scenarios of RCP4.5-SSP2 and RCP8.5-SSP3. The results were compiled to produce the risk maps at the 0.25° grid level and country level.

2 Method

Figure 1 shows the technical flowchart for mapping flood mortality risk of the world. The study revised the existing vulnerability functions by adjustment coefficient that is calculated based on recorded death tolls. Then future death tolls were estimated using predicted inundation data and population data, and the adjusted vulnerability functions. Future death tolls at the grid level were then aggregated to other geographic units. Finally, the risk size and model uncertainty are analyzed.

2.1 Estimation of Risks

2.1.1 Estimation of Losses for the Baseline Period

The mortality vulnerability function is represented by Eq. (1) (Jonkman et al. 2008). Using the function, historical death tolls were estimated by Eqs. (2) and (3).

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Fig.1 Technical flowchart for mapping global risk of river flood mortality. AOGCM = Atmosphere–Ocean General Circulation Model; RCP = Representative Concentration Pathway; SSP = Shared Socioeconomic Pathway

$$V(d) = \Phi \left[\frac{\ln(d) - 7.60}{2.75} \right] \quad (1)$$

where Φ is the cumulative normal distribution. d is the water depth.

$$L_{his_i_j} = V(d_{his_i_j}) \times S_{his_j} \times f_{his_i_j} \quad (2)$$

$$L_{his} = \frac{1}{11 \times 20} \sum_{j=1}^{20} \sum_{i=1}^{11} L_{his_i_j} \quad (3)$$

where i is the order of the 11 Atmosphere–Ocean General Circulation Models (AOGCMs); j is the sequence of the 20 years; his is the baseline period (1986–2005); $L_{his_i_j}$, $d_{his_i_j}$, and $f_{his_i_j}$ are the estimated death tolls, water depth, and inundation fraction for the i th AOGCM in the j th year for the baseline period, respectively; S_{his_j} is the population size in the j th year of the baseline period; L_{his} is the annual average death tolls, that is, the multi-model ensemble for the baseline period; $V(d)$ is the vulnerability function.

2.1.2 Calculation of Adjustment Coefficients

The study revised the mortality vulnerability function (Eq. 1) for countries to reduce the diversity of vulnerability functions in different areas.

Using Eq. (4), the adjustment coefficients (K_c values) were calculated for the countries with total recorded deaths and estimated deaths both greater than zero during the baseline period. On this basis, the adjustment coefficient is the minimum of above calculated K_c values for the countries with total recorded death tolls equal to zero during the baseline period; and the adjustment coefficient is the average of above calculated K_c values for the countries with total recorded death tolls greater than zero but total estimated deaths equal to zero.

$$K_c = \frac{\sum_{j=1}^{20} SL_{his_c_j}}{L_{his_c}} \quad (4)$$

where K_c is the adjustment coefficient of country c ; j represents the sequential number of the 20 years in the baseline period; $SL_{his_c_j}$ is the recorded death tolls of country c .

The adjusted vulnerability function is shown in Eq. (5).

$$AdjV_c(d) = K_c \times V(d) \quad (5)$$

where $AdjV_c(d)$ is the adjusted vulnerability function of country c .

2.1.3 Calculation of Future Losses and Change

Future death tolls of a grid in country c were estimated according to Eq. (6), based on future predicted inundation and population data and adjusted vulnerability function. Next, the study averaged the results of 20 years for all AOGCMs (Eq. 7) to compute uncertainties; then we averaged the results of the 11 AOGCMs as the death tolls of the 2030s or the 2050s to reduce model uncertainties (Eq. 8). Finally, the changes of death tolls from the baseline period to future periods were calculated by Eq. (9).

$$L_{fut_i_j} = AdjV_c(d_{fut_i_j}) \times S_{fut_j} \times f_{fut_i_j} \quad (6)$$

where $L_{fut_i_j}$, $d_{fut_i_j}$, and $f_{fut_i_j}$ are the estimated death tolls, water depth, and inundation fraction for the i th AOGCM in the j th year for a future period, respectively; S_{fut_j} is the population data in the j th year of a future period.

$$L_{fut_i} = \frac{1}{20} \sum_{j=1}^{20} L_{fut_i_j} \quad (7)$$

where L_{fut_i} is the average death tolls of 20 years (2016–2035 or 2046–2065) for the i th AOGCM.

$$L_{fut} = \frac{1}{11} \sum_{i=1}^{11} L_{fut_i} \quad (8)$$

where L_{fut} is the death tolls of the 2030s or the 2050s for the multi-model ensemble, which averaged the results from the 11 AOGCMs.

$$\Delta L = L_{fut} - L_{his} \quad (9)$$

where ΔL is the change of death tolls for the 2030s or the 2050s relative to the baseline period.

2.2 Model Uncertainty

The result uncertainty of multi-models is measured by standard deviation (Eq. 10) and coefficient of variation CV, the ratio of SD to L in Eq. 10.

$$SD = \sqrt{\frac{\sum_{i=1}^{11} (L_i - L)^2}{11}} \quad (10)$$

where L_i is the average death tolls of 20 years for the i th AOGCM (L_{his_i} or L_{fut_i}). L is the average death tolls of 20 years for the multi-model ensemble (L_{his} or L_{fut}).

3 Results

Globally, the annual average death tolls of the 2030s are approximately 21 thousand persons for the RCP4.5-SSP2 scenario and 23 thousand persons for the RCP8.5-SSP3 scenario; they increase 0.57 and 0.69 times relative to the baseline period, respectively. The annual average death tolls of the 2050s are approximately 26 thousand persons for the RCP4.5-SSP2 scenario and 32 thousand persons for the RCP8.5-SSP3 scenario; they increase 0.88 and 1.31 times relative to the baseline period. The patterns of spatial distribution are similar for different scenarios; high-risk areas are located in East Asia, South Asia, and Southeast Asia, particularly in eastern coastal China and the Ganges River Basin.

Fig.2 Annual average death tolls of the top 10 high-risk countries (in descending order by death toll). **The error bar represents** the standard deviations across the 11 Atmosphere–Ocean General Circulation Models (AOGCMs)

Using zonal statistics of the death toll results, we calculated the annual average death tolls at the national level. Figure 2 shows the annual average death tolls and errors (measured by standard deviation) of the top ten high-risk countries. The death tolls are higher for India, Bangladesh, China, Haiti, and Indonesia, and lower in Pakistan, Somalia, Algeria, Viet Nam, and the United States. For most

countries, the death tolls of the 2050s are higher than that of the 2030s; and the death tolls of the RCP8.5-SSP3 scenario are higher than that of the RCP4.5-SSP2 scenario. The changes of death tolls are higher in India and Bangladesh, increasing 1.22–3.63 times for India and 2.82–5.16 times for Bangladesh. The risk changes of Haiti are the lowest, about 0.03–0.27 times (Fig. 2).

4 Maps

Global flood mortality risk (Baseline)

Global flood mortality risk (2030s, RCP4.5-SSP2)

Global flood mortality risk (2030s, RCP8.5-SSP3)

Global flood mortality risk (2050s, RCP4.5-SSP2)

Global flood mortality risk (2050s, RCP8.5-SSP3)

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