Evaluation of flood damage reduction throughout Japan from adaptation measures taken under a range of emissions mitigation scenarios

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Abstract

This study aimed to evaluate the impact of climate change on flood damage and the effects of mitigation measures and combinations of multiple adaptation measures in reducing flood damage. The inundation depth was calculated using a two-dimensional unsteady flow model. The flood damage cost was estimated from the unit evaluation value set for each land use and prefectures and the calculated inundation depth distribution. To estimate the flood damage in the near future and the late twenty-first century, five global climate models were used. These models provided daily precipitation, and the change of the extreme precipitation was calculated. In addition to the assessment of the impacts of climate change, certain adaptation measures (land-use control, piloti building, and improvement of flood control level) were discussed, and their effects on flood damage cost reduction were evaluated. In the case of the representative concentration pathway (RCP) 8.5 scenario, the damage cost in the late twenty-first century will increase to 57% of that in the late twentieth century. However, if mitigation measures were to be undertaken according to RCP2.6 standards, the increase of the flood damage cost will stop, and the increase of the flood damage cost will be 28% of that in the late twentieth century. By implementing adaptation measures in combination rather than individually, it is possible to keep the damage cost in the future period even below that in the late twentieth century. By implementing both mitigation and adaptation measures, it is possible to reduce the flood damage cost in the late twenty-first century to 69% of that in the late twentieth century.

Keywords Global warming · Land-use control · GCM · Climate change impacts · Piloti building · Flood simulation

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1 Introduction

In recent years, society has been focusing on developing measures to cope with climate change caused by global warming. In the Global Risk Report 2020 presented at the World Economic Forum Annual Meeting held in January 2020, extreme weather, major natural disasters, and failure of climate change mitigation and adaptation have been ranked high in the list of long-term risks that are likely to occur over next 10 years (World Economic Forum 2020). This indicates that dignitaries and experts around the world are focusing on the impact of climate change and natural disasters. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) pointed out that it is very likely that heat waves will occur more often and last longer and that extreme precipitation events will become more intense and frequent in many regions (IPCC 2014). Therefore, countermeasures against climate change should be urgently developed.

Climate change countermeasures can be roughly divided into “mitigation measures” and “adaptation measures.” Mitigation measures are measures to reduce the emission of greenhouse gases that cause global warming, control the increase in global warming, and stabilize the concentration of greenhouse gases in the atmosphere. Examples of mitigation measures include the efficient use and conservation of energy; the capture, storage, and control of CO₂; and an increase in CO₂ sinks. However, reports have indicated that the effect of the mitigation measures is limited. For instance, the IPCC AR4 report published in 2007 states that the mitigation measures against global warming have limitations and that even if appropriate mitigation measures are developed and implemented, the temperature rise will continue for centuries (IPCC 2007). Adaptation measures are adopted to reduce the effects of rising temperature and sea levels caused by climate change by regulating human, social, and economic activity systems and increasing disaster prevention investments. Examples of adaptation measures include the construction of embankments and breakwaters for coastal protection and efforts to increase the efficiency of water use. To reduce the negative impact of climate change on human society, measures that combine mitigation and adaptation measures must be adopted. In addition, according to the IPCC AR5 report, as the global average temperature rises, extreme precipitation is very likely to become stronger and more frequent in most of the mid-latitude land areas and moist tropical regions by the end of this century (IPCC 2013). Because this prediction suggests an increase in the frequency of heavy rainfall, an increase in the activity of tropical cyclones, and a rise in sea levels, it is essential to establish adaptation measures against water-related disasters, which are expected to increase in the future because of climate change.

It is predicted that in Japan, climate change may alter precipitation levels and patterns and intensify tropical cyclones, which may cause an increase in the risk of flood damage. Iizumi et al. performed future stochastic climate calculations by a weather generator-based bootstrap method and indicated that heavy rainfall is likely to increase in spring and summer in Japan between 2081 and 2100 (Iizumi et al. 2012). By performing high-resolution downscale experiments, Tsuboki et al. predicted a considerable increase in the maximum intensity of super typhoons in the latter half of the twenty-first century and suggested the need for future disaster prevention plans (Tsuboki et al. 2015). Using an atmospheric global circulation model, Mori et al. predicted a long-term ensemble and estimated that the height of storm surges in Tokyo Bay and Osaka Bay would increase by 0.30–0.45 m (Mori et al. 2019). Tezuka et al. performed flood calculations using stochastic flood-contributing rainfall data for the entire region of Japan and quantitatively showed an increase in the flood damage cost (Tezuka et al. 2014). However, only a few studies have previously evaluated adaptation measures targeting the entire region of Japan.

In countries other than Japan, impact assessments of climate change and various adaptation measures are being examined and evaluated. As an example of climate change impact assessment, Dottori et al. assessed the damage to global human, economic, and indirect welfare caused by global warming (Dottori et al. 2018). Hirabayashi et al. presented details of the global flood risk for the end of this century (Hirabayashi et al. 2013). Arnell et al. evaluated the impact of climate change on flood risk on a global scale (Arnell and Gosling 2016). They analyzed four indicators—flood frequency, exposed population, exposed arable land area, and regional flood risk—using 21 climate models and the Special Report on Emissions Scenarios. Despite the high uncertainty due to variations between models, they suggested that climate change had the potential to considerably increase flood exposure. Huong and Pathirana estimated the impact of urbanization and climate change on floods in Can Tho, Vietnam, and indicated the possibility of a considerable increase in floods in the future (Huong and Pathirana 2013). In terms of adaptation measures, DiFrancesco et al. used a bottom-up approach to evaluate the robustness of flood management strategies concerning climate change in the American River, California, USA (DiFrancesco et al. 2020). Poussin et al. examined the adaptive effect of flood proofing, i.e., reinforcing buildings to improve their flood resistance, in France (Poussin et al. 2015). Furthermore, Ward et al. carried out a cost–benefit analysis of flood protection using embankments on a global scale (Ward et al. 2017). Sinay and Carter presented 80 adaptation options for coastal communities that could be adopted by local governments (Sinay and Carter 2020).

In Japan, with the progress of urbanization and the development of river basins, the risk of flood damages has increased significantly. In response to this situation, in addition to promoting river improvement and maintenance of flood control facilities, comprehensive river basin management measures such as ensuring water retention and developing anti-flood ponds and comprehensive flood control measures based on damage mitigation are being promoted (Ministry of Land, Infrastructure, Transport and Tourism (MLIT) 2006). Specific measures include river channel maintenance activities such as embankment construction and dredging for river improvement; basin management measures in water retention areas, such as land-use control and natural land conservation; basin management measures in lowland areas, such as the development of inland water drainage facilities; and damage mitigation measures such as the promotion of water-resistant buildings. However, studies have not been conducted on the evaluation of the flood damage mitigation effectiveness of these measures under changing climate conditions. The Japanese government has been accelerating the preparations for more severe flooding due to climate change with a trans-sectoral and basin-wide approach, as a part of integrated flood management (IFM) (Konami et al. 2021). There is a need to evaluate various flood control measures in combination with the effects of climate change.

In this study, to elucidate the effectiveness of adaptation measures against floods caused by climate change, the effectiveness on reducing flood damage of land-use control, piloti building, and the improvement of the flood control level was estimated in the framework of mitigation measures.

2 Datasets

(1) Daily precipitation data for the late twentieth century

In assessing the risk of flood damage in the whole of Japan, it is necessary to give the flood discharge with equal probability in each basin. Extreme precipitation is given instead of extreme discharge data, because it is difficult to obtain discharge data for all rivers in Japan.

If extreme precipitation is given to the entire basin, the flow rate will be excessive in the downstream area where the catchment area increases. Therefore, Tezuka et al. developed a method to evaluate flood risk using extreme precipitation with equal probability for all rivers in Japan by determining the runoff rate (runoff coefficient) for each mesh using the catchment area and accumulated precipitation and reducing the extreme precipitation (Tezuka et al. 2013). The extreme daily discharge was determined by GEV distribution in each class A water system, and regression equations were developed to show the relationship between catchment area, discharge, and precipitation in the basin. The extreme runoff coefficient (RF) was calculated by the following equation.

$$RF_m = 86.4 \times \frac{D_m}{A \cdot R_m}$$

where D_m is the discharge (m^3/s) in year m of the return period, A is the catchment area (km^2), R_m is the daily precipitation (mm/day) in year m of the return period, and m is the return period (year). 86.4 is a coefficient to adjust the dimensions. The extreme runoff coefficient decreases exponentially with the increase of catchment area. When the runoff coefficient specific to each mesh (point runoff coefficient) is set, the following relationship is established between the extreme runoff coefficients specific to each basin.

$$RF_m(A_n) \times \sum_{i=1}^n R_m(A_i) = \sum_{i=1}^n \{RC_m(A_i) \times R_m(A_i)\}$$

$$n = 2, 3, \dots \quad RF_m(A_1) = RC_m(A_1) = 1$$

where $R_m(A_i)$ is the daily precipitation (mm/day) in the catchment area A_i for the return period m years. $R_m(A_i)$ is the daily precipitation (mm/d), n is the number of the catchment area of each cell (1, 2, etc., starting from the most upstream), and $RC_m(A_n)$ is the point runoff coefficient. The most upstream point has only runoff and no inflow. Therefore, the extreme runoff coefficient and the point runoff coefficient are set to 1, assuming that the given rainfall is completely discharged. Based on this relationship, the rainfall distribution data for the return period for the entire region of Japan were weighted according to the catchment area, and the rainfall distribution was obtained to generate the maximum stochastic discharge during the return period at any point. This distribution is called the stochastic flood-contributing distribution. Based on this method, a 250-m resolution precipitation data was made. For this data, the point discharge coefficient was determined from the relationship between the catchment area and the stochastic flow rate aggregated by 250-m resolution for the extreme rainfall distribution data with a 1-km resolution for each probability scale created by Kawagoe et al. (2008). Kawagoe et al.'s data are based on the 1-km resolution distribution of mean daily precipitation and are constructed by correlating mean and extreme precipitation values for each climate category. Return periods of 5, 10, 30, 50, 70, 100, 150, and 200 years were used.

(2) Global climate model and scenario data

As climate prediction data, daily precipitation data downscaled to a 1-km resolution (Regional Climate Projection Dataset NARO2017-V2.7r, National Agriculture and Food Research Organization) were used (Nishimori et al. 2019). Here, five global climate models (GCMs) and two radiative forcing scenarios based on representative concentration pathways (RCPs) were employed. The five GCMs were GFDL-CM23, HadGEM2-ES, MIROC5, MRI-

CGCM3, and CSIRO-Mk3-6-0, and the two target scenarios were RCP8.5 and RCP2.6. By adopting extreme climate scenarios, the range of future flood damage costs can be assessed. Therefore, RCP2.6 and RCP8.5 were adopted. Three target periods were considered: 1981–2000 (the late twentieth century), 2031–2050 (the near future), and 2081–2100 (the late twenty-first century).

(3) Land-use data

The land-use data stored in the fifth-order mesh of the Digital National Land Information download services (Ministry of Land, Infrastructure, Transport and Tourism) were used for calculating the damage cost from the flood inundation calculation and inundation depth. The breakdown of land use is as follows: (1) paddy field; (2) field; (3) forest; (4) barren land; (5) land for building use; (6) land for main transportation; (7) land for other uses; (8) rivers, lakes, and marshes; (9) beach; (10) seawater area; and (11) golf course. When calculating the damage cost, the “land for building use” was classified into residential areas and business establishments using the zoned area data obtained from the Digital National Land Information download services.

(4) Flood control level data

In order to reflect the level of flood control safety, the river channel elevation was lowered by excavating the river channel based on the method of Tanaka et al. (2019). Tanaka et al. established the level of flood control safety for each river section by mapping the planned scale of the water system to the data of the type of manager of the river section. The level of flood control safety in the late twentieth century was assumed to be 50% of the planned level of flood control maintenance. The correspondence between the planned scale of the water system and the section type of the river is as follows: Class A rivers are set to half the planned scale of the water system, whereas class A designated rivers are set to half the planned scale of the class A rivers. Rivers not designated as class A are set to half the planned scale of the class A designated rivers. Class B rivers are set to a 10-year stochastic scale, whereas class B designated rivers are set to a 5-year stochastic scale. For the assigned flood control safety level, the excavation depth at which a flood of that scale can be safely discharged is determined from the inundation analysis. The elevation of the river channel is lowered by the calculated excavation depth.

(5) Ground gradient data

For the ground gradient data, the average tilt angle data stored in the elevation and gradient fifth-order mesh of the Digital National Land Information download services were used. The ground gradient data were used to calculate the damage cost.

(6) Population data

For the population data, the estimated population values for 2015 based on the estimated future population data stored in a 1-km mesh of the Digital National Land Information download services (2018 National Bureau Estimates) was used. The population data were used to set the target area for land-use control and piloti building.

3 Analysis method

The general flow for determining the damage cost is as follows: (1) calculation of the inundation depth during the flood and (2) calculation of the damage cost based on the Manual for Economic Evaluation of Flood Control Investment (Draft) (Ministry of Land, Infrastructure, Transport and Tourism (MLIT) 2005). The details are described below.

(1) Flood inundation analysis

In the flood inundation calculation, a two-dimensional unsteady flow model was used to calculate the inundation depth (Tezuka et al. 2014). The spatial resolution used was the fifth-order mesh resolution (approximately 250×250 m²). Regarding the effectiveness of flood control improvement, although the elevation data reflect the river improvement effects such as those of embankments, the data do not reflect the effects of sewers, pumping stations, dams, etc. Precipitation was given by dividing the daily precipitation into equal parts over a 24-h period.

(2) Estimation of damage cost

The calculation procedure for each land-use classification was created according to the land-use classification of the Digital National Land Information data with reference to the Manual for Economic Evaluation of Flood Control Investment (Draft). This study targeted only the direct damage to general property and agriculture. The damage to paddy fields, farmlands, residential areas, business establishments, and golf courses was taken into account. However, it was hypothesized that inundation would not cause economic damage to lands such as forests, barren lands, trunk transportation sites, sites for other uses, rivers, lakes, beaches, and seawater areas. The details are given in the [appendix](#).

The expected annual damage cost (EADC) was the cumulative product of the interval averaged probability obtained from the 30-, 50-, 100-, and 200-year return periods multiplied by the interval averaged flood damage.

(3) Estimation method for the future period

First, from the daily precipitation data obtained from each period of the target GCM and two RCP scenarios, the maximum daily precipitation for each year at each of the 1259 points throughout the country was extracted with reference to the position of the AMeDAS point where the precipitation was observed, and frequency analysis was performed. In the frequency analysis, the generalized extreme value distribution was used as the probability distribution type, and the probability weight moment method was used as the parameter estimation method (Tezuka et al. 2014). Frequency analysis was used to determine the daily precipitation for each return period at each point for the late twentieth century and future periods. The ratio of the daily precipitation obtained from the above analysis was considered as the rate of increase in precipitation. The distribution of the rate of increase in precipitation was obtained by distributing the rate throughout Japan by the inverse distance weighted method. The distribution is shown in Fig. 1. The rainfall distribution obtained by multiplying this distribution by the stochastic flood-contributing rainfall distribution in the late twentieth century was considered as the extreme rainfall distribution in the future period.

Fig. 1 Percentage change in extreme precipitation for 100-year return period (the climatic conditions for the future period are shown in the following order of GCMs (from the top): CSIRO-Mk3-6-0, GFDL-CM23, HadGEM2-ES, MIROC5, and MRI-CGCM3)

Although socioeconomic scenarios may be used simultaneously when dealing with future scenarios, they are not used in this study. Therefore, if socioeconomic scenarios are used, it is expected that the target area of adaptation measures and the absolute value of the flood damage cost will change.

(4) Evaluation of mitigation measures

The flood damages of RCP2.6 and RCP8.5 scenarios were calculated. Therefore, the mitigation measures refer to the mitigation of global warming from the RCP8.5 scenario to the RCP2.6 scenario. Therefore, the effectiveness of mitigation measures in reducing flood damages is evaluated as the difference between the damages of the RCP8.5 scenario and those of the RCP2.6 scenario.

(5) Evaluation of adaptation measures

In Japan, comprehensive flood control measures have been promoted as the efforts made by public administrators. These measures comprise three submeasures—basin management measures, damage mitigation measures, and flood control level improvement—according to regional characteristics. Land-use control, piloti building, and flood control level improvement measures, which are used to verify the adaptation effectiveness in this study, correspond to each of these three submeasures. The three adaptation measures correspond to the three major adaptation measures of Klein et al. (1999). Land-use control corresponds to retreat, piloti building corresponds to accommodation, and improvement of flood control level corresponds to protection. The method of application of each adaptation measure in this study is described below.

a) Land-use control

Fig. 2 Population density distribution

Out of the land used as a building site with an inundation depth of 3.0 m or more during a flood with a return period of 200 years in the late twentieth century, a mesh with a population density of 10,000 people/km² or less was assumed to be evacuated, and the damage cost was not calculated. The reason for setting the population density limit is that in densely populated areas such as Tokyo, land-use control is unrealistic. Figure 2 shows the population density distribution. The areas where the population density exceeds 10,000 people/km² are shown in red. The areas with a high population density are distributed mainly in Tokyo and Osaka. Because economic activity bases are concentrated in these areas, it is not easy to proceed with evacuation. Therefore, for areas with such high population densities, flood countermeasures based on piloti building will be considered. As an example of changes in land use after regulation, Fig. 3 shows the changes in land use in the lower reaches of the Arakawa River, which has a relatively large regulated area.

b) Piloti building

It was assumed that the building area where land-use control was difficult would change to a piloti building area. In the flood analysis with a population density of over 10,000 people/km² and a return period of 30 years, the building site meshes with an inundation depth (inundation above the floor) of 0.5 m or more were replaced with a piloti building mesh. In the calculation of the damage cost in the piloti building mesh, the damage cost was calculated by lowering the inundation depth by 3.0 m, assuming that the rise in height due to the piloti would be 3.0 m.

Fig. 3 Land-use distribution before and after land-use control and adoption of pilotis building (outskirts of Tokyo). Upper right: original land use; upper left: after land-use control; lower left: after the adoption of pilotis building

c) Improvement of flood control level

Using the method of Tanaka et al. (2019), river channels were excavated to reflect the planned scale of the water system and the target flood safety level of each river section, and the state of achieving a planned maintenance level of 100% was reproduced.

4 Results

Figure 4 shows the expected annual flood damage costs (average value of five models) when various measures are implemented.

(1) Reduction in flood damage cost by mitigation measures

a) Flood damage cost in the twentieth century

The EADC was estimated to be 3259 billion JPY/year. The prefectures with the highest EADC were Osaka, Tokyo, Aichi, Saitama, and Hokkaido, in that order. This EADC is the amount of damage without any adaptation measures and serves as a baseline for comparison.

b) Flood damage cost in near future

The EADC in the near future was estimated to be 4617 billion JPY/year in the RCP2.6 scenario and 4620 billion JPY/year in the RCP8.5 scenario. Compared to the end of the twentieth century,

Fig. 4 Expected annual damage cost caused by flood inundation

EADC increased by 42% in both RCP scenarios. The standard deviations of the EADC between the five models were 918 and 740 billion JPY/year for RCP2.6 and RCP8.5, respectively, with a difference of 179 billion JPY/year. These standard deviations are approximately 54 times larger than the difference of EADC of 3.3 billion JPY/year between the scenarios.

c) Flood damage in the late twenty-first century

The EADC in the late twenty-first century was estimated to be 4163 billion JPY/year in the RCP2.6 scenario and 5103 billion JPY/year in the RCP8.5 scenario. The difference in the EADC between the scenarios was 940 billion JPY/year, and the damage cost for RCP8.5 was 1.2 times that for RCP2.6. Compared to the late twentieth century, there was 28% more EADC in the RCP2.6 scenario and 57% more EADC in the RCP8.5 scenario. It is considered that unlike in the near future, mitigation effectiveness was clearly observed in the late twenty-first century. The EADC reduction rate due to mitigation for each region was as follows: Hokkaido, 27%; Tohoku, 20%; Kanto, 26%; Chubu, 18%; Kansai, 12%; Chugoku, 9%; Shikoku, 9%; and Kyushu, 5%. It was confirmed that the effect was particularly high in the region north of Kanto. In Fig. 1, the areas where the rate of increase in precipitation is large and the hazards are particularly high and the areas where the mitigation measures are effective are almost the same.

(2) Reduction in flood damage by land-use control

The number of cells targeted for land-use control was 9256, and the area was 578.5 km². The EADC was estimated to be 2613 billion JPY/year. It decreased by 20% compared to the EADC in the late twentieth century without land-use control. The three prefectures where the EADC reduction rate exceeded 50% were Nagasaki, Kagoshima, and Nara prefectures. Because these prefectures tended to be topographically less prone to flooding and the target areas of land-use control coincided with many of the areas that were originally at high risk of flooding, the effects of the measures were clearly visible.

In the near future, the EADC when the land-use control was applied was estimated to increase by 16% in both the RCP2.6 and RCP8.5 scenarios compared to the EADC in the late twentieth century where land-use control was not implemented. In the late twenty-first century, the EADC when the land-use control was applied was estimated to increase by 3% in the RCP2.6 scenario and increase by 29% in the RCP8.5 scenario compared to the EADC in the late twentieth century where land-use control was not implemented.

(3) Reduction in flood damage by piloti building

With the piloti building, the EADC was estimated to be 2668 billion JPY/year under the precipitation conditions in the late twentieth century, which was a decrease of 18% compared to the case without piloti building. The number of piloti building cells was 3714, covering an area of 232 km².

On the other hand, in the near future, the EADC was estimated to increase by 49% in RCP2.6 and 48% in RCP8.5 compared to the conditions with piloti building in the late twentieth century. The damage cost reduced by 14% compared to that in the near future without adaptation measures. However, the rate of increase in damage from the late twentieth century to the near future is slightly higher with piloti building than without adaptation. This can be attributed to the fact that the criteria for piloti building depend on the precipitation

conditions in the late twentieth century. To reduce future flood damage, land-use and building restrictions must be based on future forecasts. For the late twenty-first century, the damage cost was estimated to increase by 8% in RCP2.6 and 36% in RCP8.5 compared to that in the late twentieth century without piloti building.

(4) Reduction in flood damage by improving flood control levels

When the level of flood control was improved, the EADC amount under the precipitation conditions in the late twentieth century was estimated to be 2686 billion JPY/year, which was a decrease of 18% compared to before the improvement in flood control level. On the other hand, in the near future, the EADC was estimated to increase by 51% compared to the conditions in the late twentieth century and before the improvement of flood control level. The EADC reduced by 12% compared to that in the near future without any adaptation measures. In the late twenty-first century, compared to before the improvement in flood control level, and the late twentieth-century precipitation conditions, the EADC increased by 10% in RCP2.6 and by 40% in RCP8.5. In both scenarios, flood control level improvement was less effective than the other adaptations.

5 Discussion

(1) Accuracy of flood damage estimation model

First, the method of estimating flood damage cost should be verified for accuracy. If the amount of damage to general assets in the flood statistics (Ministry of Land, Infrastructure, Transport and Tourism) from 1980 to 2000 is aggregated by prefecture, the prefectures in descending order of damage will be Aichi, Tokyo, Kochi, Saitama, and Osaka. This is consistent with the prefectures with large damage estimated by the model. The correlation coefficient between the annual average flood damage by prefecture calculated from flood statistics and the EADC of each prefecture in this analysis was calculated to be 0.65. Therefore, the distribution of damage by prefecture is considered to roughly reflect the actual flood damage. Therefore, it is considered that the damage distribution can be generally reproduced. However, the absolute values of the damage do not match. Although the estimated result of the model is 3259 billion JPY/year for the entire region of Japan, the annual average damage cost according to the flood statistics is 207.9 billion JPY. This may be because the spatial event probability of precipitation that causes floods is not taken into consideration.

Next, the uncertainty in the model selection for future climate estimation is discussed. Under the condition of no adaptation, the standard deviation of the EADC ranges from 532 to 918 billion JPY/year, and the inter-model variability is very large. In particular, in the near future, the difference between the EADC of the five models of RCP2.6 and RCP8.5 is 3.3 billion JPY/year, which may cause a reversal of the damage amounts. Therefore, it is necessary to pay attention to the uncertainty of GCM models.

(2) Flood damage variations due to climate change and effectiveness of mitigation measures

It was estimated that the average flood damage of the five models in the RCP8.5 scenario without mitigation measures would increase toward the late twenty-first century. On the other

hand, it was estimated that the average flood damage of the five models in the RCP2.6 scenario, where mitigation measures are implemented, would peak in the near future and decrease toward the late twenty-first century. Here, we discuss this result and the uncertainty due to model selection. Figure 5 shows the estimated EADC by each GCM.

In the RCP8.5 scenario, the flood damage of the four models excluding GFDL-CM23 increase in the order of the late twentieth century, near future, and late twenty-first century. The EADC in the late twenty-first century in GFDL-CM23 decreases by more than 8% compared to the damage cost in the near future. However, compared to the RCP2.6 scenario of the same model where the decrease from the damage cost in the near future to the damage cost in the late twenty-first century is 25%, it can be said that the decrease in the damage cost in the RCP8.5 scenario is small. Therefore, it can be considered that the overall trend of the five models is that the flood damage will increase over time.

In the RCP2.6 scenario, the damage costs of the three models excluding MIROC5 and MRI-CGCM3 are the largest in the order of the late twentieth century, late twenty-first century, and near future. Although the damage cost in MIROC5 is the largest in the order of the late twenty-first century, late twentieth century, and near future, the damage cost in the late twenty-first century is only 1% smaller than that in the late twentieth century. Because the damage cost peaks in the near future, considering the transition pattern of the damage cost, the behavior can be considered to be similar to the other three models. The damage cost in MRI-CGCM3 decreases slightly from the late twentieth century to the near future and increases toward the late twenty-first century. This model clearly shows a behavior that is different from the other four models. As shown in Fig. 1, the percentage of extreme precipitation change in the near future is small. Hence, the overall trends of the five models in the RCP2.6 scenario peak in the near future and then gradually decrease. However, because there are clear exceptions such as MRI-CGCM3, the uncertainty in RCP2.6 is considered greater than that in RCP8.5.

Fig. 5 Estimate expected annual damage cost from each GCM

(3) Reduction in flood damage when applying a combination of multiple adaptation measures

It was estimated that if the three adaptation methods were implemented individually, it was hard to keep the damage cost below that in the late twentieth century. Table 1 lists the percentage of the EADC for each adaptation scenario to the expected annual damage cost for the no adaptation condition in the late twentieth century. For the patterns shown in red, orange, and yellow, the damage cost increases more than that in the late twentieth century with no adaptation measures. If the adaptation measures are implemented individually, in all cases, the pattern is such that the EADC will increase in the future period. Therefore, multiple adaptation measures should be implemented in combination. The effectiveness of flood damage reduction when multiple adaptation measures are combined is shown.

First, please note the values for the RCP8.5 scenario in Table 1. This can be considered as a scenario where only adaptation measures are implemented without mitigation methods. Damage mitigation is the most effective when the three methods—land-use control, piloti building, and improvement of flood control levels—are implemented in combination. In the late twentieth century, the damage cost was estimated to be halved. Moreover, in the near future in the RCP8.5 scenario, even if a single adaptation measure is implemented, the damage will increase more than that in the late twentieth century with no adaptation. However, it was estimated that if the adaptation measures are combined, two out of four measures could suppress the damage below that in the late twentieth century with no adaptation. Thus, it can be considered that the effectiveness of implementing the adaptation measures in combination is demonstrated. On the other hand, in the late twenty-first century in the RCP8.5 scenario, except for the pattern that combines the three adaptation measures, all the patterns exhibit a damage cost that is higher than that in the late twentieth century with no adaptation. This is considered to indicate the limitation of adaptation measures under global warming.

In Table 1, the values for the RCP2.6 scenario can be regarded as the changes in the flood damage cost when implementing the mitigation and adaptation measures simultaneously. Regardless of the presence or absence of mitigation methods, the flood damage will increase to the same extent in the near future. Therefore, no particular effects are observed by implementing both mitigation and adaptation measures. However, in the late twenty-first century, the damage cost can be greatly reduced by undertaking both measures. For example, in the RCP8.5 scenario, except for the case where land-use control, piloti building, and improvement of flood control levels are all implemented, the damage cost increases more

Table 1 Percentage of expected annual damage cost for each adaptation scenario to the expected annual damage cost for the no adaptation condition in the late twentieth century

(%)	No adaptation	Land-use control	Piloti building	Improvement of flood-control level	Land-use control & Piloti building	Land-use control & Improvement of flood-control level	Piloti building & Improvement of flood-control level	Land-use control & Piloti building & Improvement of flood-control level
Late 20 th century	100	80	82	82	62	66	68	51
Near future	RCP2.6	142	115	122	95	101	107	82
	RCP8.5	142	116	121	95	101	106	82
Late 21 st century	RCP2.6	128	103	108	83	88	94	71
	RCP8.5	157	129	136	140	107	114	94

than that in the late twentieth century where no adaptation measures are implemented. However, in the RCP2.6 scenario, the damage cost can be kept smaller than that in the late twentieth century without adaptation measures when multiple adaptation measures are used in combination and land-use control is implemented. In the case where all three adaptation measures are implemented, the damage cost can be reduced by 71% compared to that in the late twentieth century with no adaptation measures. Thus, these results support the importance of successfully implementing mitigation and adaptation measures in combating climate change.

The above discussion indicates that the adaptation measures verified in this study have a reduction effect on flood damage cost. Next, the feasibility of these adaptive measures is discussed. In Shiga Prefecture, basin flood control is being promoted and an inundation warning area has been designated. This area is designated according to a consensus between residents and the government based on the guideline that an estimated inundation area should exceed 3 m according to the 200-year probability of precipitation. In restricted areas, the system provides subsidies for construction projects wherein water resistance is provided to existing buildings. In this case, it can be considered that even if relocation from a high-risk area is difficult, it is possible to adapt by providing water resistance to structures. In this study, land-use control is carried out based on a population density of 10,000 people or less per square kilometer. However, if the population affected by land-use control amounts to several thousands, relocation may involve considerable time and cost. Looking at the actual cases, we find that most of them are group relocations for disaster prevention that were carried out after the disaster. Although the system was revised in 2020 and a disaster prevention relocation plan system was established to prompt advance relocation, because there are only a few cases of relocation before the occurrence of a disaster, it can be inferred that land-use control involving relocation of existing houses examined in this study is extremely difficult.

Thus, cases where areas with high flood risk cannot be completely regulated because of social restrictions or cases where river maintenance cannot be completed on time can be considered. In such cases, it can be said that results suggesting the importance of controlling flood damage cost by exploring possible adaptation measures for each region and implementing them in combination are achieved. Furthermore, because it is clear that the effectiveness of adaptation methods is limited, it is important to promote mitigation measures along with adaptation measures.

6 Conclusion

In this study, the EADC caused by flood inundation was estimated for all of Japan. Using five GCMs, the EADC caused by floods was estimated for the near future period around 2050 and for the late twenty-first century period around 2100. Three adaptation measures, land-use control, piloti building, and flood control level improvement, were also estimated. The conclusions drawn from this study are briefly described below.

- 1) In the no adaptation scenario, the EADC in the near future is estimated to increase by 42% from the late twentieth century, with or without mitigation; in the late twenty-first century, it was estimated to increase by 57% in the RCP8.5 scenario, while it is limited to 28% in the RCP2.6 scenario.

- 2) It was estimated that most of the scenarios in which the three adaptation measures were implemented independently would result in higher damages than the no adaptation condition in the late twentieth century.
- 3) A combination of adaptation measures was expected to be more effective in reducing damage in the near future and the late twenty-first century for the RCP2.6 scenario than in the no adaptation condition in the late twentieth century.
- 4) By implementing mitigation measures in addition to adaptation measures, it was estimated that the damage could be reduced by up to 69% in the late twenty-first century compared to the condition without adaptation measures in the late twentieth century.

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