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Novel framework for assessing long-term flood risk management pathways focusing on river channel improvement and amenity policies

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Abstract

Many urban areas at higher flood risk owing to climate change, and mitigating these risks requires a combination of structural and nonstructural adaptation measures. Previous studies assessing adaptation measures are limited in quantifying the effects of climatic and social changes. As an interdisciplinary approach, this study developed an agent-based model of household locational choices and combined an advanced method for deriving on-site analytical flood risk curves (90 m resolution) to explicitly reflect the present/future flood risk on the flood insurance rate. To evaluate river channel improvements and amenity policies, the proposed framework was applied to a middle stream area of the Yodo River basin, Japan. The simulation results indicated that (1) both the design level and river pathway improvements influence the flood risk (2) developing wider areas over low- and no-risk areas rather than the intensive induction to limited no-risk areas lead to a more effective reduction in flood risk. In addition, (3) an appropriate amenity policy may contribute to the attenuation of the inequality of flood risk among regions owing to the pathway of improvement. The proposed interdisciplinary approach will help decision makers in long-term flood risk management.

KEYWORDS

agent-based model, amenity policy, climate change, flood risk, river improvement

1 | INTRODUCTION

Flooding is one of the most hazardous natural disasters worldwide. Historically, an increase in the population and property along river lines, with continuous embankments, increases the vulnerability to catastrophic flooding (Itagaki et al., 2021; Nakamura & Oki, 2018). Furthermore, climate change is also expected to exacerbate flood risk; hence, more flood mitigation measures are required. However, it is not practical to rely exclusively on structural measures such as river channel improvements, dam construction, and/or retention ponds (Tollan, 2002). As already suggested by several studies, nonstructural alternatives should be combined for adaptation (Barraque, 2017; Itagaki et al., 2021).

Several studies have assessed the impact of climatic and social changes on flood risk. Global scale studies projected the future changes of extreme river-flow discharge

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and flood-prone populations (Arnell & Gosling, 2016; Hirabayashi et al., 2013). In addition, these studies clarified that the reliability of the obtained results differs regionally, with relative agreement, among multiple global climate models (GCMs). Catchment-scale assessments have been, therefore, presented in individual river basins worldwide using finer GCMs or regional climate models (Tachikawa et al., 2017; Teutschbein et al., 2011). The impact of social change on flood risk has been analyzed from the perspective of urbanization that leads to increased runoff in flash floods (Huong & Pathirana, 2013; Suriya & Mudgal, 2012). Recently, their interaction has garnered increasing attention. Sivapalan et al. (2012) defined sociohydrology as a research field for interactions between humans and water. Since then, an increasing number of sociohydrologic studies have been reported (Aerts et al., 2018; Di Baldassarre et al., 2013; O'Connell & O'Donnell, 2014; Viglione et al., 2014). However, most of these studies are at the stage of proposing conceptual models of human–water interaction and/or macroscale analysis.

The combined effect of climatic and social changes on future flood risk has been quantitatively explored in an increasing number of literatures on urban modeling, primarily in cellular automata (CA) approaches that express the propagation of land use change via the transition rules between a cell and its surrounding cells (Shafizadeh-Moghadam et al., 2017). The CA approach is advantageous because a wide range of variations in land use change can be expressed via model calibration. Lu et al. (2019) adopted a CA model enhanced with Markov chain analysis and fuzzy functions to project future urban growth in New York City under sea level rise and climate change effects. As mentioned in the previous studies, this approach requires careful calibration of model parameters. Furthermore, because CA models do not delineate individual behaviors of each household and/or firm, deriving qualitative interpretations of household behaviors and interactions is difficult.

Alternatively, agent-based models (ABMs) have been adopted to model human behavior in several fields, including evacuation during disasters (Dawson et al., 2011), logistic systems (Khayyat & Awasthi, 2016), and relocation processes in the market (Ettema, 2011). In the context of flood risk management, increasing number of studies are being performed. For example, Jenkins et al. (2017) developed an ABM for the flood insurance market under surface water flood risk in Greater London, UK. Abebe et al. (2019) developed a coupled flood-agent-institution model and assessed the effectiveness of three urban policies: beach policy, building ordinance and flood zone policy. Even more scenarios are analyzed such as post-hazard recovery (Coates et al., 2019) and migration (Hassani-Mahmooei & Parris, 2012; Husby & Koks, 2017). See a comprehensive review of these studies in Zhuo and Han (2020). The ABM approach is advantageous in that the behavior of each agent (person) can be directly described; hence, it facilitates the interpretation of results under different parameter values and/or input data, which helps to elucidate the dynamics of social behavior under different countermeasures. Despite the increasing number of studies in this topic as above, the ABM approaches to assess the combination of long-term flood risk management among flood insurance, river improvements, urban policies and climate change still remains limited and many lack adequate documentation enabling reproduction (Zhuo & Han, 2020), which will be achieved by complete development of both water and human models in intensive interdisciplinary collaborations as to be challenged in this study.

To apply an ABM approach to such an evaluation at the regional scale, the spatial distribution of quantitative flood risk should be provided. A flood risk curve is an effective tool for defining the relationship between the annual economic damage from floods and the exceedance probability. Flood risk curves are derived by integrating the economic damage caused by each level of flood and their probability. The probability of flooding is defined in terms of rainfall or river discharge. The latter directly adopts observed river discharges to derive the probability distribution of flood peak discharge and input to flood inundation models with conventional hydrographs; damage simulations are then used to derive flood risk curves. This approach has been preferentially adopted in previous studies (Apel et al., 2006; Merz & Thieken, 2009) because the former requires an additional step, that is, rainfall–runoff simulations, to convert rainfall to river discharge. As a rainfall-based approach, Tanaka et al. (2016) proposed an analytical flood risk curve (AFRC) and applied to the impact assessment of climate change (Tanaka et al., 2018). The discharge-based approach is sometimes more complicated because it needs to consider two types of uncertainty: hydrograph variability and dependence structure among multiple tributaries. AFRC is a more direct approach because both spatial and temporal variabilities are simplified by employing many (>1000) spatiotemporal distributions of historical rainfall events. In addition, for climate change impact assessments, even the discharge-based approach cannot fully rely on GCM outputs but still requires additional simulations depending on GCM outputs (rainfall-runoff models for rainfall data or river flow routing models for runoff). From this background, Tanaka et al. (2019) derived FRCs at each cell (90 m) (hereinafter, on-site analytical flood risk curve [OSFRC]) using AFRC in/around Kyoto City.

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By developing an ABM for household locational choices, this study aims to evaluate the temporal changes in flood risk (flood risk paths) under river improvements/redevelopment of low-flood risk areas. It adopts Kyoto City in the Yodo River basin (8240 km^2), Japan as a case study. This study first develops the OSFRC under climate change and river improvement scenarios; it then constructs the ABM of household behavior in the housing market. Flood risk reduction under different river improvement/climate change scenarios is analyzed, followed by the analysis of two redevelopment policies that increase amenity in only no-risk areas or no- and low-risk areas. The ABM in this study assumes that households anticipating flood risks purchase full-coverage flood insurance. Accordingly, flood risk is reflected in their choice of location/type/level of housing assets and asset prices in the market. Finally, we evaluate the contribution of an appropriate amenity policy to reducing flood risk in regions where river channel improvements are performed later than others. The novelty of this study is presented as follows: (1) the development of the ABM that simulates individuals on location/type/level of housing assets, dynamics of the housing market, and asset-deepening process in river basins considering flood risk; and (2) its application in evaluating flood risk paths under different types of countermeasures.

2 | STUDY AREA

The study area is a middle stream catchment of the Yodo River basin (8240 km^2), centered around the confluence of the three major tributaries: the Katsura, Kizu, and Uji rivers (Figure 1). This area has a population of around 600,000 including a part of Kyoto City (1.47 million people) which is the second largest city in the whole basin. Through the central district of Kyoto City (the red box), the Kamo River flows and joins the Katsura River. Dike systems are installed in all reaches within the study domain. Recently, a severe typhoon event triggered flooding in 2013, resulting in a dike breach at the confluence of the Katsura and Kamo Rivers and overflow in the upstream Katsura River (10 ha). This study estimates the OSFRC of this area and analyzes the effect of countermeasures by combining the OSFRC with the ABM.

3 | FLOOD RISK MAPPING

3.1 | On-site flood risk curve

The OSFRC is derived as an AFRC at each location (Tanaka et al., 2019). The AFRC disaggregates a rainfall

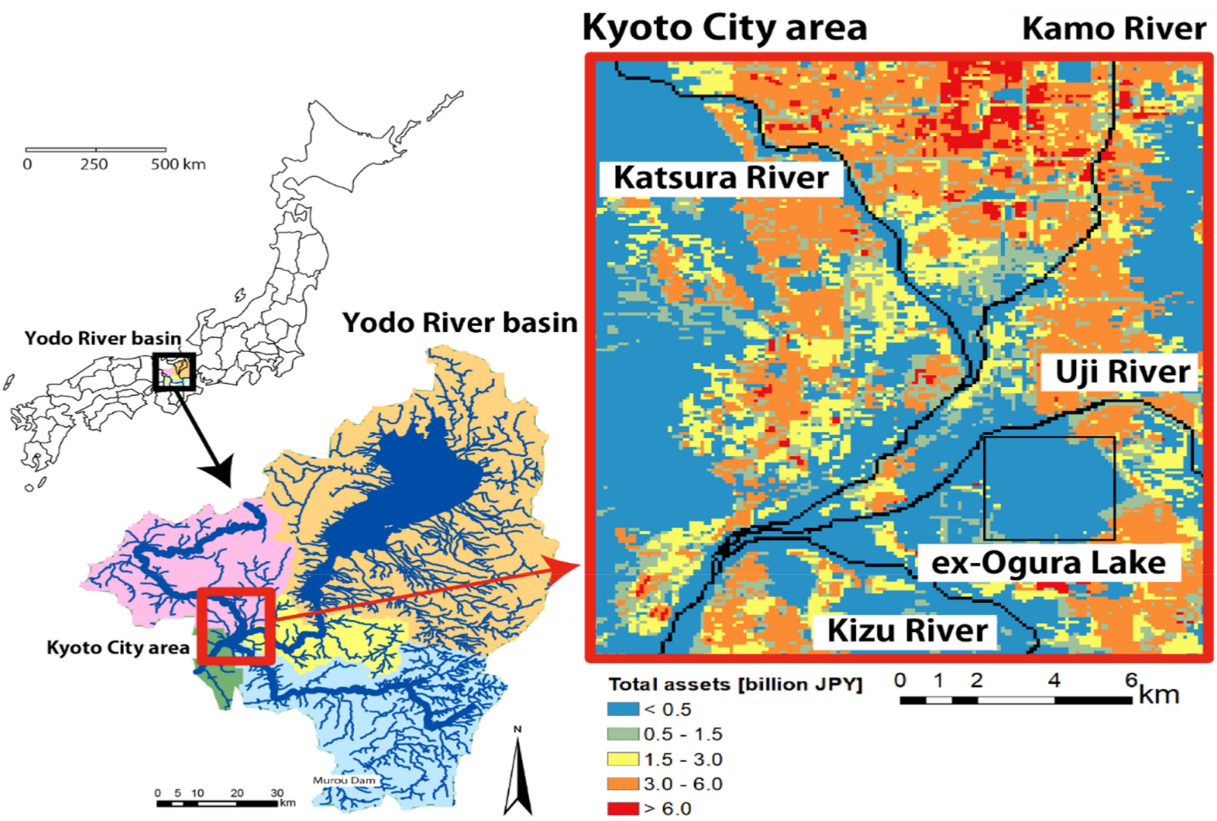

FIGURE 1 Map of the study area

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event into (1) the basin-averaged total rainfall r and (2) its spatiotemporal profile during a storm event $\xi(t,x,y)$ (t and (x,y) represent the time and location, respectively), which is the rainfall intensity normalized by total rainfall r. Evidently, $i(t,x,y) = r\xi(t,x,y)$ is the rainfall intensity at time t and location (x,y).

A spatiotemporal rainfall profile is a multidimensional random variable whose joint probability distribution is difficult to estimate. Therefore, by collecting a large number (>1000) of profiles from historical storm events, the probability of each spatiotemporal rainfall can be empirically modeled as $1/N$ (N is the number of profiles prepared). In this study, 1371 profiles were adopted. The basin-averaged total rainfall r is a single random variable whose probability distribution is estimated as follows.

The independence of total rainfall depth from spatiotemporal profiles (especially rainfall duration and spatial concentration) is an unrealistic assumption. Therefore, the conditional probability distribution of basin-averaged rainfall r on two representative characteristics of rainfall profiles, that is, rainfall duration d and spatial concentration γ, is used, applying a 3D joint probability distribution $G_{RD\Gamma}(r,d,\gamma)$ in a copula approach. Using a copula function C, the joint probability distribution is expressed as

$$G_{RD\Gamma}(r,d,\gamma) = C_{u_r u_d u_\gamma}(u_r, u_d, u_\gamma), \tag{1}$$

where u_r, u_d, and u_γ represent the cumulative probabilities of basin-averaged rainfall, duration, and spatial concentration, respectively. The spatial concentration is defined as

$$\gamma = \max_{1 \le k \le K}\left\{\frac{r_k}{r}\right\}, \tag{2}$$

where r, r_k, and K represent the basin-averaged rainfall of the whole basin, basin-averaged rainfall of the k-th tributary, and number of tributaries considered ($K = 4$ in this study), respectively. γ indicates the relative intensity of the total rainfall on a specific tributary catchment to that of the entire basin. The marginal distribution of basin-averaged rainfall $G_R(r)$ and copula function were estimated by Tanaka et al. (2019) with the generalized Pareto distribution and 3D normal copula, respectively. The marginal distribution of duration and spatial concentration is empirically derived from historical storm events.

To derive the probability of economic flood damage from that of a rainfall event, a rainfall-damage relation (RDR) for all the 1371 spatiotemporal profiles $r_i(m)$ ($i = 1, 2, ..., N$) is required at each grid cell of a flood inundation model (i is the index of profiles and m is the flood damage). Previous studies have demonstrated a single-valued relationship between basin-averaged rainfall and flood damage for a fixed spatiotemporal profile. This study estimates the relationship for each profile using rainfall–runoff, flood inundation, and flood damage simulations with an increment in the basin-averaged total rainfall from 100 to 1000 mm every 50 mm, and 20 storm events were created to develop one RDR for each profile.

The economic flood damage in each event was simulated using rainfall–runoff and flood-inundation models and depth-damage functions. Rainfall–runoff and flood-inundation models were developed by Tanaka et al. (2017). Depth-damage functions (houses, households, office buildings, and stocks targeted in this study) are based on the Flood Economic Survey conducted by the Ministry of Land, Infrastructure, Transportation and Tourism (2005).

Using the obtained relationship for all the $N(=1371)$ spatiotemporal rainfall profiles $r_i(m)$ and the conditional probability distribution of basin-averaged rainfall $G_{R|D\Gamma}(r|d_i,\gamma_i)$, the exceedance probability of rainfall causing damage m is estimated as $\sum_{i=1}^{N}\left(1 - G_{R|D\Gamma}(r_i(m)|d_i,\gamma_i)\right)/N$ per event. Then, given that the number of storm events per year follows the Poisson distribution, the probability distribution of annual economic flood damage m at a specific grid-cell $F_M(m)$ is derived as

$$F_M(m) = \exp\left[-\mu\Delta t\sum_{i=1}^{N}\frac{1}{N}\left(1 - G_{R|D\Gamma}(r_i(m)|d_i,\gamma_i)\right)\right], \tag{3}$$

where μ represents the occurrence ratio of the storm event per unit time and Δt is 1 year. In addition, d_i and γ_i are the duration and spatial concentration of the i-th storm event, respectively. Applying the same equation to all grid cells, the OSFRC is derived. Using the conditional probability distribution $G_{R|D\Gamma}(r|d,\gamma)$, a small occurrence probability is provided for unrealistic combinations of basin-averaged rainfall and a spatiotemporal profile. The expected annual flood damage (EAFD) for each cell obtained from the OSFRC is presented in Figure 2. The EAFD was estimated at a 90 m resolution, similar to in the flood inundation model. A higher EAFD is estimated around the river network, especially around the confluence of the Katsura, Uji, and Kizu rivers and the Katsura and Kamo rivers.

3.2 | Climate change and river improvement scenarios

Future changes in climates and rivers were explicitly considered. Because flood damage is triggered by extreme

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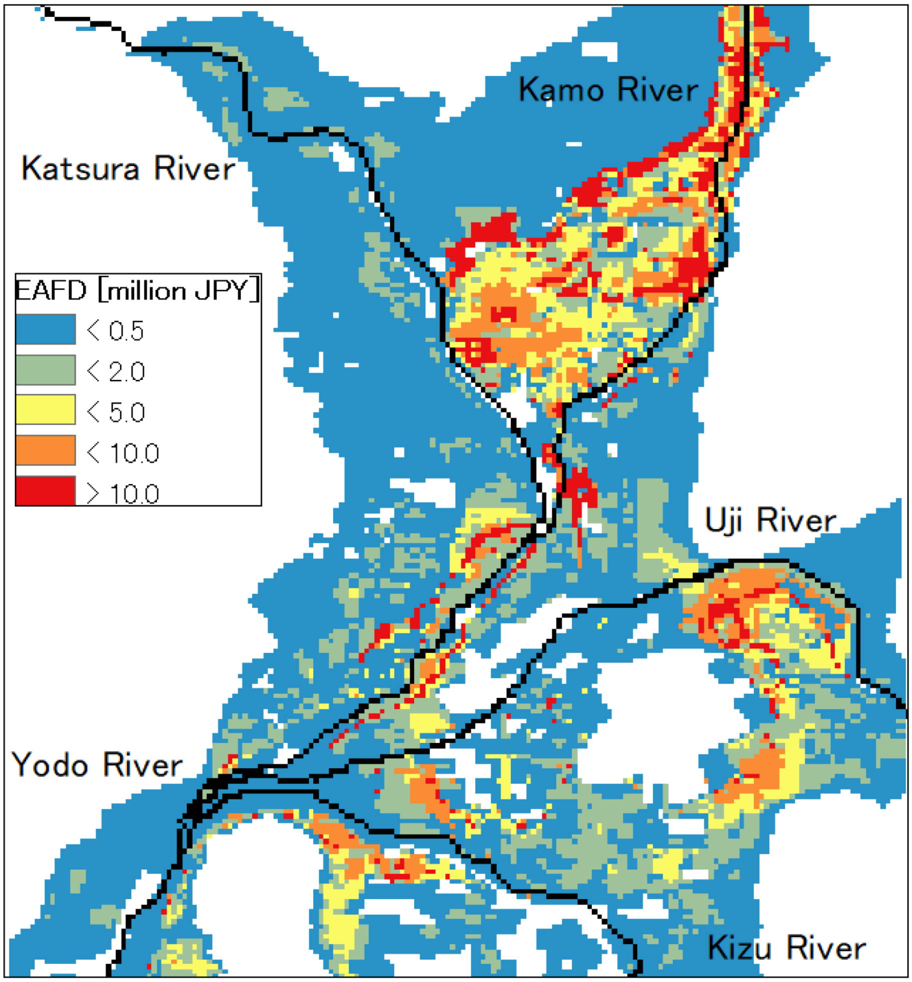
FIGURE 2 Expected annual flood damage obtained from the analytical flood risk map with a 90 m resolution



rainfall at low frequencies, a large ensemble climate simulation dataset is expected to be beneficial. This study adopted the regional experiment of d4PDF (Mizuta et al., 2017), in which a global simulation of 60 km spatial resolution was downscaled to a 20 km resolution using the Non-Hydrostatic Regional Climate Model (NHRCM) (Sasaki et al., 2008). The regional experiment consisted of 2 and 4°C rise experiments, each of which contains 50, 54, and 90 ensembles of 60-year simulations (total data lengths of 3000, 3240, and 5400 years), respectively. These three climates are assumed to represent the first 30, subsequent 30, and final 20 years of the total simulation period of 80 years in the ABM. Analytical flood risk maps for each climate were derived by estimating the conditional probability distribution of rainfall from rainfall data in each experiment. Owing to the coarse spatial resolution (20 km), spatiotemporal rainfall profiles were sampled from historical storm events, as in Tanaka et al. (2018).

Within the study area, the design return period of the Katsura, Uji, and Kizu Rivers managed by the central government is 150 years and that of the Kamo River managed by the Kyoto prefecture is 100 years. Note that the one in the Kamo River is set at 30 years in the present river improvement plan because of the difficulty in expanding the river width owing to high-valued landscape along the river (personal communication with Kyoto City). Presently, only the Uji River has been mostly improved to the design level; thus, the river improvement of the Katsura, Kizu, and Kamo Rivers are considered. River improvement in Japan is, in principle, implemented from downstream to upstream reaches to minimize risk in the downstream areas, which have larger assets than upstream areas. Therefore, the Kamo River, which is located upstream of the Katsura River, is improved with lesser priority than the Katsura River (personal communication with the Yodo River Office). To discuss feasible river improvement policies, this study examined two scenarios in which the Katsura and Kizu Rivers were first improved. The actual river improvement plan gives priority to the Katsura River because of its limited flow capacity, mainly in the downstream reach. For both rivers, embankments were already installed at the design level. River improvements there indicate river

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channel dredging. The river improvement status considered is the present level or design level, and each status is reflected in the river cross-section data in a flood-inundation model developed by Tanaka et al. (2017).

4 | ABM OF LOCATIONAL CHOICES

The ABM in this study simulates the buying and selling of houses by households and developers in the real estate market. Their decision making is modeled as follows.

4.1 | Households

Each household owns its house and lives there for approximately T_0 years on average. This study did not explicitly consider the rental house market. Those who live in a rental house are included in residents with one room in an apartment house, given that the price paid is similar to that of an owned house. In their movement, they choose a new house that maximizes T_0-year total utility. The utility function of a household is defined as

$$U\left(c_{iqj}(t), h_{qjt}, l_{qjt}, a_j(t), \epsilon_i(t)\right) = c(t)_{iqj}^{\alpha_{c,\omega_1}} h_q^{\alpha_{ch\omega_1}} l_q^{\alpha_{l,\omega_1}} a(t)_j^{\alpha_{a,\omega_1}} \left(1+\beta\epsilon(t)_i\right), \tag{4}$$

where t is the period and $c_{iqj}(t)$ is the composite commodity for consumption by a household i living in a house with type q in cell j. House type consists of four categories based on class (standard/high-grade) and style (house/apartment). As previously mentioned, the composite commodity in this study represents all goods except for the house, cost for its maintenance, moving, insurance, and commuting. h_q and l_q represent the area of floor and garden for house type q, $a_j(t)$ is the amenity level at cell j at period t, $\epsilon(t)_i$ is the random term of a household i at period t generated from the uniform distribution, β is its parameter. α_X is the parameter of variable X depending on the family type of household i, $\omega_{1,i}$ (single or family). The composite commodity for consumption c_{iqjt} is defined as

$$c_{iqj}(t) = Y(t) + \delta_M(t)\left\{\Lambda_{\hat{q}\hat{j}}(t) - \Omega_{qj}(t) - \Upsilon\right\} - \left\{\rho_q T_0 + \sum_{t'=t}^{t+T_0} \zeta_{qj}(t')\right\}\Omega_{qj}(t) - \chi d_{\omega_{1,i}} T_0, \tag{5}$$

where $Y(t)$ is the T_0-year total income from period t; $\delta_M(t)$ is the Dirichlet function (1 if moving and else 0); and $\hat{j}$ and $\hat{q}$ are the cell and house types before moving, respectively. $\Lambda_{\hat{q}\hat{j}}(t)$ is the selling price of the owned house, $\Omega_{qj}(t)$ is the buying price of a new house, Υ is the cost for moving, ρ_q is the rate of the annual maintenance cost of house type q, which is substituted by the social discount rate ρ. $\zeta_{qj}(t')$ is the insurance rate of house type q at cell j in period t'.Therefore, $\sum_{t'=t}^{t+T_0} \zeta_{qj}(t')\Omega_{qj}(t)$ indicates the total insurance cost; it is zero for those who do not anticipate the flood risk. χ is the cost of transportation over a unit distance, and $d_{\omega_{1,i}}$ is the commuting distance for family type $\omega_{1,i}$.

The T_0-year total income $Y(t)$ from period t is defined as

$$Y(t) = \sum_{t'=t}^{t+T_0} \left(1+\nu_y\right)\left(1+\beta_y\epsilon_y\right) y_{\omega_{2,i}(t')}, \tag{6}$$

where $y_{\omega_{2,i}(t')}$ represents the income of income class ω_2 (annual salary less than 3 million, between 3 to 10 million, over 10 million in Japanese yen [JPY]); ν_y is the economic growth rate; ϵ_y is the random term following the uniform distribution $[-1{:}1]$, and β_y is its coefficient. The selling price of a house to a developer is expressed as

$$\Lambda_{\hat{q}\hat{j}}(t) = \left(1+\nu_y\right)\Omega_{\hat{q}\hat{j}}(t-1) \tag{7}$$

given that it is determined by the buying price in the previous year multiplied by the economic growth rate.

As in Equations (6) and (7), both income and house prices increase over time owing to economic growth during the simulation period. In Japan, both the economics and population are expected to be nonstationary. In particular, the total population over Japan is expected to decrease in the future (National Institute of Population and Social Security Research, 2012). However, the prediction of its ratio with the cohort component method varies among cities (some are projected to even increase). Because the study period extends over decades, projecting the whole economy in the future is far more challenging owing to unexpected incidents such as the collapse of the bubble economy in 1991 or the Great East Japan Earthquake in 2011. Although it is potentially possible to include such scenarios in the model by, for example, controlling the number of agents and changing economic growth ratio over time, it makes the mechanisms of agents and the market behavior too complex to interpret. In this study, to focus on the primary reactions of residents in a typically growing economy in the model, the total population is considered stationary, and the economy is growing at a constant, typical economic growth rate over time.

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4.2 | Impact of flood risk on location choices

Flood risk is reflected in the insurance payment, given that households with risk perception purchase full cover insurance. The insurance rate $\zeta_{qj}(t')$ is expressed as

$$\zeta_{qj}(t') = \sigma \xi_{qj}(t'), \tag{8}$$

where σ is the markup rate. $\xi_{qj}(t')$ is the expected annual flood damage ratio, defined as

$$\xi_{qj}(t') = \frac{1}{M}\int_{0}^{\infty} m dF_{M,j}(m), \tag{9}$$

where $F_{M,j}(m)$ is the cumulative probability of the annual flood damage in the cell derived from Equation (3) at time t', and M represents the total current assets. As in the above equations, this study assumes that the flood risk at each location is perfectly reflected in the insurance rate with the markup rate. Households with risk perception consider the magnitude of flood risk based on the level of reduced composite commodities (i.e., available money for other consumption such as food, shopping, and savings) due to insurance payment and compare with the floor/garden area and/or the amenity of the region in the utility function. In Japan, the insurance rate is uniform across each prefecture. Recently, severe storm events have resulted in extensive payment in damage insurance. Therefore, the insurance industry has been trying to introduce flood hazard maps issued by the government or municipalities into insurance design (The General Insurance Association of Japan, 2020), justifying the proposed framework.

4.3 | Developers

Developers determine the selling price of their property Ω_{qj} to maximize the expected benefit, which is defined as

$$\Omega_{qj} = \mathrm{argmax} E\left[\Omega_{qj}\right]. \tag{10}$$

The expected benefit of a property with house type q at cell j is expressed as

$$E\left[\Omega_{qj}\right] = P\left(\Omega_{qj}\right)\Omega_{qj} + \left\{1 - P\left(\Omega_{qj}\right)\right\} E\left[(1-\gamma_{\mathrm{d}})\kappa\Omega_{qj}\right], \tag{11}$$

then transformed to

$$E\left[\Omega_{qj}\right] = \frac{P\left(\Omega_{qj}\right)\Omega_{qj}}{1 - \left\{1 - P\left(\Omega_{qj}\right)\right\}(1-\gamma_{\mathrm{d}})\kappa}, \tag{12}$$

where γ_{d} is the social discount rate, κ is the discount factor due to the degradation of a house, and $P\left(\Omega_{qj}\right)$ is the subjective probability a developer with that a house with type q at cell j is sold for price Ω_{qj}. The first term of Equation (11) indicates the income that the developer expects if a property is sold in the current period, whereas the second term corresponds to the one sold after when the house price is declined due to social discount rate and degradation of a house. Based on Ettema (2011), the subjective selling probability $P\left(\Omega_{qj}\right)$ is defined as

$$P\left(\Omega_{qj}\right) = \frac{1}{1 + \exp\left\{\lambda_1 + \lambda_2\left(\frac{1}{1 - s_{qj}(t-1)}\right)\Omega_{qj} - \lambda_3(1+\nu_y) H\left[\Omega_{qj}(t-1)\right]\right\}}, \tag{13}$$

$$H\left[\Omega_{qj}(t-1)\right] = \left\{\left(1 - \phi_{qj}\right) + \phi_{qj}\kappa(1-\rho)\right\}\Omega_{qj}(t-1), \tag{14}$$

where $s_{qj}(t-1)$ is the ratio of the number of sold properties with house type q at cell j in the previous period to that of total properties on the market. As all the parameters λ_1, λ_2 and λ_3 are positive, this indicates that the probability increases if more houses are sold in the previous period. $H\left[\Omega_{qj}(t-1)\right]$ is the weighted average of the house price in the previous period with the ratio of vacant dwelling ϕ_{qj}. This indicates that when ϕ_{qj} is higher, the weighted average house price $H\left[\Omega_{qj}(t-1)\right]$ increases; consequently, the subjective selling probability $P\left(\Omega_{qj}\right)$ decreases. The house price was determined to satisfy Equation (10). Developers can rebuild houses to maximize their expected benefits.

4.4 | Calculation procedures

The above ABM is implemented in the following steps:

1. Update the income of an agent (household) $y_{\omega_2,i}$ and the selling price of a house Λ_{qj} based on the economic growth rate using Equations (6) and (7), respectively.
2. Update the house price using Equations (10) and (12) to (14). These equations comprise a nonlinear system of equations that require iterations. This study employed the Newton method to derive Ω_{qj}, such that the 1st derivative of $E\left[\Omega_{qj}\right]$ is zero.

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3. Rebuild houses if necessary. Because it is unrealistic to rebuild all the vacant properties, some of them are rebuilt at a fixed ratio ν_r.
4. Given that all the $N_a (= 636,265)$ agents consider movement within T_0 periods, randomly select N_a/T_0 agents that consider moving. They compare the utility of the current house with N_b house candidates randomly selected; if that of a new house is higher, they move.
5. Update the period from t to $t+1$ and repeat procedures (1) to (4).

In this study, each period corresponded to 1 year. In each year, the sum of EAFD at all cells over the target area was calculated as follows:

$$M_a(t) = \sum_j \sum_q N_{qj}(t)\Omega_{qj}(t)\xi(t), \tag{15}$$

where $N_{qj}(t)$ is the total number of agents living in a q-type house at cell j and year t. Because of the randomness in selecting agents for moving, the candidates of their new house, and the random terms of salary and the utility function, the simulation results change in each trial; hence, the following results are the average of 100 trials.

4.5 | Parameter and input data

The number of total households and their ratios for each type of family/salary class/CBD (center of business district) are available from the census at 500 m resolution to which the cell size of the ABM was set. The initial house price of four house types (standard/high-grade and house/apartment) was calculated by multiplying the public land price by the land area. The ratio of households who anticipate flood risk (and in this study, buy flood insurance) is set to 33%, considering the insurance participation rate for flood disasters of 31.1% (Cabinet Office, 2017). Other social and economic parameters are summarized in Table 1. In accordance with the

TABLE 1 Model parameters of an agent-based model

Parameter	Notation	Value
Simulation conditions		
Simulation period (year)		80
Recursive period (year)	T_0	20
Number of new house candidates	b	50
Economic parameter		
Economic growth rate	ν_y	0.01^{*1}
Moving cost (hundred thousand yen)	Υ	2^{*2}
Commuting cost (yen/km)	χ	140^{*3}
Markup rate	$\sigma(\geq 1)$	2.0^{*4}
Social discount rate (used for the rate of maintenance cost to house price)	ρ	0.04^{*5}

		House property			
House type	q	Standard house	High-grade house	Standard apartment	High-grade apartment
Garden area $(m^2)^{*6}$	l_{qjt}	55	110	1	1
Floor area $(m^2)^{*6}$	h_{qjt}	90	180	50	100
Discount factor due to degradation	$\kappa(\leq 1)$	0.9			
Reconstruction ratio	ν_r	0.03^{*7}			

Source: (*1) GDP growth rate in Japan (World Bank, https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=JP). (*2) Typical prices for family (four persons) to move between cities in the same prefecture (https://hikkoshizamurai.jp/price/family-cost-rate/, in Japanese). (*3) Calculation with typical hourly wage, commuting time and distance in Kyoto. (*4) Kobayashi and Wakukawa (2005). (*5) MLIT (2018) (https://www.mlit.go.jp/road/ir/hyouka/plcy/kijun/ben-eki_h30_2.pdf, in Japanese). (*6) Statistics Bureau of Japan (https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00600120&tstat=000001016965&cycle=7&year=20180&month=0&result_back=1&tclass1val=0., in Japanese). (*7) Inverse of a service life of a typical Japanese houses (around 30 years).

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resolution of the ABM, the original EAFD estimated at approximately 90 m (Figure 2) was aggregated. Based on the EAFD, annual insurance costs for each house type on each cell widely range from hundreds to more than 10,000 JPY for a standard house. Its median is around 6900 JPY, in line with a reported range of 3000 to 9000 JPY among major companies (Suigaiji no hinan okyu taisaku kento wakingu gurupu, 2015). The parameters of the utility function of households and the subjective probability of developers should be calibrated to represent the historical tendencies of house locations. In this study, to investigate the resident reactions in a typical house market, they are set by trial and error, such that the simulated market (house price) grows at a consistent speed with the preset economic growth rate ν_y (see Section 5.2).

5 | EVALUATION OF FLOOD RISK MANAGEMENT MEASURES

5.1 | River improvement

The river improvement and climate change scenarios are summarized in Table 2. The time series of the EAFD in each scenario, calculated from Equation (14) are presented in Figure 3. To determine the impact of the combined effect of climate change and river improvements and, especially, to explore how much the changed flood risk would differ from the present situation, the baseline scenario did not include both scenarios. The baseline (green line) depicts the increasing trend of EAFD owing to the economic growth rate allocated to the house price and salary. Compared to the baseline, flood risk clearly decreases with river improvement, even when considering climate change (the scenarios KatsuraCC and KizuCC). Between the river improvement scenarios, the scenario improving the Kizu River first between 21 and 40 years presents a larger reduction in EAFD than improving the Katsura River first. The reduction in EAFD in each cell by the improvement of the Katsura and Kizu rivers is shown in Figure 4. Improvement of the Kizu River exhibits a reduction of EAFD in a wider area (blue cells) because of the larger floodplain area, especially around the reclaimed land—ex-Ogura Lake (see the black box in Figure 1). This indicates that, until all the improvements are completed, the pathway of the improvements influences the temporal change of flood risk owing to the larger impact of inundation from the Kizu River than from the Katsura River, although both are designed for the same return period of 150 years.

Comparing the results with and without climate change (solid and dashed lines, respectively), the results with climate change (solid line) exhibit significantly higher EAFD for the scenario improving the Kizu River (blue lines) between 30 and 60 years because large floodplain areas protected by improved river sections are affected by the climate change—2°C rise—which returns EAFD to a level similar to that before the improvement. On the other hand, after improving the Kamo River, EAFD reduced to a level similar to that without climate change, thus indicating that improving the Kamo River, which flows through the central area of Kyoto City, has a

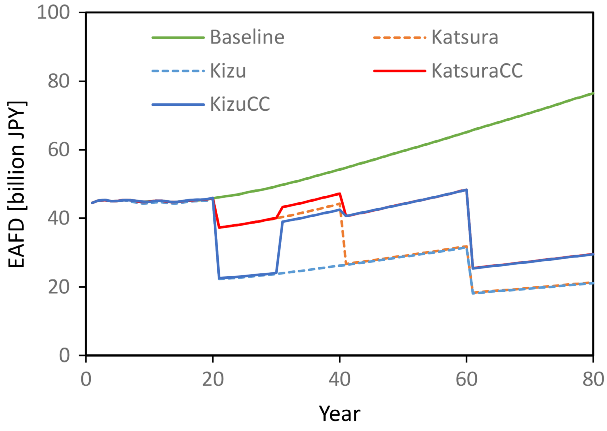

FIGURE 3 Expected annual flood damage among the baseline (green line), and two river improvements (the Katsura/Kizu River is improved earlier depicted as the red/blue line) with/without climate change (solid/dashed line). See Table 2 for the notation of each scenario

TABLE 2 River improvement/climate change scenarios (the river stated is being improved at its design level)

<table>
<tr><th></th><th colspan="5">River improvement</th></tr>
<tr><th></th><th>1–20 years</th><th colspan="2">21–40 years</th><th>41–60 years</th><th>61–80 years</th></tr>
<tr><td>Katsura</td><td>Katsura River</td><td colspan="2">Kizu River</td><td>Kamo River</td><td>Completed</td></tr>
<tr><td>Kizu</td><td>Kizu River</td><td colspan="2">Katsura River</td><td>Kamo River</td><td>Completed</td></tr>
<tr><th></th><th colspan="5">Climate change</th></tr>
<tr><th></th><th></th><th>21–30 years</th><th>31–40 years</th><th></th><th></th></tr>
<tr><td>CC</td><td>Present</td><td>Present</td><td>+2°C</td><td>+2°C</td><td>+4°C</td></tr>
</table>

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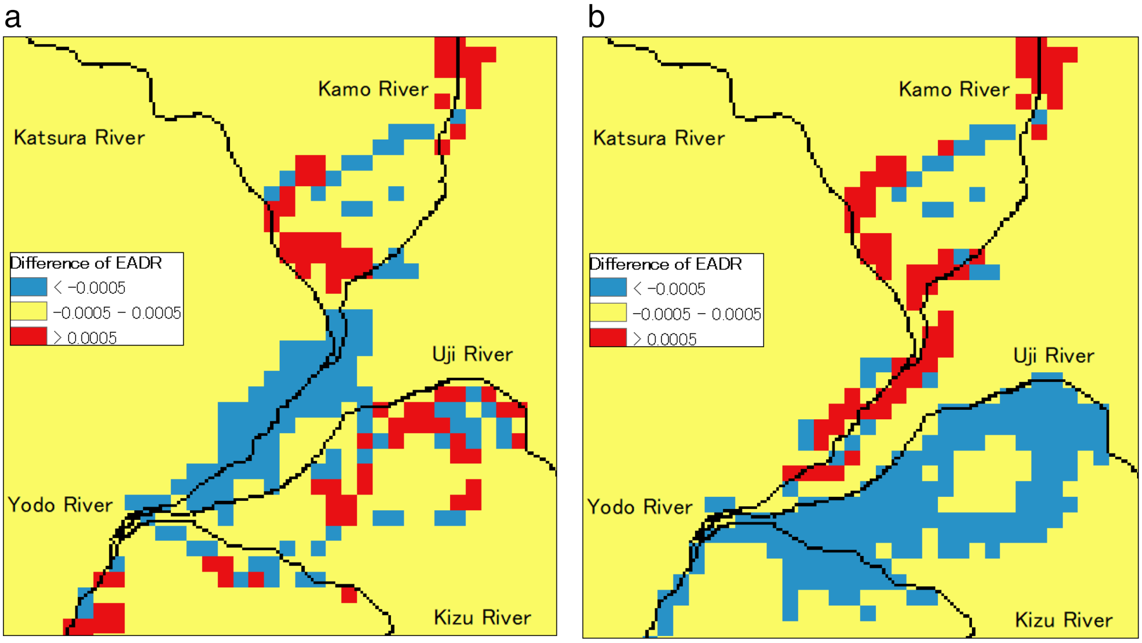
a
Kamo River
Katsura River
Difference of EADR
< -0.0005
-0.0005 – 0.0005
> 0.0005
Uji River
Yodo River
Kizu River
b
Kamo River
Katsura River
Difference of EADR
< -0.0005
-0.0005 – 0.0005
> 0.0005
Uji River
Yodo River
Kizu River

FIGURE 4 Difference in expected annual damage ratio (EADR) between after and before improving (a) the Katsura River (b) the Kizu River

significant impact on flood risk reduction, even though the 4°C rise scenario is set after 60 years.

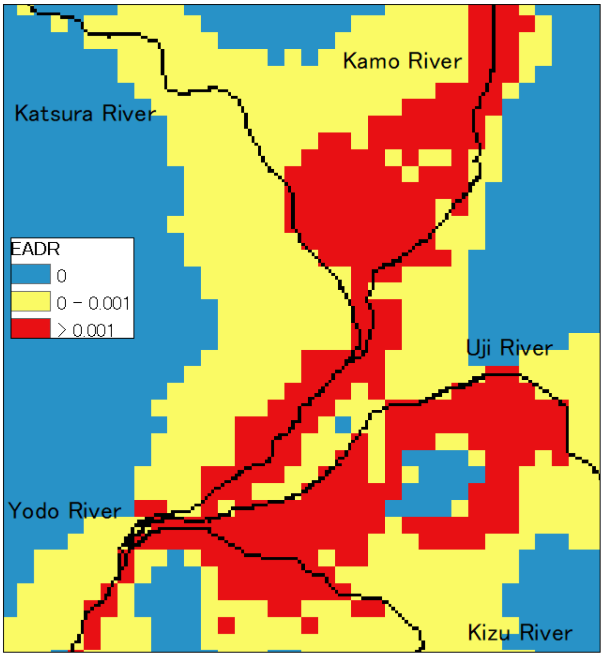
Kamo River
Katsura River
EADR
0
0 – 0.001
> 0.001
Uji River
Yodo River
Kizu River

FIGURE 5 Expected annual damage ratio (EADR) of the study area at the present condition. The cells with EADR of zero (blue), less than 0.001 (yellow), and more than 0.001 (red) are classified into no-, low-, and high-risk area, respectively

5.2 | Amenity policy

To adapt the decreasing population and the associated decline in transportation efficiency, the Japanese government ordered a location optimization plan for each municipality taking natural disaster (floods and landslides) risks into consideration, in which long-term redevelopment will be scheduled if necessary (Ministry of Land, Infrastructure, Transportation and Tourism, 2008). In this context, we apply ABM to analyze the effect of amenity policies on flood risk reduction. Amenity policies represent urban development, such as railway station redevelopment (Majoor & Schuiling, 2008) and urban park spaces (Bogle & Burnstein, 2016). Instead of actual plans, we examine the contrasting imaginary policies to conduct a trend analysis, in which the amenity of specified cells is increased by a redevelopment project. Given the fixed amount of total amenity owing to the budget limit, the two policy scenarios for allocating the amenity increase, depending on the level of annual expected damage ratio (EADR) at 500 m resolution (see Figure 5), are investigated. The baseline scenario provides a spatially uniform amenity for assessing the residents' response to the different weighting of amenity (the degree of urban development), indicating no significant difference in amenities among areas at different risk levels. The first policy (P1) distributes 22.4% of the total amenity to high-risk areas (EADR larger than 0.1% shown in red) and the remaining 77.6% to the low-risk (EADR smaller than 0.1%) and no-risk (EADR of zero) areas (the yellow and blue areas, respectively). In this scenario, the amenity assigned to a single cell is only 10% compared to the baseline in the high-risk area, whereas that in the rest is 126%. The second (P2) distributes 64% of the total amenity to the high- and low-risk areas and the remaining 36% to the no-risk area uniformly. This scenario increases the cell amenity to 263% in the no-risk area and reduces one in the high-risk area to 10% compared to the uniform cell amenity (the baseline). P1 is intended to influence the residents away from the high-risk area to the low-risk area as well as the no-risk area, whereas P2 induces people to the no-risk area more intensively.

The time series of EAFD in each scenario under the river channel improvement/climate change scenario of KizuCC is shown in Figure 6. Interestingly, P1, which allocates the same level of amenity to both the low- and no-risk areas, shows less damage than P2, with higher amenity in the no-risk area. This also applies to other river channel improvement/climate change scenarios. The average price of standard houses over the target area is shown in Figure 7. The house price in the baseline increased 2.84 times over 80 years (annual growth rate of 1.31%), showing consistency between the house market and the preset average annual growth rate of 1% in resident income. Among the three cases, P2 had the highest price. As shown in Figure 5, the no-risk area is limited; thus, house prices soared based on market principles. Therefore, it is recommended that rather than intensive induction to the limited no-risk areas, more relaxed development, including in both low- and no-risk areas, will lead to a more effective reduction in flood risk. The spatial distribution of the number of families in the first, 10th, 40th, and last year for each amenity policy is shown in Figure 8. P1 resulted in more people moving to low-risk areas (black boxes in Figure 8 for example) than P2 because more amenity is supplied to the low-risk area in P1 than in P2. On the other hand, there are no obvious differences in the number of families in the no-risk area between the policies, despite more amenity quantity being supplied there in P2. This is the consequence of the abovementioned higher house prices in P2. The presented ABM in this study is advantageous because it deals with house prices on each mesh/in each year/for each house type based on the market principle and the resulting locational choices of each household, in which the spatiotemporal distribution of flood risk based on OSFRC was explicitly reflected. As a result, the case study presented a nonmonotonic result, that is, P2 avoiding flood risk intensively (supplying the highest amenity level to the no-risk area) but P1 moderately avoiding the flood risk, resulting in the smallest EAFD.

Finally, the effects of river improvement and amenity policies were compared. The results of the river improvement scenario clarified that the pathway of improvement affects the reduction of flood risk during the improvement. From the viewpoint of the flood risk equity over the target area, we examined the difference in EAFD between the two contrasting river improvement scenarios: 1) the Katsura River first or 2) Kizu River first, with/without the policy P1 in Figure 9. From 21 to 30 years, improving the Kasura River first has a higher EAFD—by 15 billion JPY than the Kizu River—while it decreased to 10 billion JPY by introducing policy P2. This is because 33% of the total residents who anticipate flood risk through hazard maps avoid from dwelling near unimproved rivers where flood insurance is more expensive. River improvement plans are not designed based only on expected economic flood risk because they require

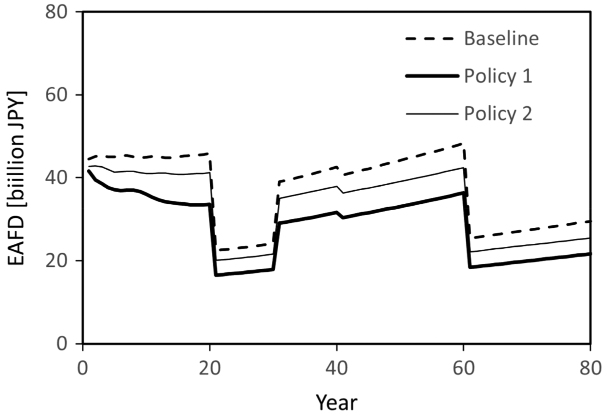

FIGURE 6 Expected annual flood damage (EAFD) of the baseline (dashed line), policies 1 (thick line) and 2 (thin line). River improvement and climate change scenarios of KizuCC is applied

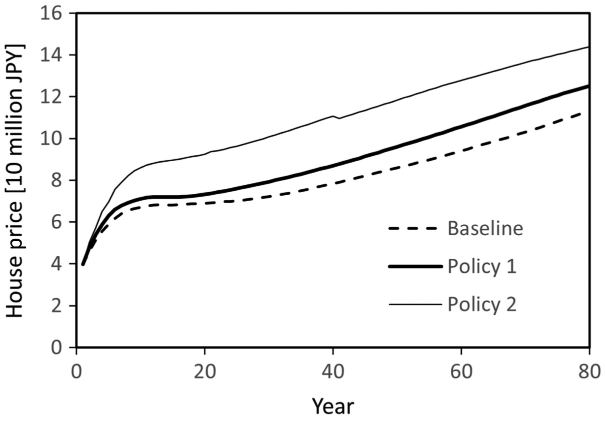

FIGURE 7 Area-averaged price of standard house of the baseline (dashed line), policies 1 (thick line) and 2 (thin line)

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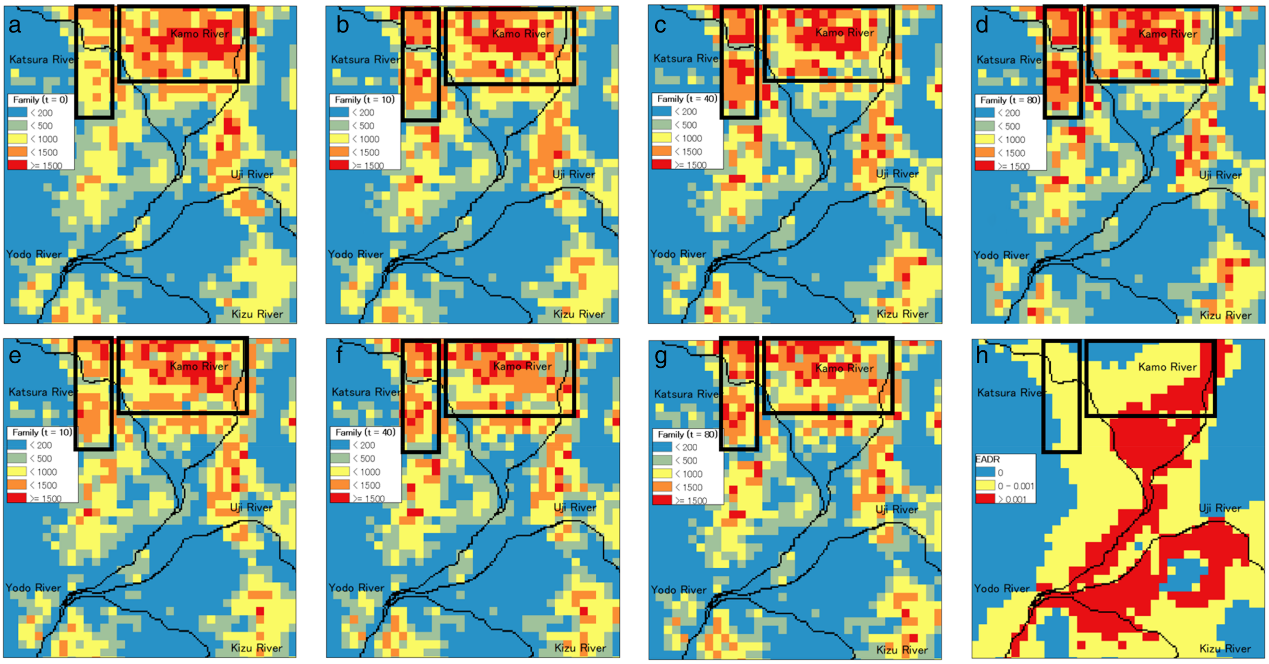

FIGURE 8 Spatial distribution of the number of families (a) in the first year, (b–d) for the amenity policy P1 in the 10th, 40th, and the last year, respectively; (e–g) for the amenity policy P2 in the 10th, 40th, and last year, respectively, and (h) expected annual damage ratio (blue: Zero (no-risk area), yellow: Less than 0.001 (low-risk area), red: More than 0.001 (high risk area), same as Figure 5). P1 led more people to the low-risk area (black boxes for example) than P2

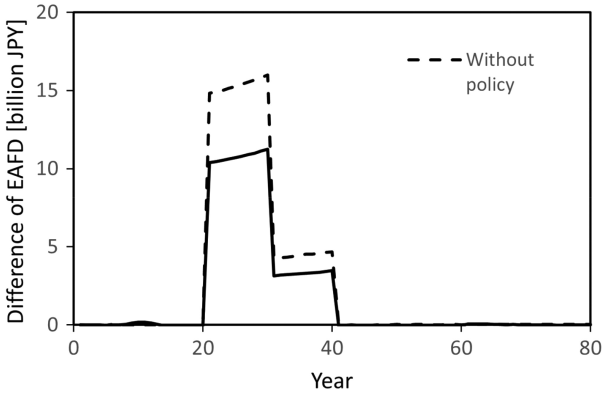

FIGURE 9 Difference in the expected annual flood damage (EAFD) between the river improvement/climate change scenarios KatsuraCC and KizuCC with (solid line)/without (dashed line) policy 1. Without policy 1 (dashed line), the scenario improving the Katsura River (completed in 2040) before the Kizu River (completed in 2060) resulted in an increased EAFD, approximately 15 billion JPY, from 2040 to 2060, whereas the increment was 10 billion JPY with policy 1 (solid line) owing to assets away from high-risk areas

various coordination in urban areas, such as the amendment of train timetables due to bridge replacement. This scenario analysis implies that appropriate urban planning may compensates the inequality of flood risk among regions during river improvements.

6 | DISCUSSIONS AND CONCLUDING REMARKS

This study constructed an ABM for housing choices considering flood risk by combining OSFRCs. This framework enabled us to express the long-term process of spatial distributions of multiple types of household dwellings at flood risk, thereby quantitatively evaluating the impact of climate change, river improvement and amenity policy scenarios. Furthermore, the constructed model was implemented in the middle stream area of the Yodo River basin, Japan, using social statistics and climate change data and actual river improvement plans, through which the following findings were obtained for the study area:

1. The combined effect of climate change and river improvements exhibited reduced flood risk, indicating the high effectiveness of the pre-designed river improvements even under a changing climate.
2. Intensive development of no-risk areas would increase house prices there; accordingly, amenity policy moderately avoiding only high-risk areas would result in more effective flood risk reduction.
3. Amenity policy combined with river improvements further reduces flood risk during the river improvements.

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This study proposed a catchment-scale agent-based model dealing with more local residential behavior under changing flood risk, river improvement and urban structures. This model is potentially applicable to policy decision making.

The ABM developed in this study relies on a few major assumptions for its simplification: stationarity in population and social affairs (no accidental incidents during the target period), no migration of people to/from or economic interaction with the outside of the study area. They were set to focus on the primary reactions of residents to different climatic and social conditions in this first developed framework. Therefore, the entire analysis and discussions focused on the differences among the scenarios, rather than the absolute values. In reality, at the national level, the entire market would be expected to gradually shrink with the decreasing population in Japan (Yamauchi et al., 2017), while there are predictions that some urban areas may escape from severe depopulation owing to in-migration. The target area of this study includes a part of Osaka and Kyoto where population inflows may be expected (Chujo et al., 2021). It is inferred that these predictions will exhibit increasing percentage of errors over time (Yamauchi et al., 2017). Considering such uncertainty in both directions, we incorporated the random factor into the utility function of households that also reflects changes in family size. From the ABM behavior revealed in this study, future research will address the following challenges: (1) more detailed validation of the constructed framework for the historical change in the spatial distribution of houses and dwelling types, (2) impacts of flood occurrence on households without insurance coverage that could result in a downgrade of a housing type, for example, (3) consideration of a population decline, and (4) connection of amenity analysis with actual development plans.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

Abebe, Y. A., Ghorbani, A., Nikolic, I., Vojinovic, Z., & Sanchez, A. (2019). A coupled flood-agent-institution modelling (CLAIM) framework for urban flood risk management. *Environmental Modelling and Software*, *111*, 483–492. https://doi.org/10.1016/j.envsoft.2018.10.015

Aerts, J. C. J. H., Botzen, W. J., Clarke, K. C., Cutter, S. L., Hall, J. W., Merz, B., Michel-Kerjan, E., Mysiak, J., Surminski, S., & Kunreuther, H. (2018). Integrating human behaviour dynamics into flood disaster risk assessment. *Nature Climate Change*, *8*(3), 193–199. https://doi.org/10.1038/s41558-018-0085-1

Apel, H., Thieken, A. H., Merz, B., & Bloschl, G. (2006). A probabilistic modelling system for assessing flood risks. *Natural Hazards*, *38*(1–2), 79–100. https://doi.org/10.1007/s11069-005-8603-7

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, *134*(3), 387–401. https://doi.org/10.1007/s10584-014-1084-5

Barraque, B. (2017). The common property issue in flood control through land use in France. *Journal of Flood Risk Management*, *10*(2), 182–194. https://doi.org/10.1111/jfr3.12092

Bogle, M. D. S., & Burnstein, E. (2016). *Equitable development planning and urban park space early insights from DC's 11th street Bridge Park project* (Research Report). Urban Institute.

Cabinet Office. (2017). *Sankoshiryo hoken kyosai niyoru saigai eno sonae no sokushin ni kansuru kentokai hokoku (Reference Materials, Study group on promotion of disaster preparedness through insurance and mutual aid).*

Chujo, T. M. Y., Takashi, O., & Shimizu, M. (2021). Chiikiburokkunai Oyobi Sandaitoshiken Tono Jinkoido – Todofukenbetsu, Nenrei 5 Sai Kaikyubetsu Tennyuritsu, Tenshutsuritsu, Tennyuchokaritsu (2018～2019)—(Population dynamics among regional units and three mega cities—Prefectural move-in and -out ratio and move-in excess ratio at every 5-year-old class [2018–2019]). *Journal of Population Problems*, *77*(1), 68–75.

Coates, G., Li, C. H., Ahilan, S., Wright, N., & Alharbi, M. (2019). Agent-based modeling and simulation to assess flood preparedness and recovery of manufacturing small and medium-sized enterprises. *Engineering Applications of Artificial Intelligence*, *78*, 195–217. https://doi.org/10.1016/j.engappai.2018.11.010

Dawson, R. J., Peppe, R., & Wang, M. (2011). An agent-based model for risk-based flood incident management. *Natural Hazards*, *59*(1), 167–189. https://doi.org/10.1007/s11069-011-9745-4

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L., & Bloschl, G. (2013). Socio-hydrology: Conceptualising human–flood interactions. *Hydrology and Earth System Sciences*, *17*(8), 3295–3303. https://doi.org/10.5194/hess-17-3295-2013

Ettema, D. (2011). A multi-agent model of urban processes: Modelling relocation processes and price setting in housing markets. *Computers, Environment and Urban Systems*, *35*(1), 1–11. https://doi.org/10.1016/j.compenvurbsys.2010.06.005

Hassani-Mahmooei, B., & Parris, B. W. (2012). Climate change and internal migration patterns in Bangladesh: An agent-based model. *Environment and Development Economics*, *17*, 763–780. https://doi.org/10.1017/S1355770x12000290

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*(9), 816–821. https://doi.org/10.1038/Nclimate1911

Huong, H. T. L., & Pathirana, A. (2013). Urbanization and climate change impacts on future urban flooding in Can Tho city, Vietnam. *Hydrology and Earth System Sciences*, *17*(1), 379–394. https://doi.org/10.5194/hess-17-379-2013

Husby, T. G., & Koks, E. E. (2017). Household migration in disaster impact analysis: Incorporating behavioural responses to risk. *Natural Hazards*, *87*(1), 287–305. https://doi.org/10.1007/s11069-017-2763-0

Itagaki, O., Bermudez, D. B. S., Zemmoto, T., & Ohara, M. (2021). Proposal of a method for assessing combined flood risk reduction effect by hazard control measures and exposure reduction measures based on limited data. *Journal of Flood Risk Management*, *14*(3), e12714. https://doi.org/10.1111/jfr3.12714

Jenkins, K., Surminski, S., Hall, J., & Crick, F. (2017). Assessing surface water flood risk and management strategies under future climate change: Insights from an agent-based model. *Science of the Total Environment*, *595*, 159–168. https://doi.org/10.1016/j.scitotenv.2017.03.242

Khayyat, M., & Awasthi, A. (2016). An intelligent multi-agent based model for collaborative logistics systems. *Transportation Research Procedia*, *12*, 325–338. https://doi.org/10.1016/j.trpro.2016.02.069

Lu, Q., Joyce, J., Imen, S., & Chang, N. B. (2019). Linking socioeconomic development, sea level rise, and climate change impacts on urban growth in New York City with a fuzzy cellular automata-based Markov chain model. *Environment and Planning B: Urban Analytics and City Science*, *46*(3), 551–572. https://doi.org/10.1177/2399808317720797

Majoor, S., & Schuiling, D. (2008). New key projects for station redevelopment in the Netherlands. In B. Bfperpphvw (Ed.), *Railway development* (pp. ix, 419). Physica-Verlag. https://doi.org/10.1007/978-3-7908-1972-4_6

Merz, B., & Thieken, A. H. (2009). Flood risk curves and uncertainty bounds. *Natural Hazards*, *51*(3), 437–458. https://doi.org/10.1007/s11069-009-9452-6

Ministry of Land, Infrastructure, Transportation and Tourism. (2005). *Chisui Keizai Chosa Manyuaru (Flood Economic Survey Manual)*.

Ministry of Land, Infrastructure, Transportation and Tourism (2008). Promotion of Urban Renovation and Compact Cities. https://www.mlit.go.jp/common/000996976.pdf

Mizuta, R., Murata, A., Ishii, M., Shiogama, H., Hibino, K., Mori, N., Arakawa, O., Imada, Y., Yoshida, K., Aoyagi, T., Kawase, H., Mori, M., Okada, Y., Shimura, T., Nagatomo, T., Ikeda, M., Endo, H., Nosaka, M., Arai, M., … Kimoto, M. (2017). Over 5,000 years of ensemble future climate simulations by 60-km global and 20-km regional atmospheric models. *Bulletin of the American Meteorological Society*, *98*(7), 1383–1398. https://doi.org/10.1175/Bams-D-16-0099.1

Nakamura, S., & Oki, T. (2018). Paradigm shifts on flood risk Management in Japan: Detecting triggers of design flood revisions in the modern era. *Water Resources Research*, *54*(8), 5504–5515. https://doi.org/10.1029/2017wr022509

National Institute of Population and Social Security Research. (2012). *Population Projections for Japan (January 2012): 2011 to 2060 Appendix: Auxiliary Projections 2061 to 2110*. http://www.ipss.go.jp/site-ad/index_english/esuikei/gh2401e.asp

O'Connell, P. E., & O'Donnell, G. (2014). Towards modelling flood protection investment as a coupled human and natural system. *Hydrology and Earth System Sciences*, *18*(1), 155–171. https://doi.org/10.5194/hess-18-155-2014

Sasaki, H., Kurihara, K., Takayabu, I., & Uchiyama, T. (2008). Preliminary experiments of reproducing the present climate using the non-hydrostatic regional climate model. *Solaiat*, *4*, 25–28. https://doi.org/10.2151/sola.2008-007

Shafizadeh-Moghadam, H., Asghari, A., Tayyebi, A., & Taleai, M. (2017). Coupling machine learning, tree-based and statistical models with cellular automata to simulate urban growth. *Computers, Environment and Urban Systems*, *64*, 297–308. https://doi.org/10.1016/j.compenvurbsys.2017.04.002

Sivapalan, M., Savenije, H. H. G., & Bloschl, G. (2012). Socio-hydrology: A new science of people and water. *Hydrological Processes*, *26*(8), 1270–1276. https://doi.org/10.1002/hyp.8426

Suigaiji no hinan okyu taisaku kento wakingu gurupu. (2015). *Suigaihoken ni tsuite (On water disaster insurance)*.

Suriya, S., & Mudgal, B. V. (2012). Impact of urbanization on flooding: The Thirusoolam sub watershed—A case study. *Journal of Hydrology*, *412*, 210–219. https://doi.org/10.1016/j.jhydrol.2011.05.008

Tachikawa, Y. M., Tanaka, T., Yorozu, K., Kato, M., Ichikawa, Y., & Kim, S. (2017). Future change analysis of extreme floods using large ensemble climate simulation data. *Journal of Japan Society of Civil Engineers, Series B1 (Hydraulic Engineering)*, *73*(3), 77–90. https://doi.org/10.2208/jscejhe.73.77

Tanaka, T., Ichikawa, Y., Yokomatsu, M., & Tachikawa, Y. (2019). Improvement of flood risk curve development by considering dependence of basin total rainfall on its spatial concentration. *Journal of Japan Society of Civil Engineers, Series B1 (Hydraulic Engineering)*, *75*(1), 112–121, 121. doi:10.2208/jscejhe.75.112

Tanaka, T., Tachikawa, Y., Ichikawa, Y., & Yorozu, K. (2016). A flood risk curve development using conditional probability distribution of rainfall on duration. *Journal of Japan Society of Civil Engineers, Series B1 (Hydraulic Engineering)*, *72*(4), I_1219–I_1224. doi:10.2208/jscejhe.72.I_1219

Tanaka, T., Tachikawa, Y., Ichikawa, Y., & Yorozu, K. (2017). Impact assessment of upstream flooding on extreme flood frequency analysis by incorporating a flood-inundation model for flood risk assessment. *Journal of Hydrology*, *554*, 370–382. https://doi.org/10.1016/j.jhydrol.2017.09.012

Tanaka, T., Tachikawa, Y., Ichikawa, Y., & Yorozu, K. (2018). Flood risk curve development with probabilistic rainfall modelling and large ensemble climate simulation data: A case study for the Yodo River basin. *Hydrological Research Letters*, *12*(4), 28–33. https://doi.org/10.3178/hrl.12.28

Teutschbein, C., Wetterhall, F., & Seibert, J. (2011). Evaluation of different downscaling techniques for hydrological climate-change impact studies at the catchment scale. *Climate Dynamics*, *37*(9–10), 2087–2105. https://doi.org/10.1007/s00382-010-0979-8

The General Insurance Association of Japan. (2020). *Mizusaigai Risuku Ni Taisuru Songaihoken Ni Tsuite (On damage insurance against water disaster risk)*.

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Tollan, A. (2002). Land-use change and floods: What do we need most, research or management? *Water Science and Technology*, *45*(8), 183–190. https://doi.org/10.2166/wst.2002.0176

Viglione, A., Di Baldassarre, G., Brandimarte, L., Kuil, L., Carr, G., Salinas, J. L., Scolobig, A., & Bloschl, G. (2014). Insights from socio-hydrology modelling on dealing with flood risk—Roles of collective memory, risk-taking attitude and trust. *Journal of Hydrology*, *518*, 71–82. https://doi.org/10.1016/j.jhydrol.2014.01.018

Yamauchi, M., Koike, S., & Kamata, K. (2017). How accurate are Japan's official subnational projections? Comparative analysis of projections in Japan, English-speaking countries and the EU. In D. A. Swanson (Ed.), *The frontiers of applied demography* (pp. 305–328). Springer. https://doi.org/10.1007/978-3-319-43329-5_15

Zhuo, L., & Han, D. W. (2020). Agent-based modelling and flood risk management: A compendious literature review. *Journal of Hydrology*, *591*, 125600. https://doi.org/10.1016/j.jhydrol.2020.125600

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