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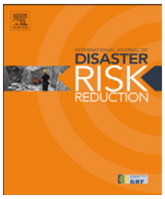

Probability assessment of flood and sediment disasters in Japan using the Total Runoff-Integrating Pathways model

Goro Mouri [a,*], Daigo Minoshima [b], Valentin Golosov [c], Sergey Chalov [d], Shinta Seto [e], Kei Yoshimura [f], Shinichiro Nakamura [g], Taikan Oki [h]

[a] *Earth Observation Data Integration & Fusion Research Initiative (EDITORIA), The University of Tokyo, Be605, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*
[b] *Trade and Industry (METI), Ministry of Economy,1-3-1 Kasumigaseki, Chiyoda-ku, Tokyo 100-8901, Japan*
[c] *Faculty of Geography, Lomonosov Moscow State University, 119991 Russia, Moscow, GSP-1, Vorob'evy Gory, MSU Moscow, Russia*
[d] *Faculty of Geography, Lomonosov Moscow State University, 119992 Russia, Moscow, GSP-1, Vorob'evy Gory, MSU Moscow, Russia*
[e] *Institute of Industrial Science, The University of Tokyo, Be505, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*
[f] *Atmosphere and Ocean Research Institute, The University of Tokyo, 211a, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8568, Japan*
[g] *Organization for Interdisciplinary Research Projects, The University of Tokyo, Ce407, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*
[h] *Institute of Industrial Science, The University of Tokyo, Be607, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*

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ABSTRACT

To address many of the problems faced in hydrological engineering planning, design, and management, a detailed knowledge of flood event characteristics, such as flood peak, volume, and duration is required. Flood frequency analysis often focuses on flood peak values and provides a limited assessment of flood events. To develop effective flood management and mitigation policies, estimation of the scale of potential disasters, incorporating the effects of social factors and climate conditions, is required along with quantitative measures of flood frequency. The Japanese flood risk index, the flood disaster occurrence probability (FDOP), was established based on both natural and social factors. It represents the expectation of damage in the case of a single flood occurrence, which is estimated by integrating a physical-based approach as a Total Runoff Integrating Pathways (TRIP) model with Gumbel distribution metrics. The resulting equations are used to predict potential flood damage based on gridded Japanese data for independent variables. This approach is novel in that it targets floods based on units of events instead of a long-term trend. Moreover, the FDOP can express relative potential flood risk while considering flood damage. The significance of the present study is that both the hazard parameters (which contribute directly to flood occurrence) and vulnerability parameters (which reflect conditions of the region where the flood occurred), including residential and social characteristics, were shown quantitatively to affect flood damage. This study examined the probability of flood disaster occurrence using the TRIP model for Japan (J-TRIP), a river routing scheme that provides a digital river network covering Japan. The analysis was based on floods from 1976 to 2004 associated with flood inundation and sediment disasters. Based on these results, we estimated the probability of flood damage officially reported for the whole region of Japan at a grid interval of 0.1 degrees. The relationship between the magnitude of the rain hazard expressed as the probability of exceedance and the probability of flood damage officially reported was expressed as an exponential function by equalizing the whole region of Japan based on excess probability. Moreover, the probabilities of flood damage occurrence according to social factors and changes in climate conditions were also examined. The probability of flood damage occurrence is high, especially in regions of high population density. The results

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* Corresponding author. Tel.: +81 3 5452 6382.
E-mail address: mouri@rainbow.iis.u-tokyo.ac.jp (G. Mouri).

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also showed the effect of the dam maintenance ratio on extreme flooding and flood damage frequency. The probability of flood damage occurrence was expected to increase during extreme weather events at the end of this century. These findings provide a sound foundation for use in catchment water resources management.

1. Introduction

Risk assessment is an important tool in natural disaster management. Risk assessment of natural disasters is defined as the assessment of both the probability of natural disaster occurrence and the degree of damage caused by natural disasters. Recently, many studies have focused on natural disaster risk analysis and assessment of flooding, earthquakes, and droughts, as well as other hazards [17,29]. In general, a disaster risk is defined as the probability multiplied by the potential losses. Main aspects of risk assessment are given by probability distributions based on historical data, which are usually converted to frequencies.

Risk assessment is the foundation of a risk management program. Accurate risk assessment allows for realistic appraisal of the types of risks a community is likely to face. However, we must also acknowledge that completely accurate prediction is impossible in many cases: uncertainty always exists and risk is inevitable. Moreover, the data available for risk assessments of natural disasters are often limited. A number of issues arise when conducting risk assessments with a small dataset. However, uncertainty may arise when considering the vocabulary used for risk analysis related to geohazards. Risk analysis is generally considered to be the combination of hazard and vulnerability, but many definitions are available for both terms [25]. Hirabayashi and Kanae [20] examined changes in future populations at high risk of experiencing flood damage. When temperatures rose by 3 °C compared on average in 1980–1999, approximately 300 million people were exposed to flood danger; the maximum rise in temperature without substantial increases in the flood-risk population was about 2 °C.

Researchers have gradually recognized that complex hydrological events such as floods and storms are multivariable events characterized by a few correlated random variables [65]. Generally, extreme events such as flood peaks and flood volumes can often be approximately represented by a Gumbel distribution [15,56,10,59,9]. Several probability distributions have been used to describe the magnitude–frequency relationship of extreme events in hydrology. One that has been widely accepted for annual maximum flood series is the double exponential or Gumbel distribution, which is an asymptotic distribution of the largest values in samples drawn from any distribution belonging to the exponential family [28].

A univariate Gumbel distribution is one of the most commonly adopted statistical distributions in hydrological frequency analysis. A Gumbel distribution constructed from specified Gumbel marginals may be useful for representing joint probabilistic properties of multivariate hydrological events such as floods and storms. The bivariate extreme value distribution model with Gumbel marginals [16] can be used to represent the joint probability distribution of flood peaks and volumes and the joint probability distribution of flood volumes and durations based on the marginal distributions of these random variables, joint distributions, conditional probability functions, and associated return periods.

Flood information can be extracted from short-term records to estimate a long-term probability structure, similar to the well-known geographic technique whereby probability estimates from gauged rivers can be extended to ungauged areas in the same region [62,30,7]. The use of predictions in ungauged basins (PUB) over the last decade has also been useful [52,8,58]. In this case, annual floods exhibiting the Gumbel distribution can satisfactorily represent the probability distribution.

Durrans [13] presented a total probability method to establish the regulated flood frequency relationship immediately downstream of a regulating reservoir from the unregulated flood frequency relationship upstream of the reservoir. Silverman [53] and Lall and Bosworth [27] implemented the non-parametric multivariate kernel method to model the joint distribution of two correlated random variables.

Typically, many hydrological events follow a Gumbel distribution [54,2,55]. The study of Gumbel distributions constructed from specified Gumbel marginals may be helpful in examining hydrological events.

The severity of a flood is defined not only by its peak value but also by other aspects of the event such as its volume and duration. A flood event can be described as a multivariate event whose main characteristics can be summarized by its peak, volume, and duration, which are mutually related. However, flood frequency analysis has often concentrated on flood peaks (or magnitudes). Extensive reviews of flood frequency research were made by Cunnane [12] and Bobée and Rasmussen [6]. Flood peak analysis provides a limited assessment of flood events, whereas as thorough examination of many hydrological problems requires a detailed knowledge of numerous aspects of the flood event (e.g., flood peak, flood volume, flood duration, hydrograph shape). Many studies have addressed this issue [26,14,13,50].

Ashkar [3] considered a flood event to be a multivariate event and derived the relationships between flood peak, duration, and volume. Correia [11] deduced the joint distribution of flood peaks and durations using the partial duration series method (PDS) based on the assumptions that (i) both flood peaks and durations are exponentially distributed and (ii) the conditional distribution of flood peaks given flood duration is normal.

At this time, traditional physical modeling is commonly applied [4,46,43,51,35]. For hydrological and water resource models using a physical approach, and using high-resolution space-time distribution information, it has been possible to determine many external parameters such as the amount of water, the amount of evapotranspiration, river water levels, and the amount of sediment transport. On the other hand, water resource analysis using a statistical approach can increase our understanding of environmental contexts [50,61,66]. These approaches have played important roles in disaster prevention, the environment, and climate change prediction (e.g., Intergovernmental Panel on Climate Change [21]). In some communities, extreme flood events no longer result in disasters [42,49] because prevention strategies have been implemented such as the construction of structured rivers and levees [47,60]. Therefore, we addressed the probability of disaster occurrence by integrating the output of hydrological simulation and Gumbel distribution statistical approaches. This is a novel approach that has allowed us to provide the first typical index. Further modeling and framework efforts are underway to define the interactions among catchment management, ecosystems, disaster prevention, and economic values in the form of conditional probabilities. Normal, continuation uniform, beta, and gamma distributions are known as absolute continuation distributions. A normal distribution is assumed in natural and statistical fields because of the central limit theorem. In probability theory and statistical fields, the gamma distribution is a continuous probability distribution and is often applied to statistical analysis in reliability engineering and hydrology.

The present study aimed to (1) estimate the probability of flood disaster occurrence associated with flood inundation and sediment disaster using the Total Runoff Integrating Pathways (TRIP) model for Japan (J-TRIP) and (2) analyze the relationship between social factors and the probability of flood disaster occurrence, incorporating the effects of population density, flood control measures, and extreme flood events. The methodology used here can also be applied to study other natural disasters. The results are expected to provide a useful reference for decision making regarding flood disaster prevention and sustainable development planning. In addition, the flood disaster occurrence probability (FDOP) index can aid in developing a compensation plan for a disaster area.

2. Definition of FDOP

The definition of FDOP is the basis for studies on flood risk. Most researchers consider that risk is the probability of occurrence of adverse events and the seriousness of their possible after effects. A disaster is defined as the situation created by a hazard (e.g., flood) acting upon certain entities in a specific environment [44,34]. Based on this definition of disaster occurrence probability, the adverse event involved in flood risk is the flood and the after effect is the situation after flood withdrawal, namely the disaster situation. Therefore, FDOP refers to the occurrence probability of floods with different intensities and the likely flood withdrawal. Three major aspects are involved: (1) the flood—measurement of the characteristics and magnitude of the flood, such as the highest water level, the flood peak discharge, the incremental grade of flood volume, and the conditions for flooding; (2) probability—the occurrence probability of the flood event mainly denotes the occurrence frequency and the recurrence interval of those flood events, incorporating the effects of flood inundation and sediment disasters that exceed a certain grade or numerical value; and (3) loss—the potential loss caused by the flooding, including casualties and social impact. Analysis of FDOP examines the probable distribution of flood loss (or of the disaster situation).

3. Methods

3.1. Data collection and statistical procedures

Flood disaster statistics (MLIT, 1976–2004) from the River Bureau of the Ministry of Land, Infrastructure and Transport (MLIT) were used as the flood disaster data. These data include information on accrual flood onset date, end date, abnormal weather, names and addresses of affected persons and properties, cause of damage, damage information, and general descriptions of flood disasters for the whole of Japan. The database includes information on flood, inundation, tidal wave, tsunami, debris flow, and landslide events (Table 1). To obtain disaster statistics, the MLIT surveyed prefectures and cities, towns, and villages and calculated the amount of flood damage. The survey objects consisted of (1) flood damage to assets, (2) flood damage to public facilities, and (3) flood damage to public utilities. This study focused on flood damage to assets. Specifically, assets refer to a house, household property, business properties, and agricultural products. Information about flood damage to such assets, including the overall area in which damage occurred as well as the amount of damage, was compiled. These statistics can be applied to any investigation of flood damage, regardless of the scale of the flood disaster. In the flood disaster statistics, the flood is named after a city, town, or village in the region, as shown in Table 1. Vulnerability parameters are selected from a group of parameters covering a wide range of attributes such as economy, health, land cover, population, rivers and vegetation. The three candidate parameters (see Table 1 for the list of parameters and data sources) were chosen based on their consistency and availability for Japan. For example, some parameters such as flood dike construction were included because this information is available throughout Japan. Although most regions may have their own data on flood dikes, the definition of a flood dike as well as the accuracy and specification of the data are consistent among regions. The following five-step screening procedure was conducted on the three candidate parameters (Table 1) to reduce the total number of parameters and improve their ability to represent flood vulnerability: (1) minimize the dependence among selected parameters; if several candidate parameters were highly correlated, only one of them was retained for further testing. This step was necessary to prevent biased results because the redundancy among intercorrelated vulnerability parameters may affect the regressed relationship and their sensitivity to

Table 1
Nine selected flood disasters included in the survey of extreme events and flood disasters in 1976. Data are from the Japan Meteorological Agency (JMA) and the Ministry of Land, Infrastructure, and Transport (MLIT).

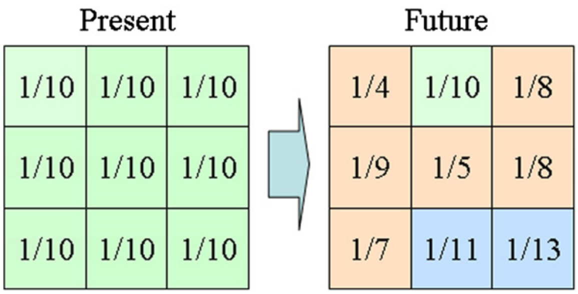
Year	Date of event onset	End of event	Extreme weather event	Region	Cause of flood disaster
1976	7/9/1976	14/9/1976	T7617, heavy rain	Handa-shi, Aichi, Japan	Dyke break
1976	7/9/1976	14/9/1976	T7617, heavy rain	Agui-cho, Aichi, Japan	Dyke break
1976	7/9/1976	14/9/1976	T7617, heavy rain	Isshiki-cho, Aichi, Japan	Flood inundation inside a levee
1976	7/9/1976	14/9/1976	T7617, heavy rain	Tokoname-shi, Aichi, Japan	Overflow stream divided with a levee
1976	7/9/1976	14/9/1976	T7617, heavy rain	Mihama-cho, Aichi, Japan	Overflow stream divided with a levee
1976	18/10/1976	21/10/1976	Heavy rain, ocean waves, wind gusts	Noboribetsu-shi, Hokkaido, Japan	Overflow stream divided with a levee
1976	18/10/1976	21/10/1976	Heavy rain, ocean waves, wind gusts	Monbetsu-cho, Hokkaido, Japan	Overflow stream without a levee
1976	19/5/1976	21/7/1976	T7609, heavy rain	Ago-cho, Mie, Japan	Flood inundation inside a levee
1976	1/8/1976	16/8/1976	Heavy rain	Yamagata city-owned wholesale market, Yamagata, Japan	Flood inundation without a levee

flood damage parameters. (2) Spatial coverage of parameters; the available data on the parameters must cover all of Japan. (3) Temporal coverage of parameters; the available data on the parameters must cover the target period (1976–2004). (4) Rationality of parameters; the selected parameters must have a logical relationship to flooding. (5) Utility for political implications; the selected parameters need to be useful for policymaking regarding flood damage mitigation. While steps (1)–(3) can be tested objectively, steps (4) and (5) have to be judged by referring to related documents and reports. If a certain parameter is known to have a logical association with floods, it is treated here as an appropriate parameter in step (4). Similarly, if a certain parameter is considered useful for establishing flood mitigation policies then it is treated as an appropriate parameter in step (5). Finally, the parameters that fulfill the test in step (1) and at least three of the remaining four tests are selected as final candidate parameters, as highlighted in Table 1 as bold.

Therefore, the latitude and longitude of each city, town, and village were also compiled, and the flood was treated in whichever model grid contained that latitude and longitude coordinate. The latitude and longitude for the cities, towns, and villages were obtained using Geocoding Tools & Utilities, developed by the Center for Spatial Information Science at the University of Tokyo [64].

3.2. Calculation method

The future FDOP by river water inundation was estimated using simulated river discharge computed for the three periods from 1981–2000, 2031–2050, and 2081–2100. As described in Section 2, based on the calculated return period of the river discharge and precipitation, the return period of river discharge was calculated in three periods for the whole region of Japan. The applied probability distribution function parameter (the Gumbel distribution) exists individually by each grid. Thus the intensity of discharge by this frequency differs for every grid, and the future change in frequency also differs for every grid. For example, the excess probability of 1/10 was assumed for all the grids using discharge for the period 1981–2000 (Fig. 1). The excess probabilities for the future periods (2031–2050, 2081–2100) of discharge change to 1/4 or 1/8. The average value of the individually calculated future discharge excess probabilities is considered the discharge excess probability for all of Japan.



1/10	1/10	1/10
1/10	1/10	1/10
1/10	1/10	1/10

1/4	1/10	1/8
1/9	1/5	1/8
1/7	1/11	1/13

Fig. 1. Conceptual diagram of future changes in river discharge frequency. The intensity of discharge of this frequency and the future changes in frequency differ for each grid.

3.3. Description of external forces

River discharge data were used to estimate inundation by river water, precipitation data were used to estimate inundation inside a levee, and river discharge data were used to estimate sediment disaster. These indices were chosen for the following reasons. Inundation by river water is mainly caused by overflow from a river and/or a dyke break, making river discharge an appropriate index in this case. Inundation inside a levee is influenced by rainfall at the occurrence point of the flooding disaster. Any increase in soil moisture had a major influence on sediment-related disasters [22,35–37]. Therefore, river discharge, which showed a strong correlation with the amount of soil moisture, was used as an index for sediment disasters. Simulated values of river discharge in 0.1-degree grids by J-TRIP were used as the river discharge data [43]. The precipitation amount was produced by spatial interpolation using the ‘inverse distance to a power’ method for data collected from 1976 to 2004 by Japan's Automated Meteorological Data Acquisition System (AMeDAS) (as hourly precipitation data). The observation point value was then expanded to a grid point value [64]. External forces of flood disasters associated with flood inundation inside a levee, flood disaster by river water, and sediment disaster was defined using the Basic Law of Natural Disasters [24]. TRIP [46] was used for river routing calculations to convert runoff from LSMs into river discharge. Details are described in Oki et al. [43], but basically the estimated annual discharge corresponded with real observations of parameters such as rainfall [45]. Compared to Oki et al. [43], the river discharge in our study is smaller than previous estimates by approximately 20%, which needs to be improved. This method incorporates the canopy as a single layer, whose albedo and bulk coefficients were evaluated based on a multilayer canopy model. Fluxes were calculated from the energy balance at the ground and canopy surfaces in snow-free and snow-covered areas considering the sub-grid snow distribution. Interception evaporation from the canopy and transpiration based on photosynthesis were also evaluated. A simplified TOPMODEL was used to calculate runoff [5]. Snow has a variable number of layers from one to three in accordance with the snow water equivalent (SWE), and the snow temperature was calculated using a thermal conduction equation. The snowmelt, refreeze of snowmelt, and the freeze of rainfall in snow were also taken into consideration.

3.4. Flood disaster classification

Flood disaster statistics include information on floods, inundations, tidal waves, tsunamis, debris flows and landslides. In this study, the flood disasters were re-classified into inundation by river water, inundation inside a levee, and sediment-related disasters (Table 2), and the FDOP was calculated for each. Tidal wave and tsunami investigations were carried out as a separate part of the study.

3.5. Calculation of the return period for river discharge and precipitation

From the daily discharge (a total of 10,593 days) of each grid from 1976 to 2004 calculated by J-TRIP, the annual maximum daily discharge was extracted for 29 years. The data were assumed to follow the Gumbel distribution. According to extreme value theory, the cumulative distribution function (CDF), probability density function (PDF), and parameters can be expressed by the following formulae.

$$F(x) = \exp[-\exp\{-a(x-b)\}] \tag{1}$$

$$f(x) = a\ \exp[-a(x-b)-\exp\{-a(x-b)\}] \tag{2}$$

$$a = \frac{\sqrt{6}\pi}{6\sigma} \tag{3}$$

$$b = \mu\frac{0.5772}{a} \tag{4}$$

where $F(x)$ is the CDF, $f(x)$ is the PDF, μ is the average of annual maximum daily discharge, and σ is the standard deviation (SD).

In the CDF of the Gumbel distribution, parameters β and μ are expressed as follows [64]:

$$F(x) = \exp(-\lambda(1-G(x))) = \exp\left(-\exp\left(-\frac{x-\mu}{\beta}\right)\right) \tag{5}$$

$$\beta = \frac{1}{M}\sum_{i=1}^{M}(x_i - x_M) \tag{6}$$

$$\mu = x_M + \beta \ln \lambda \tag{7}$$

where x is the river discharge, $F(x)$ is the CDF, x_M is the threshold value of river discharge, N is the number of years, M is the number of data exceeding a threshold value, and λ is the number of times of annual average occurrence that the data exceed a threshold value ($\lambda = M/N$).

The formula of the Gumbel distribution was formed from Eqs. (1) and (5) and was determined with two kinds of maximum data extraction methods. Probabilities which do not exceed the probable hydrological value x for a certain year (nonexceedance probability) are expressed as

$$\int_0^x f(x)dx = F(x) \tag{8}$$

Therefore, when the exceedance probability is set to $W(x)$,

$$W(x) = 1 - F(x) \tag{9}$$

Since the return period is a reciprocal of exceedance probability, return period T is calculated as

$$T = \frac{1}{W(x)} = \frac{1}{1-F(x)} \tag{10}$$

According to the above process, the parameters a and b of the CDF and PDF in each grid were determined using

Table 2
Classification of flood disasters associated with flood inundation inside a levee, flood disaster by river water, and sediment-related disasters.

Classification of flood disaster	Flood inundation inside a levee	Flood inundation by river water	Sediment disaster
External force	Precipitation	River discharge	River discharge
Individual flood disaster	Flood inundation inside a levee	Dyke break	Debris flow
	Flood inundation inside a levee of depressed ground	Overflow stream divided with a levee	Landslide
		Overflow stream without a levee	Collapse in steep slope areas
		Flood inundation without a levee	
		Scour, wash out	

annual maximum daily discharge. The return period for river discharge and precipitation in all grids for the whole region of Japan were calculated using the obtained formula for all days of 29 years from 1976 to 2004 (10,593 days). Having judged the goodness of fit of the Gumbel distribution to the annual maximum value using the standard least-squares criterion (SLSC), the average SLSC value for the whole of Japan for river discharge and precipitation was 0.04. Because a sufficient goodness of fit is considered to be around SLSC=0.04, the Gumbel distribution was applicable [33,64].

3.6. Estimation of flood occurrence probability

FDOP is based on how often damage actually occurs out of the total number external force events with a certain occurrence probability of causing flooding. The count method used for determining the occurrence of river discharge and inundation by river water is described below; the same count method was used for precipitation and inundation within a levee.

3.6.1. Occurrence of external forces

The occurrence of certain events was counted over 29 years (from 1976 to 2004) for a particular occurrence probability of river discharge. The return period of the river discharge over 29 years (10,593 days) was calculated and classified for each year based on a 100-year return period. The sum total of the number of times of occurrence of daily discharge, for each grid, was calculated for every value. For example, in a certain grid, the return period of simulated daily discharge for 1 year was 10,578 times, the return period of a simulated daily discharge for 2 years was five times, and the return period of a simulated daily discharge for 3 years was three times.

3.6.2 The occurrence frequency of flood disasters

To consider the error in the peak timing of simulated river discharge using TRIP-simulated and observed river discharge, flood occurrence (maximum daily discharge) was used to denote the discharge amount responsible for the flood damage. We examined each grid in which flooding occurred, the bottom wholly as the cause of flood occurrence. Discharge was extracted and changed into the return period of river discharge mentioned above. The number of times in which flood disasters were caused by the return period of river discharge of a certain amount was also counted for each grid.

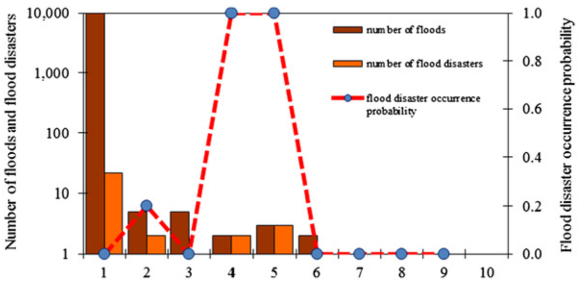


Fig. 2. Conceptual diagram of flood disaster occurrence probability. Brown bars show the number of high flows classified into each return period. Orange bars show the number of flood events for which damages are officially reported. Flood disaster occurrence probability is calculated by dividing the number of flood disasters by the number of external force events. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

3.6.3 Calculation of FDOP

FDOP refers to the number of times flood disasters occur divided by the number of times that certain external forces occur. For example, daily discharge corresponding to a return period of river discharge of 2 years was observed five times between 1976 and 2004 in a particular grid. For this grid, when 1 time is connected with damage before long, it sets to the grid, when daily discharge of return period of the river discharge of 2 years arises, the probability that disaster will occur is set to "1/5=0.2." A conceptual diagram of the above calculation is shown in Fig. 2.

4. Results

4.1. Estimating FDOP for Japan

According to the flood disaster statistics (MLIT, 1976–2004), the period between flood disaster onset and end dates was generally 1 week or more before 1993, but has more recently become 2–3 weeks; 1993 may mark a change in the length of flood disaster periods. Thus, to calculate the FDOP, we used data only from 1993 onward (from 1993 to 2004 in this study).

4.1.1. River discharge index

Okazawa [42] computed the relationship between flood damage risk, population, the concentration of property and the presence of infrastructure maintenance, which showed how much damage a flood would cause, as well as many other factors such as land use and inclination. The influence was also examined, and the social brittleness reflected features of both the increased rainfall/flux and the land (which is a direct factor of a flood) as well as the fact that a local resident can cause significant damage. Hara et al. [18] developed the Flood Vulnerability Index (FVI) to assess flood risks. This index assesses the vulnerability to flood disasters that can be applied at the river-basin scale. It consists of a precipitation factor and three components, namely, hydrogeographic factors, socio-economic factors, and countermeasures. These major components were selected based on factor diagram analysis in terms of flood disasters. Then the FVI values were estimated using multiple linear regression analysis for the major river basins around the world. Three elements of urbanization including the average rate of inclination, the number of accrual dates, and the amount of heavy rain in the main valleys were evaluated using multiple linear regression analysis, which converted the purpose variables (as well as the number of flood damage victims) into explaining variables. The United Nations Development Program (UNDP) [57] explains the variables and death toll purpose variables for the amount of exposure (average population that encountered the disaster event) and population density based on damage information from the Emergency Event Database (EM-DAT), which is a global disaster database. The Disaster Risk Index (DRI), which is used to estimate the average death toll by country for every type of disaster, was developed based on natural factors and social effects, and it shows the damage that natural phenomena such as floods and earthquakes actually cause. In the present study, quantitative evaluation was not performed to determine whether floods were actually associated with damage. That is, discussing a flood as a natural phenomenon and discussing flood damage are two different things. The DRI does not assume that flood frequency is associated with flood damage. Moreover, when the intensity of an external force is below a designated value, damage may not necessarily occur. Therefore, it is possible to treat flooding as a stochastic phenomenon regarding flood damage. Hence, to generate realistic information, flood damage was examined to quantitatively evaluate the occurrence probability of damage. Here, the number of times damage was actually generated compared to the frequency of external forces (e.g., a flood or heavy rain) was called the disaster occurrence probability. The disaster occurrence probability (especially in the flood damage field) is typically referred to as the DFOP. Because the object of this study was flood damage, these two concepts were unified into this one term.

FDOP for inundation by river water and sediment disasters was determined by calculations using simulated river discharge. When FDOP was considered for each individual 0.1-degree grid, the number of examples of flood damage was not sufficient for statistical analysis (e.g., see Fig. 3). Therefore, it was difficult to determine the tendency of flood occurrence. River discharge values were obtained using the simulated result of J-TRIP at a 0.1-degree resolution [46]. Typically, observational data are ideal for analysis and validation. However, observational data are limited; on the other hand, the simulation results of J-TRIP and river discharge data can be obtained for grid cells in the Japanese region. Also, the simulation results of J-TRIP were validated, especially during flood onset, at the end of events and at the flood peak [41]. To clarify the relationship between the return period of river discharge and FDOP, we expanded the range to a wider area than a 0.1-degree grid to secure a sufficient number of flood disaster examples. To grasp the relationship between the return period of river discharge and FDOP for all of Japan, for every return period of river discharge, the number of times that discharge occurred and the number of times flood disasters occurred over all the grids were included. FDOP was calculated by adding the total number of discharges and flood disasters that occurred in all grids. Even if equal rainfall and discharge were observed, a difference in the climate or infrastructure maintenance of a specific region resulted in different damage levels. Thus, areas with low levels of observed rainfall or discharge still influenced flood damage. The flood damage origin and catchment area differed based on the climate conditions during the analysis. This resulted in the occurrence probability of the discharge model, which cannot be easily influenced by an index error of the external force. We used rainfall observational data from the Automated Meteorological Data Acquisition System (AMeDAS) in space using the reverse-distance weighting method, which was developed from an observation point to a lattice point [31,48].

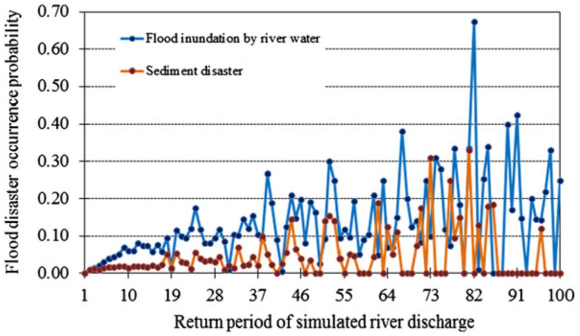


Fig. 3. Predicted flood disaster occurrence probability; the dark blue line shows inundation by river water and the brown line shows sediment-related disasters. (For interpretation of the (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)references to color in this figure caption, the reader is referred to the web version of this article.)

The results are shown in Fig. 4. In these results showing the calculated FDOP, the blue lines represent the inundation by river water while the brown lines show the sediment-related disasters. This graph shows the return period of river discharge of FDOP over 1–20 years; as the return period of the river discharge increases, the flood disaster classification gradually increases from 0.0 to 0.1. That is, the probability that a disaster will occur at a time of rare discharge generation is shown. In a range for 20 years or more, the variation in probability was large for every return period of river discharge. Statistical characteristics will be controlled by this feature.

Next, the *x*-axis was changed to model the exceedance probability of river discharge, and the results classified with a class width of 0.05 are shown (Fig. 5). The model exceedance probability of river discharge expresses the probability that discharge exceeds the flood level value in a certain year. That is, it is defined as a reciprocal of the

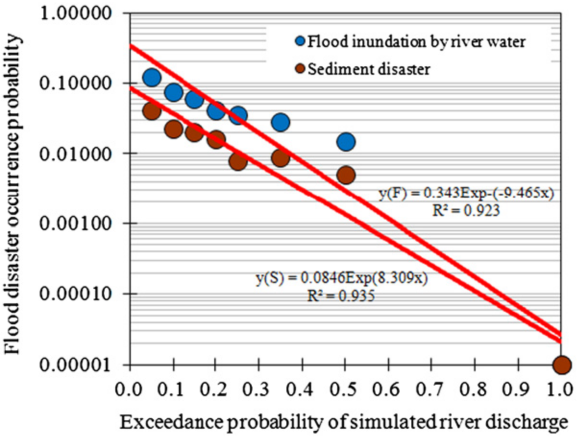


Fig. 4. Predicted flood disaster occurrence probability for all of Japan. Blue dots show inundation by river water and brown dots show sediment-related disasters. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

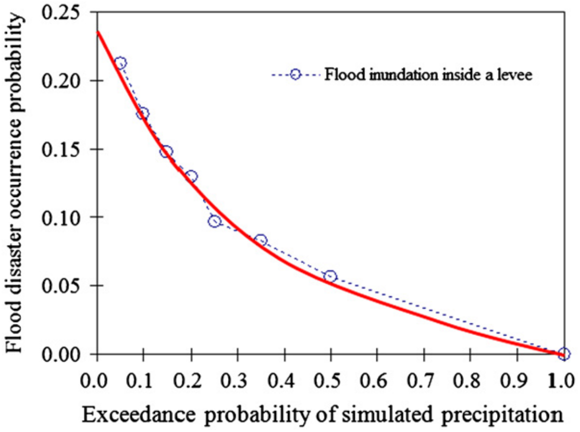


Fig. 5. Predicted flood disaster occurrence probability for all of Japan; dark blue dots show inundation inside a levee. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

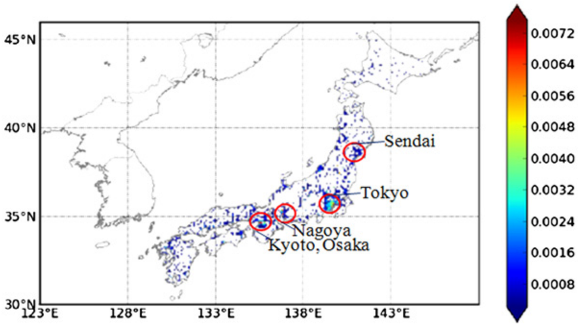


Fig. 6. Predicted flood disaster occurrence probability distribution of flood inundation inside a levee for all of Japan with a precipitation return period of 1–2 years.

return period of the river discharge. Sequentially from the larger one, FDOP is the inundation by river water and sediment disasters. The tendency for flooding increases exponentially as the exceedance probability of river discharge decreases.

4.1.2. *Precipitation index*

This section presents the FDOP of inundation inside a levee calculated using observed precipitation data. In Fig. 6 the *x*-axis denotes the exceedance probability of precipitation and results having a total probability width of 0.05 are shown. Sequentially from the largest disaster, FDOP is inundation inside a levee. The potential for disaster increases as the exceedance probability of precipitation decreases. As mentioned above, this study newly calculated the probability of flood disaster occurrence by equalizing the whole region of Japan based on the exceedance probability. While it is generally difficult to calculate the probability of flood at the time of rare external generating forces in an individual river, by standardizing the exceedance probability of simulated discharge or observed precipitation and using data for all of Japan, we can obtain a quantitative expression of flood damage.

4.2. *Difference in FDOP by various factors*

Even if events such as heavy rain, flood, and sediment disaster do not cause damage, they add to natural factors such as precipitation and river discharge, which can have various social effects such as those related to infrastructure maintenance, population, and distribution of property and land use. This section examines how FDOP changes with differences in the population density and river improvement maintenance ratio. Moreover, we consider how future climate change may also alter the probability of flood disaster.

4.2.1. *Differences caused by population*

At this time, flooding is one of the most globally serious natural disasters. According to the World Bank [63], regions affected by floods during 1985–2003 accounted for more than one third of the Earth's surface, inhabited by more than 82% of the world's population.

Floods can be caused by various events, such as intense precipitation resulting in drastic increases in river discharge, snowmelt, ice-jam, glacial lake outburst, and so forth. However, the degree of damage caused by floods in a specific region is dependent on many natural and socio-economic factors, such as the density of a population and assets, land use, infrastructure development (e.g., dikes and dams), and the speed and accuracy of information transmission (e.g., early-warning systems). However, the relationships between these factors and associated flood risk have not been fully investigated. Here, flood risk is defined as the possibility of damage from flooding. Quantifying flood risk from various natural and socio-economic factors will allow us to assess how flood risk changes corresponding to changes in the population, climate and land-use conditions, and also how the policy of flood damage mitigation can potentially reduce the flood risk. The present study aims to improve the limitations of previous flood risk studies by developing a new global flood risk index that incorporates both natural and socio-economic factors. The newly developed index is referred to as the FDOP, which quantifies the expected value of damage caused by a single flood occurrence and focuses on the event scale instead of the long-term statistical trend of floods. The FDOP is a function of the metrics of flood hazard and vulnerability stratified by different flood-generating mechanisms (i.e., flood types), estimated using a simple regression approach based on available global gridded data sets of influencing factors. It can be used to predict potential future flood damage, and the derived regression relationship between the FDOP and dependent factors are also valid to test the sensitivity of flood damage to changes in population, land cover and urbanization incorporating the effect of population. One reason could be that, in regions of increased population density with a high concentration of assets, disaster mitigation measures are likely to be implemented more effectively prior to disaster occurrence. This agrees with the concept of compact city development, where infrastructure investment is concentrated and cost-effective.

Fig. 7 shows the FDOP of inundation inside a levee in all of Japan at the time of precipitation generating a

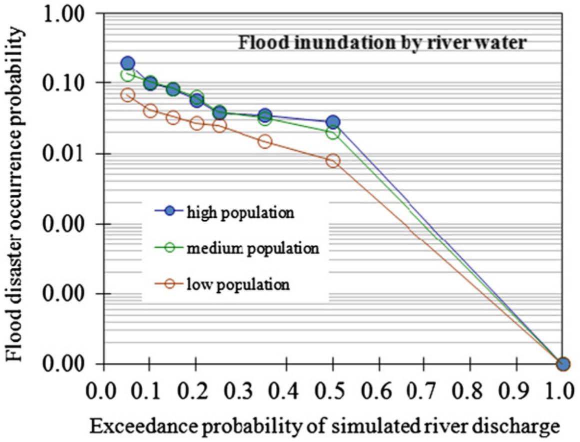


Fig. 7. Predicted flood disaster occurrence probability for flood inundation by river water for all of Japan. Blue, green, and brown dots denote high, medium, and low population densities, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

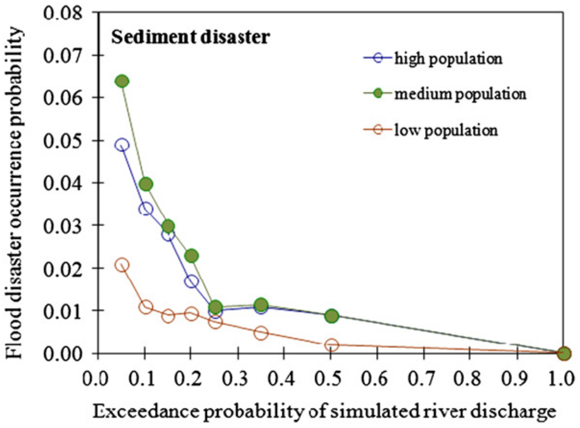


Fig. 8. Predicted flood disaster occurrence probability for sediment-related disasters for all of Japan. Blue, green, and brown dots show high, medium, and low population densities, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

1-year return period. In large cities, such as Tokyo, Nagoya, and Osaka, the probability of flood disaster occurrence is relatively large. To examine differences according to population and FDOP, we classified Japan according to population per grid and looked at inundation by river water, inundation inside a levee, and sediment disasters.

Population data were obtained from the Center for International Earth Science Information Network (CIESIN) Gridded Population of the World, Version 3 (GPWv3) database [19,38,39]. Based on the population distributed in the 0.1-degree grids from these data, the grids were classified into three categories according to population size, such that the number of grids in each category was approximately equal. The categories were as follows: 0–3000 persons/grid (low population density), 3000–13,000 persons/grid (medium population density), and 13,000 or more persons/grid (high population density).

Figs. 8–10 show the difference in FDOP for the population categories. The figures indicate that the distribution of population has a large influence on FDOP. Furthermore, flood damage generated by inundation inside a levee is more affected by population than are inundation by river water and sediment disaster. River development projects have been implemented to control river discharge floods of 10-year frequency, building on experience from past extreme flood events. River improvement maintenance has been performed by the MLIT. On the other hand, there are fewer projects to control urban flood damage caused by inundation inside a levee. Even if projects are in place to cope with inundation inside a levee, the results cannot be completely known as it is difficult to totally prevent flood disaster occurrence.

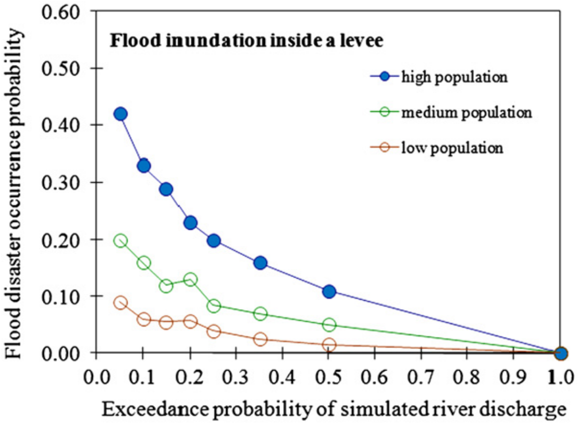


Fig. 9. Predicted flood disaster occurrence probability for flood inundation inside a levee for all of Japan. Blue, green, and brown dots show high, medium, and low population densities, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

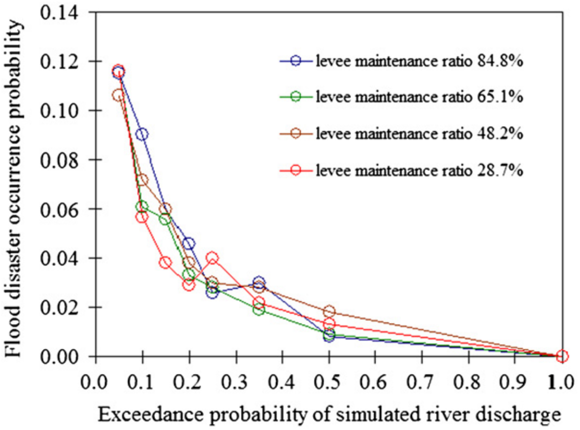


Fig. 10. Predicted flood disaster occurrence probability and the levee development index for all of Japan. The flood disaster occurrence probability is calculated by incorporating the effects of all disaster types. Blue, green, brown, and red dots represent levee maintenance ratios of 84.8%, 65.1%, 48.2%, and 28.7%, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

4.2.2. *Difference caused by flood control policies*

This section examines the effect of flood control policy on FDOP from the viewpoint of levee and dam maintenance, focusing mainly on flood inundation by river water. Here, the probability of flood disaster calculated using the simulated river discharge index is shown. Data on river improvement measures by the MLIT were also used in the analysis.

4.2.2.1. Planning scale. The planning scale is set for rivers under direct control by the MLIT, namely 109 rivers in Japan. To verify the benefits of differences in flood control, basins with the same plan scale level should be compared. For this analysis, 80 basins with 100-year planning scales were examined.

4.2.2.2. Differences arising from the levee maintenance ratio. The levee maintenance ratio is defined as the ratio of maintained levees to all those needing extension in a MLIT river maintenance plan. Using this levee maintenance ratio as an index of levee maintenance progress, we can evaluate how FDOP differs in catchments of varying degrees of levee maintenance progress. The Handbook of Rivers [23] lists 109 rivers under direct control by the MLIT; on these, levees are described as “completed”, “completed to the high water level”, and “incomplete”, with each levee extension given in kilometers (Table 3). Levee distance (km) is the sum-total length of both banks. The levee maintenance ratio was calculated for every catchment, as shown in the rightmost column of Table 3. Bold letters indicate that the levee maintenance ratio in a catchment exceeded 58.0% of the national average levee maintenance ratio. The levee maintenance ratio was calculated for approximately 80 catchments having 100-year flood plans, among the 109 rivers directly controlled by the MLIT. These approximately 80 catchments were classified according to their calculated levee maintenance ratio and the FDOP is shown (Fig. 11).

4.2.2.3. Difference arising from the dam maintenance ratio. A dam maintenance ratio is the ratio of the volume capacity of an already completed dam to the flood control volume targeted in the catchment plan. Information on the dam maintenance ratio was available for about 41 catchments in the Handbook of Rivers [23]. Because of the small number of samples, FDOP was divided into only two categories, separated at a dam maintenance ratio of 62.2% (Fig. 12). Although no large difference was found for flux larger than 0.05, for flux of 0.05 or less (rarer than once in 20 years), flood damage probability was approximately two times greater with a dam maintenance ratio of 62.2% or less. This effect explains the reduction in flood peaks at a dam.

4.2.3. *The effect of external force frequency*

The changing climate is expected to result in more episodes of heavy rain and flooding in some regions [21]. This section examines how increases in the frequency of external forces may affect FDOP. Here, the probability of flood inundation by river water was calculated using presumed future river discharge.

Table 3
Thirteen selected flood disasters included in the survey of extreme events and flood disasters in 1976. Data were obtained from the Japan Meteorological Agency (JMA) and the Ministry of Land, Infrastructure, Transport (MLIT).

Name of river	Distance of levee (km)			Levee maintenance ratio (%)
	Completed	Completed to high water level	Incomplete	
Ishikari River	715.5	230.7	144.7	65.59
Shiribetsu River	28.0	3.9	0.0	87.77
Toshibetsu River	56.9	0.2	3.4	94.05
Mukawa River	31.8	2.4	6.7	77.75
Saru River	14.6	7.4	2.0	60.83
Tokachi River	207.3	175.4	17.4	51.81
Kushiro River	56.8	22.9	37.7	48.38
Abashiri River	49.1	9.2	6.2	76.12
Tokoro River	120.4	8.6	6.2	89.05
Yubetsu River	34.6	7.7	0.4	81.03
Shokotsu River	24.0	0.0	0.0	100.00
Teshio River	141.5	144.8	33.7	44.22
Rumoi River	12.3	0.0	12.4	49.80

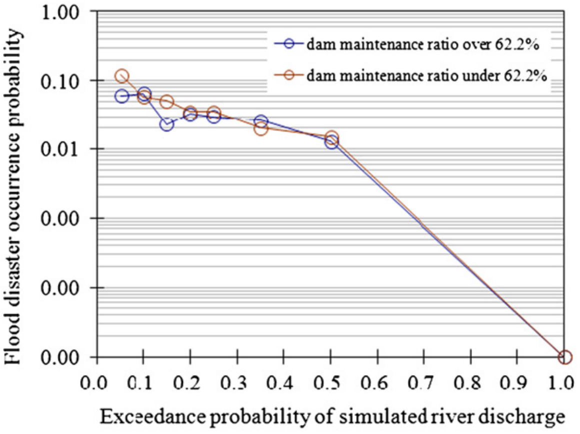


Fig. 11. Predicted flood disaster occurrence probability and the dam maintenance ratio for all of Japan. Blue dots indicate a dam maintenance ratio over 62.2%, and brown dots represent a dam maintenance ratio under 62.2%. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

4.2.3.1. Change in external force frequency. Discharge corresponding to the return periods of river discharge for the 100-year periods from 1981 to 2000 and from 2081 to 2100 and the ratio of change in discharge by year is shown in Fig. 13 [40]. The climate data were created from the local climate model RCM20 of the Meteorological Research

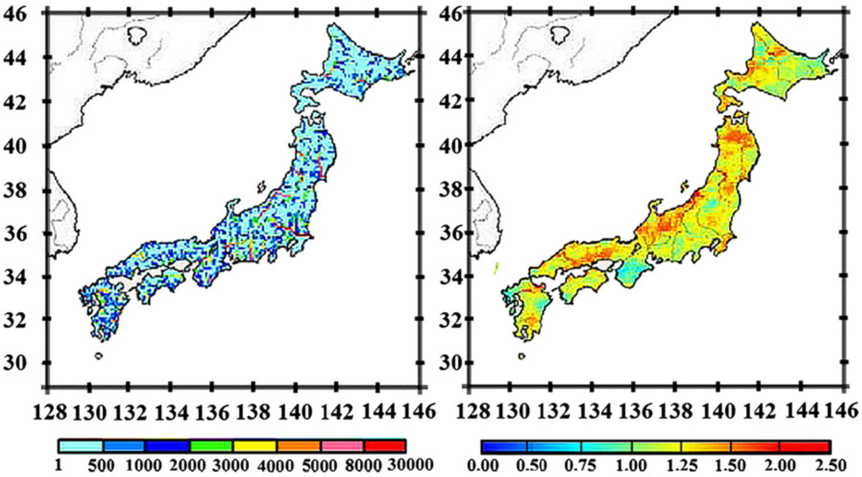


Fig. 12. Predicted flood disaster occurrence probability distribution for flood inundation inside a levee for all of Japan with a precipitation return period of 1–2 years. The right panel shows the discharge response to a 100-year return period of river discharge and the left panel shows the change ratio to a 100-year return period of river discharge.

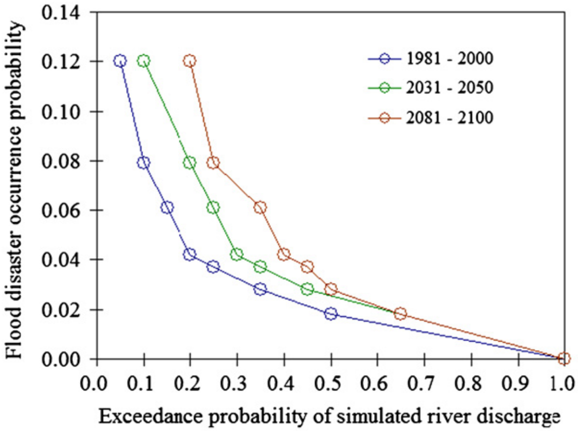


Fig. 13. Predicted flood disaster occurrence probability in the 21st century for all of Japan. Blue, green, and brown dots show the periods from 1981–2000, 2031–2050, and 2081–2100, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Institute of the Japan Meteorological Agency. River discharge was calculated by the land surface process model Iso-MATSIRO and the amount of outflow was input to J-TRIP. The result showed that the 100-year probability of discharge for 2081–2100 was much larger than that for 1981–2000. This suggests that the external generating forces will occur more frequently in 2081–2100 period and could, for example, change the frequency from a 100-year frequency to a 50-year frequency. Change of FDOP was then calculated considering this change in discharge occurrence frequency.

4.2.3.2. Estimation result. Fig. 13 shows the estimated future changes in FDOP for inundation by river water. Unless special adaptation measures are adopted in this century, FDOP will increase over time. This change is seen horizontally in the figure; for example, discharge equivalent to the present excess probability of 0.10 changes to excess probability of approximately 0.20 in 2031–2050 and approximately 0.25 in 2081–2100. This suggests that flood disaster occurrence will also increase in frequency in the future. Moreover, change is also seen vertically in the figure; for example, the absolute value of discharge equivalent to excess probability of 0.25 increases over time. Therefore, although FDOP at the time of discharge occurrence equivalent to excess probability of 0.25 is about 0.036 now, it will change to about 0.06 in 2031–2050 and to about 0.08 in 2081–2100. Thus, the discharge produced at a frequency comparable to that at present can be interpreted as a higher FDOP in the future. The technique used in this section enabled us to relate change in the external generating-force frequency with change of FDOP.

5. Discussion and conclusions

In flood damage risk assessment, a broad damage risk item is established and the mechanism of damage generation and a relationship with hazards are clarified based on the previous literature for every evaluation criterion. When this process is difficult, it is evaluated qualitatively, and the global picture of flood damage can be understood. In addition, a scenario regarding a point that does not provide sufficient information on the mechanism of damage generation is shown clearly as a precondition of evaluation. This information is combined by collecting and arranging precipitation data. Based on this result, conditions such as the maintenance of external forces, rain, the year of evaluation, and river improvement institutions are established. Also, water sentence analysis and water vein analysis of the flood style in a river are conducted, and the scale and occurrence probability of a hazard, such as the river flow rate, water level, the flood range of the area within a flood, the temporal response of the water level, and flood continuation time, are analyzed. Next, the social conditions combined with the year of evaluation are established. That is, the population in a flood region is evaluated. Flood damage risk can be combined with disaster occurrence probability to evaluate these damage phenomena [1,32].

This paper calculated the probability of flooding disasters. Using a short time series of historical flood data, flood disaster risk was estimated for all of Japan using J-TRIP, a model with superior performance compared to traditional physical and statistical models. The main research achievements are summarized below.

1. FDOP was calculated for all of Japan according to disaster factors associated with flood inundation and sediment disasters.
   - FDOP was calculated by using the J-TRIP model with a 0.1-degree grid, according to the generating mechanism of each type of flood disaster. Even with the same discharge intensity, differences in FDOP were shown to differ by area and social characteristics.
   - The average FDOP was calculated for all of Japan. The results for inundation by river water, inundation inside a levee, and sediment disaster showed that large external forces increase the probability of flood disaster occurrence exponentially. The results provide a base for policy aimed at all of Japan as a macro target and an effective index for planning policy.
2. The results revealed correlation between social factors and FDOP.
   - FDOP differed by population category. In particular, population had a remarkable influence on flood inundation inside a levee, and the results quantitatively showed that regions with high population density have a high probability of suffering damage. As a result the effect of flood inundation by river water, the difference in the characteristic of flood inundation inside a levee, and the traditional measures and policies resulting was indicated.
   - The difference in FDOP according to differences in level of flood protection was also calculated. The largest difference was not shown to be dependent on the levee maintenance ratio. However, with regard to the dam maintenance ratio, the FDOP was shown to double when large external force occurred.
   - Furthermore, future changes in FDOP according to changes in external force frequency were estimated. The results show a linear increase in FDOP in the 21st century. Future studies should extend this research by estimating the number of flood victims and amount of damage for use in designing policies covering all of Japan. The uniqueness of the new FDOP is that not only the hazard parameters that directly influence flood occurrence but also the vulnerability parameters are quantitatively represented. Moreover, it can also be applied as an objective tool to assess flood adaptation policies. For example, changes in the expected flood damage due to alterations in land use can be predicted, and subsequently the results can be used as guidelines for future urban planning. Another example is for policy makers to predict the relationships between socio-economic change (e.g., population and economic growth) and flood damage, which can be applied to estimate the expected damage from future floods and evaluate potential economic losses and the required investments to reduce losses. This in turn can lead to more accurate cost–benefit analyses and more appropriate budget allocation.

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