Future river-flood damage increases under aggressive adaptations

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Abstract

The risk of river flooding is expected to rise with climate change and socioeconomic development¹⁻⁶, and therefore additional protection measures are required to reduce increased flood damage. Previous studies have investigated the effectiveness of adaptation measures to reduce flood risks^{7,8}; however, there has been no evaluation of residual flood damage (RFD), which reflects the unavoidable increase in damage even under an aggressive adaptation strategy. Here, we evaluated RFD under several adaptation objectives. We found that China, India, Russia and countries in central Africa and Latin America can achieve a higher level of flood protection that will reduce RFD even under extreme scenarios. However, high RFD exceeding 0.1% of GDP remains, especially in eastern China, northern India, eastern Europe and central Africa. The high RFD are inevitable assuming the average construction period required for hard infrastructure (30 years), implying the need for immediate adaptation measures as well as soft adaptation.

Introductory Paragraph

The risk of river flooding is expected to rise with climate change and socioeconomic development¹⁻⁶, and therefore additional protection measures are required to reduce increased flood damage. Previous studies have investigated the effectiveness of adaptation measures to reduce flood risks^{7,8}; however, there has been no evaluation of residual flood damage (RFD), which reflects the unavoidable increase in damage even under an aggressive adaptation strategy. Here, we evaluated RFD under several adaptation objectives. We found that China, India, Russia and countries in central Africa and Latin America can achieve a higher level of flood protection that will reduce RFD even under extreme scenarios. However, high RFD exceeding 0.1% of GDP remains, especially in eastern China, northern India, eastern Europe and central Africa. The high RFD are inevitable assuming the average construction period required for hard infrastructure (30 years), implying the need for immediate adaptation measures as well as soft adaptation.

Main Text

River floods are major natural disasters, causing serious economic losses and damage worldwide. Economic damage due to river flooding is projected to increase worldwide in the future, and more threatening conditions can be anticipated with the increasing global population and socioeconomic development¹⁻⁶. Immediate effective adaptation measures should therefore be made for mitigating future damage.

Conducting effective adaptation measures at the global scale requires information about residual flood damage (RFD), which refers to unavoidable flood damage above the current protection level, even under an adaptation strategy based on feasible adaptation costs. To clarify local differences in the magnitude of RFD, estimations of the affordable adaptation level, which reflect local economic conditions and local costs of adaptation measures, are required to determine the feasibility of the adaptation measures.

Adaptation costs at the global scale have been quantified in a few previous studies. For example, Jongman et al.⁹ demonstrated that adaptation cost of approximately €1.75 billion for increasing the flood protection level in all river basins in the EU could decrease the €7 billion total expected annual flood losses by 2050. Winsemius et al.³ and Ward et al.⁷ showed that global adaptation costs for levees could produce a much higher benefit (reduced damage through additional adaptation) in most combinations of climate and socioeconomic scenarios.

Here, we estimated global RFD under the feasible maximum adaptation level, i.e. the maximum future flood protection level that is both attainable and economically beneficial. This produced the highest net benefit (i.e. the cost of additional adaptation subtracted from the benefits) and was referred to as the ‘optimized adaptation objective’. The reduced damage was estimated by considering damage with and without additional adaptation measures (see “Estimation of RFD and benefits” in the methods). We set a maximum limit of the adaptation level as a 1000-year return period of maximum flood magnitude in the past climate based on the current distribution of flood protection standards¹⁰, which was derived from the FLOod PROtection Standards (FLOPROS) database. The local adaptation level under the adaptation objective was calculated for each subnational administrative unit. It should be noted that RFD is not the total damage due to flooding, but the increase in future damage over that under the current protection level.

Figure 1 shows the ensemble mean of future flood protection levels for the optimized adaptation objective in the extreme scenario (representative concentration pathway (RCP)8.5/shared socioeconomic pathway (SSP)5). Without any adaptation objectives, future damage under a warming climate increased substantially in China, India, Indonesia, Siberia, Congo, southern Brazil, western Canada and Alaska. The future protection levels under the optimized adaptation objective in these regions were higher than the 200-year return period and the levels were higher than current flood protection levels (Supplementary Figure S1). The spatial pattern of future flood protection levels were similar in other combined RCP and SSP scenarios in most regions (Supplementary Figure S2).

The global total RFD in the extreme scenario (RCP8.5/SSP5) was 25.7 billion USD per year. This value varied among the different combinations of scenarios and adaptation objectives (Table 1). Evaluating the RFD for subnational administrative units demonstrated that significant RFD (>0.05% of the subnational GDP) was observed in most parts of the globe, e.g. China, India, north-eastern Australia, Siberia, eastern Europe, Nigeria, Alaska and northern Argentina under the extreme scenario combination (RCP8.5/SSP5) (Figure 2). A similar spatial pattern was observed in the other RCP/SSP scenarios, except for in eastern Europe and central USA (Supplementary Figure S3).

Table 1. Summary of global evaluation. Modelled benefits, adaptation costs and RFD for the two adaptation objectives for the four selected representative RCP/SSP combinations.

	Benefits (B) [US\$ Billion/year]	Adaptation cost (C) [US\$ Billion/year]	RFD [US\$ Billion/year]	NPV (B-C) [US\$ Billion/year]
Additional adaptation objective				
RCP8.5/SSP5	146.3	15.3	25.7	131.0
RCP6.0/SSP3	46.3	8.7	13.1	37.6
RCP4.5/SSP2	84.5	12.2	10.3	72.3
RCP2.6/SSP1	94.1	14.2	16.7	79.9
Maximum adaptation objective				
RCP8.5/SSP5	147.7	20.2	25.2	127.5
RCP6.0/SSP3	48.3	15.2	12.5	33.1
RCP4.5/SSP2	86.6	18.2	9.8	68.4
RCP2.6/SSP1	96.0	19.9	16.1	76.1

Interestingly, the RFD was still very high under the low emission scenario (16.7 billion USD per year, RCP2.6/SSP1), which was due to the high level of economic development in the inundation areas exposed to flooding. Because the estimated adaptation costs were similar among the scenarios (8.7–15.3 billion USD per year), the flood protection level reached the level required to obtain the maximum net benefit (i.e. reduced flood damage minus the adaptation cost) (see “Estimation of RFD and benefits” in the Methods section). On the other hand, flood protection levels remained low in countries where the adaptation costs were higher than the benefits of adaptation (i.e. the amount of damage reduction), which was observed in many regions of Africa, Bolivia and Paraguay. The estimated RFD under the assumption of an economic limitation identified regions or countries where aid funding agencies or international cooperative frameworks should support adaptation to the effects of climate change in terms of flood risk. To assess the economic limitation on future flood protection levels, we conducted a similar analysis under the maximum adaptation objective, which minimized future flood damage (maximized benefits) without considering the local economic limitation. The maximum adaptation objective would reduce future flood damage by 73.6 billion USD per year. However, a significant RFD still remained in regions, such as China, north-eastern Australia, southern and northern India, Siberia, eastern Europe, Nigeria, Alaska and northern Argentina. The main reason for the significant RFD was flood damage that occurred during construction (i.e. 2020–2050) (Supplementary Figure S4). Hardware adaptation measures require a long time to become effective; therefore, early decisions and other soft measures are also needed to reduce the increased flood damage under a warming climate⁸.

The RFD was high in areas of Asia, central Africa and Latin America that have experienced strong socioeconomic development, where the magnitude and frequency of flooding are projected to increase in the future². In these regions, the flood protection standard required a high return period (Figure 1). On the other hand, the RFD in Europe and North America exceeded 0.01% of the GDP for the optimized adaptation objective. In these regions, adaptation costs would be greater than the benefits. This is because the high level of flood protection already exist (>50-year return period, Supplementary Figure S1), and because the frequency of large floods in the future (e.g. 100-year flood) would decrease². The maintenance of current flood protection levels was the best economic option under the optimized

adaptation objectives. This trend did not change with the lower or higher adaptation unit costs (Supplementary Figure S5).

The regions of eastern Asia, Siberia, western China, southern India, western and central Africa, north-eastern Latin America, southern Canada and Alaska had large RFD values (Figure 3a). Among the different parameter–scenario combinations implemented in this study (e.g. SSPs, RCPs, discount rate, unit cost, operation and maintenance (O&M) costs, and protection area), more than 50% produced a significant RFD in these regions for the optimized adaptation objective. However, most regions had a much lower RFD for the maximum adaptation objective (Figure 3b), implying the potential needs for an international financial mechanism to increase the resilience of these regions to future increases in flooding.

We found a significant RFD under the optimized and maximum adaptation objectives for most parts of the world, indicating a limit to adaptation. In this study, the limit to adaptation was caused mainly by the economic costs in subnational administrative units and assumed construction period, indicating that early decisions and international funding support are key factors for conducting effective adaptation measures at the global scale. Furthermore, the enhancement of autonomous adaptation via social adaptation activities is important for increasing the limit to adaptation because vulnerability was decreased by autonomous adaptation^{6,11,12}. Future studies are needed to clarify the relationship between autonomous adaptation and flood protection measures.

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Method Summary

The overall modelling framework consisted of the following steps: (1) global river flood simulation, (2) downscaling flood inundation, (3) damage calculation, (4) estimation of adaptation costs by adaptation level and (5) estimation of RFD and benefits of the two adaptation objectives.

Global river flood simulation. The return period of river flooding under various climate scenarios was calculated from the daily total water storage derived from the global river flood simulation. We used the Catchment-based Macro-scale Floodplain (CaMa-Flood) model¹³ to conduct a simulation forced by the daily runoff at a $0.5^\circ \times 0.5^\circ$ resolution and output daily total storage at a $0.25^\circ \times 0.25^\circ$ horizontal resolution. For future river flood simulation, we used five general circulation models (GCMs) (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M) and four RCPs (2.6, 4.5, 6.0 and 8.5 Wm^{-2}). The cumulative distribution function-based downscaling method (i.e. a nonparametric bias-correction method) using percentiles of empirical cumulative distribution functions removed the biases of climatic variables in the GCMs¹⁴. A global flood inundation simulation was conducted for the period 1961–2005 for historical climate conditions and for the period 2006–2100 for future climate conditions, except for HadGEM2-ES (2006–2098). We did not consider the effects of flood protection levels, human modification of river discharge, or channel bifurcation in the global river flood simulation. This resulted in uncertainty regarding the inundation areas in mega delta regions (see SI6)^{15,16}, and caused over- and underestimations of RFD, especially in downstream regions.

Downscaling flood inundation. The simulated overflow floodwater volume at a $0.25^\circ \times 0.25^\circ$ resolution was downscaled to obtain the inundation area at a $30'' \times 30''$ resolution. First, the overflow floodwater volume was calculated from the annual maximum total water storage when the return period of the annual maximum flood water exceeded the local protection levels. The return period and corresponding

river water storage were estimated based on the Gumbel distribution using the L-moment method¹⁷ and were calculated from the annual maximum total water storage for the period 1961–2005 derived from the river flood reanalysis (see SI1). The current local protection levels were obtained from the model layer of FLOPROS¹⁰ (Supplementary Figure S1). Finally, the overflow floodwater volume was downscaled to a 30" × 30" horizontal resolution using a high-resolution digital elevation model. The flooded area fraction was calculated at the same resolution.

Damage calculation. The RFD was calculated as the increase in flood damage over the present level (1971–2000) that would still occur despite the implementation of additional adaptation measures. To quantify RFD, the damage (*Risk*) was calculated based on the following equation:

$$Risk = Hazards \times Exposure \times Vulnerability$$

where *Hazards* is the magnitude of the flood, *Exposure* is the value of assets potentially affected by flooding, and *Vulnerability* is the susceptibility to harm or lack of the socioeconomic capacity to cope with flood risk. *Hazards* were derived from the overflow flood water depth from the downscaling flood inundation. *Exposure* was derived from the asset map, which was constructed from a gridded GDP map (see SI2). *Exposure* was targeted on the assets in the flooded areas, and therefore we used an asset map multiplying by the overflow flooded area fraction derived from the downscaling flood inundation. We used the global damage-depth function derived from Huizinga et al.¹⁸ as a *Vulnerability* index, which was based on a literature survey, and this index covered each region (Asia, Africa, Europe, Oceania, North America and Central and South America). The damage–depth function was derived from the mean value for commercial buildings, industrial buildings, transport and infrastructure (roads) sectors. It was noted that flood protection levels were considered as *Vulnerability* in previous studies^{7,19,20}; however, we did not explicitly consider flood protection levels in the damage calculation, because we already included flood protection levels in the downscaling flood inundation.

The modelled damage forced by the river flood reanalysis (see SI1) captured not only the global fluctuations of flood damage (Supplementary Figure S6), but also the event-scale damage (Supplementary Figure S7). We compared the modelled damage forced by the historical simulation with the values calculated by other studies. Our estimation was within the range of other estimates (Supplementary Table S1), indicating that it was likely valid.

Estimation of adaptation costs by adaptation level. The adaptation costs of hardware measures were considered in this study. They were composed mainly of the costs of construction and O&M. The construction costs were calculated as the dimensions of the required flood protection levels multiplied by their unit costs. The unit cost was set as 2.404 [million USD/km/log₂(flood protection level)], which was derived from the original unit cost database of hardware measures (see SI3). The dimensions of the required protection measures were composed of their construction length and future flood protection levels. The construction length of a flood protection structure was calculated as the river length in a unit catchment (corresponding to a 0.25° × 0.25° horizontal resolution), derived from CaMa-Flood boundary data overlaid on the mask of the protection area. We assumed that the unit catchment was protected when the urban population density derived from the spatially explicit population scenarios in 2050²¹ was higher than 400 persons km⁻². This value corresponded to the definition of urban in Canada. The total length of the flood protection structure was calculated for subnational administrative units. The future protection levels were determined by adaptation levels for subnational administrative units. Because

there were no future scenarios for flood protection levels, we defined the relationship between future flood protection level (FPL) and adaptation level by the following equation:

$$FPL_{Future} = FPL_{Current} \times 2^L$$

where FPL_{Future} and $FPL_{Current}$ are the future and current flood protection levels described by return periods [year], respectively, and L is the adaptation level. In this study, L ranged from 0.0 to 10.0 at 0.25 intervals. FPL_{Future} and $FPL_{Current}$ ranged from 0 to 1000 years. If $FPL_{Current}$ was 0.0, FPL_{Future} was set to 2 years when $L = 1.0$. We assumed that the costs of workers, materials and land acquisition were included in the construction costs. We assumed the construction period was from 2020 to 2050. The O&M costs that were equal to 1% of the construction costs occurred during the period 2051–2100. Finally, we calculated the adaptation costs as the total cost of construction and O&M, with a 5% discount rate.

Estimation of RFD and benefits of the two adaptation objectives. The RFD and benefits were determined under consideration of the adaptation objectives. This analysis was conducted with a discount rate of 5% for subnational administrative units and for the evaluation period 2020–2100. The two adaptation objectives were the ‘optimize adaptation objective’ and ‘maximum adaptation objective’. The optimize adaptation objective maximized the difference between benefits and adaptation costs (i.e. net present value). The adaptation objectives reduced RFD if there were adaptation limitations (i.e. a future protection level within a 1000-year return period). On the other hand, the maximum adaptation objective is an ideal adaptation objective that minimizes RFD as much as possible. The RFD under the optimize adaptation objective was the most affordable option under the specific socioeconomic conditions, while the maximum adaptation objective indicates a limit to adaptation. The RFD was estimated as the difference between future damage with additional adaptation and the relative damage equivalent to the present level (1971–2000).

The benefits were defined as the annual average of the integrated total reduced damage during the evaluation period (2020–2100). The benefits were a combination of increased flooding due to climate change and the increases in local assets associated with socioeconomic development, which became high if local socioeconomic development improved from 2020 to 2100. The benefits were calculated by considering the differences in future damage (2020–2100) with and without additional adaptation for the adaptation level. The flood protection levels increased from the present level to a targeted adaptation level for the construction period (2020–2050), which achieved the expected future protection level in 2051. Therefore, benefits gradually increased even before the construction was complete.

Declarations

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Author Contributions

M.T. developed the database, designed the modeling framework, conducted the analysis, and made the figures. M.T. and Y.H. contributed to the analysis of results. R.T., H.A., and M.T. performed the inundation model simulations. M.T. and Y.H. wrote the manuscript. Y.H. contributed to the foundation.

Competing Interests statement

The authors declare no competing interests.

Additional information

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Data availability

Data generated and analyzed during this study are available for research purpose at <http://www.db.shibaura-it.ac.jp/~hirabayashi/research/adaptation>. Additional datasets used for the modelling are available from the corresponding author upon request.

Code availability

The code used for the modelling framework are available from the corresponding author upon request.

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Figures

Figure 1

Future flood protection levels for the optimized adaption objective. The results for the RCP8.5/SSP5 scenario are shown. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Residual flood damage (RFD) as a proportion of the subnational administrative GDP for the optimized adaptation objective. The results for the RCP8.5/SSP5 scenario are shown. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Probability of significant residual flood damage (RFD) (>0.05% of GDP) in all scenarios. The probability of the optimized adaptation objective (a) and maximum adaptation objective (b). Gray shading indicates 0%. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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