Water Resources Management (2023) 37:4159–4175
https://doi.org/10.1007/s11269-023-03544-7

Evaluation of an Adaptation Strategy for Flood Damage Mitigation Under Climate Change Through the Use of Irrigation Reservoirs in Japan

Atsuya Ikemoto[1] · **So Kazama**[1] · **Takeo Yoshida**[2] · **Hayata Yanagihara**[1]

Received: 15 January 2023 / Accepted: 22 May 2023 / Published online: 15 June 2023

Abstract

This study performed flood analysis, considering the water storage of irrigation reservoirs, to realize flood control by reservoirs, which are traditional irrigation facilities. The effect on flood control was determined through flood analysis performed by varying the reservoir storage rates. Based on the flood analysis results, Japan's flood damage costs were estimated. Using three Shared Socioeconomic Pathways (SSPs) (SSP1-2.6, SSP2-4.5, and SSP5-8.5), we evaluated the flood control potential of reservoirs under future climate conditions. When the reservoirs were empty, the damage cost reduction rate resulting from the use of reservoirs across Japan was small, ranging from 1.1% to 2.3%, but as the damage cost reduction rate did not change under all future scenarios, reductions in flood damage were not affected by changes in rainfall under future climate conditions. Moreover, some prefectures showed high damage cost reduction effects. In northern part of Japan and numerous prefectures in western Japan, the potential to reduce damage through flood control by irrigation reservoirs was high. Some prefectures experienced similar reduction levels as those under alternative adaptation strategies. In the Kanto region, flood control by irrigation reservoirs had low potential for reducing damages. Even among prefectures with low water storage capacities of irrigation reservoirs, the potential to mitigate the effect of damage was high.

Keywords Agricultural facilities · Irrigation reservoir · Water utilization · Flood control · Flood inundation analysis

1 Introduction

Human activities have increased greenhouse gases concentrations (IPCC 2021). As the earth warms, rain will become heavier and occur more frequently, which will likely exacerbate the intensity and frequency of flood damage. The July 2021 rain in Germany caused

---

✉ Atsuya Ikemoto
ikemoto.atsuya.s1@dc.tohoku.ac.jp

So Kazama
so.kazama.d3@tohoku.ac.jp

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

[2] National Agriculture and Food Research Organization, Tsukuba, Ibaraki, Japan

extensive damage throughout Western Europe (Kreienkamp et al. 2021), whereas in the US and Canada, two days of heavy rain caused floods (Gillett et al. 2022).

Adaptation strategies and flood countermeasures against increasingly intense and frequent floods are urgently required. To mitigate intensifying flood disasters, global efforts are being made. In the US, the Federal Emergency Management Agency (FEMA) proposed the Innovative Drought and Flood Mitigation Project in 2017, which evaluates candidate adaptation strategies to obtain climate change adaptation and future risk plans (FEMA 2017). To reduce the frequency and severity of floods, changes in the water storage, vegetation, and roughness of floodplains have been evaluated. In addition, the FEMA Strategic Plan (FEMA 2021) was proposed, which includes strategies against the risk of disasters due to climate change, such as increased flooding. The European EU Floods Directive (European Environment Agency 2007) was issued in 2007. The 2018–2019 EU Floods Directive established a framework for flood risk management to determine the overall risk to river basins. This framework improved the awareness regarding flood risks and enhanced the coordination and cooperation among sectors. Furthermore, Nature-Based Solutions (NBS), recently implemented in Europe, has garnered attention to rainwater management. Qiu et al. (2021) evaluated the cost-effectiveness of NBS implementation scenarios for semi-urban basins and found a relationship between the NBS distribution and damage mitigation effects. Costa et al. (2021) evaluated the effect of NBS on urban floods caused by rainfall with return periods of 5, 10, and 100 years. Alfieri et al. (2016) evaluated four adaptation strategies against abnormal floods—improving flood protection levels by increasing the flow capacity of rivers; reducing peak flow rates by using reservoirs, reforestation, and river refurbishment; introducing an early alarm system; and reducing the vulnerability and transfer of people and assets at risk by using floating buildings. Kefi et al. (2018) evaluated the flood damage reduction effect of Water-Sensitive Urban Design and storage of floodwater in lakes and ponds to predict the future flood damage at ToLich River, Hanoi, Vietnam, as occurrences of natural disasters are increasing dramatically, and the risk of natural disasters in Asia is higher than that in Europe and Africa. As such, discussions on flood damage mitigation under climate change are being held worldwide.

To mitigate flood damage, which intensifies with climate change, Japan's Basin Flood Control Project (MLIT 2020a), with the collaboration of the central government, basin municipalities, and companies, was issued in 2021. It explores flood control measures, focusing on the maintenance of water systems, including rainwater storage and infiltration facilities, land-use regulations, and the pre-discharge of water utilisation dams, in addition to river maintenance. Discharging water at agricultural facilities ahead of time and storing rainwater and flood water at agricultural land/agricultural facilities are expected to mitigate flood water (MLIT 2023). Linnerooth-Bayer et al. (2015) discussed challenges using flood/drought risk management policies for Poland's Warta River basin in the water and agricultural sectors under climate change, arguing that farmers should adopt adaptation strategies. Hamel and Tan (2022) stated that studies quantitatively evaluating paddies, irrigation systems, and flood risk reduction are limited and reviewed the role of agricultural lands in delaying peak flow. Hanazaki et al. (2022) targeted multipurpose reservoirs worldwide to determine the impact of changes in the operating rule on flood discharge. Li et al. (2022) determined the future impacts of a design flood using a group of large reservoirs in Yichang Station. They considered multi-purpose reservoirs with flood control as an objective. Ding et al. (2023) developed a dynamic control framework to limit flood water levels in reservoirs, considering rainfall forecast and its uncertainty, and they examined the relationship between uncertainties in rainfall forecasts and flood risk. Komori et al. (2012) suggested flood disaster prevention by using a group of dams, including those used for irrigation and power generation, and considered dam utilisation for flood control. Jung et al. (2021) selected irrigation reservoirs in a Korean basin and suggested an irrigation reservoir operation method using a scenario involving advanced water discharge and limited water levels against the background of advanced water discharge before heavy rain or water quality maintenance. Although reservoirs dedicated to agriculture have been utilized for flood control, studies have not explored the conversion of reservoirs dedicated to agriculture for flood control and their future effectiveness.

In Japan, flood control by irrigation reservoirs is being considered. Reservoirs are artificial ponds created to ensure agricultural water supply and are used as irrigation facilities. Many Japanese reservoirs were built before the Edo period and were maintained for centuries through numerous repairs, as they were existing stocks and a group of small dams. To utilize them for other purposes, effective utilisation of irrigation reservoirs requires evaluation. Yoshisako et al. (2013), Tanakamaru et al. (2020), and Ikemoto et al. (2022) evaluated the flood water mitigation effect of reservoirs in a basin area in Japan. However, they used the baseline climate in Ikemoto et al. (2022), which is unsuitable when examining measures under future climate change conditions. Thus, under climate change, to utilize irrigation reservoirs for flood control, it is inappropriate to consider only the baseline climate. In Japan, evaluations of adaptation strategies that consider future climate have been conducted (Yamamoto et al. 2021); however, adaptation strategies utilising existing resources have not been explored. Although reservoirs vary in size, when used simultaneously, flood damage decreases. The novelty of this study is to explore the effectiveness of flood control using agricultural reservoirs as existing resources considering future climates. Thus, we conducted a flood inundation analysis, considering the storage capacity of reservoirs, and evaluated the damage cost. The aim of this study was to demonstrate the flood control potential of reservoirs across Japan for flood damage mitigation under future climate conditions.

2 Datasets

2.1 Climate Scenario Data

This study used bias-corrected climate scenario data for the Japan region (Ishizaki et al. 2021, hereafter NIES2020), using the cumulative distribution function–based downscaling method based on Coupled Model Intercomparison Project Phase 6 (CMIP6) to obtain rainfall data reflecting the impact of climate change. The cumulative distribution function–based downscaling method proposed by Iizumi et al. (2014, 2017). This method places interpolating daily data in each GCM into a 1-km grid by using bilinear interpolation, and correction is performed by identifying the bias in each percentile. In NIES2020, by performing bias correction, the root mean square error in MIROC6 changed from 2.19 mm/day to 0.32 mm/day (June to August) and from 1.71 mm/day to 0.13 mm/day (December to February) (Ishizaki et al. 2022). From NIES2020, this study obtained daily rainfall scenarios of five Global Climate Models (GCMs) and three shared socioeconomic pathways (SSPs). The five GCMs (ACCESS-CM2, IPSL-CM6A-LR, MIROC6, MRI-ESM2-0, and MPI-ESM1-2-HR) were selected by Shiogama et al. (2021). Shiogama et al. (2021) selected the five GCMs for Japan using the statistical method to widely capture the uncertainty range of CMIP6 for eight climate variables including rainfall. The five GCMs were selected considering not only rainfall but also other climate variables. Thus, the results using the GCMs selected by Shiogama et al. (2021) can be compared with climate change impact assessments in other sectors. NIES2020 has one ensemble member per GCM. SSP1-2.6, SSP2-4.5, and SSP5-8.5 were shown as important scenarios that also extensively cover uncertainties by O'Neill et al. (2016). This study used SSP1-2.6, SSP2-4.5, and SSP5-8.5 daily rainfall scenarios to discuss highly important SSPs with consideration for uncertainties. The spatial resolution was approximately 1 km. Data periods were 1981–2000 (baseline period), 2031–2050 (near future), and 2081–2100 (late 21st century).

2.2 Rainfall Data Generating Extreme Discharge

Rainfall data are rainfall distributions generating the extreme discharge during each return period at any point. The rainfall distribution was proposed by Tezuka et al. (2013) and used by Yamamoto et al. (2021). Rainfall data with return periods of 30, 50, 100, and 200 years were obtained at a spatial resolution of 7.5" × 11.25" (approximately 250 m) from Yamamoto et al. (2021). Tezuka et al. (2013) and Yamamoto et al. (2021) described the rainfall data in detail, as follows. Extreme discharge was estimated based on extreme rainfall. If extreme rainfall affects an entire basin area, extreme discharge was overestimated downstream. To avoid overestimation of extreme discharge, extreme rainfall was reduced according to the catchment area. The ratio of extreme discharge to extreme rainfall (extreme runoff coefficient) during the same return period was estimated to clarify the relationship between the extreme runoff coefficient and the catchment area to reduce the extreme rainfall according to the catchment area. The estimation targeted 109 river systems specified by national government. Yamamoto et al. (2021) used extreme discharge identified using a frequency analysis based on the generalised extreme value distribution for the annual maximum daily discharge from 1974 to 2003. The extreme runoff coefficient decreased exponentially with increasing catchment area. The runoff coefficient for each cell was determined based on the relationship between the amount of runoff multiplied by the extreme runoff coefficient and the extreme rainfall for the entire river basin, and the sum of the amounts of runoff obtained from the point runoff coefficient and the extreme rainfall for each cell were equal. The rainfall distribution, which shows extreme discharge, was then calculated by multiplying the runoff coefficient for each cell and the extreme rainfall.

The rainfall distribution under future climates was determined by estimating the rainfall increase rate from the baseline climate to the future climate and by multiplying it with the rainfall distribution of the baseline climate (Yanagihara et al. 2022a, b). Below, this study presents the method used to estimate the distribution of the extreme rainfall increase rate. First, we obtained the annual maximum rainfall of each cell from daily rainfall data with a spatial resolution of 1 km from NIES2020. Next, we performed frequency analysis for each period—the baseline climate, near future, and late 21st century—for each cell. The generalised extreme value distribution was used as the probability distribution. Parameters were estimated using the probability weight moment method (Tezuka et al. 2014). For each return period, this study obtained the rainfall increase rate from the baseline climate to future climate in each cell and estimated the distribution of the extreme rainfall increase rate. Because of the distribution of the extreme rainfall increase rate at a 1-km spatial resolution, the increase rate for a 1-km square was assumed to be the same, and the increase rate distribution was multiplied by the rainfall distribution of the baseline climate at a spatial resolution of approximately 250 m. As this study only examined the flood control effect of reservoirs with changes in rainfall, changes in land use were not considered in the flood analysis.

2.3 Land-Use Data

The land use data used for the flood analysis and damage cost calculation was the land use subdivision mesh data (L03-b16) of the digital national land information (hereafter DNLI, MLIT n.d.). Japanese city planning sorts the purpose of land use according to the environment and activities. The purpose of land use data has such as residential areas, industrial areas, and commercial areas. DNLI (MLIT n.d.) stores purpose information data on land use (A29-11). This study used this data and classified lands for buildings as residential for cells in the areas specified for residential use and office for other cells (Yamamoto et al. 2020).

2.4 Elevation Data/Ground Slope Data

For the elevation data and ground slope data, this study used the average elevation and the average slope angles stored in the elevation and slope of the approximately 250 m mesh data (G04-d11) of the DNLI (MLIT n.d.). The grid was same as that of the precipitation data. Elevation data were used for flood analysis, and ground slope data were used to calculate damage costs.

2.5 Irrigation Reservoir Data

Data from the Reservoir Disaster Prevention Support System used in this study were generously provided by the National Agriculture and Food Research Organization. Some irrigation dams are not listed in the reservoir data. Therefore, irrigation dams were added to Japan’s reservoir data, which were obtained from the dam data (W01-05) in the 2014 DNLI (MLIT n.d.). To incorporate different agricultural dam and reservoir data, requirements similar to those in Ikemoto et al. (2022) used to compare results were set for irrigation dams not listed in the reservoir data, as follows: 1/60 degrees or further away from the coordinates listed in the reservoir data longitudinally and latitudinally, and the difference between the total water storage of reservoirs and total water storage of irrigation dams being 20% or more than the total water storage of the reservoirs. The targets of dam data were from 577 out of 1,214 irrigation dams. In this study, irrigation dams from the DNLI were added to the data of the Reservoir Disaster Prevention Support System and then used as reservoir data.

3 Analysis Methods

3.1 Flood Inundation Analysis

For flood inundation analysis, this study used a two-dimensional (2D) unsteady flow model of the Cartesian coordinate system (Machida et al. 2007). The analysis was performed for the whole of Japan simultaneously, and the 2D unsteady flow model was uniformly applied to rivers and floodplains. The grid mesh size was approximately 250 m, which was same as that of the elevation data. For the analysis, this study applied the precipitation data within 24 hours, when precipitation intensity was constant. The 2D unsteady flow model was applied to Japan's Naruse River Basin, where serious damage occurred during Typhoon Hagibis, and its validity is shown in Yanagihara et al. (2021). The Manning's roughness coefficient of each cell was obtained using the weighted average of the Manning's roughness coefficient corresponding to land use and the area of each type of land use. The Manning's roughness coefficient of each land use was the same as that in Yamamoto et al. (2020). Other parameters used for the analysis are the same as those in Tanaka et al. (2019) and Yamamoto et al. (2020) (see Sect. S1 in Supplementary Information).

3.2 Method of Reflecting the Degree of Flood Control Safety in Flood Inundation Analysis

Japan has river systems specified by national government (class A river systems) and river systems specified by prefectural government (class B river systems) under the River Law. In national river systems, huge damage to livelihoods and property due to floods, storm surges, and other disasters has been predicted. Prefectural river systems have a substantial bearing on public interest. Tanaka et al. (2019) determined the degree of flood control safety for each river section through flood inundation analysis by using data from a water system design scale and river section types such as national and prefectural river systems. This study was redesignated using Horton–Strahler's rank rule, based on Yanagihara et al. (2022b) (see Sect. S2 in Supplementary Information).

3.3 Method to Reflect Irrigation Reservoirs Effect to Inundation Analysis

The water storage of reservoirs effects the inundation analysis. We calculated the total water storage for reservoirs in each mesh of the irrigation reservoir data. This was because there were cases of multiple reservoirs being present within the same cell. The limit of the water storage level, which is amount of water storage per unit area, was then calculated by dividing the sum of the total water storage for reservoirs in each mesh by the mesh area. In the inundation analysis, the inundation depths were not considered because the reservoirs could store rain water and inundated water until they reached their limit of the water storage level. The process of reflecting irrigation reservoirs effect to inundation analysis is shown in Fig. S1 in Supplementary Information. The water storage capacities of the irrigation reservoirs were initially 0%, 25%, 50%, and 75%, as water was stored for agriculture. Additionally, the water did not decrease due to the short time between the forecasted heavy rainfall and the onset of rain. By varying the water storage rates, the sensitivity of the damage reduction rate to changes in water storage rate was examined.

3.4 Method of Estimating the Flood Damage Cost and Reduction Rate of the Damage Cost

Damage cost was estimated using the same method utilized by Yanagihara et al. (2022b) by multiplying the assets of inundated lands with the damage rate corresponding to the inundation depth, referring to the Flood Control Economic Survey Manual (Draft) (MLIT 2005; MLIT 2020b) (see Sect. S3 in Supplementary Information). The expected annual damage cost (EADC) was calculated by accumulating the average damage cost for each flood scale, where the damage cost from floods with return periods of 30, 50, 100, and 200 years was multiplied by the flood occurrence probability. The reduction rate of the EADC was calculated using Eq. (1).

$$P = \frac{C - Cres}{C} \tag{1}$$

where *P*: reduction rate of the EADC; *C*: EADC, not considering reservoirs; and *C*res: EADC, considering the total water storage of reservoirs.

4 Results

4.1 Flood Damage Mitigation in Japan Through the Use of Irrigation Reservoirs for Flood Control

Figure 1 shows the rate of increase in the EADC (average value of five GCMs) from the baseline climate to the future climate for each rate of water storage when flood control measures are used for the reservoirs. For the near future, the results under the SSP5-8.5, SSP1-2.6, and SSP2-4.5 showed the largest increases in the EADC, in that order. For the late 21st century, increases in the EADC were larger for SSP5-8.5, SSP2-4.5, and SSP1-2.6, in that order. For SSP2-4.5 and SSP5-8.5, the rate of increase in the late 21st century was greater than that in the near future. The results for the late 21st century show that SSP5-8.5, SSP2-4.5, and SSP1-2.6 had the largest increases in the EADC, in that order. In the near future in SSP2-4.5, the maximum and minimum values of five GCMs shows

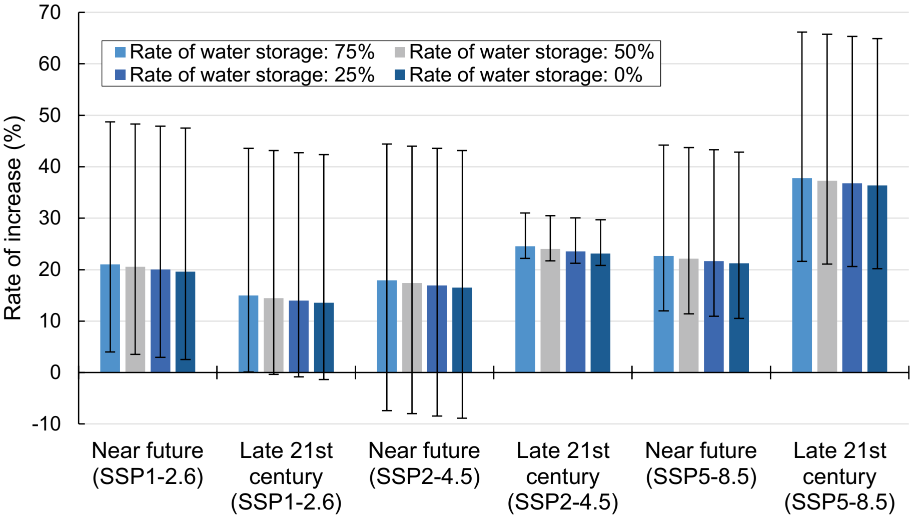

Fig. 1 Rate of increase in the EADC from the baseline climate to future climates when flood control measures using reservoirs are taken. The error bar shows maximum and minimum values of five GCMs

that the damage were approximately 1.5 times higher and lower than that in the baseline climate, respectively. However, in the late 21st century in SSP2-4.5 difference between the minimum and maximum values were the smallest.

Table 1 shows the rate of decrease in the EADC when flood control measures using reservoirs were used for each GCM. Table 1 shows these results under two water storage rates (0% and 50%). Table S1 in Supplementary Information also shows these results under two water storage rates (25% and 75%). Under all future scenarios, when the water storage rate was 0%, damage decreased from 1.1% to 2.3%; when the rate was 25%, damage decreased from 0.8% to 1.8%; when the rate was 50%, damage decreased from 0.6% to 1.3%; and when the rate was 75%, damage decreased from 0.3% to 0.7%. For all water storage rates, the scenario with the most flood damage reduction was SSP2-4.5 (MRI-ESM2-0) for the near future. The water storage rate of 75% in MIROC6 reduced flood damage the most. As the water storage rate increased, the reduction rate of the EADC decreased. When the rate was 0%, the reduction rate of the EADC remained almost constant with changing GCMs; for example, the reduction rate for SSP1-2.6 and SSP5-8.5 ranged from 1.2–2.1% and 1.1–1.7%, respectively. Therefore, there were no significant changes in the GCMs or scenarios. Figure 1, Tables 1, and S1 show the trends of the EADC by rates of water storage.

4.2 Flood Damage Mitigation by the Use of Irrigation Reservoirs in each Prefecture

Figure 2 shows the reduction rate of the EADC with the use of reservoirs as a flood control measure for each prefecture (water storage rate: 0%). Figure 2 shows that the reduction rate of the EADC was generally high in western Japan. The reduction rate of the EADC was high in prefectures located in northern Japan. Around Tokyo (Kanto region), the reduction in the damage cost was low under all future scenarios. The spatial differences in the reduction rate of the EADC were the same when the water storage rate was 0%, even when the storage rate was increased (see Figs. S2–S4 in Supplementary Information). As shown in Fig. 2b, in the same prefectures as those presented in Fig. 2a, the reduction rate of the EADC was high. However, even among prefectures with a high reduction rate of the EADC in Fig. 2a, some had low values in Fig. 2b, indicating that the ranges of the reduction rate of the EADC between five GCMs differed between Fig. 2a, b. For all future scenarios, prefectures with high damage cost reduction rates were mostly found in western Japan (Fig. 2c). Furthermore, the damage cost reduction rate was relatively high for prefectures located in northern Japan. On the contrary, the reduction rate of the EADC was low in Tokyo and prefectures around Tokyo.

4.3 Relationship Between Irrigation Reservoir Water Storage and Damage Cost Reduction in Each Prefecture

As the total water storage of reservoirs differed between prefectures, the flood control effect of reservoirs will likely differ between prefectures. Figure 3 shows the relationship between the damage cost reduction rate and reservoir depth in each prefecture. The reservoir depth of each prefecture was obtained by dividing the reservoir water storage of each

Table 1 Rate of decrease in the EADC when flood control measures using reservoirs are taken (unit: %)

Rate of water storage		**0%**	**50%**	**0%**	**50%**	**0%**	**50%**	**0%**	**50%**	**0%**	**50%**	**0%**	**50%**
Scenario	**Period**	**ACCESS-CM2**		**IPSL-CM6A-LR**		**MIROC6**		**MPI-ESM1-2-HR**		**MRI-ESM2-0**		**Average**	**Average**
SSP1-2.6	Near future	1.2	0.7	2.1	1.1	1.7	1.0	1.7	1.0	2.0	1.0	1.7	1.0
	Late 21st century	1.2	0.7	1.8	1.0	2.2	1.2	1.7	1.0	1.9	1.1	1.8	1.0
SSP2-4.5	Near future	1.3	0.7	1.9	1.1	1.6	0.9	1.8	1.0	2.3	1.3	1.8	1.0
	Late 21st century	1.6	0.9	1.5	0.8	1.6	0.9	1.5	0.9	1.7	0.9	1.6	0.9
SSP5-8.5	Near future	1.4	0.8	1.9	1.1	1.7	1.0	1.6	1.0	1.9	1.1	1.7	1.0
	Late 21st century	1.1	0.6	1.7	1.0	1.3	0.7	1.7	1.0	1.6	0.9	1.5	0.8

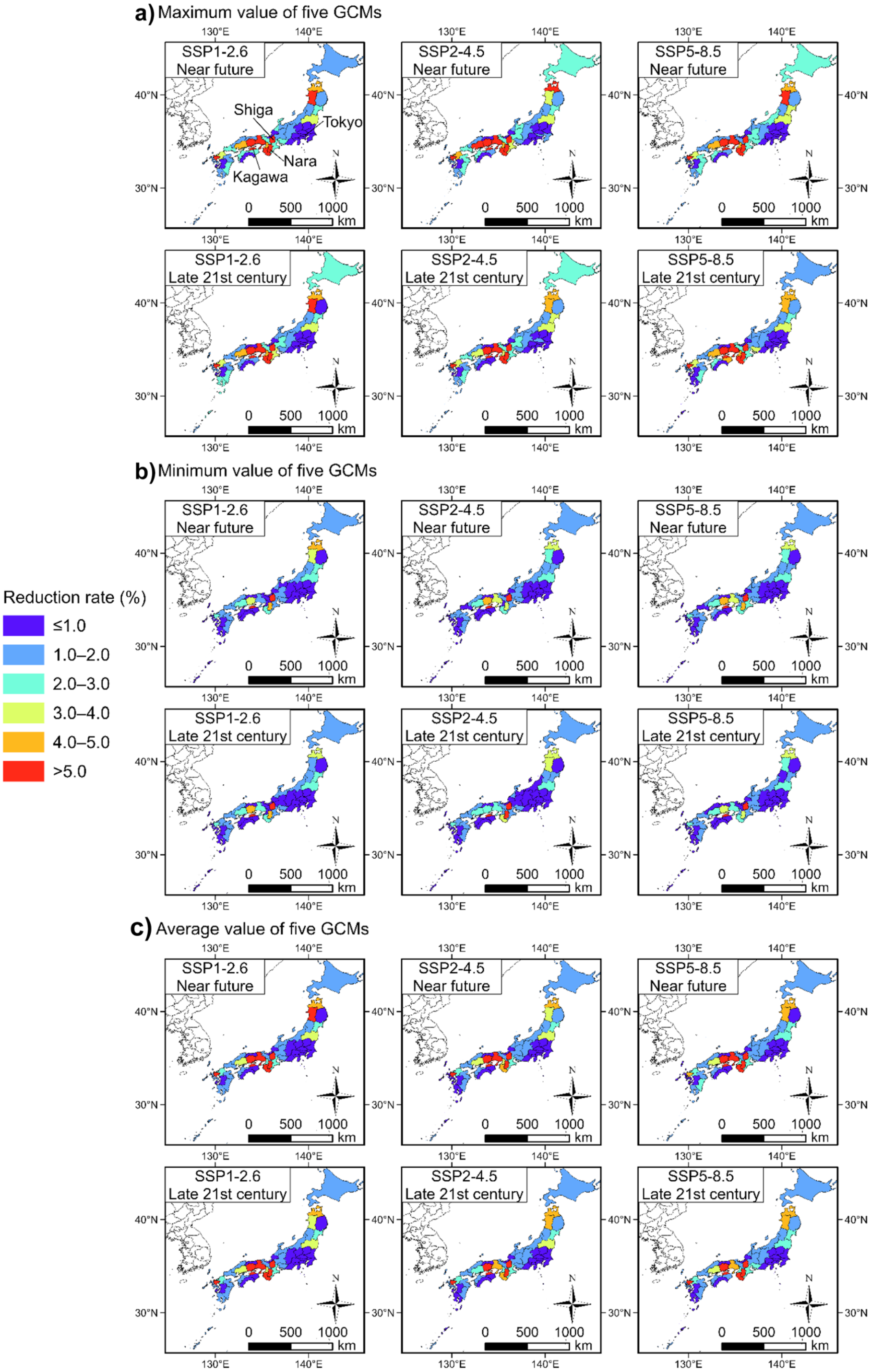

Fig. 2 Reduction rate of the EADC (water storage rate: 0%)

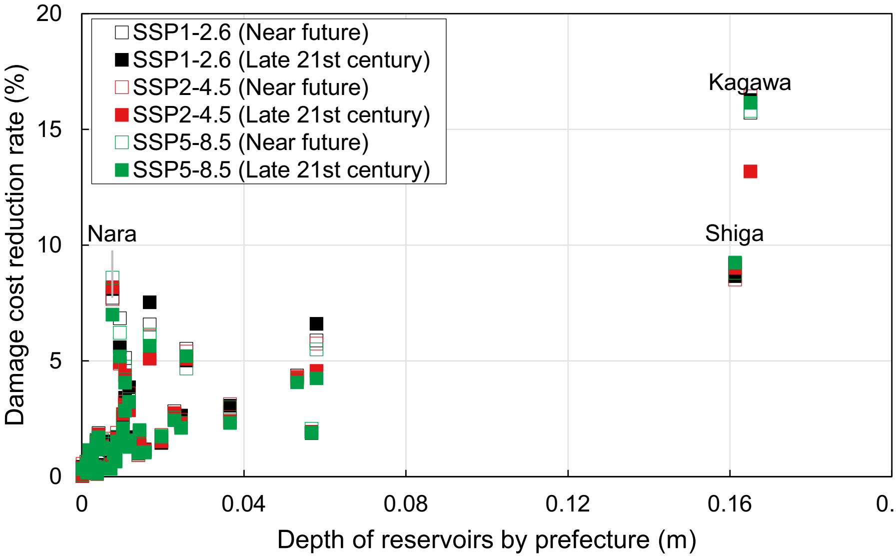

Fig. 3 Relationship between damage cost reduction rate and depth of reservoirs by prefecture

prefecture by the area of each prefecture. The prefecture area was obtained from surveys of municipality areas in each prefecture of Japan, published by the Geospatial Information Authority of Japan (MLIT 2022). The damage cost reduction rate in Fig. 2c is the average damage cost reduction rate of each GCM in each scenario; the reduction rate for the EADC is shown in Fig. 2c. The damage reduction rate according to the irrigation reservoir depth was higher in the Kagawa, Shiga, and Nara prefectures. Despite shallow irrigation reservoir depths, the damage cost reduction rate was high in the Nara prefectures. Prefectures with deep reservoirs, as well as those with shallow reservoirs, including Nara Prefecture, had a high potential for damage cost reduction through the use of reservoirs.

4.4 Water Storage by Irrigation Reservoirs and Damage Cost Reduction Amount

Figure 4 shows the relationship between the area of lands for buildings in each prefecture where the damage cost was reduced, the damage cost reduction rate, and the water storage by reservoirs. To calculate the rate of the damage cost reduction in the vertical axis, this study used the damage cost calculated from the precipitation with a return period of 200 years under the baseline climate. The size of circles in Fig. 4 indicates the size of the total water storage for reservoirs in each prefecture. Lands for buildings exhibited the highest damage cost among the various land uses; thus, we focused on lands for buildings. The Kagawa, Shiga, and Nara prefectures showed high damage reduction rates and large reductions in lands for buildings in Fig. 4. Specifically, the Nara prefecture, despite its small water storage capacity, showed a high damage reduction rate and a large area of lands for buildings with reduced damage.

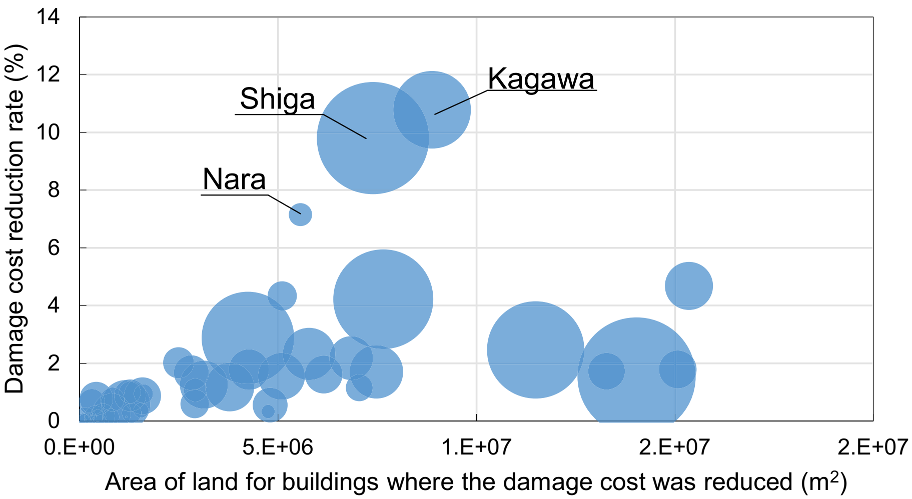

Fig. 4 Relationship between the area of land for buildings where the damage cost was reduced, damage cost reduction rate, and total water storage by reservoirs

5 Discussion

5.1 Damage Cost Reduction Effect of Flood Control Use of Reservoirs

The damage cost reduction effect of flood control use of reservoirs for Japan was from 1.1% to 2.3%. Although the reservoirs had a flood control effect, they did not reduce future flood damages to levels below the damages under the baseline climate. However, the damage cost reduction rate did not change across all future scenarios, and the reduction of flood damage was not changed substantially by changes in rainfall under future climate, as Table 1 shows that the range of the damage cost reduction rate was almost constant.

In prefectures where the average, maximum, and minimum values of the damage cost reduction rate differed, uncertainties in flood control use of reservoirs are likely high. In western Japan, where the damage cost reduction rate was high under all future scenarios, reservoirs had a high potential for flood damage mitigation. In the Kanto region, where the damage cost reduction rate was low under all future scenarios, the potential of reservoirs to reduce flood damage was low.

Ikemoto et al. (2022) anticipated the flood control use of reservoirs in western Japan, such as in the Kagawa prefecture, where the damage cost reduction rate was high in this study. In these prefectures, the reduction rate for the EADC was high under all future scenarios. Therefore, excluding prefectures with high uncertainties, drafting plans to use reservoirs for flood control is anticipated in the prefectures with high damage cost reduction rates shown in this study and in Ikemoto et al. (2022).

5.2 Impact of Reservoirs

Ikemoto et al. (2022) showed the relationship between the total water storage of reservoirs and the maximum water storage of dams used for flood control in each prefecture and discussed the potential of the flood control use of reservoirs in each prefecture. From the relationship between the total water storage of reservoirs and the maximum water storage of dams used to control floods in each prefecture, the reservoirs could control floods, such as in the Shiga and Kagawa prefectures. As these prefectures have high reservoir water storage, the rate of the damage cost reduction was high. Damage cost reduction rates were not necessarily high in areas with high reservoir water storage (Fig. 3). In contrast, some prefectures had high damage cost reduction rates despite having low reservoir water storage. Therefore, not only water storage but also other elements, such as the distribution of reservoirs (Qiu et al. 2021), affected damage reduction. Not only prefectures with deep prefectural reservoirs but also prefectures with shallow prefectural reservoirs had high potential for damage cost reduction through the flood control use of reservoirs, specifically in the above-mentioned prefectures, including the Nara prefecture (Fig. 3). Although the reservoir water storage in this prefecture was low, the area of land for buildings that experienced a reduction in damage cost was large, and the rate of the damage cost reduction was higher than those in prefectures with high water storage (Fig. 4). The rate of damage cost reduction could be increased by reducing the damage in the area of land for buildings, that is, by reducing the damages in areas with high-value assets.

5.3 Comparison with Other Adaptation Strategies

Under all future scenarios, a similar rate of reduction was obtained. Although Japan's damage cost reduction rate was below 3.0%, considering each prefecture, the reduction effect is high, exceeding 15% in each prefecture. We compared the results of this study with those of Yamamoto et al. (2021), who also used the same rainfall data and considered Japan and other adaptation strategies such as land-use regulations and piloti construction. Yamamoto et al. (2021) showed that flood damage can be reduced by 19.8%, 65.5%, and 17.6% through land-use regulations, piloti construction, and improved flood control, respectively. Comparisons with other adaptation strategies showed that reservoirs allow prefectures to achieve similar damage reductions as with other adaptation strategies using new constructions and expansions. Although the water storage of each facility was smaller than that of a dam, this adaptation strategy may increase the damage reduction effect in western Japan.

5.4 Limitations of this Study

To discuss the flood control effect of reservoirs built for irrigation and promote flood control by reservoirs, the damage mitigation effect of the maximum storage capacity of reservoirs requires estimation. This study is important because it provides information on the budget, staffing, installation, and flood control plan depending on the damage mitigation effect as a basic reference for the flood control of reservoirs. Presently, gate operation by a system is being optimized using a mobile phone. By optimizing the gate operation, the flood control effects of reservoirs may improve. Furthermore, effective flood control of reservoirs is anticipated. However, in this study, the potential risks of rainfall forecast failure were not considered, and the risks to agriculture, such as the production risk to rice, were not discussed.

6 Conclusions

This study conducted flood analysis, considering the water storage of irrigation reservoirs, to realize flood control by irrigation reservoirs (traditional irrigation facilities) according to rate of water storage. Based on the flood analysis results, the flood damage cost across Japan was estimated. Using three SSPs, we evaluated the flood control potential of reservoirs under future climate conditions. The major finding are: 1) the damage mitigation rate due to the use of reservoirs across Japan is small (1.1% to 2.3%), but as the damage cost reduction rate remained constant across all future scenarios, the reduction of flood damage is not changed by rainfall changes under future climate conditions; 2) in some prefectures in northern part of Japan and many prefectures in western Japan, the potential to reduce damage by the flood control of reservoirs showed high damage cost reduction effects. Some prefectures experienced similar levels of reduction as with other adaptation strategies. Flood damage reduction effects can be expected by actively maintaining reservoirs as a group of small dams.

Utilisation of only one reservoir had a minor impact on flood damage because of the low water storage per reservoir. In this study, maintaining a group of small dams as flood prevention facilities was cheaper than constructing a large dam; therefore, decreases in construction cost were small when the effectiveness of flood damage reduction was small, achieved by using a group of reservoirs. Additionally, the effective the required flood prevention can be obtained in the future by setting the rate of water storage or the water level to efficiently control floods.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11269-023-03544-7.

Acknowledgment To obtain the reservoir data, we received support from Professor Toshikazu Hori of the National Agriculture and Food Research Organization. Part of the calculation results from this study was obtained using the large-scale scientific calculation system of Tohoku University Cyberscience Center. We would like to extend our most sincere appreciation.

Author Contributions A. Ikemoto, S. Kazama, and H. Yanagihara contributed to the conception of the study. A. Ikemoto and T. Yoshida collected and maintained data on irrigation reservoirs. Other data collection, maintenance and analysis were done by A. Ikemoto and H. Yanagihara. The first draft of the manuscript was written by A. Ikemoto, and all authors commented on earlier versions. The final manuscript was read and approved by all authors.

Funding This research was performed by the Environment Research and Technology Development Fund (JPMEERF20S11813) of the Environmental Restoration and Conservation Agency of Japan. In addition, this research was supported by JHPCN (jh220018, jh230024), Joint Usage / Research Center for Interdisciplinary Large-scale Information Infrastructures. This work was supported in part by MEXT WISE Program for Sustainability in the Dynamic Earth.

Data Availability The datasets will be available upon reasonable request, except irrigation reservoir data.

Declarations

Ethical Approval The authors confirm that this article is original research and has not been published or presented previously in any journal or conference in any language (in whole or in part).

Consent to Participate Participation in the study was voluntary; all participants agreed to participate in the study.

Consent to Publication The authors approved the version to be published.

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Alfieri L, Feyen L, Di Baldassarre G (2016) Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. Climatic Chang 136:507–521. https://doi.org/10.1007/s10584-016-1641-1

Costa S, Peters R, Martins R et al (2021) Effectiveness of nature-based solutions on pluvial flood hazard mitigation: The case study of the city of Eindhoven (The Netherlands). Resources 10(3):24. https://doi.org/10.3390/resources10030024

Ding W, Zhang C, Lin J et al (2023) Flood risk quantification, transmission, and propagation analysis for flood water utilization of parallel reservoirs. J Hydrol 618:129202. https://doi.org/10.1016/j.jhydrol.2023.129202

European Environment Agency (2007) Floods Directive. European Environment Agency's home page. https://www.eea.europa.eu/themes/water/interactive/by-category/floods-directive. Accessed 16 May 2023

FEMA (2017) Innovative Drought and Flood Mitigation Projects. FEMA. https://www.fema.gov/sites/default/files/documents/fema_innovative-drought-flood-mitigation-projects.pdf. Accessed 16 May 2023

FEMA (2021) 2022–2026 FEMA Strategic Plan. FEMA. https://www.fema.gov/sites/default/files/documents/fema_2022-2026-strategic-plan.pdf. Accessed 16 May 2023

Gillett NP, Cannon AJ, Malinina E et al (2022) Human influence on the 2021 British Columbia floods. Weather Clim Ext 36:100441. https://doi.org/10.1016/j.wace.2022.100441

Hamel P, Tan L (2022) Blue-green infrastructure for flood and water quality management in Southeast Asia: Evidence and knowledge gaps. Environ Manag 69:699–718. https://doi.org/10.1007/s00267-021-01467-w

Hanazaki R, Yamazaki D, Yoshimura K (2022) Development of a reservoir flood control scheme for global flood models. J Adv Model Earth Syst 14:e2021MS002944. https://doi.org/10.1029/2021MS002944

Iizumi T, Okada M, Yokozawa M (2014) A meteorological forcing data set for global crop modeling: Development, evaluation, and intercomparison. J Geophys Res Atmos 119:363–384. https://doi.org/10.1002/2013JD020130

Iizumi T, Takikawa H, Hirabayashi Y et al (2017) Contributions of different bias-correction methods and reference meteorological forcing data sets to uncertainty in projected temperature and precipitation extremes. J Geophys Res Atmos 122:7800–7819. https://doi.org/10.1002/2017JD026613

Ikemoto A, Kazama S, Yoshida T et al (2022) Potential of irrigation reservoirs for flood prevention and evaluation of the reduction rate of flood damage cost for each prefecture. J Japan Soc Civil Eng Ser B1 (Hydraulic Eng) 78(2):I_265–I_270. https://doi.org/10.2208/jscejhe.78.2_i_265

IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte V, P Zhai, A Pirani, SL Connors, C Péan, S Berger, N Caud, Y Chen, L Goldfarb, MI Gomis, M Huang, K Leitzell, E Lonnoy, JBR Matthews, TK Maycock, T Waterfield, O Yelekçi, R Yu and B Zhou (eds.)]. Cambridge University Press, Cambridge

Ishizaki NN (2021) Bias corrected climate scenarios over Japan based on CDFDM method using CMIP6 (NIES2020), Ver.1. Natl Inst Environ Stud. https://doi.org/10.17595/20210501.001. Accessed 11 Oct 2021

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

Jung H, Lee S, Kim K et al (2021) Evaluation of agricultural reservoirs operation guideline using K-HAS and ratio correction factor during flood season. J Korean Soc Agric Eng 63(4):97–104. https://doi.org/10.5389/KSAE.2021.63.4.097

Kefi M, Mishra BK, Kumar P et al (2018) Assessment of tangible direct flood damage using a spatial analysis approach under the effects of climate change: Case study in an urban watershed in Hanoi Vietnam. ISPRS Int J Geo-Inform 7(1):29. https://doi.org/10.3390/ijgi7010029

Komori D, Nakamura S, Kiguchi M et al (2012) Characteristics of the 2011 Chao Phraya River flood in central Thailand. Hydrologic Res Lett 6:41–46. https://doi.org/10.3178/hrl.6.41

Kreienkamp F, Philip SY, Tradowsky JS et al (2021) Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021. World Weather Attribution – Exploring the contribution of climate change to extreme weather events. https://www.worldweatherattribution.org/wp-content/uploads/Scientific-report-Western-Europe-floods-2021-attribution.pdf. Accessed 16 May 2023

Li R, Xiong L, Zha X et al (2022) Impacts of climate and reservoirs on the downstream design flood hydrograph: a case study of Yichang Station. Nat Hazards 113:1803–1831. https://doi.org/10.1007/s11069-022-05370-3

Linnerooth-Bayer J, Dubel A, Sendzimir J et al (2015) Challenges for mainstreaming climate change into EU flood and drought policy: Water retention measures in the Warta River Basin, Poland. Reg Environ Change 15:1011–1023. https://doi.org/10.1007/s10113-014-0643-7

Machida S, Kawagoe S, Kazama S et al (2007) Evaluation of flood damages for climatic change. Proc Symp Global Environ 15:155–160. https://doi.org/10.2208/proge.15.155

MLIT (2005) Manual for Economic Evaluation of Flood Control Investment (Draft). MLIT. https://www.mlit.go.jp/river/kokusai/pdf/pdf06.pdf. Accessed 16 May 2023

MLIT (2020a) Basin Flood Control Project. MLIT. https://www.mlit.go.jp/river/kasen/ryuiki_pro/index.html. Accessed 16 May 2023

MLIT (2020b) Manual for Economic Evaluation of Flood Control Investment (Draft). MLIT. https://www.mlit.go.jp/river/basic_info/seisaku_hyouka/gaiyou/hyouka/r204/chisui.pdf. Accessed 16 May 2023

MLIT (2022) Technical report of the geospatial information authority of Japan, E2-No.78, the report of statistical reports on the land area by prefectures and municipalities in Japan in 2022. Geospatial Information Authority of Japan. https://www.gsi.go.jp/KOKUJYOHO/MENCHO/backnumber/GSI-menseki20221001.pdf. Accessed 16 May 2023

MLIT (2023) Index for Basin Flood Control Project (2023/3/31). MLIT. https://www.mlit.go.jp/river/kasen/ryuiki_pro/pdf/sihyo.pdf. Accessed 16 May 2023

MLIT (n.d.) Digital National Land Information. Digital National Land Information download site. https://nlftp.mlit.go.jp/ksj/index.html. Accessed 16 May 2023

O'Neill BC, Tebaldi C, van Vuuren DP et al (2016) The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci Model Dev 9:3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Qiu Y, Schertzer D, Tchiguirinskaia L (2021) Assessing cost-effectiveness of nature-based solutions scenarios: Integrating hydrological impacts and life cycle costs. J Clean Prod 329:129740. https://doi.org/10.1016/j.jclepro.2021.129740

Shiogama H, Ishizaki NN, Hanasaki N et al (2021) Selecting CMIP6-based future climate scenarios for impact and adaptation studies. SOLA 17:57–62. https://doi.org/10.2151/sola.2021-009

Tanaka Y, Kazama S, Tada T et al (2019) Assessment of the risk on flood and storm surge with flood control facilities. J Japan Soc Civil Eng Ser B1 (Hydraulic Eng) 75(2):I_109–I_114. https://doi.org/10.2208/jscejhe.75.2_I_109

Tanakamaru H, Tatebayashi N, Mori R et al (2020) Simple estimation method of flood mitigation effect of irrigation ponds. Water Land Environ Eng 88(9):737–740. https://doi.org/10.11408/jjsidre.88.9_737

Tezuka S, Ono K, Kazama S (2013) Spatial flood damage estimations based on relationship between extreme precipitation and extreme discharge. J Japan Soc Civil Eng Ser B1 (Hydraulic Eng) 69(4):I_1603–I_1608. https://doi.org/10.2208/jscejhe.69.I_1603

Tezuka S, Takiguchi H, Kazama S et al (2014) Estimation of the effects of climate change on flood-triggered economic losses in Japan. Int J Disaster Risk Reduct 9:58–67. https://doi.org/10.1016/j.ijdrr.2014.03.004

Yamamoto T, Kazama S, Tada T et al (2020) Estimation of the mitigation and the landuse control for climate change based on the flood analysis in Japan. J Japan Soc Civil Eng Ser G (Environ Res) 76(5):I_141–I_150. https://doi.org/10.2208/jscejer.76.5_I_141

Yamamoto T, Kazama S, Touge Y et al (2021) Evaluation of flood damage reduction throughout Japan from adaptation measures taken under a range of emissions mitigation scenarios. Clim Change 165:60. https://doi.org/10.1007/s10584-021-03081-5

Yanagihara H, Yamamoto T, Kazama S et al (2021) Regional evaluation of potential flood damage reduction by paddy field dam in Japan. J Japan Soc Civil Eng Ser G (Environ Res) 77(5):I_33–I_42. https://doi.org/10.2208/jscejer.77.5_I_33

Yanagihara H, Kazama S, Tada T et al (2022a) Estimation of the effect of future changes in precipitation in Japan on pluvial flood damage and the damage reduction effect of mitigation/adaptation measures. PLoS Clim 1(7):e0000039. https://doi.org/10.1371/journal.pclm.0000039

Yanagihara H, Kazama S, Tada T et al (2022b) Changes in flood damage throughout Japan due to climate change and land-use change using shared socioeconomic pathways. J Japan Soc Civil Eng Ser G (Environl Res) 78(5):I_387–I_395. https://doi.org/10.2208/jscejer.78.5_I_387
Yoshisako H, Koyama J, Ogawa S et al (2013) Flood peak mitigation effects by irrigation ponds group of valley type in the Mukunashi River Valley, Hiroshima Prefecture, Japan. Transact Jpn Soc Irrig Drain Rural Eng 81(3):205–214. https://doi.org/10.11408/jsidre.81.205