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RESEARCH ARTICLE

# Estimation of the effect of future changes in precipitation in Japan on pluvial flood damage and the damage reduction effect of mitigation/adaptation measures

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## Abstract

This study estimated the effect of changes in the amount of precipitation associated with climate change on pluvial flood damage and the effectiveness of mitigation and adaptation measures throughout Japan. First, the cost of damage caused by pluvial flooding was calculated based on extreme rainfall, assuming a situation in which river levels are high, and rainwater does not drain into the rivers. Additionally, extreme rainfall in future climates was estimated from the output values of five general circulation models. Then, using these figures for extreme rainfall, the cost of pluvial flood damage in future climates was estimated. Improving the maintenance level of inland water drainage facilities and converting buildings to a piloti design were selected as adaptation measures. The results showed that in the Representative Concentration Pathway (RCP) 8.5 scenario, the expected annual damage cost (EADC) in the late 21st-century climate (2081–2100) scenario increases to approximately 2.3 times that of the baseline climate (1981–2000). If climate change is mitigated to RCP 2.6, the EADC in the late 21st-century climate scenario is estimated to be reduced by 28% compared to the EADC in the RCP 8.5 scenario. It is also estimated that the EADC in future climates could be kept lower than in the baseline climate by taking multiple rather than single measures. However, in the RCP 8.5 scenario for the late 21st-century climate, even if multiple adaptation measures are taken, the EADC was estimated to increase by 9% compared to the EADC in the baseline climate.



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## Introduction

In 2015, the United Nations Sustainable Development Summit was held, and the outcome document "Transforming our world: the 2030 Agenda for Sustainable Development" was adopted [1]. In this agenda, Sustainable Development Goals (SDGs) comprising 17 goals and 169 targets were identified. One of these SDGs was to "take urgent action to combat climate change and its impacts." Additionally, in "The Global Risks Report 2021," failure to adapt to climate

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change was ranked among both the global risks with the highest likelihood of occurrence and the global risks with the highest impact [2]. These statements reflect the fact that adaptation to climate change has become a global priority.

On global warming, the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that warming of the climate system is unequivocal [3]. In addition, it is predicted that climate warming will change the amount of precipitation in Japan. Fujita et al. (2019) [4] showed that, unless additional mitigation efforts are made, statistically significant increases, not only in annual average daily precipitation but also annual maximum daily precipitation, may occur in mid- and high latitude regions, including Japan, in the near future (between 2030 and 2050). Hatsuzuka and Sato (2019) [5] suggested that extreme monthly precipitation with a return period of 100 years between June and August would increase in many parts of Japan due to global warming. Nayak and Takemi (2020) [6] applied a pseudo-global warming experiment to four typhoons that made landfall in northern Japan in August 2016 and showed that three of these typhoons could cause more rainfall in the north under future climate conditions. These studies suggest that flood damage will become more severe in the future. Further, since precipitation is predicted to increase even before the end of the 21st century, it is necessary to consider adaptation to flood damage given the rainfall increases associated with climate change. In considering specific adaptation measures, it is necessary to evaluate the flood risk and the effectiveness of the adaptation measures quantitatively.

Multiple flood assessments have been done in many countries around the world. On a global scale, Winsemius et al. (2013) [7] proposed a framework for assessing the global risk of river flooding that could also be applied to future scenarios. Arnell and Gosling (2016) [8] used multiple climate models to evaluate the impact of climate change on flood frequency, exposed population, exposed cropland area, and flood risk indexed by average annual flood loss. Dottori et al. (2018) [9] evaluated human losses, direct economic damage, and indirect welfare losses due to river flooding associated with global warming. As an example of a flood risk assessment targeting Japan, Kazama et al. (2009) [10] estimated the cost of flood damage throughout Japan, assuming flood protection facilities suitable for a 50-year return period flood. Tezuka et al. (2014) [11] evaluated the impact of climate change on the cost of flood damage throughout Japan. These studies mainly focused on flooding from rivers (fluvial flooding). However, a lack of research on the risk assessment of pluvial flooding has been identified [12,13].

In Japan, following damage caused to many homes in eastern Japan by pluvial flooding resulting from Typhoon Hagibis in 2019 [14], the importance of taking measures against pluvial flooding has grown. On a city scale, pluvial flooding risk assessments [15–18] and climate change impact assessments [19–21] have been conducted. Several assessments of pluvial flooding targeting large areas, such as entire countries, have also been carried out [22,23], but these are few compared with the number of studies on a city scale. For this reason, there is insufficient knowledge about the spatial distribution of pluvial flooding risk throughout Japan taking account of climate change. Climate change impact assessments for entire countries are useful for identifying areas in which the importance of measures against pluvial flooding is increasing. On adaptation measures, evaluations of adaptation measures against pluvial flooding have been conducted on a city scale [24–26]. Meanwhile, evaluations of adaptation measures against river flooding have been conducted on a global and national scale [27,28]. However, no studies have examined the effectiveness of adaptation measures against pluvial flooding targeting entire countries, including Japan. Evaluating adaptation measures for an entire country makes it possible to discuss the adaptation measures needed to reduce the impact of climate change by region.

This study estimated the effect of changes in the amount of precipitation associated with climate change on pluvial flood damage and the damage reduction effect of pluvial flooding adaptation measures throughout Japan. In addition, it also evaluated the pluvial flood damage reduction effect due to mitigation measures. It is hoped that the results obtained in this study will be useful in predicting future changes in pluvial flood damage and examining the effectiveness of adaptation measures.

## Datasets

### Rainfall data for baseline climate

Extreme rainfall data with a spatial resolution of 1 km prepared for the whole of Japan by Kawagoe et al. (2010) [29] were used as rainfall data for the late 20th-century climate that serves as the baseline (baseline climate). These rainfall data were created using 24-hour precipitation data from 1980 to 2000 at Automated Meteorological Data Acquisition System stations and Mesh Climatic Data 2000 (published by the Japan Meteorological Agency). Therefore, we used the baseline period from 1980 to 2000. Previous studies on river flooding [10,11,28] also used extreme rainfall data created by Kawagoe et al. (2010) [29]. These rainfall data show the probable precipitation for each return period at a spatial resolution of 1 km. In addition, extreme rainfall data were used as input data for the flood analysis to estimate pluvial flood damage, taking into account regional climate characteristics. In this study, the analysis was performed using data on extreme rainfall with return periods of 5, 10, 30, 50, and 100 years.

### Predicted future precipitation data

To estimate extreme rainfall in future climates, daily precipitation statistically downscaled to a spatial resolution of 1 km in the Regional Climate Projection Dataset NARO2017-v2.7r of the National Agriculture and Food Research Organization created by Nishimori et al. (2019) [30] was used. Nishimori et al. (2019) [30] applied the Gaussian-type Scaling approach [31] for bias correction. Five General Circulation Models (GCMs) and two Representative Concentration Pathway (RCP) scenarios are used in the Regional Climate Projection Dataset NARO2017-v2.7r. The GCMs are GFDL-CM3, HadGEM2-ES, MIROC5, MRI-CGCM3, and CSIRO-Mk3-6-0, and the RCP scenarios are RCP 2.6 and RCP 8.5. These GCMs were selected by Nishimori et al. (2019) [30], and many researchers have recently used these GCMs to perform impact assessments in Japan [32]. Representative Concentration Pathway 2.6 is a scenario in which strict measures to cut greenhouse gas emissions are implemented. In contrast, RCP 8.5 is a scenario in which greenhouse gas emissions continue. This study used data from all these GCMs and RCP scenarios. The Regional Climate Projection Dataset NARO2017-v2.7r provides historical data from 1981 to 2005 and future data from 2006 to 2100. This dataset was used in many previous studies on climate change impact assessment in Japan [28,33–35]. Thus, this dataset allows for a comparison of impact assessments. Four data periods were used: 1981–2000 (baseline climate), 2006–2025 (early 21st-century climate), 2031–2050 (near-future climate), and 2081–2100 (late 21st-century climate). The future periods were set to 20 years as well as the baseline climate [28].

### Elevation data and ground-slope data

The elevation data were average elevation with a spatial resolution of 250 m stored in the elevation/slope-angle fifth mesh data of the Digital National Land Information download services [36]. The ground slope data were average slope angle with a spatial resolution of 250 m stored in the elevation/slope-angle fifth mesh data. The elevation data were used in the flood analysis, and the ground slope data were used to calculate the damage cost.

### Land-use data

The land-use data used in the flood and damage cost calculations were from the Digital National Land Information download services [37]. The land-use classifications were: (1) paddy field; (2) field; (3) forest; (4) wasteland; (5) land for building; (6) trunk transportation land; (7) other land; (8) river area, lake, and marsh; (9) beach; (10) seawater body; and (11) golf course.

### River data

There are two main types of pluvial flooding. One is caused by rainfall that exceeds the rainwater drainage capacity, while the other is caused by river levels rising and preventing rainwater from draining into the rivers. To analyze the risk of the latter type of pluvial flooding, it is necessary to understand the river location information. Therefore, in this study, a combination of meshes designated as either Class A river (directly managed section), Class A river (designated section), or Class B River section in the land-use data and fifth mesh river data were taken as rivers. The fifth mesh river data is a rasterized version of river data (line data) from the Digital National Land Information download services [38].

## Methodology

### Summary of flood analysis

In this study, a flood analysis was performed assuming the worst-case scenario in which river levels are high and rainwater does not drain into rivers at all. The reason for assuming this worst-case scenario is as follows. Rainfall in the upper and middle reaches of a river influences the water level that determines the possibility of drainage into the river. Therefore, in the areas near the river, the risk of pluvial flooding differs depending on the river level, even for the same intensity of rainfall. Given this, it was considered important to assume the worst-case scenario when evaluating the adaptation measures. Additionally, according to Ministry of Land, Infrastructure, Transport and Tourism (MLIT) [14], approximately 80% of the damage to residential buildings caused by pluvial flooding due to the heavy rain event of July 2018 and Typhoon Hagibis in 2019 occurred in areas where the river level exceeded the planned high-water level. Therefore, a flood analysis that assumes poor drainage into rivers reflects the reality of pluvial flooding.

In the flood analysis, as well as analyzing the whole of Japan simultaneously, rivers and floodplains were analyzed without distinction by applying a two-dimensional unsteady flow model [11]. The governing equations of the two-dimensional unsteady flow model are shown below.

Continuity equation:

$$\gamma \frac{\partial D}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = R$$

Momentum equation in the $x$ direction:

$$\lambda \frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\lambda \frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{MN}{D}\right) + \gamma g D \frac{\partial (D+h)}{\partial x}$$

$$+\gamma g n^2 \frac{M\sqrt{M^2+N^2}}{D^{7/3}} + \frac{1}{2}\frac{(1-\gamma)}{B} C_D \frac{M\sqrt{M^2+N^2}}{D} = 0$$

Momentum equation in $y$ direction:

$$\lambda\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\lambda\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{N^2}{D}\right)+\gamma gD\frac{\partial(D+h)}{\partial y}$$

$$+\gamma gn^2\frac{N\sqrt{M^2+N^2}}{D^{7/3}}+\frac{1}{2}\frac{(1-\gamma)}{B}C_D\frac{N\sqrt{M^2+N^2}}{D}=0$$

Equation of $\lambda$:

$$\lambda=\gamma+(1-\gamma)C_M$$

Here, $t$: time, $D$: water depth, $h$: elevation, $M$: discharge flux in the $x$ direction, $N$: discharge flux in the $y$ direction, R: rainfall, $g$: gravitational acceleration, $n$: Manning's roughness coefficient, $(1-\gamma)$: house occupancy ratio, $B$: house size, $C_M$: additive mass coefficient, $C_D$: house drag coefficient. The grid size of the flood calculation was fifth mesh (approximately 250 m×250 m). The extreme rainfall data was assigned a constant intensity over 24 hours. In the two-dimensional unsteady flow model, the resistance of residential buildings was taken into account by assuming that water did not infiltrate residential building areas. The parameters used in the flood analysis were the same as those used by Tezuka et al. (2014) [11]. Yanagihara et al. (2021) [39] tested the two-dimensional unsteady flow model in the Naruse River basin in Japan and confirmed its accuracy. This analysis was performed by taking the inflow into rivers as zero, since this is the condition for no drainage of rainwater into rivers at all. Additionally, by always taking the river water depth as zero, only pluvial flooding was dealt with.

## Drainage of rainwater by inland water drainage facilities

In this study, inundation depths taking into account the inland water drainage facilities were estimated by subtracting a rainfall amount corresponding to the maintenance level of inland water drainage facilities from the rainfall amounts used in the flood analysis.

In Japan, maintenance of existing inland water drainage facilities is planned to handle rainfall with a return period of approximately five years in most regions. Additionally, a standard for the achievement rate of urban flooding countermeasures, an indicator of measures against urban flooding using Japan's sewerage systems, is that the system should be able to handle rainfall with a return period of approximately five years [14]. Therefore, with reference to current maintenance targets, the analysis assumed that all rainfall with a return period of five years in the baseline climate could be drained. Fig 1 shows the five-year return period extreme rainfall data for the baseline climate, which serves as the baseline for rainwater drainage.

## Method of estimating damage cost

Damage cost was estimated with reference to the Manual for Economic Evaluation of Flood Control Investment [40]. In this study, the target of the damage cost estimation was taken to be direct damage to general assets and agriculture. The damage cost was calculated by multiplying the asset value of the flooded land by the damage rate according to inundation depth. The asset value was determined according to an asset valuation by land use and prefecture. Flooding was assumed to cause economic damage to the land uses: paddy field, field, land for building, and golf course. On the other hand, flooding was assumed to cause no economic damage to the land uses: forest; wasteland; trunk transportation land; other land; river area, lake, and marsh; beach; and seawater body. For details about the method of estimating damage cost, please refer to the appendix of Yamamoto et al. (2021) [28]. However, in this study, the following points differ from the damage cost estimation method of Yamamoto et al. (2021) [28].

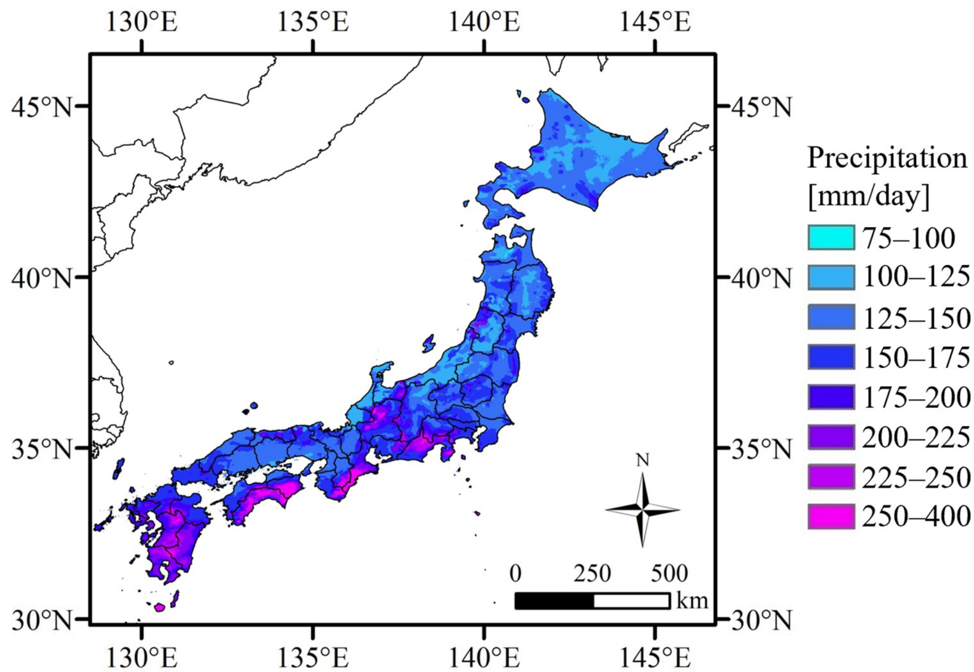


**Fig 1. Five-year return period extreme rainfall in baseline climate.** Souce of the base layer of the map: https://www.naturalearthdata.com/downloads/10m-cultural-vectors/.

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1. In the Manual for Economic Evaluation of Flood Control Investment revised in 2020 [41], the damage rate by inundation depth was updated to reflect recent disasters. This study estimated the damage cost using the updated damage rate for damage to residential buildings and office depreciation/inventory asset damage.
2. For the number of households included in the estimation of damage to household items, 500-m mesh data [42] was used, rather than data by prefecture.
3. For the number of employees included in the estimation of office depreciation/inventory asset damage, 500-m mesh data [43] was used, rather than data by prefecture.

The impact of changes in precipitation amounts due to climate change on the cost of damage in future climates was considered without assuming changes in asset distribution associated with population shifts or population decline. Using the cost of damage caused by extreme rainfall with each return period, the expected annual damage cost (EADC) was calculated from Eq (1).

$$D = \sum_{i=1}^{4} \frac{(1/m_i - 1/m_{i+1})(d_{m_i} + d_{m_{i+1}})}{2} \qquad (1)$$

Here, $D$: EADC, $m_i$: return period, $d_{m_i}$: cost of damage caused by extreme rainfall with return period $m_i$. The return period $m_i$ corresponding to $i$ = 1, 2, 3, 4, 5 is 5, 10, 30, 50, and 100 years.

## Method of estimating extreme rainfall data for future climates

Extreme rainfall data for future climates were created by estimating the distribution of the rate of increase in extreme rainfall between the baseline climate and the future climate and multiplying that by the extreme rainfall data for the baseline climate [28]. The method of estimating the distribution of the rate of increase in extreme rainfall was as follows. First, daily precipitation data for 1981–2000 (baseline climate), 2006–2025 (early 21st-century climate), 2031–2050 (near-future climate), and 2081–2100 (late 21st-century climate) were extracted from the Regional Climate Projection Dataset NARO2017-v2.7r. Then, daily precipitation data were extracted from 1,284 points throughout Japan with reference to the Automated Meteorological Data Acquisition System station location. Next, the annual maximum daily precipitation at each point was found, and a frequency analysis was performed for each period (baseline climate, early 21st-century climate, near-future climate, late 21st-century climate). In the frequency analysis, the generalized extreme value distribution was used as the type of probability distribution, and the probability weight moment method was used as the parameter estimation method [11]. Lastly, for each return period, the rate of increase in precipitation at each point between the baseline climate and the future climate was found, and the distribution of the rate of increase in extreme rainfall was estimated by distributing this rate of increase throughout Japan using the inverse distance weighting method. The climate change mitigation measures were evaluated by the difference in the EADC according to the extreme rainfall data in the RCP 2.6 scenario and the RCP 8.5 scenario estimated by the above method.

## Evaluation of reduction effect on pluvial flood damage due to adaptation measures

In Japan, the government has implemented comprehensive flood control measures [44]. For example, measures to counteract pluvial flooding include improving the maintenance level of inland water drainage facilities and promoting flood-resistant architecture, such as piloti constructions. Therefore, improving the maintenance level of inland water drainage facilities and converting buildings to piloti constructions were selected as adaptation measures, and the effect of these measures on reducing pluvial flood damage in future climates was evaluated. The details of each adaptation measure are provided below.

**Improving the maintenance level of inland water drainage facilities (Plan 1).** It was assumed that improving the maintenance level of inland water drainage facilities increases the drainage capability throughout Japan from rainfall with a return period of five years to rainfall with a return period of 10 years. In this study, the EADC was calculated assuming that all rainfall with a return period of 10 years in the baseline climate could be drained. Specifically, the inundation depth was calculated using rainfall amounts obtained by subtracting extreme rainfall with a return period of 10 years from the extreme rainfall with each return period, and the EADC was estimated. Improving the maintenance level of inland water drainage facilities is referred to as Plan 1.

**Converting buildings to piloti construction (Plan 2).** In this study, in the flood analysis for a return period of 10 years, meshes of land for building where flooding of 0.45 m or more above floor level had occurred [40] were replaced with piloti constructions. Piloti construction is a type of architecture in which the first floor of the building is an exterior space containing only columns. Therefore, by converting buildings to piloti constructions, flooding of the first-floor area does not cause damage. In piloti construction meshes, assuming that the buildings had been raised by 3 m due to the piloti construction, EADC was calculated by reducing the inundation depth by 3 m. For that reason, the flood analysis did not consider the effect of replacement with piloti construction [28]. Converting buildings to piloti construction is referred to as Plan 2.

# Results

Since statistical data from Japan were used, the estimation of EADC was based on the Japanese yen (JPY). In this paper, the EADC is converted into United States dollars (USD), taking 1 USD as 100 JPY.

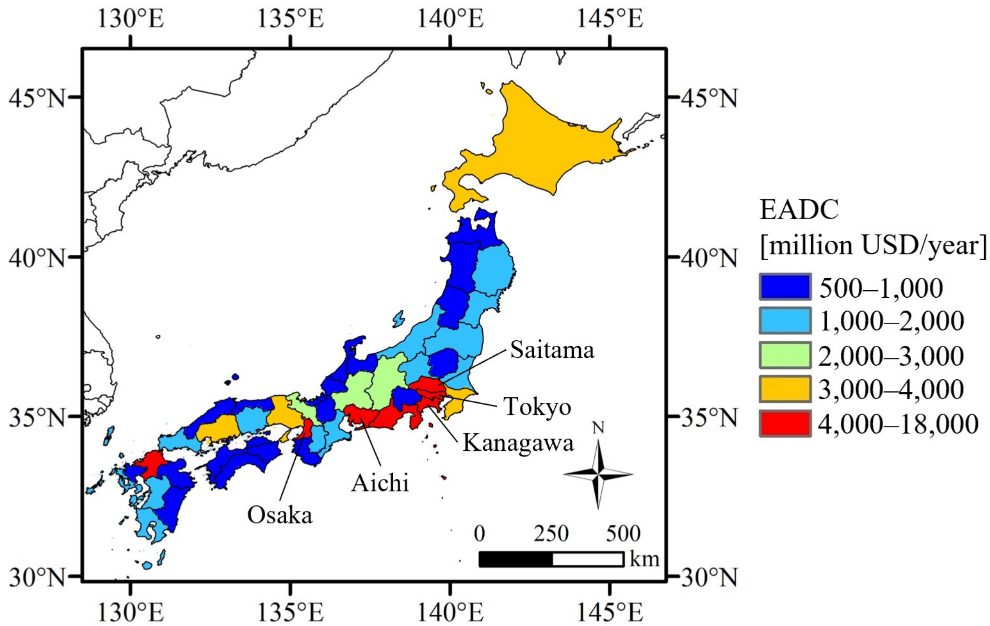


**Fig 2. EADC by prefecture for baseline climate.** Souce of the base layer of the map: https://www.naturalearthdata.com/downloads/10m-cultural-vectors/.

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## Pluvial flood damage for baseline climate

Fig 2 shows the EADC by prefecture for the baseline climate. The EADC for the baseline climate was estimated to be 109,284 million USD/year. The prefectures with the highest EADC were Tokyo, Kanagawa, Osaka, Aichi, and Saitama, in that order. This EADC is the cost without any adaptation measures taken, and it serves as a baseline for comparison.

## Rate of increase in extreme rainfall in future climates

Table 1 shows the national average rate of increase in extreme rainfall compared to the baseline climate (average value of five GCMs). No striking differences between the RCP scenarios were found in the national average rate of increase in extreme rainfall in the early 21st-century climate and near-future climate. Differences between the RCP scenarios were found in the national average rate of increase in extreme rainfall in the late 21st-century climate. Extreme rainfall in the RCP 8.5 scenario was approximately 1.6–1.8 times the extreme rainfall in the RCP 2.6 scenario.

## Pluvial flood damage in future climates without adaptation measures

Fig 3 shows the rate of increase in EADC by prefecture between the baseline climate and each future climate when adaptation measures are not taken.

**Table 1. National average rate of increase in extreme rainfall compared to baseline climate (average value of five GCMs, unit: %).**

| Return period | Early 21st-century climate | | Near-future climate | | Late 21st-century climate | |
|---|---|---|---|---|---|---|
| | RCP2.6 | RCP8.5 | RCP2.6 | RCP8.5 | RCP2.6 | RCP8.5 |
| 5-year | 13 | 16 | 26 | 25 | 24 | 39 |
| 10-year | 15 | 18 | 27 | 26 | 25 | 42 |
| 30-year | 18 | 20 | 31 | 30 | 27 | 46 |
| 50-year | 20 | 22 | 32 | 32 | 28 | 49 |
| 100-year | 23 | 24 | 36 | 35 | 30 | 53 |

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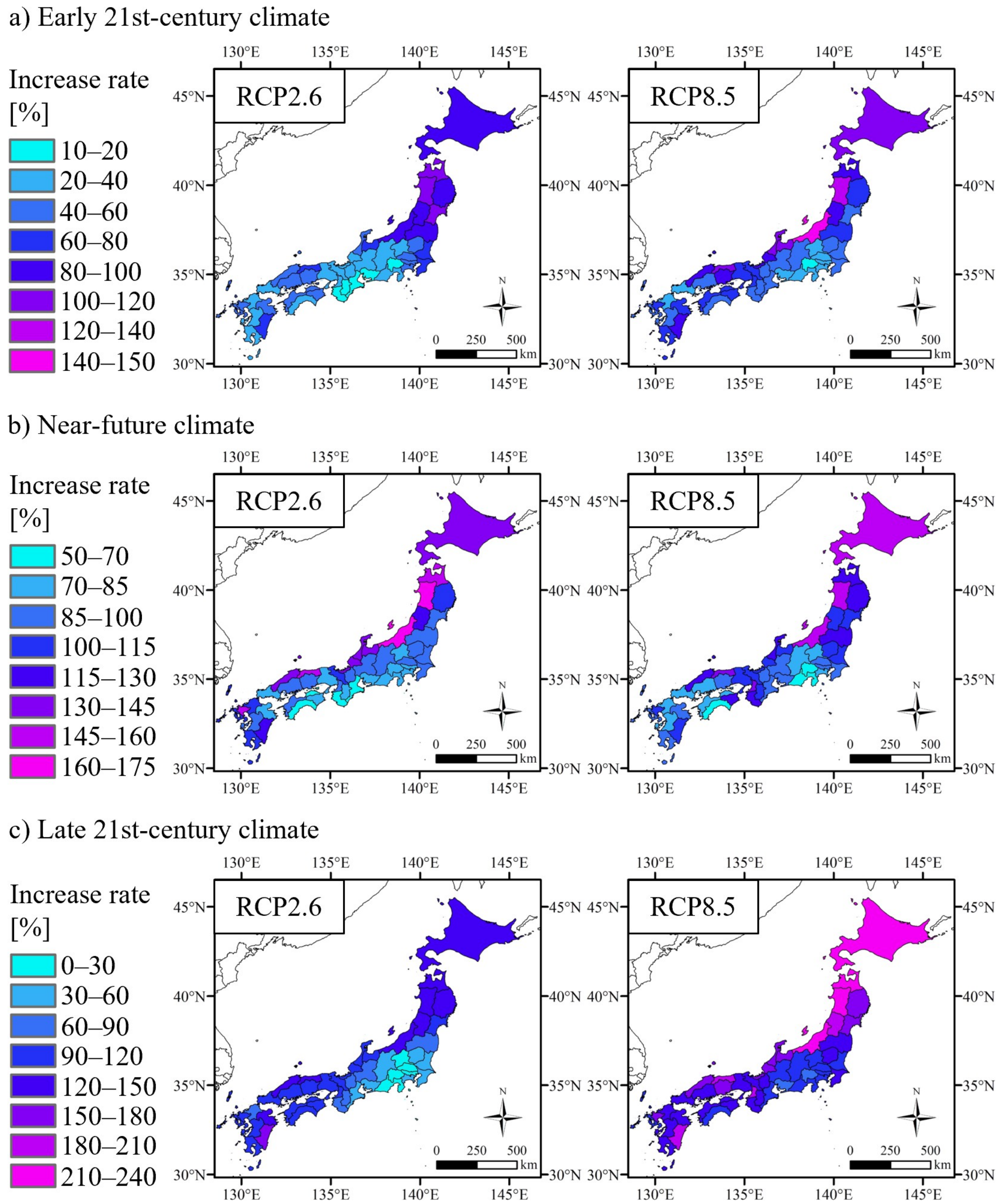


**Fig 3. Rate of increase in EADC by prefecture between baseline climate and each future climate without adaptation measures.** Souce of the base layer of the map: https://www.naturalearthdata.com/downloads/10m-cultural-vectors/.

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**Early 21st-century climate.** The EADC (average value of five GCMs) in the early 21st-century climate was 159,131 million USD/year (standard deviation: 30,897 million USD/year) in the RCP 2.6 scenario, and 168,764 million USD/year (standard deviation: 44,951 million USD/year) in the RCP 8.5 scenario. Between the baseline climate and the early 21st-century climate, the EADC increased by approximately 1.5 times in both RCP scenarios.

**Near-future climate.** The EADC (average value of five GCMs) in the near-future climate was 212,709 million USD/year (standard deviation: 57,312 million USD/year) in the RCP 2.6 scenario, and 216,301 million USD/year (standard deviation: 48,522 million USD/year) in the

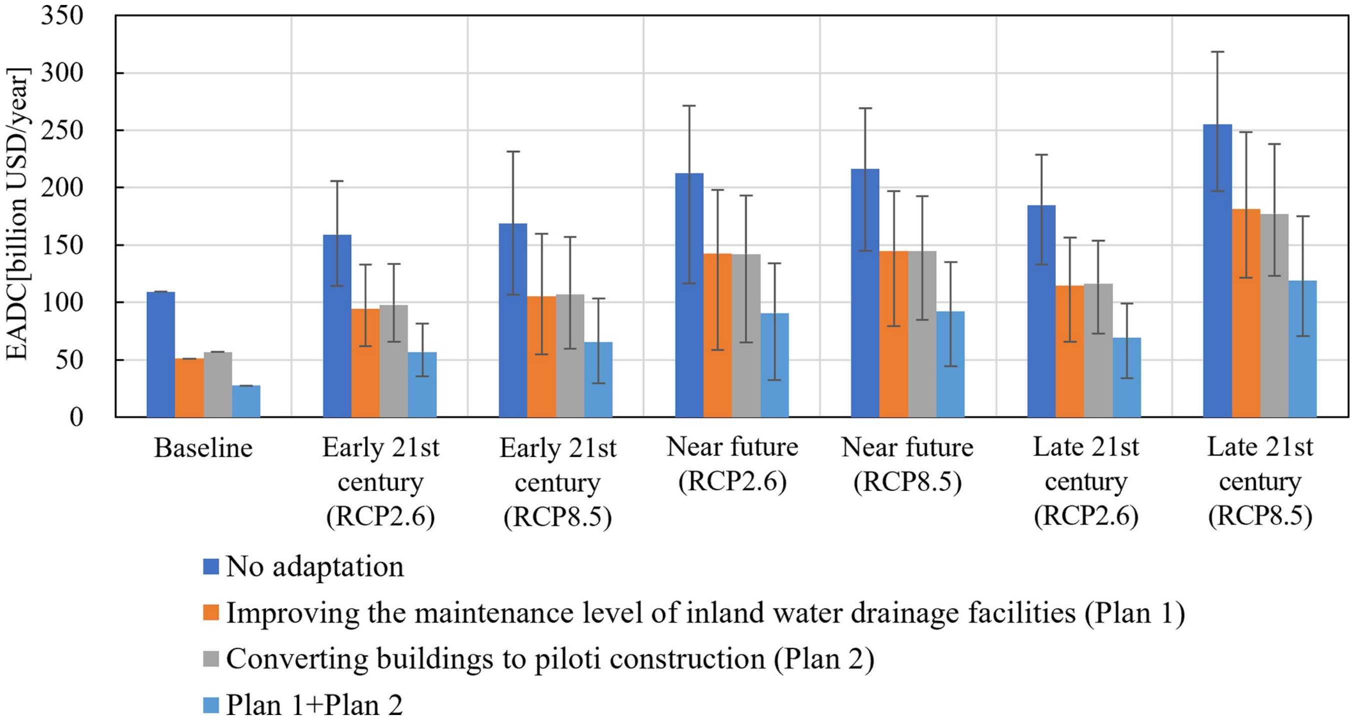


**Fig 4. EADC when each adaptation measure is implemented.** Error bar indicates maximum and minimum values of five GCMs.

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RCP 8.5 scenario. Between the baseline and the near-future climates, the EADC increased by approximately 1.9 times in the RCP 2.6 scenario and approximately 2.0 times in the RCP 8.5 scenario.

**Late 21st-century climate.** The EADC (average value of five GCMs) in the late 21st-century climate was 184,661 million USD/year (standard deviation: 31,558 million USD/year) in the RCP 2.6 scenario, and 255,110 million USD/year (standard deviation: 41,084 million USD/year) in the RCP 8.5 scenario. Between the baseline and the late 21st-century climates, the EADC increased by approximately 1.7 times in the RCP 2.6 scenario and approximately 2.3 times in the RCP 8.5 scenario. Unlike in the early 21st-century and near-future climates, in the late 21st-century climate, a difference in EADC due to climate change mitigation was found. The EADC was estimated to be reduced by 28% due to climate change mitigation.

## Reduction of pluvial flood damage due to adaptation measures

Fig 4 shows the EADC (average value of five GCMs) when each adaptation measure is implemented; Table 2 shows the ratio of the EADC in each scenario to the EADC when adaptation measures are not implemented in the baseline climate. Fig 5 shows the rate of increase in EADC by prefecture between the baseline climate and each future climate when each adaptation measure is implemented. In Fig 4 and Table 2, the EADC when adaptation measures are not implemented is included for comparison. Additionally, Fig 4, Table 2, and Fig 5 show the results when both adaptation measures (i.e., improving the maintenance level of inland water drainage facilities and converting buildings to piloti construction) are included.

**Improving the maintenance level of inland water drainage facilities.** When the maintenance level of inland water drainage facilities is improved, the EADC for the baseline climate was estimated to be 51,134 million USD/year. Improving the maintenance level of inland

**Table 2. Ratio of EADC in each scenario to EADC when adaptation measures are not implemented in baseline climate (unit: %).**

| Period | RCP scenario | No adaptation | Improving the maintenance level of inland water drainage facilities (Plan 1) | Converting buildings to piloti construction (Plan 2) | Plan 1 + Plan 2 |
|---|---|---|---|---|---|
| Baseline | - | 100 | 47 | 52 | 25 |
| Early 21st century | RCP2.6 | 146 | 87 | 90 | 52 |
| | RCP8.5 | 154 | 96 | 98 | 60 |
| Near future | RCP2.6 | 195 | 130 | 130 | 83 |
| | RCP8.5 | 198 | 133 | 132 | 85 |
| Late 21st century | RCP2.6 | 169 | 105 | 107 | 63 |
| | RCP8.5 | 233 | 166 | 162 | 109 |

The red and blue colors indicate the scenarios in which the EADC increased and decreased, respectively, compared to the EADC when adaptation measures are not implemented in the baseline climate.

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water drainage facilities caused the EADC to decrease by 53%. Furthermore, the damage cost reduction rate by prefecture was in the range of 51–55%, showing that the effect obtained by improving the maintenance level of inland water drainage facilities was roughly equal in all prefectures.

In the early 21st-century climate, when the maintenance level of inland water drainage facilities had been improved, the EADC was estimated to decrease by 13% in the RCP 2.6 scenario and 4% in the RCP 8.5 scenario compared to the EADC when adaptation measures were not implemented in the baseline climate. In the near-future climate, when the maintenance level of inland water drainage facilities was improved, the EADC was estimated to increase by 30% in the RCP 2.6 scenario and 33% in the RCP 8.5 scenario compared to the EADC when adaptation measures had not been implemented in the baseline climate. In the late 21st-century climate, when the maintenance level of inland water drainage facilities was improved, the EADC was estimated to increase by 5% in the RCP 2.6 scenario and 66% in the RCP 8.5 scenario compared to the EADC when adaptation measures were not implemented in the baseline climate. These results showed that the EADC in the near-future climate and late 21st-century climate increases above the baseline climate even if the maintenance level of inland water drainage facilities is improved.

Based on the rates of increase in EADC by prefecture shown in Fig 5, there are prefectures where the EADC in the near future and late 21st-century climates can be kept below that of the baseline climate by improving the maintenance level of inland water drainage facilities. In the RCP 2.6 and RCP 8.5 scenarios for the near-future climate, the EADC was kept below that of the baseline climate in two prefectures and one prefecture, respectively. In the RCP 2.6 scenario for the late 21st-century climate, the number of prefectures where the EADC was kept below that of the baseline climate was eleven prefectures.

**Converting buildings to piloti construction.** When buildings were converted to piloti construction, the EADC for the baseline climate was estimated to be 56,905 million USD/year. Converting buildings to piloti construction caused the EADC to decrease by 48%. The number of cells where buildings are converted to piloti construction was 12,143, and the area was 759 $km^2$. This area was 3.7% of the area of all land for building. The damage cost reduction rate by prefecture was in the range of 34–61%, showing differences among the prefectures. The correlation coefficient between the ratio of piloti construction zones to land for building by prefecture and the damage cost reduction rate was 0.50, and a positive correlation was observed.

In the early 21st-century climate, when buildings are converted to piloti construction, the EADC was estimated to decrease by 10% in the RCP 2.6 scenario and 2% in the RCP 8.5

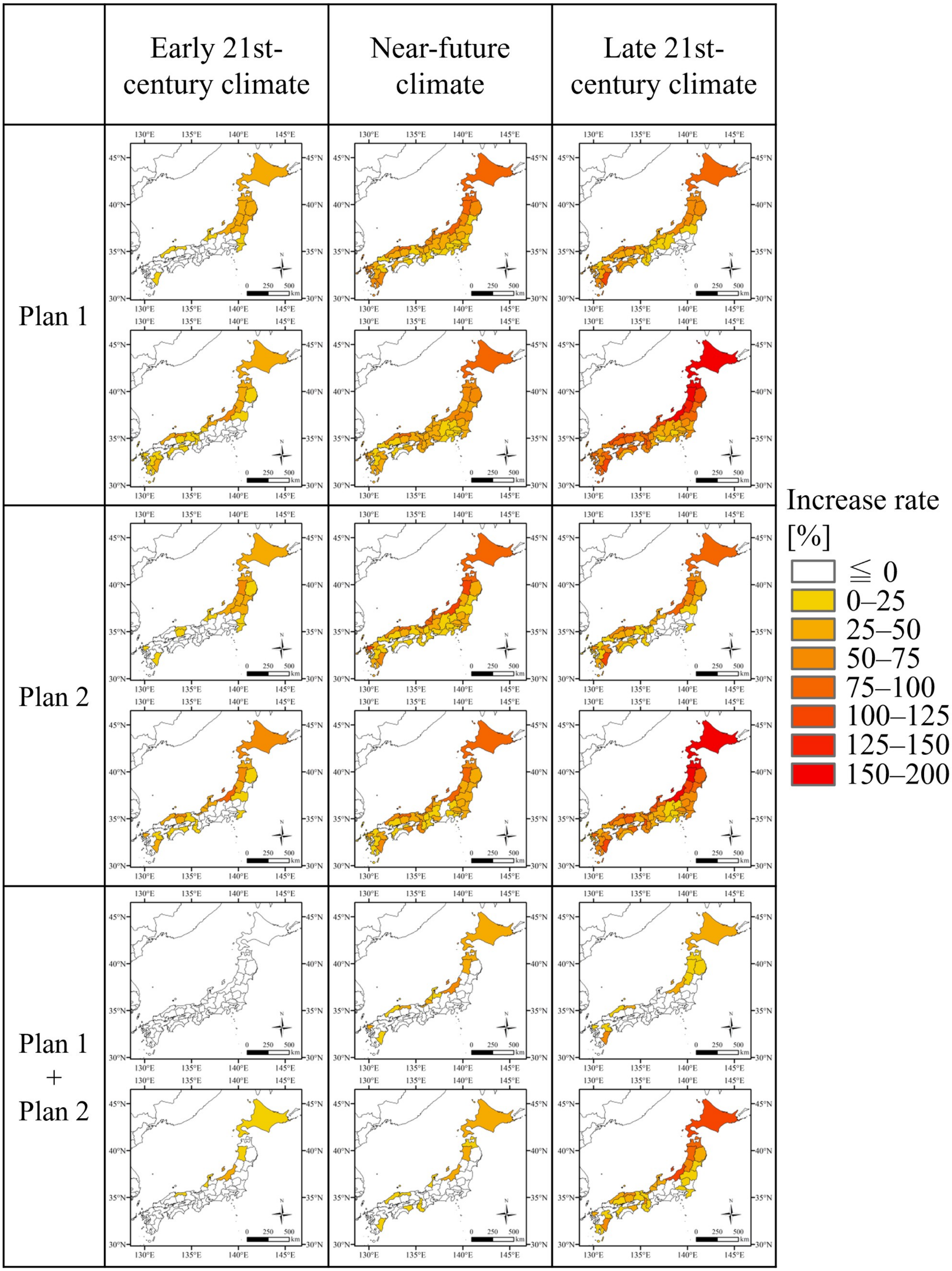
Early 21st-century climate
Near-future climate
Late 21st-century climate
Plan 1
Plan 2
Plan 1 + Plan 2
Increase rate [%]
≦ 0
0–25
25–50
50–75
75–100
100–125
125–150
150–200
130°E
135°E
140°E
145°E
30°N
35°N
40°N
45°N
0 250 500 km
N

**Fig 5. Rate of increase in EADC by prefecture between baseline climate and each future climate when each adaptation measure is implemented.** Top: RCP 2.6 scenario, bottom: RCP 8.5 scenario. Souce of the base layer of the map: https://www.naturalearthdata.com/downloads/10m-cultural-vectors/.

https://doi.org/10.1371/journal.pclm.0000039.g005

scenario compared to the EADC when adaptation measures were not implemented in the baseline climate. When buildings were converted to piloti construction in the near-future climate, the EADC was estimated to increase by 30% in the RCP 2.6 scenario and 32% in the RCP 8.5 scenario compared to the EADC when adaptation measures were not implemented in the baseline climate. In the late 21st-century climate, when buildings were converted to piloti construction, the EADC was estimated to increase by 7% in the RCP 2.6 scenario and 62% in the RCP 8.5 scenario compared to the EADC when adaptation measures were not implemented in the baseline climate. The results showed that the EADC in the near-future and late 21st-century climates increased above the baseline climate even if buildings had been converted to piloti construction.

Based on the rates of increase in the EADC by prefecture, shown in Fig 5, there are prefectures where the EADC in the near-future and late 21st-century climates can be kept below that of the baseline climate by converting buildings to piloti construction. In the RCP 2.6 and RCP 8.5 scenarios for the near-future climate, the EADC was kept below that of the baseline climate in three prefectures and four prefectures, respectively. In the RCP 2.6 scenario for the late 21st-century climate, the EADC was kept below that of the baseline climate in 13 prefectures.

## Discussion

### Validity of method of estimating pluvial flood damage cost

This section verifies the validity of the EADC estimation method. For this verification, damage to general assets, including agricultural products damaged by pluvial flooding, in the Flood Damage Statistics Survey from 1980 to 2000 [45] was aggregated by prefecture. The correlation coefficient between the annual average cost of pluvial flood damage and the EADC estimated by this analysis was 0.79, and a positive correlation was observed. Therefore, the distribution of EADC by prefecture reflects the distribution of actual damage cost. In research that estimated the EADC caused by flooding throughout Japan using the same framework, the correlation coefficient between the EADC and the annual average flood damage cost was calculated to be 0.65 [28]. Consequently, this estimation method can be judged to ensure the same level of validity as the previous research.

### Future changes in pluvial flood damage cost due to changes in precipitation amounts associated with climate change

The EADC in future climates was estimated using five GCMs to account for the uncertainty of the GCMs. The standard deviation of the EADC in the early 21st-century climate without adaptation measures was between 19% and 27% of the EADC. The standard deviation of the EADC in the near-future climate without adaptation measures was between 22% and 27% of the EADC. The standard deviation of the EADC in the late 21st-century climate without adaptation measures was between 16% and 18% of the EADC. Therefore, the uncertainty of the EADC in the early 21st-century climate and the near-future climate was shown to be substantial. In the RCP 2.6 scenario in which climate change is mitigated, the EADC (average value of five GCMs) reached a peak in the near future and decreased toward the late 21st century. Looking at the trend in EADC of each GCM, excluding MRI-CGCM3, four models were consistent with the trend in the average EADC of the five GCMs. Meanwhile, in the RCP 8.5 scenario in which climate change is not mitigated, the EADC (average value of five GCMs) was greatest in the late 21st century. Looking at the EADC of each GCM, the EADC was greatest in the late 21st century in four models, excluding GFDL-CM3. Therefore, the results show that, even taking the uncertainty of the GCMs into account, it is highly likely that the EADC in the RCP 2.6 scenario will reach a peak in the near future and decrease toward the late 21st century, while the EADC in the RCP 8.5 scenario will increase toward the late 21st century.

From Tables 1 and 2, it is clear that the rate of increase in the pluvial flood damage cost is high compared to the rate of increase in precipitation. This is similar to the result obtained by Kazama et al. (2009) [10] and Tezuka et al. (2014) [11] when they estimated the cost of damage caused by flooding from rivers throughout Japan. Fig 3, which shows the rate of increase in pluvial flood damage cost quantitatively and by prefecture, could be useful in considering adaptation measures for climate change. This study could be used to identify areas where measures against pluvial flooding are becoming increasingly important, and it could therefore allow Japan's policymakers to determine areas where adaptation measures should be prioritized.

## Reduction of pluvial flood damage cost due to mitigation and adaptation measures

The results showed that, in the future climates, the EADC (average value of five GCMs) is greater in the RCP 8.5 scenario than in the RCP 2.6 scenario. However, in the early 21st-century and near-future climates, the difference between the EADC in the RCP 2.6 scenario and the RCP 8.5 scenario was less than the standard deviation, and there was no marked difference between the two. In the late 21st-century climate, a striking difference in the EADC due to the effect of mitigation measures was observed.

In this study, it was estimated to be impossible to keep the nationwide EADC in the near-future and late 21st-century climates below the EADC in the baseline climate when the two selected adaptation measures were implemented singly. Therefore, the damage reduction effect when the two adaptation measures were implemented simultaneously was also considered. In the near-future climate, when the two adaptation measures were implemented simultaneously, the EADC in both RCP scenarios was below the EADC in the baseline climate. In the late 21st-century climate, when the two adaptation measures are implemented simultaneously, the EADC in the RCP 2.6 scenario was below the EADC in the baseline climate. However, the EADC in the RCP 8.5 scenario was estimated to increase above the baseline climate, even when the two adaptation measures are implemented simultaneously. This result indicates the importance of implementing mitigation and adaptation measures simultaneously. Fig 5 shows that in the near-future and late 21st-century climates, there are prefectures where the EADC increases above the baseline climate even when mitigation measures and the two adaptation measures are implemented. In these prefectures, the rate of increase in precipitation associated with climate change is predicted to be high, and it may be impossible to adapt to the impacts of climate change using the two adaptation measures selected in this study (improving the maintenance level of inland water drainage facilities, converting buildings to piloti construction). This indicates the need to consider adaptation measures other than these two measures. Meanwhile, there are also prefectures where the EADC can be kept below the baseline climate with only a single adaptation measure. Fig 5 can provide this kind of information, and it can be used to gain a quantitative understanding of the adaptation effect of each adaptation scenario so that adaptation plans can be made more specific.

### Limitations of this study

The EADC was estimated assuming a worst-case scenario in which rainwater does not drain into rivers. This study showed that the regional characteristics of actual damage cost are captured as a result. However, in an actual disaster, if there is little precipitation in the upper and middle reaches of a river, the river level falls, and so there are circumstances in which rainwater does drain into the rivers. Therefore, the EADC is overestimated compared to the actual annual average damage cost. It is important to note that the EADC in this study is the pluvial flood damage cost when the worst possible scenario happens. Given the above, the regional characteristics of damage cost, the rate of increase of damage cost, and the damage cost reduction rate due to mitigation/adaptation measures can be discussed using the EADC in this study. However, the EADC cannot be used to discuss the absolute values of damage cost and the magnitude of benefits from adaptation measures. Further studies are necessary to consider the probability of poor drainage into rivers to calculate benefits.

## Conclusion

In this study, the cost of damage caused by pluvial flooding throughout Japan was estimated. Using five GCMs and two RCP scenarios, the cost of damage caused by pluvial flooding in future climates was also estimated. Further, the damage reduction effect of two adaptation measures, namely, improving the maintenance level of inland water drainage facilities and converting buildings to piloti construction, was examined. The key points of this study are as follows.

1. The results suggest that pluvial flood damage cost in the RCP 2.6 scenario will reach a peak in the near-future climate and decrease toward the late 21st century. However, the results also suggest that pluvial flood damage costs in the RCP 8.5 scenario will increase toward the late 21st century.
2. When adaptation measures were not implemented in the late 21st-century climate, the pluvial flood damage cost increased by approximately 2.3 times in the RCP 8.5 scenario, while in the RCP 2.6 scenario, the increase was suppressed to approximately 1.7 times.
3. When the adaptation measures were implemented singly, the pluvial flood damage costs in the near future and late 21st-century climates increased above the baseline climate.
4. When the two adaptation measures were implemented simultaneously, excluding the RCP 8.5 scenario for the late 21st-century climate, the pluvial flood damage costs in the future climates were kept below those of the baseline climate. The pluvial flood damage costs in the RCP 8.5 scenario for the late 21st-century climate increased above that in the baseline climate even if the two adaptation measures were implemented simultaneously.
5. There are prefectures where it is possible to suppress the future increase in pluvial flood damage costs even if single adaptation measures are implemented. However, there are also prefectures where it is not possible to suppress the future pluvial flood damage costs even if mitigation measures and the two adaptation measures are implemented.

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## References

1. United Nations. Transforming our world: the 2030 Agenda for Sustainable Development [Internet]. New York: United Nations; 2015 [cited 2021 Nov 26]. Available from: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.
2. World Economic Forum. The Global Risks Report 2021 [Internet]. Cologny: World Economic Forum; 2021 Jan 19 [cited 2021 Nov 26]. Available from: https://www3.weforum.org/docs/WEF_The_Global_Risks_Report_2021.pdf.
3. IPCC. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, et al., editors. Cambridge: Cambridge University Press; 2013.
4. Fujita M, Mizuta R, Ishii M, Endo H, Sato T, Okada Y, et al. Precipitation changes in a climate with 2-K surface warming from large ensemble simulations using 60-km global and 20-km regional atmospheric models. Geophys Res Lett. 2019; 46: 435–442. https://doi.org/10.1029/2018GL079885
5. Hatsuzuka D, Sato T. Future changes in monthly extreme precipitation in Japan using large-ensemble regional climate simulations. J Hydrometeorol. 2019; 20: 563–574. https://doi.org/10.1175/JHM-D-18-0095.1
6. Nayak S, Takemi T. Robust responses of typhoon hazards in northern Japan to global warming climate: cases of landfalling typhoons in 2016. Meteorological Applications. 2020; 27: e1954. https://doi.org/10.1002/met.1954
7. Winsemius HC, Van Beek LPH, Jongman B, Ward PJ, Bouwman A. A framework for global river flood risk assessments. Hydrol Earth Syst Sci. 2013; 17: 1871–1892. https://doi.org/10.5194/hess-17-1871-2013
8. Arnell NW, Gosling SN. The impacts of climate change on river flood risk at the global scale. Clim Change. 2016; 134: 387–401. https://doi.org/10.1007/s10584-014-1084-5
9. Dottori F, Szewczyk W, Ciscar JC, Zhao F, Alfieri L, Hirabayashi Y, et al. Increased human and economic losses from river flooding with anthropogenic warming. Nat Clim Chang. 2018; 8: 781–786. https://doi.org/10.1038/s41558-018-0257-z
10. Kazama S, Sato A, Kawagoe S. Evaluating the cost of flood damage based on changes in extreme rainfall in Japan. Sustain Sci. 2009; 4: 61–69. https://doi.org/10.1007/s11625-008-0064-y

11. Tezuka S, Takiguchi H, Kazama S, Sato A, Kawagoe S, Sarukkalige R. Estimation of the effects of climate change on flood-triggered economic losses in Japan. Int J Disaster Risk Reduct. 2014; 9: 58–67. https://doi.org/10.1016/j.ijdrr.2014.03.004
12. Van Ootegem L, Verhofstadtb E, Van Herck K, Creten T. Multivariate pluvial flood damage models. Environ Impact Assess Rev. 2015; 54: 91–100. https://doi.org/10.1016/j.eiar.2015.05.005
13. Tanaka T, Kiyohara K, Tachikawa Y. Comparison of fluvial and pluvial flood risk curves in urban cities derived from a large ensemble climate simulation dataset: A case study in Nagoya, Japan. J Hydrol. 2020; 584: 124706. https://doi.org/10.1016/j.jhydrol.2020.124706
14. Study Group on Countermeasures for Urban Inundation Considering Climate Change. Promotion of countermeasures for urban inundation by sewage systems considering climate change, Proposal, Reference material (Partial revision) [Internet]. Tokyo: MLIT; 2021 [cited 2021 Nov 29]. Available from: https://www.mlit.go.jp/mizukokudo/sewerage/content/001403570.pdf.
15. Blanc J, Hall JW, Roche N, Dawson RJ, Cesses Y, Burton A, et al. Enhanced efficiency of pluvial flood risk estimation in urban areas using spatial–temporal rainfall simulations. J Flood Risk Manag. 2012; 5: 143–152. https://doi.org/10.1111/j.1753-318X.2012.01135.x
16. Olsen AS, Zhou Q, Linde JJ, Arnbjerg-Nielsen K. Comparing methods of calculating expected annual damage in urban pluvial flood risk assessments. Water. 2015; 7: 255–270. https://doi.org/10.3390/w7010255
17. Nicklin H, Leicher AM, Dieperink C, Van Leeuwen K. Understanding the costs of inaction–An assessment of pluvial flood damages in two European cities. Water. 2019; 11: 801. https://doi.org/10.3390/w11040801
18. Elboshy B, Kanae S, Gamaleldin M, Ayad H, Osaragi T, Elbarki W. A framework for pluvial flood risk assessment in Alexandria considering the coping capacity. Environ Syst Decis. 2019; 39: 77–94. https://doi.org/10.1007/s10669-018-9684-7
19. Martínez-Gomariz E, Locatelli L, Guerrero M, Russo B, Martínez M. Socio-economic potential impacts due to urban pluvial floods in Badalona (Spain) in a context of climate change. Water. 2019; 11: 2658. https://doi.org/10.3390/w11122658
20. Zhou Q, Leng G, Su J, Ren Y. Comparison of urbanization and climate change impacts on urban flood volumes: Importance of urban planning and drainage adaptation. Sci Total Environ. 2019; 658: 24–33. https://doi.org/10.1016/j.scitotenv.2018.12.184 PMID: 30572212
21. Hosseinzadehtalae P, Ishadi NK, Tabari H, Willems P. Climate change impact assessment on pluvial flooding using a distribution-based bias correction of regional climate model simulations. J Hydrol. 2021; 598: 126239. https://doi.org/10.1016/j.jhydrol.2021.126239
22. Bhattarai R, Yoshimura K, Seto S, Nakamura S, Oki T. Statistical model for economic damage from pluvial floods in Japan using rainfall data and socioeconomic parameters. Natural Hazards and Earth System Sciences. 2016; 16: 1063–1077. https://doi.org/10.5194/nhess-16-1063-2016
23. Guerreiro SB, Glenis V, Dawson RJ, Kilsby C. Pluvial flooding in European cities—A continental approach to urban flood modelling. Water. 2017; 9: 296. https://doi.org/10.3390/w9040296
24. Löwe R, Urich C, Sto. Domingo N, Mark O, Deletic A, Arnbjerg-Nielsen K. Assessment of urban pluvial flood risk and efficiency of adaptation options through simulations–A new generation of urban planning tools. J Hydrol. 2017; 550: 355–367. https://doi.org/10.1016/j.jhydrol.2017.05.009
25. Zhou Q, Leng G, Huang M. Impacts of future climate change on urban flood volumes in Hohhot in northern China: benefits of climate change mitigation and adaptations. Hydrol Earth Syst Sci. 2018; 22: 305–316. https://doi.org/10.5194/hess-22-305-2018
26. Qiu Y, Schertzer D, Tchiguirinskaia I. Assessing cost-effectiveness of nature-based solutions scenarios: Integrating hydrological impacts and life cycle costs. J Clean Prod. 2021; 329: 129740. https://doi.org/10.1016/j.jclepro.2021.129740
27. Ward PJ, Jongman B, Aerts JCJH, Bates PD, Botzen WJW, Loaiza AD, et al. A global framework for future costs and benefits or river-flood protection in urban areas. Nat Clim Chang. 2017; 7: 642–646. https://doi.org/10.1038/nclimate3350
28. Yamamoto T, Kazama S, Touge Y, Yanagihara H, Tada T, Yamashita T, et al. Evaluation of flood damage reduction throughout Japan from adaptation measures taken under a range of emissions mitigation scenarios. Clim Change. 2021; 165: 60. https://doi.org/10.1007/s10584-021-03081-5
29. Kawagoe S, Kazama S, Sarukkalige PR. Probabilistic modelling of rainfall induced landslide hazard assessment. Hydrol Earth Syst Sci. 2010; 14: 1047–1061. https://doi.org/10.5194/hess-14-1047-2010
30. Nishimori M, Ishigooka Y, Kuwagata T, Takimoto T, Endo N. SI-CAT 1km-grid square regional climate projection scenario dataset for agricultural use (NARO2017). Journal of the Japan Society for Simulation Technology. 2019; 38: 150–154. Japanese.

31. Haerter JO, Hagemann S, Moseley C, Piani C. Climate model bias correction and the role of timescales. Hydrol Earth Syst Sci. 2011; 15: 1065–1079. https://doi.org/10.5194/hess-15-1065-2011

32. Ishizaki NN, Nishimori M, Izumi T, Shiogama H, Hanasaki N, Takahashi K. Evaluation of two bias-correction methods for gridded climate scenarios over Japan. SOLA. 2020; 16: 80–85. https://doi.org/10.2151/sola.2020-014

33. Toriyama J, Hashimoto S, Osone Y, Yamashita N, Tsurita T, Shimizu T, et al. Estimating spatial variation in the effects of climate change on the net primary production of Japanese cedar plantations based on modeled carbon dynamics. PLoS ONE. 2021; 16: e0247165. https://doi.org/10.1371/journal.pone.0247165 PMID: 33596265

34. Shibata H, Ban R, Hirano N, Eguchi S, Mishima S, Chiwa M, et al. Comparison of spatial and temporal changes in riverine nitrate concentration from terrestrial basins to the sea between the 1980s and the 2000s in Japan: Impact of recent demographic shifts. Environ Pollut. 2021; 288: 117695. https://doi.org/10.1016/j.envpol.2021.117695 PMID: 34252718

35. Ishigooka Y, Hasegawa T, Kuwagata T, Nishimori M, Wakatsuki H. Revision of estimates of climate change impacts on rice yield and quality in Japan by considering the combined effects of temperature and $CO_2$ concentration. Journal of Agricultural Meteorology. 2021; 77: 139–149. https://doi.org/10.2480/agrmet.D-20-00038

36. MLIT. Elevation/slope-angle fifth mesh data (ver1.0); 2011 [cited 2021 May 19]. Database: Digital National Land Information download services [Internet]. Available from: https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-G04-d.html.

37. MLIT. Land-use subdivision mesh data (ver2.5); 2015 [cited 2018 Jan 3]. Database: Digital National Land Information download services [Internet]. Available from: https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-L03-b.html.

38. MLIT. River data (ver3.1); 2011 [cited 2021 May 18]. Database: Digital National Land Information download services [Internet]. Available from: https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-W05.html.

39. Yanagihara H, Yamamoto T, Kazama S, Touge Y, Chai Y, Tada T. Regional evaluation of potential flood damage reduction by paddy field dam in Japan. Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research). 2021; 77: I_33–I_42. Japanese. https://doi.org/10.2208/jscejer.77.5_I_33

40. MLIT. Manual for Economic Evaluation of Flood Control Investment (Draft) [Internet]. Tokyo: MLIT; 2005 [cited 2021 Nov 30]. Available from: https://www.mlit.go.jp/river/kokusai/pdf/pdf06.pdf.

41. MLIT. Manual for Economic Evaluation of Flood Control Investment (Draft) [Internet]. Tokyo: MLIT; 2020 [cited 2021 Nov 30]. Available from: https://www.mlit.go.jp/river/basic_info/seisaku_hyouka/gaiyou/hyouka/r204/chisui.pdf.

42. Statics Bureau of Japan. Total population and number of households by gender (500-m mesh, 2005 National Census); 2010 [cited 2021 Oct 27]. Database: e-Stat [Internet]. Available from: https://www.e-stat.go.jp/gis/statmap-search?page=1&type=1&toukeiCode=00200521&toukeiYear=2005&aggregateUnit=H&serveyId=H002005112005&statsId=T000387.

43. Statics Bureau of Japan. Total number of business establishments and employees in all industries (500-m mesh, 2001 Establishment and Enterprise Census of Japan); 2011 [cited 2021 Oct 27]. Database: e-Stat [Internet]. https://www.e-stat.go.jp/gis/statmap-search?page=1&type=1&toukeiCode=00200551&toukeiYear=2001&aggregateUnit=H&serveyId=H002005112001&statsId=T000388.

44. MLIT. Rivers in Japan [Internet]. Tokyo: MLIT; 2006 [cited 2021 Dec 1]. Available from: https://www.mlit.go.jp/river/basic_info/english/pdf/riversinjapan.pdf.

45. MLIT. Flood damage statics. 1980–2000 ed. Tokyo: MLIT; 1982–2002.