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ORIGINAL ARTICLE

Evaluating the cost of flood damage based on changes in extreme rainfall in Japan

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Abstract We estimated the cost of flood damage using numerical simulations based on digital map data and the flood control economy investigation manual submitted by the Ministry of Land, Infrastructure, Transportation, and Tourism in Japan. The simulation was carried out using a flood model incorporating representative precipitation data for all of Japan. The economic predictions, which estimate flood damage caused by extreme rainfall for the return periods of 5, 10, 30 50, and 100 years, are as follows: (1) the cost of flood damage increases nearly linearly with increases in extreme precipitation; (2) assuming that flood protection is completed for a 50-year return period of extreme rainfall, the benefit of flood protection for a 100-year return period of rainfall is estimated to be 210 billion USD; (3) the average annual expected damage cost for flooding is predicted to be approximately 10 billion USD per year, based on the probability of precipitation for a return period of 100 years and assuming that flood control infrastructures will be completed within the 50-year return period and will be able to protect from flooding with a 50-year return period; (4) urban and rural areas are predicted to suffer high and low costs of damage, respectively. These findings will help to derive measures to enhance flood protection resulting from climate change.

Keywords Climate change · Flood simulation · Land use · Economic loss · Countermeasure

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Introduction

The fourth report of the Intergovernmental Panel on Climate Change (IPCC) provoked a significant amount of controversy, as experts have sought to apply it to climate change in Japan. In particular, the Ministry of Land, Infrastructure, Transportation, and Tourism (MLIT) organized a committee of experts responsible for implementing flood control policies (MLIT 2008). Japan is particularly vulnerable to flooding because of its steep geography and humid climate characterized by typhoons. Consequently, Japan has been coping with the problem of flood control for a long time (Takahasi and Uitto 2004). The number of floods, and, hence, the damage due to flooding, has increased since 2004. Even though these flood events may not be caused directly by climate change, many researchers are interested in the various problems of climate change and its broader implications for economic development.

General circulation models (GCMs) developed by a number of organizations have recently brought to light studies on the frequency of flooding and related projections. Kay et al. (2006a, b) used the regional climate model (RCM) based on HadRM3H and applied it to a simple hydrological model in 15 catchments of the UK smaller than 500 km^2. They then estimated changes in flood characteristics in each basin using a return period calculation. Here, the return period of extreme rainfall is the expected value of the recurrent interval deriving from frequency analysis. Cameron (2006) also derived a relationship between the return period and flood discharge by applying the RCM and hydrological model called TOPMODEL to a smaller dataset based on the UKCIP02 climate change scenarios. Combining GCMs and hydrological models can provide information not only on the impact of climate change but also on the influence of hydrological processes on change-of-surface conditions (Loukas et al. 2002) and the uncertainty of statistical evaluations on the flood regime (Prudhomme et al. 2003). These results require discussion on change of not only climate condition but also land use and social conditions.

In order to discuss different strategies and prioritize different options for implementing regional countermeasures against flooding associated with climate change, it is helpful to understand the costs of flood damage. There already exists an established literature estimating the costs of flooding due to climate change (e.g., Cline 1992). The IPCC (2007) reported estimates on economic damage caused by climate change, while the Stern (2006) report collected a variety of data and potential economic risks for each region in more detail. Over the period 2000–2100, Wada et al. (2005) predicted that the probability of daily maximum precipitation levels would increase by 20% throughout Japan and by approximately 40% for eastern Japan. For other examples, in an applied evaluation of the cost of adaptation to climate change, Gleick and Maurer (1990) assessed various options for adapting to flooding with return periods in the Bay area of California. In addition, Haddad and Merritt (2001) used hydrological data to evaluate water storage capacity and its costs for the regional scale management of water resources. The results of these researches can contribute to estimating the economic damage due to flooding and are helpful in planning and designing flood prevention methods.

Adapting to flooding caused by climate change is a matter of national policy. For example, Mirza (2002) discussed the implications of flooding in Bangladesh based on hydrological and damage data. Although flood prevention is a policy concern at the national level, we must consider the needs of each region and how these differences may influence the program design. For instance, Naess et al. (2005) mentioned different policy implications at the national and municipal levels in Norway. In contrast, Kitajima et al. (1993) estimated the cost of measures to counteract the rise in sea level in Japan by accounting for the total cost of all shorelines in Japan, but there is no discussion regarding which region should select countermeasures. The government should decide which adaptation methods would be the most appropriate for each region. Regardless of whether flooding countermeasures are considered in the context of climate change or more as a question of crisis management, it is important to develop these measures by taking into account regional variations in geology, population, and culture.

This kind of research has shown that a distributed hydraulic model can provide more detailed information on flood risks and flood prevention on a regional scale. For example, Dutta et al. (2006) assessed flooding countermeasures and their cost using distributed hydrological and hydraulic models on a small scale. Ichikawa et al. (2007) performed a cost–benefit analysis of land-use regulations using a hydraulic model with numerical map data. These studies have provided detailed understanding of the spatial distribution of flood protection effects in such small basins. However, no studies have yet attempted to show the costs of flood damage throughout an entire nation in order to compare the costs of regional countermeasures. Therefore, in the present study, we developed a method for estimating the costs of flood damage across Japan. This method relies on a hydraulic model based on extreme rainfall data as an input. The extreme rainfall intensity is calculated for every return period using past rainfall data and is used for discussion on flood damage by climate change shifting the return period in the future.

Methodology

Rainfall data and inundation model

The distribution of extreme 24-h rainfall was obtained using the Auto Meteorological Data Acquisition System (AMeDAS) data from 1980 to 2000, as described by Ushiyama and Takara (2003). Here, it is noted that extreme and maximum rainfalls have different definitions (Chow et al. 1988). Past data decides the maximum rainfall and static statistics analysis provides extreme rainfall using past data in simple description. First, we carried out a frequency analysis on annual maximum 24-h rainfall data at every AMeDAS gauge station to calculate the return period for extreme rainfall. We used the generalized extreme value (GEV) probability distribution function with the probability weight moment (PWM) method in order to evaluate the GEV function parameters. The distribution function can estimate the return period of extreme rainfall (Chow et al. 1988). There are 1,024 AMeDAS stations throughout Japan. In addition, the Japan Meteorology Agency (JMA) provides a numerical map of average 24-h rainfall data every month; this map is generated from factor analysis and shows the spatial distribution of rainfall (JMA 1988). Second, we used regression to estimate the linear relationship between the average 24-h rainfall and maximum 24-h rainfall for each return period. Some data were not included either because they were unavailable or they were unreliable. The relationship was calculated for each different season, as shown in Fig. 1. Extreme rainfall data were estimated from the AMeDAS records, and maximum precipitation was defined to be the maximum value for the monthly average 24-h rainfall data during each season. Third, we inferred the distribution of extreme rainfall from the numerical map of average 24-h rainfall using the regression analysis expressed in Fig. 1. It is important to

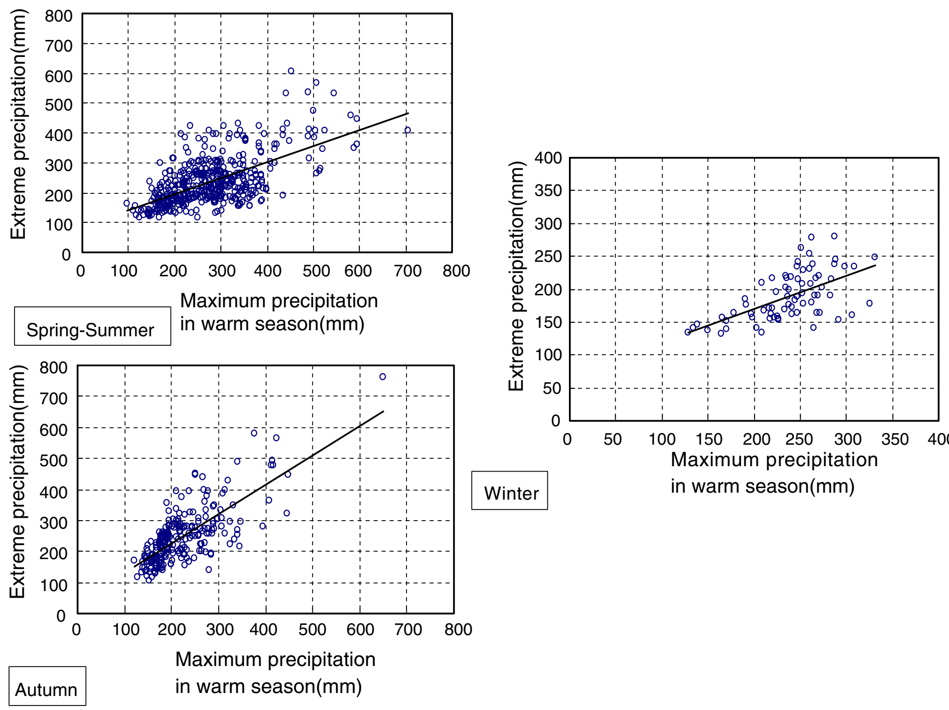


Fig. 1 Relationship between extreme rainfall and maximum precipitation in different seasons (maximum precipitation is selected as the maximum value in the dataset of monthly average 24-h rainfall during each season)

note that the estimation of extreme rainfall from this linear relationship (Fig. 1) does not have a small scatter, and we observed heavy rainfall patterns, such as typhoons or baiu rainfall, during some seasons. In order to consider the effects of climate change, we must pay attention to changes in the shape of the distribution function, which depend on the rainfall pattern. This means that changes in the rainfall pattern alter the distribution of extreme rainfall. Therefore, this study could detect extreme rainfall change based on current climate conditions, but not climate change.

The inundation model is a two-dimensional non-uniform flow model that uses a Manning roughness coefficient to take into account land use. The roughness values were estimated by calibration with respect to many Japanese basins. The land use data were obtained from the Geographical Survey Institute (GSI) of Japan. Extreme rainfall data from continuous periods of 24 h were applied spatially to the inundation model as the input data. Given the topography of Japan, a flood wave caused by extreme rainfall in most rivers can reach the river mouth within 24 h, except in a few cases. Following data input, the inundation simulation was carried out for 1 week to determine the maximum water depth and inundation period, which were needed to calculate damage costs.

Inundation models in large areas usually apply hydrological functions, but we ignored these processes because, in the case of extreme rainfall, the soil is saturated, causing less infiltration; full water depth on leaves involves no interception with vegetation; and the saturation of the ambient air leads to less evapotranspiration. The 2D non-uniform flow models are shown in the following equations (Chow et al. 1988; Kazama et al. 2007). This model consists of a continuity equation and a momentum equation in two directions, which are applied to all regions:

$$\gamma \frac{\partial D}{\partial t} + \frac{\partial \gamma M}{\partial x} + \frac{\partial \gamma N}{\partial y} = 0 \quad (1)$$

$$\lambda \frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\lambda \frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\gamma \frac{MN}{D}\right) + \gamma g D \frac{\partial (D+h)}{\partial x} + \frac{\gamma g n^2 M\sqrt{M^2+N^2}}{D^{7/B}} + \frac{1}{2}\frac{(1-\gamma)}{B} C_D \frac{M\sqrt{M^2+N^2}}{D} = 0 \quad (2)$$

$$\lambda \frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\lambda \frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\gamma \frac{N^2}{D}\right) + \gamma g D \frac{\partial (D+h)}{\partial y} + \frac{\gamma g n^2 N\sqrt{M^2+N^2}}{D^{7/B}} + \frac{1}{2}\frac{(1-\gamma)}{B} C_D \frac{N\sqrt{M^2+N^2}}{D} = 0 \quad (3)$$

$$\lambda = \gamma + (1-\gamma) C_M \quad (4)$$

where $M = uD$ represents the discharge flux in the x-direction, while $N = vD$ represents the discharge flux in the y-direction (m^2/s), g is gravitational acceleration (m/s^2), v and u represent the velocity (m/s) in the x- and y-directions, respectively, h represents elevation (m), n is the Manning coefficient ($s/m^{1/3}$) and D is the water depth (m), $1-\gamma$ is the house occupancy ratio, B the house size (m), C_M the additive mass coefficient (=0.2), and C_D is the house drag coefficient (=1.0). It was supposed that B and γ are, respectively, given as constants of 14.941 and 0.411 in a residential area of land use data referring to the flood control economy investigation manual (MLIT 2005). Although original equations include non-linear terms, we have ignored them so as to avoid complex calculations and to consider the average amount within the dxdy area. Also in this model, the time interval and ground resolution have been selected as 1 s and 1 km, respectively. The Manning coefficient of the inundation flow has been referred in hydraulics formulas [Japan Society of Civil Engineers (JSCE) 1999] depending on land use. The equations have been solved using a finite difference technique expressing a forward difference scheme in time and a central difference scheme in space. This 2D, non-uniform flow model was tested in the eastern part of Sendai City in Japan, and was found to work well (Kazama et al. 2002). In addition, some inundation models involving finer spatial datasets can calculate accurate velocities that influence house destruction. The model proposed here does not require such a level of detail because it was carried out at the national level, and the manual for damage cost estimation does not include physical damage caused by hydraulic momentum.

Calculating the costs of flood damage

The procedures for calculating the damage cost for each type of land use were determined based on the flood control economy investigation manual published by the MLIT (2005) and land-use grid data (KS-META-L03-09 M) (National Land Information Office, MLIT 2007). The following types of land use were included in the analysis: (1) paddy fields, (2) other agricultural lands, (3) residential areas, (4) golf courses, (5) traffic zones, (6) forests, (7) barren lands, (8) other land, (9) rivers and lakes, (10) beaches, and (11) coastal zones. The calculation method used for each type of land use type is described below.

Agricultural damage in paddy fields and other agricultural lands was calculated by multiplying agricultural assets by the damage rate corresponding to the inundation depth and inundation period. The agricultural assets were calculated by multiplying the paddy field surface area and other agricultural land areas by the price of agricultural production per unit area.

Paddy field damage was calculated using the following formula:

$$\begin{aligned}\text{damage (USD)} = {} & 489\ (\text{t/km}^2) \times 2{,}480\ (\text{USD/t}) \\ & \times \text{inundation area}\ (\text{km}^2) \\ & \times \text{damage rate by inundation depth} \qquad (5)\end{aligned}$$

where 489 t/km^2 is the national median of the average harvest volume per unit area of paddy field in Japan and 2,480 USD/t is the unit price of rice in Japan in 1999. The damage rate is obtained from an empirical function, which will be explained later.

Damage to other agricultural lands was determined using the following formula:

$$\begin{aligned}\text{damage (USD)} = {} & 5{,}770\ (\text{t/km}^2) \times 2{,}300\ (\text{USD/t}) \\ & \times \text{inundation area}\ (\text{km}^2) \\ & \times \text{damage rate by inundation depth} \qquad (6)\end{aligned}$$

where 5,770 t/km^2 is the national median of the average volume of tomatoes harvested per unit of land area in Japan and 2,300 USD/t is the unit price of tomatoes in Japan in 1998.

Since the goal of this study was to determine the distribution of flood damage throughout Japan, the production of various agricultural crops other than paddy rice was considered. Nevertheless, assessing the damage to all types of agricultural production proved to be difficult in this study. As a result, tomatoes were chosen to represent Japanese agricultural production, since they are widely grown throughout the country. In fact, average agricultural production is around 2,360 USD/t (Ministry of Agriculture, Forestry and Fisheries [MAFF] 2002). Tomato production, with a yield of 2,300 USD/t, approximates this value most closely.

In addition to crop type, the cost of agricultural damage depends on the stage of crop growth when flooding happens. For example, flooding in the winter causes almost no damage. However, the modeling in this study did not take into account the timing of flooding, and it assumed the worst case of damage occurring at the height of the growing season.

The types of land use suffering the most damage in flooding models are in areas of strong economic activity, i.e., residential and office areas with large assets and production. This type of land use can be divided into two subcategories (residential buildings and office buildings) based on national data on land use, reutilization changes, and economic and policy changes (site mesh KS-META-A02-60 M) (National Land Information Office, MLIT 2007):

$$\begin{aligned}\text{residential building damage} = {} & \text{house damage} \\ & + \text{household furniture damage} \qquad (7)\end{aligned}$$

$$\begin{aligned}\text{office building damage} = {} & \text{office building damage} \\ & + \text{redemption and inventory assets} \qquad (8)\end{aligned}$$

Damage to houses was calculated by multiplying house assets in each prefecture by the damage rate as a function of the water depth estimated by the inundation model. House assets were taken from data on prices per unit area summarized by the MLIT (2005), and the damage rate was obtained directly from the empirical data by the MLIT:

$$\text{house damage (USD)} = \text{house assets}\left(\text{USD}/\text{m}^2\right) \times \text{inundation area}\left(\text{m}^2\right) \times \text{damage rate by inundation depth} \tag{9}$$

Household furniture damage was calculated by multiplying household furniture assets by the damage rate to the flood depth. Household furniture assets were calculated by multiplying the number of households by the unit price per household:

$$\text{house furniture damage (USD)} = 129{,}720\ (\text{USD}/\text{household}) \times \text{inundated household (household)} \times \text{damage rate by inundation depth} \tag{10}$$

where 129,720 USD/m^2 is the national median of the valuation per household in Japan in 2004.

Office building damage was calculated in the same manner as house damage. Office depreciable assets and inventory asset damage was calculated by multiplying office depreciable assets and inventory assets by the damage rate as the flood depth evaluated by the inundation model. Office depreciable assets and inventory assets were calculated by multiplying the number of employees by the unit price per employee:

$$\text{depreciable asset damage (USD)} = 56{,}210\ (\text{USD}/\text{employee}) \times \text{inundation influence working force (employee)} \times \text{damage rate by inundation depth} \tag{11}$$

$$\text{inventory asset damage (USD)} = 49{,}150\ (\text{USD}/\text{employee}) \times \text{inundation influence working force (employee)} \times \text{damage rate by inundation depth} \tag{12}$$

where 56,210 USD/employee is the average amount of depreciable assets per employee in Japan (except in agriculture, forestry, and fisheries), and 49,150 USD/employee is the average amount of inventory assets per employee in Japan (except in agriculture, forestry, and fisheries).

Golf course damage was calculated as service sector damages. In this case, depreciable assets and inventory assets were used to estimate golf course damage:

$$\text{golf course damage} = \text{depreciable assets} + \text{inventory assets (service industry)} \tag{13}$$

$$\text{depreciable asset damage (USD)} = 42{,}360\ (\text{USD}/\text{employee}) \times \text{inundation influence working force (employee)} \times \text{damage rate by inundation depth} \tag{14}$$

$$\text{inventory asset damage (USD)} = 3{,}200\ (\text{USD}/\text{employee}) \times \text{inundation influence working force (employee)} \times \text{damage rate by inundation depth} \tag{15}$$

where 42,360 USD/employee is the average amount of depreciable assets per employee in the service sector in Japan in 2005 (MLIT 2005) and 3,200 USD/employee is the average amount of inventory assets per employee in the service sector in 2005 (MLIT 2005).

Traffic zone damage was calculated from the relationship to general asset damage because it is too difficult to estimate traffic damage directly from traffic assets:

$$\text{traffic zone damage} = \text{general asset damage} \times 1.694 \tag{16}$$

where "general asset damage = house damage + furniture damage + office depreciable assets and inventory asset damage," and 1.694 is the ratio of the cost of damage to public facilities to the cost of damage to general assets (MLIT 2005).

Flood damage to the following land types was taken to be zero: forests, barren land, other land, rivers and lakes, beaches, and coastal zones. Moreover, the recovery cost for damages was also not considered for all land uses. Damage should actually be weighted based on local estate values and the type of industry, but we assumed uniform conditions throughout Japan based on the manual, which does not take into account frequent price changes.

The damage rate depends on two parameters: floodwater depth and inundation period. The rate was obtained by the MLIT (2005) from empirical analysis using past data and was shown as discrete data used to prepare a continuous formula using a high-dimensional function for inundation analysis. Figure 2 shows the continuous relationship between the damage rate and inundation depth in the case of 1–2 days of inundation. Inundation depth and period are

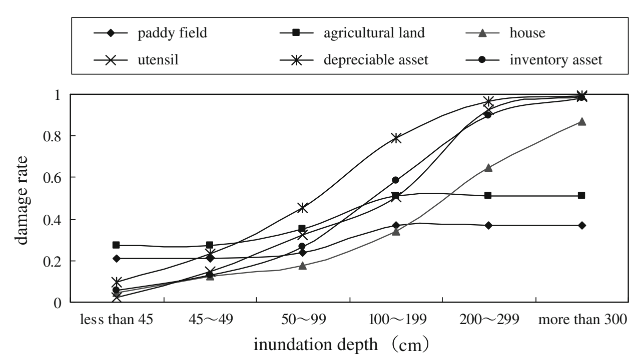


Fig. 2 Relationship between damage rate and inundation depth

the maximum water depth and duration of water existence, respectively, with 7 days defined as the maximum inundation period in the simulation. Figure 2 shows that paddy fields and other agriculture lands undergo a gradual change in the damage rate compared to the other items. On the other hand, the damage rates of housing and assets show significant increases with increasing inundation depth. When the inundation depth exceeds 200 cm, the damage rate reaches nearly 100%. The relationship between the damage rate and inundation period is shown in Fig. 3. The damage rate of agricultural production rises depending on the flood period. For example, the damage rate increases by 30–40% for a 7-day inundation period. When the inundation depth in paddy fields exceeds 1 m with an inundation period of 7 days, the damage rate is 70%, while in other agricultural lands under the same conditions, the damage rate reaches nearly 100%. The overall effect of the inundation period shows that the damage rate increases with inundation period.

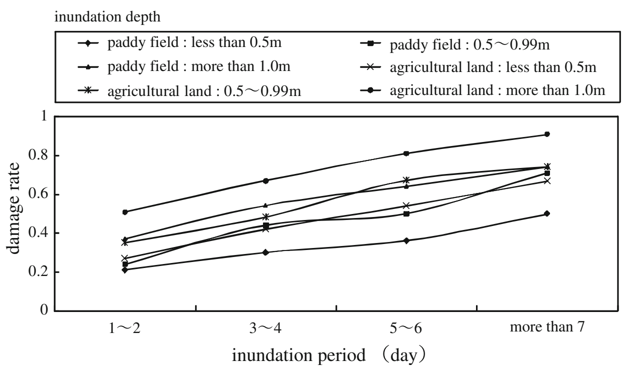


Fig. 3 Relationship between damage rate and inundation period

Results

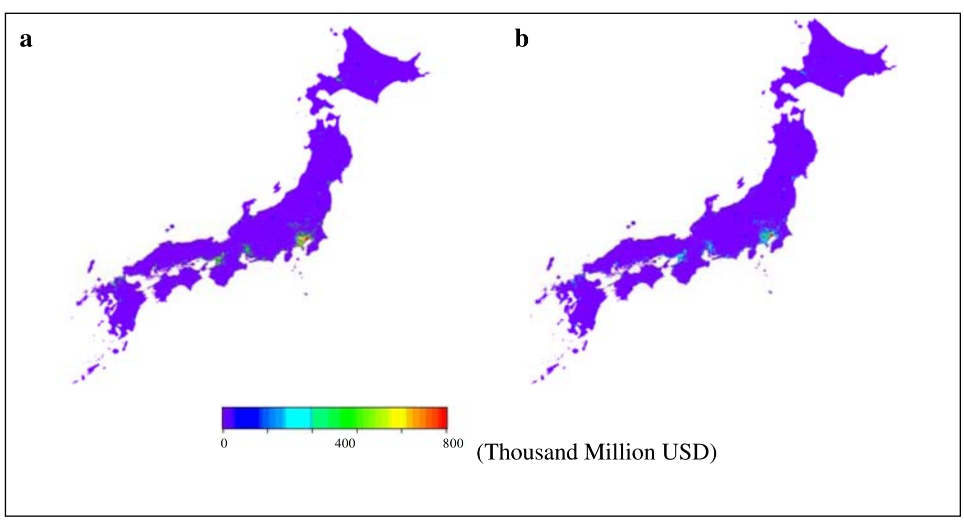
We applied the inundation simulation to a scenario in which Japan implements no flood control measures and is subjected to extreme rainfall. We selected 5, 10, 30, 50, and 100 years as the return periods and estimated potential damage costs for the flooding. Figure 4 shows the distribution of damage costs in Japan for extreme rainfall with 50- and 100-year return periods. The cost of damage in the different areas is very similar because Japan is primarily mountainous and only has small plain areas. Therefore, inundation areas do not expand to wider regions, even though the floodwater depth increases. This means that damage costs in the same areas increase as rainfall intensity increases. Large and highly populated cities have large damage costs due to the concentration of assets. These cities include Tokyo, Nagoya, and Osaka, which are located in lowlands.

Figure 5 shows the almost linear relationship between the rate of increase in extreme rainfall and the rate of increase in flood damage costs from a 5-year return period. This relationship is due to the steep Japanese topography that concentrates flooding in limited plain areas surrounding steep mountains and does not allow it to expand widely, in contrast to the increase in water depth. The results of this simulation accurately characterize the damage from typical Japanese flooding events. Shifting from a 5- to 100-year return period doubles the extreme rainfall intensity and triples damage costs. The ratio of the rate of increase in damage to the rate of increase in extreme rainfall is 1.5.

Discussion

In our evaluation of the potential flood damage for no flood countermeasures, we assumed that, by developing its

Fig. 4 Potential damage costs of flooding in Japan (thousand million USD). **a** Damage costs for 100-year extreme rainfall. **b** Damage costs for 50-year extreme rainfall



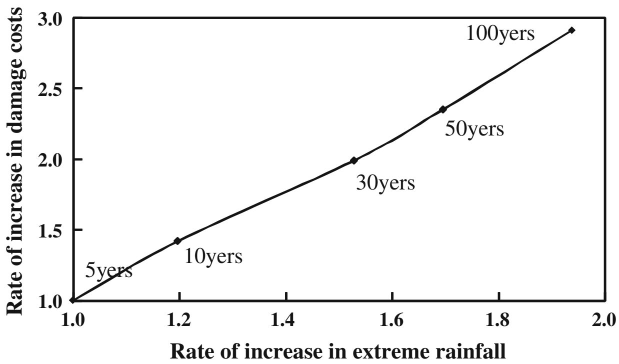


Fig. 5 Relationship between the rates of increase in extreme rainfall and flood damage costs from a 5-year return period of extreme rainfall

Table 1 Annual expected damage cost and return periods

Return period	Annual extreme probability	Damage cost	Interval av. damage	Interval probability	Av. annual expected damage cost
5	0.200	380			
10	0.100	550	470	0.1	47
30	0.033	770	660	0.067	44
50	0.020	910	840	0.013	11
100	0.010	1,120	1,020	0.010	10
150	0.007	1,130	1,130	0.003	3

Interval average damage is estimated from damage costs associated to two return periods. For example, the interval average damage, interval probability, and average annual expected damage cost of the 30-year return period are, respectively (770 + 550)/2.0, 0.100–0.033, and 660 × 0.067 (unit: billion USD)

infrastructure, Japan can minimize flood damage in the case of extreme rainfall within a 50-year return period. The return period of 50 years is determined as the average of urban and rural areas that actually have infrastructures with almost 70- and 30-year return periods in Japan, respectively, although the infrastructure development should be different in each region. According to the assumption that Japan completed flood infrastructure for the 50-year return period extreme rainfall, the benefit of protective measures against flooding potentially caused by climate change can be estimated from the difference in damage costs between current and future situations. The MLIT uses this method to calculate the benefit of infrastructure renovation for flood control based on the flood control economy investigation manual (2005). The manual does not take into account the possibility that extreme rainfall will be affected by climate change: the return period shift caused by climate change is not taken into account, and changes in rainfall intensity are considered by only using a return period estimated from current statistical calculations. The benefit of these measures for flood protection with return periods of 50–100 years nearly equals the different potential damage costs.

Our simulation method was verified by estimating downpour damages in the Hokuriku district of Japan in 2004. The 2004 flooding occurred in a wide area and involved a variety of inundation cases in various regions in the Niigata prefecture. This disaster was determined to have a mean return period of 113 years and to cause 2 billion USD of damage in the Niigata prefecture alone (MLIT 2004). Similar to these numbers, our simulation calculates a return period of 100 years in the Niigata prefecture and a cost of approximately 1.7 billion USD, assuming a flood defense completion for 50 years of extreme rainfall.

To estimate investment costs for infrastructure construction, it is necessary to discuss cost–benefit ratios. To prepare for cost–benefit analysis in the future, we evaluate the benefit of flood protection. Table 1 shows the damage cost for each return period. In the same approximation of flood defense completion for 50-year flooding, the benefit to protect from 100-year flooding is the difference in damage costs between a return period of 50 years and of 100 years, which equals about 210 billion USD. Furthermore, the numerical simulation can show the distribution of the increase of potential damage cost from extreme rainfall with 50- to 100-year return periods (Fig. 6). The increase of the potential damage cost is the same as the benefit to protect from 100-year flooding. The high-benefit areas are located in urban areas due to the high costs of flood damage in these areas.

Table 1 shows the relationship between the average annual expected damage costs and return periods. In this calculation, the interval average damage is the average value of damage costs in both return periods, the interval probability is the difference between both annual average extreme probabilities, and the product of these values is the average annual expected damage cost. The extreme rainfall shifting from 50- to 100-year return periods results in damages of approximately 10 billion USD damage per year, which is equal to the benefit of implementing infrastructure construction for flood protection. The annual expenditure for flood control in the MLIT regular budget is nearly 10 billion USD, which is similar to the expected damage costs. An analysis of cost–benefit ratios is necessary in order to estimate construction costs, which will make up a lower percentage of the MLIT budget.

There are a wide variety of options with different costs for flood countermeasures. Countermeasures should be evaluated according to regional differences, social structure, and culture. Although the absolute cost of damage or infrastructure investment estimated in our simulation is insufficient for decision-making, our modeling does indicate the relative distribution of damage costs, which is helpful for discussing countermeasures for protection from

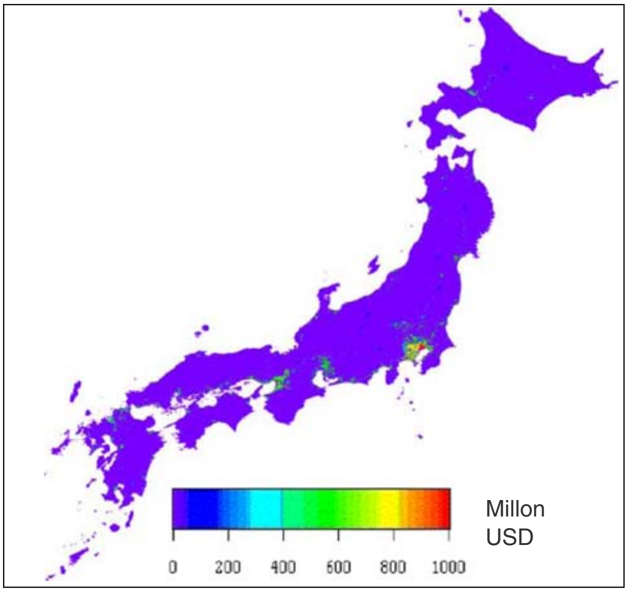


Fig. 6 Distribution of the increase of potential damage costs from rainfall with 50- to 100-year return periods (million USD)

floods caused by climate change. The areas susceptible to large flood damage require complete flood defenses, such as super dikes or underground channels, because of the economic implications of flooding. On the other hand, areas vulnerable only to small flood damage require mitigation measures, warning systems, or evacuation plans. Recently, the MLIT has begun to discuss measures to protect against flooding caused by climate change, and the agency has presented many options for countermeasures (MLIT 2008). However, no discussions have dealt with measures tailored to specific regions of the country. Distribution maps of damage, such as that shown in Fig. 6, should prove to be helpful for developing such regional countermeasures to protect against flooding due to climate change.

Conclusions

This present study developed a method for estimating the costs of flood damage cost across Japan, which relies on a hydraulic model based on extreme rainfall data as an input. The extreme rainfall intensity is calculated for every return period using past rainfall data and is used for discussion on flood damage by climate change shifting the return period in the future.

Based on the above findings, we draw the following conclusions:

1. The rate of increase in extreme rainfall varies linearly with the rate of increase in damage costs.
2. Assuming that flood protection is completed for a 50-year return period of extreme rainfall, the benefit of flood protection for a 100-year return period of rainfall is estimated to be 210 billion USD.
3. The average annual expected damage cost for flooding is predicted to be approximately 10 billion USD per year, based on the probability of precipitation for a return period of 100 years and assuming that flood control infrastructures will be completed within the 50-year return period and will be able to protect from flooding with a 50-year return period.
4. Urban and rural areas are predicted to suffer high and low costs of damage, respectively.

Using numerical flood simulations with digital elevation data, we can obtain a map of damage costs across Japan, and this map can also be taken to approximate the investment needed for flood defenses. This map makes it easy to understand which areas are the most vulnerable to flooding in Japan. In this way, the present study will help in the development of flood prevention and protection options that take into account regional variations.

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