https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

Integrating flood-induced population movements into future flood damage estimates in Japan

Hayata Yanagihara[1, †], So Kazama[1], Kei Gomi[2], Yusuke Hiraga[1], Atsuya Ikemoto[1]

[1]Department of Civil and Environmental Engineering, Graduate School of Engineering, Tohoku University, Sendai, Miyagi 980-8579, Japan

[2]Regional Environmental Renovation Section, Fukushima Regional Collaborative Research Center, National Institute for Environmental Studies, Miharu, Fukushima 963-7700, Japan

[†]Current affiliation: Sustainable System Research Laboratory, Central Research Institute of Electric Power Industry, Abiko, Chiba 270-1194, Japan

Correspondence to: Hayata Yanagihara (yanagihara41381@criepi.denken.or.jp)

Abstract. Recent studies have highlighted that flooding can influence population dynamics. However, existing estimates of future flood damage primarily consider population changes driven by births, deaths, and migration unrelated to flooding. As a result, the potential impacts of flood-induced population movements (FIPMs) on future flood damage costs remain largely unexplored. This study evaluated the impacts of FIPMs on future flood damage costs in Japan, a country that faces flood risk and population decline. We develop a methodological framework that uses statistical causal inference to quantify FIPMs, integrates these estimates into future population and land-use projections, and evaluates future flood damage costs under scenarios of climate and land-use change. The results indicate that incorporating FIPMs leads to only modest changes in estimated flood damage costs at the national level (generally below 1 %), and similarly modest impacts at the prefectural level, except for a few prefectures with changes of approximately 2 %. However, greater variability is observed at the municipal level, with approximately 10 % of municipalities experiencing changes exceeding 1 % and some municipalities showing reductions in estimated flood damage costs exceeding 10 %. These findings highlight the importance of accounting for FIPMs in flood risk management frameworks and policy evaluations.

1 Introduction

According to the Emergency Events Database, flood disasters caused by heavy rainfall occurred in 115 countries from 2015 to 2024 (Delforge et al., 2025). Accordingly, flood disasters are a pressing issue across many countries. In response, flood damage assessments have been conducted to inform the development of flood mitigation strategies (Marvi, 2020; Merz et al., 2010; Redondo-Tilano et al., 2025). Moreover, changes in precipitation patterns caused by global warming are expected to affect the extent of flood damage. For example, Alfieri et al. (2017) demonstrated that, under a 4 °C global warming scenario, flood damage costs could increase by an average of 500 % in countries collectively accounting for 79 % of the global gross domestic product. In addition to climate change, flood damage costs and population exposure have been assessed considering population change (Rogers et al., 2025; Swain et al., 2020; Wing et al., 2022). Future changes in flood damage

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

costs driven by climate and population change have also been assessed using Shared Socioeconomic Pathways (SSPs) downscaled for national-scale assessments (Yanagihara et al., 2024). These studies utilized existing population projections at the county or grid-cell level to estimate flood damage costs and population exposure. However, such population projections typically consider demographic changes driven only by births, deaths, and migration, without explicitly accounting for flood-induced population movements (FIPMs). Such approaches assume that future population projections are independent of flood damage estimates.

In contrast, recent studies have highlighted the importance of FIPMs (Del Rio Amador et al., 2025; Kakinuma et al., 2020; Kam et al., 2021). FIPMs can alter patterns of exposure to flood hazards, thereby influencing the extent of flood damage. Therefore, FIPMs may influence future flood damage costs. However, the extent to which such movements affect future flood damage costs remains underexplored. For example, while Shu et al. (2023) evaluated the impact of flooding on future population projections across the United States, they did not incorporate these impacts into estimates of future flood damage costs. They reported that population responses to observed flood exposure have already emerged in some areas, leading to reduced population growth rates. This projected decrease in growth rates could result in fewer people and assets being exposed to flood hazards, thereby potentially lowering future flood damage costs. Since lower flood damage costs may diminish the estimated total benefits of flood mitigation strategies (Yanagihara et al., 2024), overlooking FIPMs could result in the overestimation of their effectiveness. Therefore, it is essential to evaluate the influence of FIPMs on flood damage estimates. Moreover, socio-hydrology has received increasing attention as a framework for comprehensively understanding the interactions between human activities and water systems (Sivapalan et al., 2012). Accordingly, quantitatively assessing the impact of FIPMs on future flood damage costs is important from a socio-hydrological perspective.

In Japan, many urban areas lie below river water levels, making them highly vulnerable to large-scale flood damage (Ministry of Land, Infrastructure and Transport of Japan [MLIT], 2006). Moreover, Japanese rivers are steeper than major rivers in other countries (MLIT, 2006), causing rainfall to flow rapidly and making the rivers more susceptible to sudden increases in water levels. In addition, Japan's average annual precipitation is approximately twice the global average (MLIT, 2006). These topographical and climatic conditions contribute to Japan's high susceptibility to flooding. Furthermore, Japan is projected to experience a significant population decline (Jarzebski et al., 2021). Given the dual challenges of flood damage and population decline, evaluating the impact of FIPMs on future flood damage costs in Japan is essential. However, no existing assessments of future flood damage costs in Japan have incorporated FIPMs. This gap is largely due to a lack of sufficient quantitative understanding of how flooding influences population movements. Although previous studies have indicated that floods can influence population movements in Japan (Ujihara et al., 2019; Namikawa et al., 2022), few have quantitatively analyzed intermunicipal population movements in relation to flood magnitude (Okamoto et al., 2023). Even internationally, quantitative analyses of the relationships between flood magnitude and population movements at fine spatial scales remain limited (Shu et al., 2023; Tsuda and Tebakari, 2023). Therefore, to incorporate FIPMs into future population projections and integrate these projections into flood damage cost assessments, a more advanced quantitative understanding of population movements in relation to flood magnitude is required.

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

Against this background, this study aims to evaluate the impacts of FIPMs on future flood damage costs in Japan. To achieve this, we propose a methodological framework for projecting future population and estimating flood damage costs that accounts for FIPMs. To quantify population movements between and within municipalities in response to varying flood magnitudes, this study employs the difference-in-differences (DiD) method – a statistical causal inference technique developed in the fields of econometrics and sociology.

2 Methodological framework

The proposed methodological framework for estimating future flood damage costs, accounting for FIPMs, is presented in Fig. 1. This framework comprises four main processes: quantifying FIPMs, projecting future population incorporating FIPMs, projecting land use based on future population, and estimating future flood damage costs considering changes in rainfall and land use. These processes follow a sequential relationship: quantified FIPMs inform projections of future population

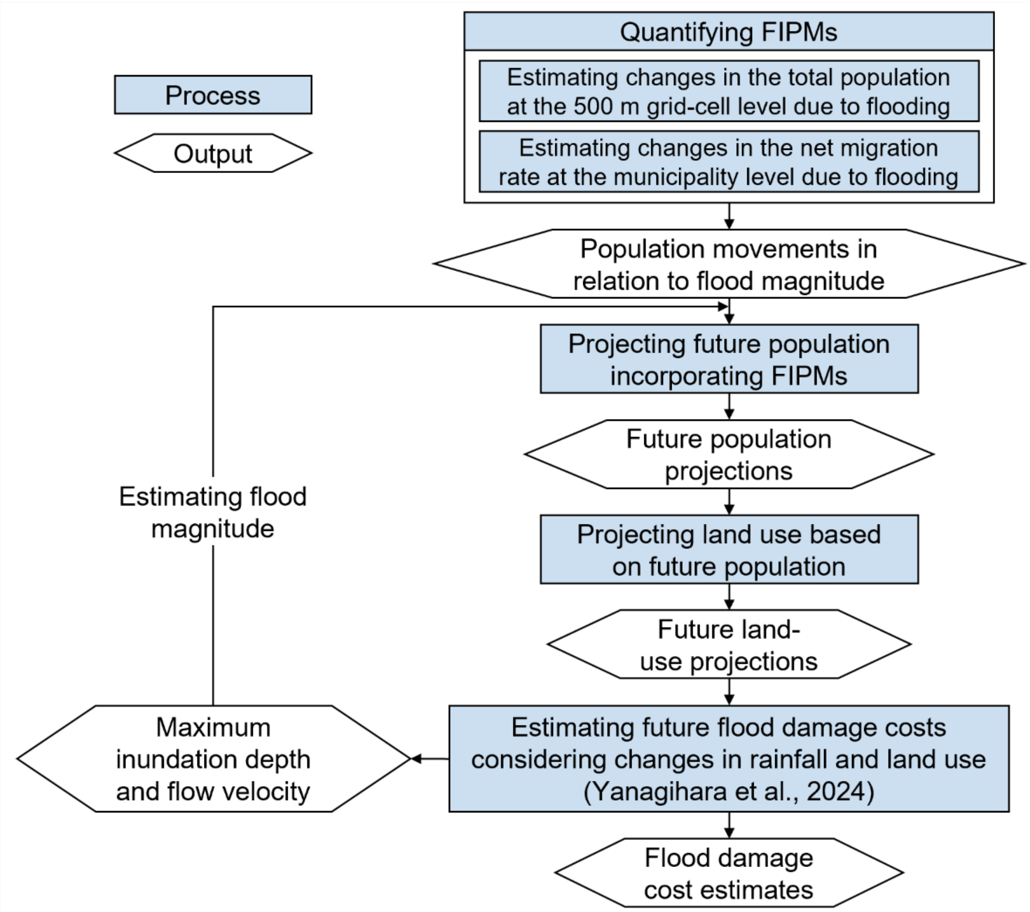

Figure 1: Methodological framework for estimating future flood damage costs accounting for FIPMs.

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

distributions, subsequent changes in population distribution determine shifts in land-use patterns, and these land-use changes influence the estimation of flood damage costs. FIPMs were quantified at both the grid-cell and municipality levels utilizing available demographic data to capture population movements occurring within and between municipalities in response to varying flood magnitudes. Detailed methodologies for quantifying FIPMs are presented in Sect. 3, while methodologies for the subsequent processes of the framework are described in Sect. 4.

3 Quantifying FIPMs

3.1 Estimating changes in the total population at the 500 m grid-cell level due to flooding

3.1.1 Analysis target and period

This study analyzed the impact of flooding on the total population at the 500 m grid-cell level in areas affected by Typhoon Hagibis (2019) and the heavy rainfall event of July 2020 in Japan. Population data at five-year intervals from 2005 to 2020 were used. To isolate the effects of population movements, data excluding natural changes resulting from births and deaths would be preferable; however, such data are unavailable at the grid-cell level. Grid cells inundated during the selected events were designated as the treatment group, while the control group consisted of grid cells in municipalities that did not experience residential water-related disasters between 2005 and 2020. Affected municipalities were identified using data on areas affected by water-related disasters, while inundated grid cells were identified using flood inundation maps. Criteria for excluding grid cells from the analysis are detailed in Sect. S1 of the Supplement. Given data availability, flood magnitude was represented using the maximum inundation depth estimated within each grid cell. For grid cells in the treatment group, the maximum inundation depth was calculated based on values provided in the flood inundation maps. Details regarding the total population data at the 500 m grid-cell level, data on areas affected by water-related disasters, and flood inundation maps are provided in Sect. S2. Descriptive statistics are presented in Tables S1 and S2 of the Supplement.

3.1.2 Covariates

Based on previous studies of population movements in Japan (Arakawa and Noyori, 2023; Ushiki et al., 2019), we selected 21 covariates, including climatological variables, socioeconomic indicators, accessibility to public and social facilities, demographic composition, and flood risk. Covariates and their descriptive statistics are listed in Table S3. All covariates were compiled at the 500 m grid-cell level (see Sect. S3).

3.1.3 Analytical method

As the difference in the total population before and after a flood does not solely reflect the flood's impact on the population but also reflects the effects of other unrelated factors, our framework incorporates the DiD method (see Sect. S4) to evaluate changes in the total population attributable to flooding. We applied DiD using the following regression model:

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

$$\ln(P_{i,t}) = \gamma_i + \varepsilon_t + \zeta_i t + \boldsymbol{\eta}\boldsymbol{X}_{i,t-5}^{\text{cell}} + \delta^{\text{cell}} D_{i,t} + e_{i,t}^{\text{cell}} \quad (1)$$

where $i = \{1, 2, \ldots, n\}$ denotes grid-cell indices; n denotes the number of grid cells analyzed; $t = \{2005, 2010, 2015, 2020\}$ denotes years; $P_{i,t}$ denotes the total population (persons); γ_i denotes grid-cell fixed effects; ε_t denotes year fixed effects; $\zeta_i t$ denotes grid-cell-specific linear time trends; $\boldsymbol{X}_{i,t-5}^{\text{cell}}$ denotes the covariate vector excluding time-invariant covariates; $\boldsymbol{\eta}$ denotes the parameter vector for $\boldsymbol{X}_{i,t-5}^{\text{cell}}$; $D_{i,t}$ denotes the maximum inundation depth (m); δ^{cell} denotes the parameter for $D_{i,t}$; and $e_{i,t}^{\text{cell}}$ denotes the error term. The key parameter is δ^{cell}, which quantifies the effect of the maximum inundation depth on the total population. The variable $D_{i,t}$ records the maximum inundation depth only for treatment-group grid cells in flood years and takes a value of 0 otherwise. Because the dependent variable is specified as the natural logarithm of the total population, δ^{cell} allows us to estimate the percentage change in the total population per 1 m increase in maximum inundation depth at the 500 m grid-cell level, calculated as $(e^{\delta^{\text{cell}}} - 1) \times 100$ % (Morita, 2014). This percentage change represents the difference relative to a counterfactual scenario in which flooding did not occur. A negative δ^{cell} implies a decrease in the total population resulting from flooding. Details of the analytical method are provided in Sect. S5.

In regression-based DiD analysis, the overall fit of the regression model is not the primary concern (Nguyen, 2022). To interpret δ^{cell} as the causal effect of treatment on the outcome, the parallel trends assumption must be satisfied (Kono et al., 2021). This assumption states that the treated and control grid cells would have followed parallel trends in the outcome variable over time had the treatment not occurred. Since the counterfactual outcomes for the treated grid cells (i.e., outcomes that would have occurred without flooding) cannot be observed, the parallel trends assumption cannot be tested directly. Following previous studies, we conducted an indirect test of the parallel trends assumption by checking for statistically significant differences in the outcome variable between the treatment and control grid cells before treatment (Alves et al., 2022). No statistically significant difference in the total population was observed, suggesting that the parallel trends assumption may hold (see Sect. S6).

3.2 Estimating changes in the net migration rate at the municipality level due to flooding

3.2.1 Analysis target and period

This study analyzed the impact of flooding on the net migration rate at the municipality level in Japanese municipalities that experienced flood disasters between 2014 and 2020. The net migration rate was calculated by subtracting the number of out-migrants from the number of in-migrants during the target period and dividing the result by the initial population. We focused on the net migration rate rather than the total population change to isolate the effects of migration from natural population changes such as births and deaths. The net migration rate was calculated using annual migration data for Japanese nationals from 2014 to 2020. Municipalities that experienced flood disasters were assigned to the treatment group, while those that did not were assigned to the control group. The classification into treatment and control groups varied by year. To represent flood magnitude, we used the following municipality-level indicators: the proportion of households affected below

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

floor level by flooding, the proportion of households affected above floor level by flooding, and the proportion of households that were completely destroyed (including washed away) by flooding. These indicators were expressed as percentages of the total households, following the method of Okamoto et al. (2023). Details regarding the net migration rate data at the municipality level and data on the proportion of households affected by flooding are provided in Sect. S7. Descriptive statistics are presented in Table S5.

3.2.2 Covariates

Based on previous domestic studies on population movements within Japan (Arakawa and Noyori, 2023), we selected 32 covariates, including indicators of water-related disasters other than flooding, climatological variables, socioeconomic factors, access to public and social facilities, demographic composition, and flood risk. Covariates and their descriptive statistics are listed in Table S6. All covariates were compiled at the municipality level (see Sect. S8).

3.2.3 Analytical method

The DiD method was employed to quantify the impact of flooding on the net migration rate. However, because flood disasters occurred in different years across municipalities, applying a standard DiD approach (Eq. (S1) of the Supplement) may result in inappropriate comparisons between treated and non-treated units, introducing bias into the estimated results (Baker et al., 2022; Goodman-Bacon, 2021). To address this, we employed the stacked regression approach for the DiD analysis (Cengiz et al., 2019). To prevent inappropriate comparisons, we constructed separate datasets for each year using the method described in Sect. S9. The datasets for each year were then stacked, and the following regression model was applied for the DiD analysis:

$$N_{i',t',g'} = \theta_{i',g'} + \iota_{t',g'} + \kappa_{i',g'}t' + \boldsymbol{\lambda}\boldsymbol{X}^{\text{mun}}_{i',t'-1,g'} + \delta^{\text{mun}}_{\text{bf}}R^{\text{bf}}_{i',t',g'} + \delta^{\text{mun}}_{\text{af}}R^{\text{af}}_{i',t',g'} + \delta^{\text{mun}}_{\text{cd}}R^{\text{cd}}_{i',t',g'} + e^{\text{mun}}_{i',t',g'} \quad (2)$$

where $i' = \{1, 2, \dots, n'_{g'}\}$ denotes indices of municipalities; $g' = \{1, 2, \dots, 6\}$ denotes indices for each year-specific dataset; $n'_{g'}$ denotes the number of municipalities analyzed within each year-specific dataset; $t' = \{2014, 2015, \dots, 2020\}$ denotes years; $N_{i',t',g'}$ denotes the net migration rate (%); $\theta_{i',g'}$ denotes municipality fixed effects for each year-specific dataset; $\iota_{t',g'}$ denotes year fixed effects for each year-specific dataset; $\kappa_{i',g'}t'$ denotes municipality-specific linear time trends within each dataset; $\boldsymbol{X}^{\text{mun}}_{i',t'-1,g'}$ denotes the covariate vector excluding time-invariant covariates; $\boldsymbol{\lambda}$ denotes the parameter vector for $\boldsymbol{X}^{\text{mun}}_{i',t'-1,g'}$; $R^{\text{bf}}_{i',t',g'}$, $R^{\text{af}}_{i',t',g'}$, and $R^{\text{cd}}_{i',t',g'}$ denote the proportions (%) of households affected by flooding – below floor level, above floor level, and completely destroyed, respectively; $\delta^{\text{mun}}_{\text{bf}}$, $\delta^{\text{mun}}_{\text{af}}$, and $\delta^{\text{mun}}_{\text{cd}}$ denote the parameters for $R^{\text{bf}}_{i',t',g'}$, $R^{\text{af}}_{i',t',g'}$, and $R^{\text{cd}}_{i',t',g'}$, respectively; and $e^{\text{mun}}_{i',t',g'}$ denotes the error term. The key parameters are $\delta^{\text{mun}}_{\text{bf}}$, $\delta^{\text{mun}}_{\text{af}}$, and $\delta^{\text{mun}}_{\text{cd}}$, which quantify the effects of the proportions of households affected by flooding on the net migration rate. Due to multicollinearity between the covariates and the proportions of households affected by flooding, we excluded the following two covariates: (a) the proportion of households affected above floor level by water-related disasters other than flooding, and (b) the proportion of

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

primary industry workers. Multicollinearity was assessed using the variance inflation factor, adopting a threshold value of 5. The variables $R^{\mathrm{bf}}_{i',t',g'}$, $R^{\mathrm{af}}_{i',t',g'}$, and $R^{\mathrm{cd}}_{i',t',g'}$ represent the proportions of households affected by flooding – below floor level, above floor level, and completely destroyed, respectively – in municipalities experiencing flooding in the year of occurrence. These variables take a value of 0 for municipalities not affected by flooding during that year. We used the net migration rate instead of the net number of migrants because the latter substantially varies with population size. If the net number of migrants was employed, a logarithmic transformation would be required to interpret proportional changes. However, this is infeasible because the net number of migrants can be negative. Therefore, we used the net migration rate to account for differences in population size without necessitating a logarithmic transformation. The changes in the net migration rate at the municipality level per 1 % increase in the proportions of households affected by flooding – below floor level, above floor level, and completely destroyed – can be estimated using $\delta^{\mathrm{mun}}_{\mathrm{bf}}$, $\delta^{\mathrm{mun}}_{\mathrm{af}}$, and $\delta^{\mathrm{mun}}_{\mathrm{cd}}$, respectively, expressed in percentage points (Morita, 2014), interpreted relative to a counterfactual scenario in which flooding did not occur. A negative value indicates that flooding resulted in a decrease in the net migration rate. Finally, we indirectly validated the parallel trends assumption following the procedure described in Sect. 3.1.3. No statistically significant differences in net migration rates were observed between the treated and control groups before the flood events, suggesting that the parallel trends assumption may hold (see Sect. S10).

4 Projecting future population and land use and estimating flood damage costs

4.1 Projecting future population incorporating FIPMs

In Japan, municipality-level projections of future population aligned with the downscaled SSPs (JSSPs) (Chen et al., 2020) have been developed for national-scale assessments by the National Institute for Environmental Studies, Japan (NIES) (NIES, 2021a, b). Based on these municipality-level projections, population projections at the 1 km grid-cell level have also been developed under the JSSPs (NIES, 2021c). We incorporated the impacts of FIPMs into the JSSP-based future population projections developed by NIES. These projections use 2015 as the base year and cover 2015 to 2100 at five-year intervals, projecting population by sex and five-year age group up to age 85 and older. Figure 2 illustrates the workflow for projecting future population incorporating FIPMs. Detailed information and definitions of assumed parameters for future population projections are presented in Table S9 and Sect. S11, respectively. Except for the population changes due to FIPMs at the municipality and 500 m grid-cell levels and population by sex and five-year age group at the 250 m grid-cell level, this study adopted the methodologies and assumptions used in the JSSP-based future population projections developed by NIES (NIES, 2021a, b). To reflect FIPMs in future population projections, this study incorporated the expected annual values of variables that represent flood magnitude. In the JSSP-based projection methodology, municipality-level population projections by sex and five-year age group are adjusted to ensure that the aggregated national totals match the values specified by Chen et al. (2020) for each JSSP scenario. Specifically, an adjustment coefficient is calculated by dividing the JSSP-based national total

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

population for each sex and five-year age group by the sum of unadjusted municipality-level projections for the corresponding group. This coefficient is then multiplied by the corresponding unadjusted municipality-level population projections to obtain the adjusted projections. As a result, even after incorporating FIPMs, the total population of Japan remains consistent with the national totals specified in the JSSP scenarios. As described in Sect. 4.3, future estimates of flood damage costs incorporate the effects of climate change using climate scenario data from the Coupled Model Intercomparison Project Phase 6 (CMIP6), specifically SSP1–RCP2.6 and SSP5–RCP8.5. Therefore, future population projections incorporating FIPMs were conducted under both the JSSP1 and JSSP5 scenarios.

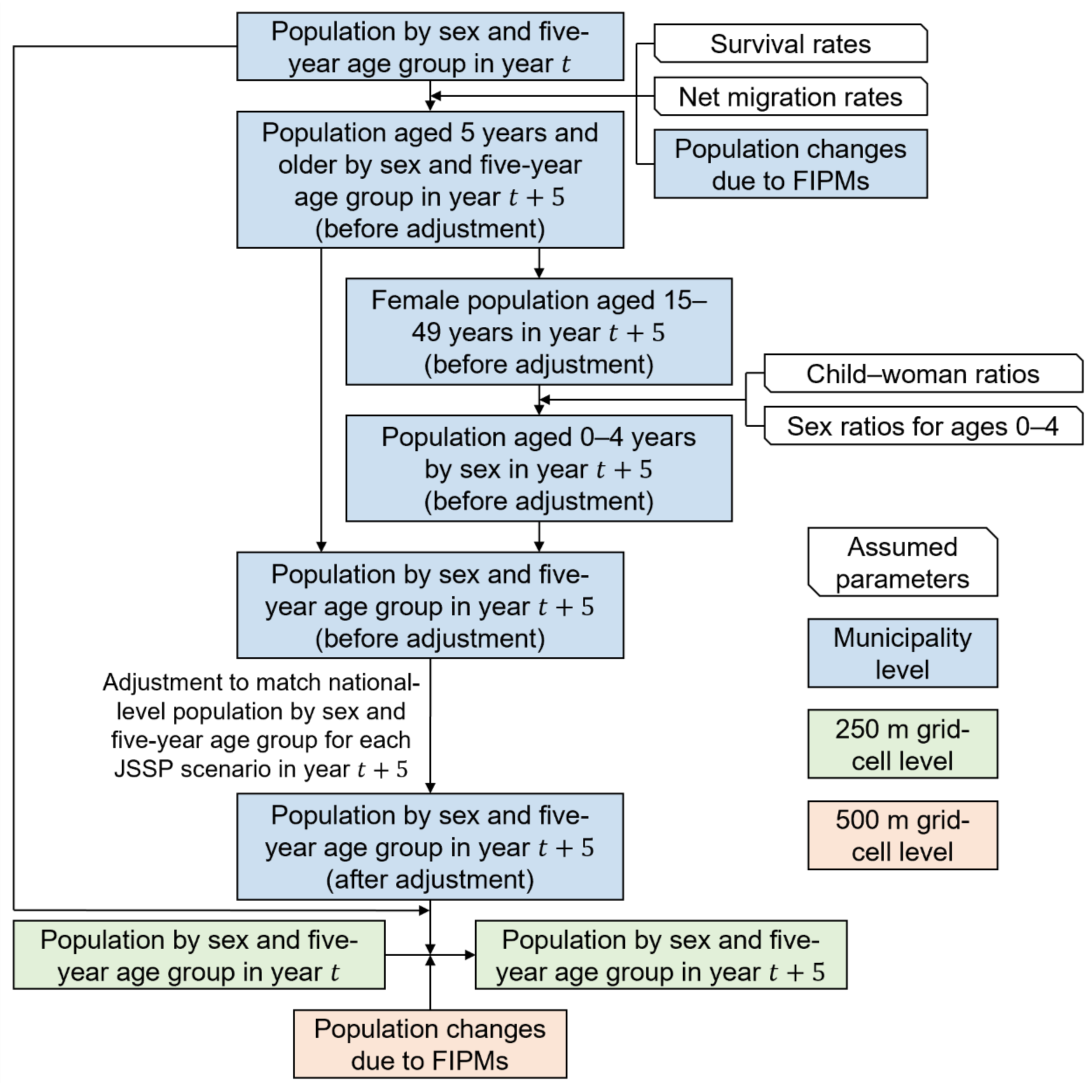

Figure 2: Workflow for projecting future population incorporating FIPMs.

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

4.1.1 Population changes due to FIPMs at the municipality level

To incorporate inter-municipality FIPMs into future population projections, we applied the following equations to each municipality to estimate population changes:

$$C_{T+b-1\rightarrow T+b,S,(X+b-1\text{ to }X+b+3)\rightarrow(X+b\text{ to }X+b+4)} = \left(\frac{\delta_{\mathrm{bf}}R_{\mathrm{bf},T+b}+\delta_{\mathrm{af}}R_{\mathrm{af},T+b}+\delta_{\mathrm{cd}}R_{\mathrm{cd},T+b}}{100}\right)P^{\mathrm{mun}}_{T+b-1,S,X+b-1\text{ to }X+b+3} \quad (3)$$

$$C_{T\rightarrow T+5,S,(X\text{ to }X+4)\rightarrow(X+5\text{ to }X+9)} = \sum_{c=1}^{5} C_{T+c-1\rightarrow T+c,S,(X+c-1\text{ to }X+c+3)\rightarrow(X+c\text{ to }X+c+4)} \quad (4)$$

where $T = \{2015, 2020, \ldots, 2100\}$ denotes years for which the population is projected; $b, c = \{1, 2, 3, 4, 5\}$ denote each year within a five-year interval; $C_{T+b-1\rightarrow T+b,S,(X+b-1\text{ to }X+b+3)\rightarrow(X+b\text{ to }X+b+4)}$ denotes the population changes due to FIPMs (persons) over one year from year $T+b-1$ to $T+b$, representing individuals of sex S who are aged $X+b-1$ to $X+b+3$ in year $T+b-1$ and transition to age $X+b$ to $X+b+4$ in year $T+b$, within each municipality; δ_{bf}, δ_{af}, and δ_{cd} denote the changes in the net migration rate (percentage points) at the municipality level per 1 % increase in the proportions of households affected by flooding – below floor level, above floor level, and completely destroyed, respectively; $R_{\mathrm{bf},T+b}$, $R_{\mathrm{af},T+b}$, and $R_{\mathrm{cd},T+b}$ denote the expected annual proportions (%) of households affected by flooding – below floor level, above floor level, and completely destroyed, respectively – in year $T+b$, within each municipality; $P^{\mathrm{mun}}_{T+b-1,S,X+b-1\text{ to }X+b+3}$ denotes the population (persons) of sex S, aged $X+b-1$ to $X+b+3$ in year $T+b-1$, within each municipality; $C_{T\rightarrow T+5,S,(X\text{ to }X+4)\rightarrow(X+5\text{ to }X+9)}$ denotes the population changes due to FIPMs (persons) over the five-year period from year T to $T+5$, representing individuals of sex S who are aged X to $X+4$ in year T and transition to age $X+5$ to $X+9$ in year $T+5$, within each municipality; and $C_{T+c-1\rightarrow T+c,S,(X+c-1\text{ to }X+c+3)\rightarrow(X+c\text{ to }X+c+4)}$ denotes the population changes due to FIPMs (persons) over one year from year $T+c-1$ to $T+c$, representing individuals of sex S who are aged $X+c-1$ to $X+c+3$ in year $T+c-1$ and transition to age $X+c$ to $X+c+4$ in year $T+c$, within each municipality.

Based on the quantified changes in net migration rates at the municipality level due to flooding (Sect. 3.2), the values of δ_{bf}, δ_{af}, and δ_{cd} were determined, representing the impacts of flooding on the annual net migration rate. Accordingly, Eq. (3) was employed to estimate the population changes due to FIPMs over a one-year period, and Eq. (4) was applied to calculate the population changes due to FIPMs over five years by summing the annual estimates. For any of δ_{bf}, δ_{af}, and δ_{cd} that were not statistically significant at the 5 % level, values were set to zero. The expected annual proportions of households affected by flooding ($R_{\mathrm{bf},T+b}$, $R_{\mathrm{af},T+b}$, $R_{\mathrm{cd},T+b}$) were calculated using the maximum inundation depth and maximum flow velocity obtained from fluvial flood inundation analyses that incorporate climate change impacts, based on Yanagihara et al. (2024), as described in Sect. 4.3, following a similar method outlined in Sect. S8. Since fluvial flood inundation analyses were conducted only for specific periods (baseline period: 1981–2000, near future: 2031–2050, and end of the 21st century: 2081–2100), values for the maximum inundation depth and maximum flow velocity caused by flooding in year $T+b$ under each return period were obtained using linear interpolation. For linear interpolation, representative years were set as follows: baseline period, 2000; near future, 2050; and end of the 21st century, 2100. This study considered the impacts of climate

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

change by using climate scenario data from five global circulation models (GCMs) and accordingly conducted future population projections incorporating FIPMs for each of the five GCMs (see Sect. 4.3). The number of households used in the calculation of the proportions of households affected by flooding was derived from the population by sex and five-year age group at the 250 m grid-cell level in year T. Specifically, based on the future household projection method aligned with the JSSP proposed by Yoshikawa et al. (2024), the number of households in each grid cell was projected by multiplying the population by the household head rate and then aggregated at the municipality level. The household head rate refers to the proportion of household heads in the total population and was taken from Yoshikawa et al. (2024). The number of households was assumed to remain constant for each year within the five-year period.

For $b \geq 2$, $P^{\text{mun}}_{T+b-1,S,X+b-1\text{ to }X+b+3}$ was calculated using the following equation:

$$P^{\text{mun}}_{T+b-1,S,X+b-1\text{ to }X+b+3} = P^{\text{mun}}_{T,S,X\text{ to }X+4} + \frac{b-1}{5}\left(NM_{T\to T+5,S,(X\text{ to }X+4)\to(X+5\text{ to }X+9)}\right.$$
$$\left.+SVR_{T\to T+5,S,(X\text{ to }X+4)\to(X+5\text{ to }X+9)} - 1\right)P^{\text{mun}}_{T,S,X\text{ to }X+4}$$
$$+\sum_{c=1}^{b-1} C_{T+c-1\to T+c,S,(X+c-1\text{ to }X+c+3)\to(X+c\text{ to }X+c+4)} \quad (5)$$

where $P^{\text{mun}}_{T,S,X\text{ to }X+4}$ denotes the population (persons) of sex S, aged X to $X+4$ years in year T, within each municipality; $NM_{T\to T+5,S,(X\text{ to }X+4)\to(X+5\text{ to }X+9)}$ denotes the net migration rate; and $SVR_{T\to T+5,S,(X\text{ to }X+4)\to(X+5\text{ to }X+9)}$ denotes the survival rate. Detailed definitions of $NM_{T\to T+5,S,(X\text{ to }X+4)\to(X+5\text{ to }X+9)}$ and $SVR_{T\to T+5,S,(X\text{ to }X+4)\to(X+5\text{ to }X+9)}$ are provided in Sect. S11. Using Eq. (5), the five-year net migration and deaths were evenly distributed across each of the five years to derive annual values. The municipality-level population changes due to FIPMs obtained using the method described above were incorporated into the future population projections shown in Fig. 2. If the projected population by sex and five-year age group became negative due to the incorporation of FIPMs, the negative values were replaced with zero.

4.1.2 Population changes due to FIPMs at the 500 m grid-cell level

Considering population changes due to FIPMs at the 500 m grid-cell level, we projected the future population by sex and five-year age group at the 250 m grid-cell level by applying the following equation to each grid cell:

$$P^{250\text{m}}_{T+5,S,X\text{ to }X+4} = P^{250\text{m}}_{T,S,X\text{ to }X+4}\frac{P^{\text{mun}}_{T+5,S,X\text{ to }X+4}}{P^{\text{mun}}_{T,S,X\text{ to }X+4}}\prod_{c=1}^{5}\left(1+\frac{\delta_{\text{depth}}}{100}E_{T+c}\right) \quad (6)$$

where $P^{250\text{m}}_{T+5,S,X\text{ to }X+4}$ denotes the population (persons) by sex S and age group X to $X+4$ in year $T+5$ in each 250 m grid cell; $P^{250\text{m}}_{T,S,X\text{ to }X+4}$ denotes the corresponding population (persons) in year T; $P^{\text{mun}}_{T+5,S,X\text{ to }X+4}$ denotes the population by sex S and age group X to $X+4$ in year $T+5$ in each municipality; δ_{depth} denotes the percentage change (%) in the total population per 1 m increase in maximum inundation depth at the 500 m grid-cell level; and E_{T+c} denotes the expected annual maximum inundation depth (m) in year $T+c$ for each 500 m grid cell. Consistent with the projections at the 1 km grid-cell level based on the JSSPs (NIES, 2021c), the rate of population change for each grid cell was assumed to be the

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

same as that of the municipality to which the grid cell belongs. In addition, population changes due to FIPMs at the 500 m grid-cell level were incorporated into the projections.

Based on the quantified changes in the total population at the 500 m grid-cell level, δ_{depth} was determined, representing the impact of a single flooding event on the total population. In Eq. (6), population changes induced by the expected annual maximum inundation depth for each of the five years were considered. When δ_{depth} was not statistically significant at the 5 % level, its value was set to zero. In calculating E_{T+c}, the maximum inundation depth for each return period in year $T + c$ was determined using the method described in Sect. 4.1.1. Since the maximum inundation depth was used at the 250 m grid-cell level, the maximum inundation depth within each 250 m grid cell located inside each 500 m grid cell was extracted. During this process, inundation within river-channel grid cells was disregarded, and the inundation depth for these cells was assumed to be 0 m. After applying Eq. (6), any negative projected population by sex and five-year age group for each 250 m grid cell was replaced with zero. The municipality-level population, aggregated from the 250 m grid-cell projections of $P^{\mathrm{250m}}_{T+5,S,X\ \mathrm{to}\ X+4}$, did not match the corresponding population $P^{\mathrm{mun}}_{T+5,S,X\ \mathrm{to}\ X+4}$. This discrepancy arose due to the population decrease caused by FIPMs. Therefore, the decreased population was adjusted by uniformly scaling the populations of all 250 m grid cells – excluding specific cases such as river-channel grid cells – to ensure consistency with the municipality-level totals (see Sect. S12).

4.2 Projecting land use based on future population

To estimate future flood damage costs, future land-use data are required. Yoshikawa et al. (2024) projected the future number of households at the 1 km grid-cell level based on population changes under the JSSPs and used them to project shortages and unused residential building land areas at the 1 km grid-cell level. Accordingly, we projected future land use for each 1 km grid cell using the relationships between the number of households and both the shortage and unused residential building land areas obtained from Yoshikawa et al. (2024) (see Sect. S13). Yoshikawa et al. (2024) also projected shortages of land for industrial and commercial/business buildings in response to population changes under the JSSPs. The starting point of population decline for each prefecture was used. If this starting point remains unchanged regardless of whether FIPMs are considered, the projected shortage of land for industrial and commercial/business buildings will also remain unchanged. Therefore, we compared prefecture-specific population data based on the JSSPs (NIES, 2021a, b) with the projected prefecture-specific population data incorporating FIPMs. The comparison showed that the starting point of population decline was unchanged across all prefectures. Therefore, this study adopted the projected shortages of land for industrial and commercial/business buildings calculated by Yoshikawa et al. (2024). The land use based on the future population projected using the above method was spatially downscaled to the 250 m grid-cell level using the method described in Sect. S14. Using the projected land-use data for 2050 and 2100, we estimated future flood damage costs considering FIPMs for the near future and the end of the 21st century.

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

4.3 Estimating future flood damage costs considering changes in rainfall and land use

Future damage costs were estimated using an existing fluvial flood damage model (Yanagihara et al., 2024) that considered rainfall changes associated with climate change and land use changes associated with population changes across Japan for the baseline period, the near future, and the end of the 21st century. The costs were evaluated as expected annual values derived from damage calculations for return periods of 30, 50, 100, and 200 years. Maximum inundation depths were calculated using a fluvial flood inundation analysis on a 250 m grid, and corresponding damage costs were estimated based on these depths using depth-specific damage rates. The effects of rainfall changes were incorporated by adjusting the input rainfall used in the fluvial flood inundation analysis. Rainfall changes were incorporated using climate scenario data derived from five GCMs based on CMIP6 for the SSP1–RCP2.6 and SSP5–RCP8.5 scenarios (Ishizaki, 2021, 2022). In addition, the effects of land use changes were reflected through adjustments to the roughness coefficient and house occupancy ratio in the fluvial flood inundation analysis and to asset values in the damage cost calculations. This study estimated future flood damage costs by modifying the land use projections of Yanagihara et al. (2024) to account for FIPMs. To reduce computational demands, land use changes were not incorporated into the fluvial flood inundation analysis, as variations in asset values accounted for the majority of changes in flood damage costs. As in Yanagihara et al. (2024), this study focused on percentage changes in flood damage costs rather than absolute values to reduce uncertainty.

5 Results

5.1 Quantifying FIPMs

Figure 3 illustrates the population responses to flood exposure, as quantified using the DiD approach. Figure 3a shows the percentage change in the total population at the 500 m grid-cell level per 1 m increase in maximum inundation depth.

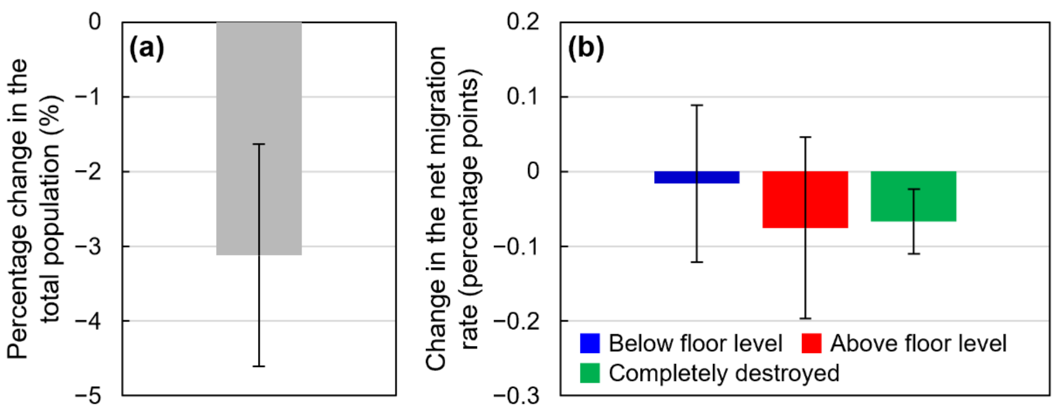

Figure 3: Population responses to flood exposure. (a) Percentage change in the total population at the 500 m grid-cell level per 1 m increase in maximum inundation depth. (b) Changes in the net migration rate at the municipality level per 1 % increase in the proportions of households affected by flooding. Error bars represent 95 % confidence intervals.

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

Statistical significance at the 5 % level is indicated when the 95 % confidence interval (shown as error bars) does not include zero – a criterion consistently applied in this study. A statistically significant negative change in the total population due to flooding is evident, confirming that the total population decreases as the maximum inundation depth increases. Specifically, the percentage change in the total population at the 500 m grid-cell level per 1 m increase in maximum inundation depth was estimated to be −3.1 %. Figure 3b presents changes in the net migration rate at the municipality level per 1 % increase in the proportions of households affected by flooding. No statistically significant (5 % level) changes were observed in the net migration rate at the municipality level per 1 % increase in the proportions of households affected by flooding below floor level and above floor level, indicating no clear impact on migration from these levels of damage. However, the change in the net migration rate at the municipality level per 1 % increase in the proportion of households completely destroyed by flooding was statistically significant (5 % level), confirming that net migration rate decreases as the proportion of completely destroyed households increases. The change in the net migration rate due to flooding was estimated at −0.07 percentage points per 1 % increase in the proportion of households that were completely destroyed by flooding, indicating that flooding led to a population decline in municipalities. Detailed results of parameter estimation for Eqs. (1) and (2) can be found in Tables S10 and S11.

5.2 Population changes due to FIPMs

Figure 4 presents the aggregated national-level population changes due to FIPMs at the municipality and the 500 m grid-cell levels. At the municipality level, absolute population changes due to FIPMs were obtained using Eq. (4) and summed across all municipalities in Japan. In contrast, at the 500 m grid-cell level, absolute differences in population with and without

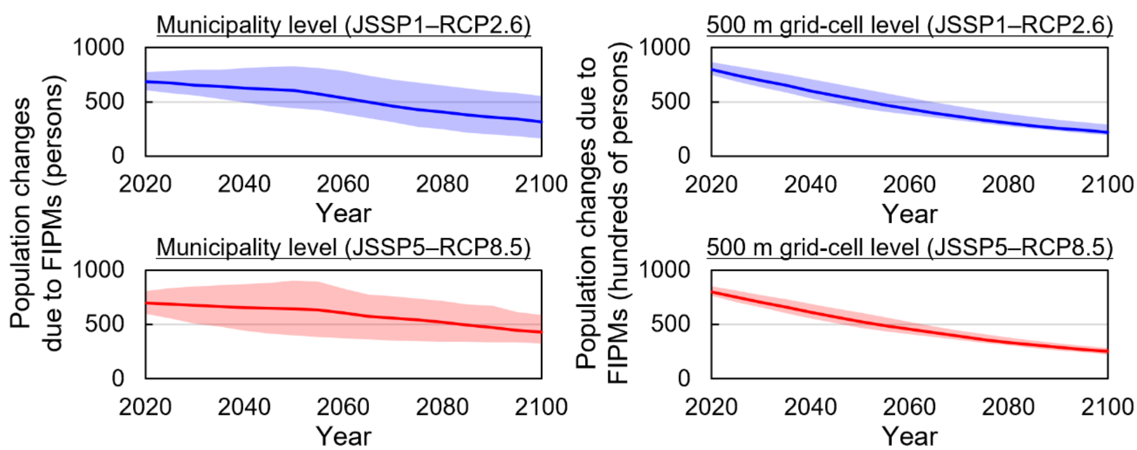

Figure 4: Aggregated national-level population changes due to FIPMs at the municipality and the 500 m grid-cell levels. Population changes are shown at five-year intervals from 2020 to 2100, with each value representing the cumulative population change over the preceding five-year period. The changes were calculated based on the average values estimated from five GCMs. Error bands indicate the range between the maximum and minimum population changes derived from the five GCMs.

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

FIPMs were calculated using Eq. (6) and aggregated nationwide. The five-year population changes due to FIPMs at the municipality level ranged from approximately 320 to 690 persons under the JSSP1–RCP2.6 scenario and from approximately 430 to 700 persons under the JSSP5–RCP8.5 scenario, between 2020 and 2100. Similarly, the five-year population changes at the 500 m grid-cell level ranged from approximately 22,300 to 79,700 persons under the JSSP1–RCP2.6 scenario, and from approximately 25,200 to 80,200 persons under the JSSP5–RCP8.5 scenario, during the same period. Population changes due to FIPMs declined over time. Notably, changes at the 500 m grid-cell level were approximately 59 to 116 times greater than those at the municipality level. Additionally, differences in population changes between JSSP5–RCP8.5 and JSSP1–RCP2.6 gradually increased over time. Specifically, by 2100, the population changes due to FIPMs under JSSP5–RCP8.5 were 34 % greater at the municipality level and 13 % greater at the 500 m grid-cell level compared to those under JSSP1–RCP2.6.

5.3 Changes in flood damage costs due to FIPMs

This section examines the impact of FIPMs on future flood damage costs. Here, the percentage change in flood damage costs due to FIPMs is defined as the relative difference from estimates without considering FIPMs. At the national level, under JSSP1–RCP2.6, the percentage change due to FIPMs across Japan was −0.2 % in the near future and +0.3 % at the end of the 21st century, based on flood damage costs averaged across five GCMs. In contrast, under the JSSP5–RCP8.5 scenario, these percentage changes were −0.2 % and +0.1 %, respectively. Figure 5 presents the percentage changes in flood damage costs due to FIPMs at the prefectural level. Under JSSP1–RCP2.6, these ranged from −1.7 % to +0.1 % in the near future and −1.1 % to +1.0 % by the end of the 21st century. Under the JSSP5–RCP8.5 scenario, these values ranged from −1.7 % to +0.1 % and −1.3 % to +0.8 %, respectively. In the near future, FIPMs generally reduced flood damage costs in many prefectures, though the number of prefectures experiencing increases rose toward the end of the 21st century. However, only two prefectures exhibited absolute percentage changes exceeding 1 %, reaching approximately 2 %. At the municipal level, as shown in Fig. 6, under JSSP1–RCP2.6, percentage changes due to FIPMs ranged from −11.2 % to +1.7 % in the near future and −6.7 % to +2.9 % by the end of the 21st century. Under JSSP5–RCP8.5, these values ranged from −11.4 % to +1.2 % and −7.0 % to +1.9 %, respectively. Municipalities with absolute percentage changes greater than 1 % accounted for approximately 12 % of all municipalities under both scenarios in the near future, and approximately 7 % by the end of the 21st century. Municipalities with reductions exceeding 10 % were concentrated in areas heavily impacted by flooding.

6 Discussion

6.1 Population changes due to FIPMs and their validity

Section 5.2 presented quantitative results of population changes due to FIPMs. Here, we interpret these findings and validate them through comparisons with independent data sources. The decreasing trend in population changes due to FIPMs observed over time primarily reflects Japan's projected population decline rather than impacts directly attributable to climate

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

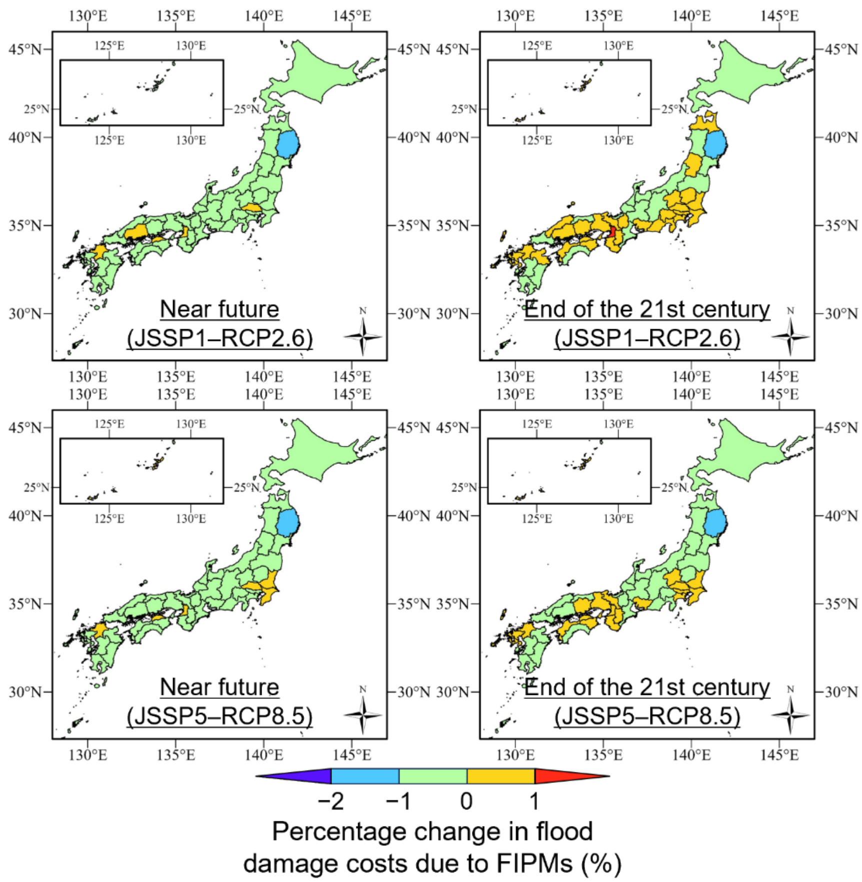

Figure 5: Percentage change in flood damage costs by prefecture due to FIPMs. The percentage changes were calculated from average flood damage costs estimated across five GCMs.

change. Although Yanagihara et al. (2024) indicated that flood damage costs across Japan are expected to increase under future climate scenarios, our findings suggest demographic trends are more dominant. Additionally, our results show that population changes due to FIPMs are substantially greater at the 500 m grid-cell level than at the municipality level, highlighting the dominance of intra-municipality movements. Population changes due to FIPMs under JSSP5–RCP8.5 consistently exceeded those under JSSP1–RCP2.6, reflecting higher population projections and increased precipitation under JSSP5–RCP8.5 (Yanagihara et al., 2024).

To validate our estimates, we compared them with internal displacement data provided by the Internal Displacement Monitoring Centre (IDMC). The IDMC dataset (IDMC, 2023) includes event-based, national-level internal displacement data from 2008 to 2024, explicitly representing forced displacement. In contrast, our estimates also include voluntary population movements, such as decisions to avoid relocating into flood-affected areas, which are not captured by the IDMC dataset. Since the IDMC categorizes Typhoon Hagibis (2019) – a key event in our analysis – as "Storm," we included both "Flood" and "Storm" categories in our validation. Furthermore, internal displacement caused solely by fluvial flooding could

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

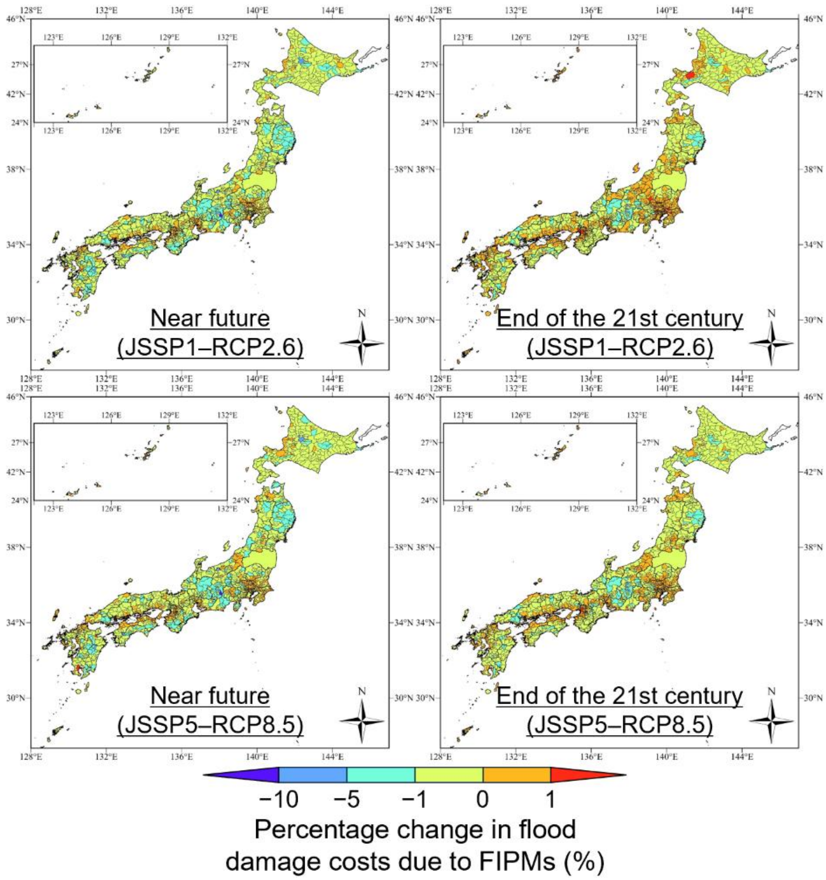

Figure 6: Percentage change in flood damage costs by municipality due to FIPMs. The percentage changes were calculated from average flood damage costs estimated across five GCMs. Fukushima Prefecture is presented as a single region.

not be extracted from the IDMC dataset because the dataset does not distinguish among flood types. As suggested by Kakinuma et al. (2020), differentiating displacement due to fluvial flooding remains challenging. Nonetheless, the IDMC dataset is the most comprehensive and reliable independent source providing internal displacement data related to floods.

As our estimates represent expected annual population changes based on expected annual flood magnitudes, we arranged internal displacement numbers for each event from the IDMC dataset by year and calculated average annual internal displacement numbers. We compared population changes due to FIPMs at the 500 m grid-cell level to these average annual internal displacement numbers. Comparing our estimates at the municipality level with independent data sources was difficult due to a lack of relevant data. To align data periods, we compared the estimated population changes due to FIPMs specifically for the year 2020. The average annual internal displacement number (approximately 212,000 persons) substantially exceeded our estimate for 2020 (approximately 16,000 persons, calculated by dividing the five-year population changes due to FIPMs shown in Fig. 4 by five). This discrepancy is largely attributable to the fact that the IDMC dataset includes displacements caused by various types of flooding, capturing all forced movements regardless of duration. In

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

contrast, our estimates are based on total population data at five-year intervals, excluding individuals who returned after displacement events within these intervals. Similarly, our municipality-level estimates rely on annual net migration rates derived from resident registration data, thus excluding short-term evacuees who returned without registering a new address. Methodological limitations (see Sect. 6.3) likely also contribute to this discrepancy. Considering these limitations, achieving a direct quantitative match remains challenging.

While recognizing these limitations, our methodological approach, rather than employing a basic DiD model, incorporates grid-cell or municipality-specific linear time trends, careful consideration of covariates, propensity score matching, and a stacked regression approach. This extended approach explicitly captures population changes due to FIPMs at both municipality and 500 m grid-cell levels, which cannot be resolved using IDMC datasets alone. Similarly, Shu et al. (2023) utilized a regression model to estimate the relationship between flooding and population dynamics. They validated their model through external predictive accuracy, assessing whether their model accurately predicted population changes in previously unused datasets. We did not adopt it because our study explicitly aims to integrate the causal impacts of flooding on population movements into existing population projections developed by NIES, and predictive accuracy alone does not necessarily reflect causal validity. Specifically, even highly predictive models may suffer from multicollinearity or spurious correlations, leading to misinterpretation of causal relationships. Therefore, our study employs the extended DiD methodology to quantify the causal effects of flooding on population movements. Although further methodological refinements remain necessary, our proposed framework can be considered a valid approach for evaluating population changes due to FIPMs.

6.2 Influence of FIPMs on future flood damage costs

National-level impacts of FIPMs on future flood damage costs are minimal, with absolute percentage changes consistently below 1 %. This limited impact at the national scale likely results from counterbalancing effects, wherein regions experiencing population increases offset those with population losses, leading to negligible net changes when aggregated. Similarly, at the prefectural level, absolute percentage changes rarely exceed 1 %, reinforcing that the overall impact of FIPMs remains limited at broader spatial scales. In contrast, at the municipality level, localized effects become more apparent. Some municipalities experienced reductions in future flood damage costs exceeding 10 %, suggesting that the finer the spatial resolution, the greater the influence of FIPMs. Nonetheless, given that most municipalities exhibited absolute changes below 1 %, the overall influence of FIPMs is not large enough to overturn conclusions from prior studies – such as Swain et al. (2020), Wing et al. (2022), and Yanagihara et al. (2024) – showing that population change alone, even without explicitly considering FIPMs, can exceed the impacts of climate change. To the best of our knowledge, no previous national-scale studies have explicitly incorporated FIPMs into future flood damage cost estimations. However, Shu et al. (2023) conducted a related analysis in the United States, showing that exposure to high-frequency flooding (5- and 20-year return periods) led to 2–7 % lower population growth rates compared to baseline projections. Our findings extend this understanding, showing that reductions in population growth can translate into lower future flood damage costs. From a

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

practical perspective, although only a limited number of municipalities experienced notable cost reductions due to FIPMs, overlooking these effects could lead to an overestimation of the effectiveness of flood mitigation measures. These findings highlight the importance of incorporating FIPMs into future flood risk assessments and policy evaluations, particularly at the local level.

6.3 Limitations and future research directions

This study had some limitations that future research should address. First, when incorporating FIPMs into future population projections, expected annual values of flood magnitude variables were used, capturing only average annual impacts. Consequently, the specific impacts of population movements associated with individual flood events were not considered. When considering individual flood events, computational resource constraints must be addressed. Approaches such as emulating physical models with machine learning (Momoi et al., 2023) and extracting essential precipitation events based on hydrological concepts (Chen et al., 2025) may help address these constraints. These methods would enable future studies to assess how event-specific FIPMs influence the findings of the current study. Second, this study assumed uniformity in population movement responses to flood magnitude across different regions. However, regional differences may exist due to factors such as accessibility and occupational composition, potentially leading to variations in population movement responses even at similar flood magnitudes. By employing causal inference methods that explicitly account for such interaction effects (e.g., Lee and Lee, 2025), future research should quantitatively incorporate regional variations when evaluating population movements. Third, while integrating FIPMs into future population projections, the current framework does not explicitly consider the specific destinations of population movements. Instead, population distributions were uniformly scaled by applying adjustment factors across areas to ensure consistency with overall national or municipal totals. Recent studies have developed population migration models capable of explicitly incorporating pull factors influencing migration (Niu, 2022). Future research should utilize these models to explicitly consider the destinations of population movements, thereby enhancing the methodological framework. Fourth, values quantified by the DiD method contain uncertainties. To better understand uncertainties associated with FIPMs, future research should include a detailed analysis of uncertainties in estimated flood damage costs considering FIPMs. Despite these limitations, this study is novel in its evaluation of the impacts of FIPMs on future flood damage costs. Addressing these limitations will be crucial for improving the accuracy and practical applicability of future flood damage estimations.

7 Conclusions

This study evaluated the impact of FIPMs on future flood damage costs in Japan. The main findings are summarized as follows:

- The impacts of FIPMs on national-level future flood damage costs in Japan were minor, with absolute percentage changes of less than 1 %. Furthermore, only two prefectures showed percentage changes greater than 1 %, with

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

maximum absolute changes of approximately 2 %, suggesting that the prefectural-level impacts of FIPMs on flood damage costs are limited.

- At the municipal level, although only approximately 10 % of municipalities exhibited percentage changes in flood damage costs exceeding 1 % due to FIPMs, some municipalities experienced reductions exceeding 10 %. Thus, future assessments and policy evaluations at the local scale should explicitly consider the effects of FIPMs.

While this study represents a case study focused on Japan, it contributes by demonstrating a methodological framework for estimating future flood damage costs that integrates FIPMs. Future research should improve the understanding of the impacts of FIPMs on future flood damage costs through consideration of individual flood events, regional characteristics, population movement destinations, and uncertainties related to population movements, ultimately enhancing the effectiveness of flood risk management strategies. In addition, to apply the methodological framework to other countries, adjustments based on data availability and specific regional contexts will be required.

Code availability

The code used in this study is available from the corresponding author upon reasonable request.

Data availability

The sources of the statistical datasets used in this study are provided in the Supplement. Other data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author contribution

Conceptualization: HY, SK; Data curation: HY, YH, AI; Formal analysis: HY; Funding acquisition: HY, SK, YH; Investigation: HY; Methodology: HY, SK, KG; Project administration: HY, SK; Resources: HY, SK, KG, YH; Software: HY, SK, KG; Supervision: SK; Validation: HY, SK, KG; Visualization: HY, AI; Writing (original draft preparation): HY; Writing (review and editing): HY, SK, KG, YH, AI

Competing interests

The authors declare that they have no conflict of interest.

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

Financial support

This study was supported by JSPS KAKENHI (Grant Number JP23KJ0119), the Environment Research and Technology Development Fund (Grant Number JPMEERF20S11813) of the Environmental Restoration and Conservation Agency provided by the Ministry of the Environment of Japan, and the Joint Usage/Research Center for Interdisciplinary Large-scale Information Infrastructures (JHPCN), Japan (Project IDs: jh230024 and jh240013).

References

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P., Wyser, K., and Feyen, L.: Global projections of river flood risk in a warmer world, Earth's Future, 5, 171–182, https://doi.org/10.1002/2016EF000485, 2017.

Alves, P. J., Lima, R. C. de A., and Emanuel, L.: Natural disasters and establishment performance: Evidence from the 2011 Rio de Janeiro Landslides, Reg. Sci. Urban Econ., 95, 103761, https://doi.org/10.1016/j.regsciurbeco.2021.103761, 2022.

Arakawa, K. and Noyori, S. S.: The relationship of socioeconomic factors and migration from large cities to rural areas, Socio-Informatics, 11, 19–33, https://doi.org/10.14836/ssi.11.3_19, 2023.

Baker, A. C., Larcker, D. F., and Wang, C. C. Y.: How much should we trust staggered difference-in-differences estimates? J. Financ. Econ., 144, 370–395, https://doi.org/10.1016/j.jfineco.2022.01.004, 2022.

Cengiz, D., Dube, A., Lindner, A., and Zipperer, B.: The effect of minimum wages on low-wage jobs, Q. J. Econ., 134, 1405–1454, https://doi.org/10.1093/qje/qjz014, 2019.

Chen, H., Matsuhashi, K., Takahashi, K., Fujimori, S., Honjo, K., and Gomi, K.: Adapting global shared socio-economic pathways for national scenarios in Japan, Sustain. Sci., 15, 985–1000, https://doi.org/10.1007/s11625-019-00780-y, 2020.

Chen, J., Sayama, T., Yamada, M., and Sugawara, Y.: Reducing the computational cost of process-based flood frequency estimation by extracting precipitation events from a large-ensemble climate dataset, J. Hydrol., 655, 132946, https://doi.org/10.1016/j.jhydrol.2025.132946, 2025.

Del Rio Amador, L., Boudreault, M., and Carozza, D. A.: Projecting climate and socioeconomic contributions to global flood-induced displacements using a data-driven approach, Nat. Hazards, 121, 16935–16973, https://doi.org/10.1007/s11069-025-07457-z, 2025.

Delforge, D., Wathelet, V., Below, R., Sofia, C. L., Tonnelier, M., van Loenhout, J. A. F., and Speybroeck, N.: EM-DAT: the Emergency Events Database, Int. J. Disaster Risk Reduct., 124, 105509, https://doi.org/10.1016/j.ijdrr.2025.105509, 2025.

Goodman-Bacon, A.: Difference-in-differences with variation in treatment timing, J. Econom., 225, 254–277, https://doi.org/10.1016/j.jeconom.2021.03.014, 2021.

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

Internal Displacement Monitoring Centre: Global Internal Displacement Database - Disasters, https://www.internal-displacement.org/database/displacement-data/ (last access: 10 July 2025), 2023.

Ishizaki, N. N.: Bias corrected climate scenarios over Japan based on CDFDM method using CMIP6 (NIES2020), Ver.1, National Institute for Environmental Studies, Japan [data set], https://doi.org/10.17595/20210501.001 (last access: 11 October 2021), 2021.

Ishizaki, N. N., Shiogama, H., Hanasaki, N., and Takahashi, K.: Development of CMIP6-based climate scenarios for Japan using statistical method and their applicability to heat-related impact studies, Earth Space Sci., 9, e2022EA002451, https://doi.org/10.1029/2022EA002451, 2022.

Jarzebski, M. P., Elmqvist, T., Gasparatos, A., Fukushi, K., Eckersten, S., Haase, D., Goodness, J., Khoshkar, S., Saito, O., Takeuchi, K., Theorell, T., Dong, N., Kasuga, F., Watanabe, R., Sioen, G. B., Yokohari, M., and Pu, J.: Ageing and population shrinking: implications for sustainability in the urban century, npj Urban Sustain., 1, 17, https://doi.org/10.1038/s42949-021-00023-z, 2021.

Kakinuma, K., Puma, M. J., Hirabayashi, Y., Tanoue, M., Baptista, E. A., and Kanae, S.: Flood-induced population displacements in the world, Environ. Res. Lett., 15, 124029, https://doi.org/10.1088/1748-9326/abc586, 2020.

Kam, P. M., Aznar-Siguan, G., Schewe, J., Milano, L., Ginnetti, J., Willner, S., McCaughey, J. W., and Bresch, D. N.: Global warming and population change both heighten future risk of human displacement due to river floods, Environ. Res. Lett., 16, 044026, https://doi.org/10.1088/1748-9326/abd26c, 2021.

Kono, T., Tatano, H., Ushiki, K., Nakazono, D., and Sugisawa, F.: Relocation of firms due to public release of tsunami hazard map, Journal of Japan Society of Civil Engineers, Ser. D3 (Infrastructure Planning and Management), 77, 301–315, https://doi.org/10.2208/jscejipm.77.4_301, 2021.

Lee, Z. and Lee, K.: Causal interaction and effect modification: a randomization-based approach to inference, J. Korean Stat. Soc., 54, 665–684, https://doi.org/10.1007/s42952-025-00313-7, 2025.

Marvi, M. T.: A review of flood damage analysis for a building structure and contents, Nat. Hazards, 102, 967–995, https://doi.org/10.1007/s11069-020-03941-w, 2020.

Merz, B., Kreibich, H., Schwarze, R., and Thieken, A.: Review article "Assessment of economic flood damage", Nat. Hazards Earth Syst. Sci., 10, 1697–1724, https://doi.org/10.5194/nhess-10-1697-2010, 2010.

Ministry of Land, Infrastructure and Transport of Japan: Rivers in Japan, https://www.mlit.go.jp/river/basic_info/english/pdf/riversinjapan.pdf (last access: 2 July 2025), 2006.

Momoi, M., Kotsuki, S., Kikuchi, R., Watanabe, S., Yamada, M., and Abe, S.: Emulating rainfall-runoff-inundation model using deep neural network with dimensionality reduction, Artificial Intelligence for the Earth Systems, 2, e220036, https://doi.org/10.1175/AIES-D-22-0036.1, 2023.

Morita, H.: Introduction to empirical analysis, Nippon Hyoron Sha, Tokyo, 344 pp., ISBN 978-4-535-55793-2, 2014.

Namikawa, K., Koyama, N., and Yamada, T.: Analysis of impact of catastrophic flooding on the local population and its causes, Advances in River Engineering, 28, 385–390, https://doi.org/10.11532/river.28.0_385, 2022.

https://doi.org/10.5194/egusphere-2025-5949
Preprint. Discussion started: 11 December 2025

National Institute for Environmental Studies, Japan: Results of Environment Research and Technology Development Fund 2-1805 (Japanese SSP Population Scenarios for Municipalities, 2nd Edition), https://adaptation-platform.nies.go.jp/data/socioeconomic/index.html (last access: 2 July 2025), 2021a.

National Institute for Environmental Studies, Japan: Japanese SSP Population Projections for Municipalities (2nd Edition), http://adaptation-platform.nies.go.jp/data/socioeconomic/pdf/population_manual_v2.pdf (last access: 2 July 2025), 2021b.

National Institute for Environmental Studies, Japan: Results of Environment Research and Technology Development Fund 2-1805 (Japanese SSP Third Mesh Population Scenarios, 2nd Edition), https://adaptation-platform.nies.go.jp/data/socioeconomic/index.html (last access: 2 July 2025), 2021c.

Nguyen, M.: A Guide on Data Analysis, https://bookdown.org/mike/data_analysis/ (last access: 2 July 2025), 2020.

Niu, F.: A push-pull model for inter-city migration simulation, Cities, 131, 104005, https://doi.org/10.1016/j.cities.2022.104005, 2022.

Okamoto, A., Yanagihara, H., Kazama, S., and Hiraga, Y.: Statistical analysis of municipal population change and their factors caused by flood damage, Japanese Journal of JSCE, 79, 23-27044, https://doi.org/10.2208/jscejj.23-27044, 2023.

Redondo-Tilano, S. A., Boucher, M.-A., and Lacey, J.: Emerging strategies for addressing flood-damage modeling issues: A review, Int. J. Disaster Risk Reduct., 116, 105058, https://doi.org/10.1016/j.ijdrr.2024.105058, 2025.

Rogers, J. S., Maneta, M. P., Sain, S. R., Madaus, L. E., and Hacker, J. P.: The role of climate and population change in global flood exposure and vulnerability, Nat. Commun., 16, 1287, https://doi.org/10.1038/s41467-025-56654-8, 2025.

Shu, E. G., Porter, J. R., Hauer, M. E., Olascoaga, S. S., Gourevitch, J., Wilson, B., Pope, M., Melecio-Vazquez, D., and Kearns, E.: Integrating climate change induced flood risk into future population projections, Nat. Commun., 14, 7870, https://doi.org/10.1038/s41467-023-43493-8, 2023.

Sivapalan, M., Savenije, H. H. G., and Blöschl, G.: Socio-hydrology: A new science of people and water, Hydrol. Process., 26, 1270–1276, https://doi.org/10.1002/hyp.8426, 2012.

Swain, D. L., Wing, O. E. J., Bates, P. D., Done, J. M., Johnson, K. A., and Cameron, D. R.: Increased flood exposure due to climate change and population growth in the United States, Earth's Future, 8, e2020EF001778, https://doi.org/10.1029/2020EF001778, 2020.

Tsuda, H. and Tebakari, T.: A macroscopic analysis of the demographic impacts of flood inundation in Thailand (2005–2019), Prog. Earth Planet. Sci., 10, 36, https://doi.org/10.1186/s40645-023-00569-9, 2023.

Ujihara, T., Wake, H., and Morinaga, Y.: Changing population and land prices in areas damaged by torrential rains in Kanto and Tohoku, September 2015, Journal of the City Planning Institute of Japan, 54, 57–63, https://doi.org/10.11361/journalcpij.54.57, 2019.

Ushiki, K., Kono, T., Tatano, H., Nakazono, D., and Sugisawa, F.: Understanding changes in population distribution by age group due to the publication of tsunami inundation estimates using difference-in-differences analysis, Proceedings of Infrastructure Planning, 60, 02-03, 2019.

Wing, O. E. J., Lehman, W., Bates, P. D., Sampson, C. C., Quinn, N., Smith, A. M., Neal, J. C., Porter, J. R., and Kousky, C.: Inequitable patterns of US flood risk in the Anthropocene, Nat. Clim. Change, 12, 156–162, https://doi.org/10.1038/s41558-021-01265-6, 2022.

Yanagihara, H., Kazama, S., Yamamoto, T., Ikemoto, A., Tada, T., and Touge, Y.: Nationwide evaluation of changes in fluvial and pluvial flood damage and the effectiveness of adaptation measures in Japan under population decline, Int. J. Disaster Risk Reduct., 110, 104605, https://doi.org/10.1016/j.ijdrr.2024.104605, 2024.

Yoshikawa, S., Takahashi, K., Wu, W., Matsuhashi, K., and Mimura, N.: Development of common socio-economic scenarios for climate change impact assessments in Japan, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2022-169, 2022.

Yoshikawa, S., Imamura, K., Yamasaki, J., Nitanai, R., Manabe, R., Murayama, A., Takahashi, K., Matsuhashi, K., and Mimura, N.: Estimation of future building area by use for data development associated with Japan SSPs, Japanese Journal of JSCE, 80, 24-27049, https://doi.org/10.2208/jscejj.24-27049, 2024.