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

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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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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.

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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.

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