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A rainfall design method for spatial flood risk assessment: considering multiple flood sources

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Abstract

Information about the spatial distribution of flood risk is important for integrated urban flood risk management. Focusing on urban areas, spatial flood risk assessment must reflect all risk information derived from multiple flood sources: rivers, drainage, coastal flooding etc. that may affect the area. However, conventional flood risk assessment deals with each flood source independently, which leads to an underestimation of flood risk in the floodplain. Even in floodplains that have no risk from coastal flooding, flooding from river channels and inundation caused by insufficient drainage capacity should be considered simultaneously. For integrated flood risk management, it is necessary to establish a methodology to estimate flood risk distribution across a floodplain. In this paper, a rainfall design method for spatial flood risk assessment, which considers the joint effects of multiple flood sources, is proposed. The concept of critical rainfall duration determined by the concentration time of flooding is introduced to connect response characteristics of different flood sources with rainfall. A copula method is then adopted to capture the correlation of rainfall amount with different critical rainfall durations. Rainfall events are designed taking advantage of the copula structure of correlation and marginal distribution of rainfall amounts within different critical rainfall durations. A case study in the Otsu River Basin, Osaka prefecture, Japan was conducted to demonstrate this methodology.

1 Introduction

Floods are among the most serious disasters in the word. Annually, flooding affects about 520 million people and their livelihoods, claiming about 25 000 lives worldwide. The annual cost of flooding and other water-related disasters to the world economy ranges between USD 50 and 60 billion (Teegavarapu, 2012). Moreover, recent studies have shown that, with climate change and global warming, intensification of heavy precipitation events was observed over approximately two-thirds of Northern Hemisphere land areas for which data were available (Min et al., 2011). It is also very likely that global warming has increased the probability of severe flooding in some areas (Pall et al., 2011). In East Asia, enhanced summer monsoon precipitation and increased rainfall extremes caused by typhoons making landfall in coastal areas have been asserted (Qin et al., 2014). On the other hand, the increasing exposure in floodplains has increased flood risk, although the vulnerability may be reduced with social development (Mechler and Bouwer, 2014). Therefore, flood-related disasters may present more severe challenges in future decades.

To protect people from flood-related disasters and reduce economic losses, integrated flood risk management, which includes different types of countermeasures, multiple stakeholders, and authorities is required (Tatano, 2003; Okada, 2004). Conventional flood risk assessment may be aimed at building hydrological structures or planning evacuations, simulating so-called “worst-case scenarios.” However, flood risk can be reduced through integrated strategies such as integration of risk control and risk financing (Plate, 2002; Tatano and Takagi, 2005). This implies that, besides consideration of worst-case scenarios, detailed risk information about the entire floodplain, namely a probability distribution of spatial consequences of flood-related disasters is required. In order to integrate and efficiently manage flood risk, it is necessary to know the flood risk for each location on the entire floodplain (Taki et al., 2013).

Focusing on urban areas, spatial flood risk assessment should reflect all risk information derived from multiple flood sources including rivers, drainage, coast etc., which may affect urban areas. In conventional studies, each flood source is studied independently, but the joint effects of multiple flood sources are ignored, which may lead to an underestimation of the spatial flood risk. Since the risk is represented by a probability distribution of loss (Knight, 2012), a challenge in assessing spatial flood risk is how to evaluate the joint probability distribution of maximum water depth, which may derive from different flood sources, and the joint probability distribution of loss.

Although floods may originate from many sources, for most areas, heavy rainfall is the main cause and most flood risk assessments start with rainfall. Scholars usually use the following procedure to estimate a probabilistic flood risk curve: (1) design rainfall corresponding to a certain return period. (2) Input the designed rainfall into an integrated or separated rainfall–runoff–inundation model to simulate water depth at each location in the area. (3) Change the dyke break or overtopping point to produce several flooding scenarios. (4) Calculate losses for each scenario and calculate the risk curve.

As the first step of the flood risk assessment procedure, rainfall connects the flood simulations to the statistical risk analysis. A variety of methods for rainfall design exist in the literature (Keifer and Chu, 1957; Huff, 1967; Yen and Chow, 1980; Watt et al., 1986; SCS, 1986; USACE, 2000). Most rainfall design methods can be classified into four categories: specification of simple geometrical shapes anchored to a single point of the intensity–duration–frequency (IDF) curve, use of the entire IDF curve, use of standardized profiles obtained directly from rainfall records, and simulation from stochastic models (Veneziano and Villani, 1999). The first two methods are commonly used in flood risk assessment, but the IDF curve is usually determined by means of univariate statistical analysis of the mean intensity of a rainfall event (Grimaldi and Serinaldi, 2006) that under same return period, the correlation between rainfall intensity within different durations could be independent. This will be a disadvantage for rainfall design, as for instance, 2 and 3 h rainfall intensities have no relationship in the design of the rainfall event. The third method is an experience-based method and the fourth method, which includes Poisson cluster models (Wheater, 2005) usually focuses on generation of continuous rainfall series and does not consider the return period of a flooding event. Recently, studies using multivariate statistical analysis of the depth, volume, and peak duration intensity of rainfall have been proposed (Grimaldi and Serinaldi, 2006; Genest and Favre, 2007).

Conventional methods of rainfall designs such as design from intensity–duration–frequency (IDF) curves or extrapolation from typical rainfall events are not suitable for spatial flood risk assessment considering multiple flood sources for two reasons. First, an intensity–duration–frequency (IDF) curve is usually determined by means of univariate analysis of the mean intensity of a rainfall event, but only one type of rainfall can be designed with these methods for a certain return period and it is difficult to predict whether this type of rainfall will likely occur for a given return period. Second, floods may be derived from different sources such as larger rivers, smaller rivers, or urban drainage. Different flood sources may have different responses to a designed rainfall: larger rivers may require a longer duration of rainfall to produce a flood peak, while urban drainage may be more sensitive to shorter rainfall duration or peak rainfall. Therefore, the rainfall design should consider the response characteristics of different flood sources.

In this paper, a method of rainfall design for spatial flood risk assessment considering joint effects of multiple flood sources is proposed. The concept of critical rainfall duration based on concentration time of a flood event is introduced to connect the response characteristics of different flood sources with rainfall. A copula method is then adopted to capture the correlation of rainfall amount with different critical rainfall durations. The rainfall events are designed by taking advantage of correlation and marginal distribution of rainfall amounts with different critical rainfall durations. Therefore, the joint effects of multiple flood sources are reflected in the rainfall design.

This paper is arranged in the following way. Section 2 introduces the proposed rainfall design procedure and related concepts and methods. Section 3 presents a case study, in which this rainfall design procedure is applied to the Otsu River Basin in Osaka, Japan for spatial flood risk assessment. Section 4 consists of a discussion and conclusions.

2 Methodology

The rainfall design presented in this paper is used for spatial flood risk assessment and considers the relationship between response characteristics of different flood sources. In this section, two processes are emphasized: (1) the use of the concentration time of floods, which reflects rainfall response characteristics of different flood sources to identify critical rainfall duration; and (2) the use of a copula method to analyze rainfall in the critical rainfall duration and generate correlated artificial rainfall events.

2.1 Concentration time of a flood event

The response of a catchment to a rainfall event can be measured by the concentration time of a flood event, which is defined as the time required for rainwater to propagate from the top of a slope at the most remote portion of the basin to the outlet (Kadoya and Fukushima, 1976). It is reasonable to set the concentration time of a flood event as the critical rainfall duration, in which rainfall, including peak rainfall, will form the flood peak volume. A number of previous methods for calculating the concentration time of a flood event have been reported such as the Kraven formula, the uniform flow velocity formula, the Public Works Research Institute formula, and the Kadoya formula (JSCE, 1986). As the concentration time of a flood may be different for different flood sources, the critical rainfall duration may also be different. Therefore, to assess the spatial flood risk considering the joint effects of multiple flood sources, it is significant to understand the correlation of different critical rainfall durations and their distributions.

2.2 Copula method

A copula method is a popular and flexible way to measure correlation and construct multivariate distributions. Copulas are functions that join or "couple" multivariate distribution functions to their one-dimensional marginal distribution functions (Nelsen, 2006). In the bivariate case, the joint cumulative distribution function $H(x,y)$ of any pair (x,y) of continuous random variables can be written as:

$$H(x,y) = C(F(x), G(y)) x, y \in \mathrm{R} \tag{1}$$

where $F(x)$ and $G(y)$ are continuous marginal distributions, so that $C : [0,1]^2 \rightarrow [0,1]$ such that for all is copula (Sklar, 1959). This method separates the joint distribution into a copula function and marginal distributions and has the advantage that the selection of an appropriate model for the dependence between varieties, represented by the copula, can then proceed independently from the choice of marginal distributions. As for the basic theory and concepts of copula, readers may refer to the monographs by Joe (1997) and Nelsen (2006) for additional details. For construction of high-dimensional copulas, such as nested Archimedean construction (NAC) and pair copula construction (PCC), readers may refer to Aas and Berg (2009), Savu and Trede (2010), and Czado (2010).

Copulas are applied primarily in actuarial and financial fields, particularly for calculating value at risk (VaR) (Bouyé et al., 2000); however, they have also been applied to the hydrological research of Salvadori and De Michele (2004), Zhang and Singh (2006), and Ghosh (2010). Moreover, basic information on copula theory and practice in hydrology has been reported by Salvadori et al. (2007) and Genest and Favre (2007). Application of copula to rainfall analysis can be found in the works of Grimaldi and Serinaldi (2006), Genest and Favre (2007), and Serinaldi (2009). In this study, the copula method was adopted to analyze the correlation of rainfall amounts with critical rainfall durations for different flood sources and to build joint distributions of rainfall amounts with critical rainfall durations.

2.3 Methodology framework

The rainfall design procedure for spatial flood risk assessment considering joint effects of multiple flood sources is shown in Fig. 1. First, rainfall data and basin information must be collected. Based on basin information, the flood assessment area can be defined. Note that the term “basin” refers to the entire area including the runoff area and flood assessment area. From the viewpoint of integrated flood risk assessment, the entire rainfall–runoff–inundation process is important. Centered on the risk assessment area, the flood risk sources can be traced and the concentration time from flood risk sources to flood risk assessment area can be calculated. As stated above, the concentration time of a flood can be thought of as the critical rainfall duration, in which rainfall, including peak rainfall, will form the flood peak volume. In addition, rainfall time series are produced. The basin average rainfall must be calculated because flood risk assessment at small scales requires basin average rainfall as input. This can be achieved by interpolation methods such as the Thiessen polygons method, Inverse Distance Weighted method, polynomial methods, or Kriging methods (Jones and Hulme, 1996; Goovaerts, 2000; Vicente et al., 2003). Then, the rainfall time series is divided into rainfall events using the interval time method or mean time method (Huff, 1967; Dairaku et al., 2004). In this study, the interval time method was used to subdivide the rainfall time series. The maximum critical rainfall duration was used as interval time. Up to this point, the rainfall data were prepared for statistical analysis. Next, the correlation of rainfall amounts with different critical rainfall durations, e.g., 1 h rainfall, 2 h rainfall, 3 h rainfall etc., was estimated using the copula method. For each rainfall duration, a probability distribution was fitted. The joint distribution of rainfall amounts and different durations can be constructed by a correlation structure and marginal distributions. In fact, whether the correlation structure or the marginal distribution is estimated first depends on the chosen estimation method of the copula. If the inference from margins (IFM) method is chosen, the marginal distribution should be estimated first, whereas if non-parametric methods are chosen, the correlation structure can be estimated directly from data (Joe, 1997; Choroś et al., 2010). The joint probability distribution was used to generate critical rainfall durations according to return periods. Finally, the generated correlated critical rainfall duration was used to produce rainfall events. The entire procedure was applied to a case study described in the following section.

3 Case study

3.1 Study area

The study area is located in the southern part of Osaka prefecture, Japan. The Otsu River is a river within the Osaka prefecture, which originates in the Katuragi Mountains and flows about 68 km westward to Osaka Bay. The river consists of five branches, including the Chichioni River, the Higashimakio River, the Makio River, the Matsuo River, and the Ushitaki River. The river basin extends from 34°20′ to 34°30′ N and from 135°23′ to 135°21′ E. The area of the river basin is 102.2 km^2 and includes the three cities of Izumi, Kishiwada, and Izumiotsu and the town of Tadaoka. The basin is the largest secondary drainage system in Osaka prefecture. The upper portion of the basin is located in an undeveloped mountainous area; the middle part of the basin has hilly topography and is partly developed; the downstream portion of the basin consists of well-developed urban areas. In the study area, the average annual temperature is 16 °C and the average annual rainfall is about 1200 mm. The plum rain season in June and the typhoon season in September account for most of the annual rainfall. A map of the Otsu River Basin is shown in Fig. 2. In this study, the previously outlined method was used to design an average basin rainfall for the Otsu River Basin for the purpose of spatial flood risk assessment. Geographic data include a digital map of Osaka prefecture and digital elevation data (DEM) as well as river system data that were provided by the Geospatial Information Authority of Japan. Rainfall data were derived from four rain gauging stations with 49 years of hourly rainfall records. Historical flood records and field survey data were provided by the river management department of Osaka prefecture.

3.2 Identification of critical rainfall durations

Historical record shows that the study area has been prone to flood-related disasters. From 1950 to 2011, 14 flooding events were recorded. Local inundation and river flooding are the main causes of flood-related disasters. Especially the downstream portion of the basin, which is flat and characterized by the confluence of three rivers, has a high probability of flooding from these rivers and local inundation. In addition, population and properties are concentrated in the downstream portion of the basin. Accordingly, this area should first be considered as a risk assessment area. For the risk assessment area, flood sources include river flooding from the Ushitaki River, which is controlled by runoff in the upper part of the Ushitaki sub-basin (SB1); river flooding from the Matsuo

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

River, which is controlled by runoff in the upper part of the Matsuo sub-basin (SB2); river flooding from the Makio River, which is controlled by runoff in upper part of the Makio sub-basin (SB3); and local inundation from urban drainage or slope flow, which is controlled by runoff in the flood risk assessment area (RAA).

According to the empirical Kraven formula (JSCE, 1986), the flood concentration time for the Ushitaki sub-basin is 2 h, that for the Matsuo sub-basin is 1.6 h, and that for the Makio sub-basin is 2.7 h. Because there is no big reservoir or dam in the runoff areas, the flood concentration time suggests that a 2 h rainfall event in the Ushitaki and Matsuo sub-basins and a 3 h rainfall event in the Makio sub-basin will produce a flood peak to the risk assessment area. For the flood concentration time in the risk assessment area itself, a 1 h rainfall event is considered critical. Thus, the analysis of the joint probability of flooding from multiple sources becomes an analysis of the joint probability of 1, 2, and 3 h rainfall events under the assumption of basin average rainfall.

The Thiessen polygon method was used to calculate the basin average rainfall, although Kriging interpolation families, which are labeled considering both location information and observed value information, may be a better method (Haylock, 2008). The precision of Kriging interpolation largely depends on the number of rain gauging stations (Hughes and Lettenmaier, 1981; Dirks et al., 1998), which are few in our study area. Three hours was used as the interval to divide basin average rainfall series into rainfall events. Although all rainfall data could have been used to evaluate the rainfall dependence structure, flood risk analysis is more concerned with extreme rainfall events. Therefore, annual maximum rainfall events corresponding to 1, 2, and 3 h durations were selected.

3.3 Copula-based joint probability analysis of rainfall amounts with different critical rainfall durations

3.3.1 Correlation estimates of rainfall events

A widely used method for estimation of the copula parameter is a parametric two-step procedure, which is often referred to as the “inference from margins” or IFM method (Joe, 1997). This method requires first fitting of a marginal distribution and then estimation of the copula parameter by maximum likelihood estimation using data transferred from the marginal distribution. This method usually performs well, but estimates of the association parameters derived by the IFM technique clearly depend on the choice of the marginal distributions, and thus always run the risk of being unduly affected if the models selected for the margins turn out to be inappropriate (Genest and Favre, 2007). As the dependence structure captured by a copula has nothing to do with the individual behavior of the variables, inference about the parameter of copulas relies only on the ranks of the observations. Instead of using a parametric method, rank-based non-parametric methods such as inversion of Kendall’s tau or Spearman’s rho and semi-parametric methods, such as Maximum Pseudo Likelihood are available (Choroś, 2010). In this study, to reduce uncertainties from the choice of the marginal distributions, the Maximum Pseudo Likelihood method was used.

In our case study, 1, 2, and 3 h rainfall events were considered; therefore, a three-dimensional copula analysis was required. There are two methods to construct a high-dimensional copula: nested Archimedean construction and pair copula construction (PCC). Compared with nested Archimedean construction, pair copula construction is a more flexible method for multivariate copulas, because it adopts a hierarchical idea and takes advantage of the density function. The modeling scheme is based on a decomposition of a multivariate density into $d(d-1)/2$ bivariate copula densities, of which the first $d-1$ is unconditional, and the rest are conditional (Aas and Berg, 2009). There are two main types of PCC: canonical vines and D-vines (Kurowicka and Cooke, 2007). Compared with D-vines, fitting a canonical vine is advantageous when a particular variable is known to be a key variable that governs interactions in the data set (Aas et al., 2009). In our study, peak rainfall is the key variable, and the relationship between 1 h rainfall and 2 h rainfall or the relationship between 1 h rainfall and 3 h rainfall is relatively more important than the relationship between 2 h rainfall and 3 h rainfall.

Some 20 types of copulas introduced by Genest and Favre (2007) that may be suitable for hydrological study were considered for this study, including Archimedean copulas, extreme value copulas, meta-elliptical copulas, and other miscellaneous families of copulas. For the selection of a copula, the Akaike information criterion (AIC) was adopted. The AIC shows that a Gumbel survival copula with a parameter of 3.357, a Gaussian copula with a parameter of 0.804, and a BB7 copula with parameters of 2.923 and 3.451 can properly fit the 1 h/2 h rainfall correlation, the 1 h/3 h rainfall correlation, and the conditional 2 h/3 h rainfall correlation, respectively. Figure 3 shows the 3-D scatter points of pseudo data and fitted copula densities for 1 h/2 h, 1 h/3 h, and conditional 2 h/3 h rainfall events, from which the correlation of rainfall events of different durations can be illustrated.

3.3.2 Fitting of marginal rainfall distributions

Numerous studies on fitting of extreme rainfall distributions have been conducted and several types of distributions have been found that provide a good fit with rainfall data. However, no distribution can be universally fitted to all rainfall data due to the variable nature of rainfall, different purposes of study, different locations, etc. For example, Generalized Pareto was shown to be the best fitted distribution in De Michele and Salvadori's (2003) paper but found to be the weakest fit in Kao and Govindaraju's (2007) paper. Therefore, a set of distributions, including Pearson distribution families, Generalized Pareto distribution (GP), Generalized Extreme Value distribution (GEV), Exponential distribution (EXP), Gamma distribution (GM), lognormal distribution, and Weibull distribution families were selected as candidates and tested by a Kolmogorov–Smirnov test as well as AIC. The tests indicate that for annual maximum 1 h rainfall, the best fitting distribution is a lognormal distribution with parameter (3.098, 0.359); for annual maximum 2 h rainfall, the best fitting distribution is Pearson 3 with parameter (1.76, 16.259, 10.725); for annual maximum 3 h rainfall, the best fitting distribution is lognormal with parameter (1.223, 20.889, 17.387), as shown in Fig. 4.

3.3.3 Construction of joint distributions and generation of correlated critical rainfall

According to Sklar's theorem, a joint distribution can be separated into a copula model with a marginal distribution as follows:

$$F(x_1,x_2,x_3) = C_{1,2,3}(F_1(x_1),F_2(x_2),F_3(x_3)) \tag{2}$$

where, in our study, x_1,x_2,x_3 denote 1, 2, and 3 h rainfall, respectively. Using the chain rule, results in:

$$f(x_1,x_2,x_n) = c_{1,2,3}(F_1(x_1),F_2(x_2),F_3(x_3)) \cdot f_1(x_1) \cdot f_2(x_2) \cdot f_3(x_3) \tag{3}$$

where $c_{1,2,3}$ denotes the densities of $C_{1,2,3}$. The copula densities $c_{1,2,3}$ can be calculated using PCC as:

$$c_{1,2,3}(x_1,x_2,x_3) = c_{1,2}(F_1(x_1),F_2(x_2)) \cdot c_{1,3}(F_1(x_1),F_3(x_3)) \cdot c_{2,3|1}(F(x_2|x_1),F(x_3|x_1)) \tag{4}$$

Therefore, once marginal distributions and copula model are determined, the joint distribution can be constructed. The algorithms for sampling values from vine copulas were proposed by Aas et al. (2009). Taking advantage of these algorithms, a random copula value can be generated. Then, based on the marginal distributions, the random value of rainfall amount with critical durations can be obtained. Figure 5 shows 10 000 random values generated by copula functions and the observed real rainfall data. From this figure, it can be seen that the correlation of real rainfall data is captured by the copula model. Therefore, it is reasonable to use the simulated random values for flood risk assessment.

3.3.4 Application of correlated critical rainfall durations to rainfall event generation

Flood risk assessment requires information about the probability distribution of water depth, which is simulated from corresponding rainfall events. The simulated random rainfall points include four-dimensional information of joint probability and 1, 2, and 3 h rainfall amounts. To complete the rainfall events, we assumed peak appears at the center of each rainfall event. Based on this assumption, the amount of 1, 2, and 3 h rainfall can be determined, as shown on the left of Fig. 6. Since the generated points also contain information about joint probability, the designed rainfall will share the same probability. Besides the critical durations of rainfall, the rest part of a rainfall event will also affect runoff, but contribute less to the flood peak. Therefore, the rest part can simply be completed by statistical average of historical rainfall events.

Taking advantage of this rainfall design method, the basin average rainfall was designed for the case study area. Because the joint probability was adopted, the rainfall values for a certain return period is a surface and more than one rainfall value can be expected for a certain return period. In Fig. 7, five rainfall events with 20, 50, and 100 yr return periods are shown, respectively. The generated rainfall can be interpreted as the designed basin average rainfall, which includes contributions from multiple flood sources such as, in our study, river flooding from the Ushitaki, Matsuo, and Makio Rivers and local inundation from urban drainage. It is obvious that even at the same return period, the variety of generated rainfall reflects different combinations of floods from different sources.

3.3.5 Application of generated rainfall events to flood risk assessment

The generated rainfall events were used to drive cascading flood simulations to assess flood risk at each location of the floodplain. A GIS-based integrated rainfall–runoff–inundation model was developed. The model applied unstructured irregular meshes and simplified 2-D shallow water equations to simulate flooding and inundation in the risk assessment area. Moreover, it applied a hydrological analysis and 1-D kinematic wave equations to a rainfall–runoff simulation in the runoff area and was able to simulate runoff, flooding, and inundation together (Jiang et al., 2011,2013). Simulating each rainfall event, inundation could be estimated and further loss could be calculated with the addition of information from a fragility curve and exposure distribution. The fragility curve information can be found in the manual of economic survey for water management (MLIT, 2005) and exposure information can be obtained from the mesh-based areal economy census of Japan (Sinfonica, 2009).

Using a conventional method, because one return period corresponds to one event, the event curve is adopted to describe the relationship between loss and exceedance probability. An event curve can be created by plotting loss of an event along the horizontal axis and exceedance probability along the vertical axis. However, as was pointed out, even at the same return period, loss will be different because of the joint effect of multiple flood sources. A risk curve that includes this kind of uncertainty can be adopted to describe the relationship between loss and exceedance probability. Readers may refer to Tatano and Takagi (2005) for details about event and risk curves.

It is possible to create a risk curve from events using the following formula:

$$\mathrm{EP}(x) = \sum_{i} \left[\lambda_i \times P_i\left(x;\overline{x},\sigma\right)\right] \tag{5}$$

where x is loss, $\mathrm{EP}(x)$ is the exceedance probability of loss x, λ_i is the probability of event i, $P_i(X)$ is the exceedance probability of loss X, and σ is the standard deviation. The risk curve for mesh No. 6881 is shown in Fig. 8. A similar risk curve can be calculated for each mesh of the risk assessment area, and spatial flood risk assessment can be achieved.

4 Discussion and conclusion

This paper proposed a new rainfall design methodology for spatial flood risk assessment considering multiple flood sources. In this methodology, two processes are emphasized: (1) using the concentration time of flooding from each flood source to identify critical rainfall duration, and (2) using a copula method to analyze the critical rainfall duration and generate correlated artificial rainfall events. This methodology of rainfall design enables spatial flood risk assessment considering uncertainties caused by joint effects of multiple flood sources. It fulfills the requirement of integrated flood risk management. A case study, conducted in the Otsu River Basin, Osaka prefecture, Japan demonstrated this methodology.

Concentration time of flooding was adopted to reflect the response of a flood source to a rainfall event. It was calculated using empirical formulas, which consider geographical information about the catchment and rainfall amount. It is obvious that the larger the rainfall event, the shorter the concentration time of the flood. In this study, the concentration time of flooding refers to the concentration time of flooding caused by the smallest rainfall event that can cause flooding.

A copula method is the suitable method to construct a joint probability distribution for rainfall design. It offers a way to measure dependence independent of scale as well as to construct families of joint distributions. The application of a copula to the creation of a joint probability to rainfall analysis has the advantage that even for the same return period, different rainfall events can occur. In the case study, it can be clearly seen that even when joint probability was the same, marginal probability can be different, and rainfall events can be different as well. The study also demonstrated the necessity to consider joint probability rather than a single marginal distribution. In the case study, the joint effects from multiple flood sources were represented by different critical rainfall durations. Joint probability offers more different types of rainfall events, which is important for spatial flood risk assessment.

The proposed methodology is suitable for small study areas in which spatial distribution of rainfall can be treated as basin average rainfall. For large study areas, the spatial distribution of rainfall cannot simply be treated as basin average rainfall. Spatially separated rainfall events should be used for spatial flood risk assessment. In these situations, different rainfall events should be designed for different areas. The proposed methodology can be expanded to deal with such challenges by considering the spatial correlation of rainfall data in future studies.

In the case study, flood sources were river floods from different basins and local inundation. Both river floods and local inundation are derived from rainfall. This methodology can be expanded to cover additional flood sources such as storm surges by including a correlation of rainfall and storm surge based on statistical data from typhoons.

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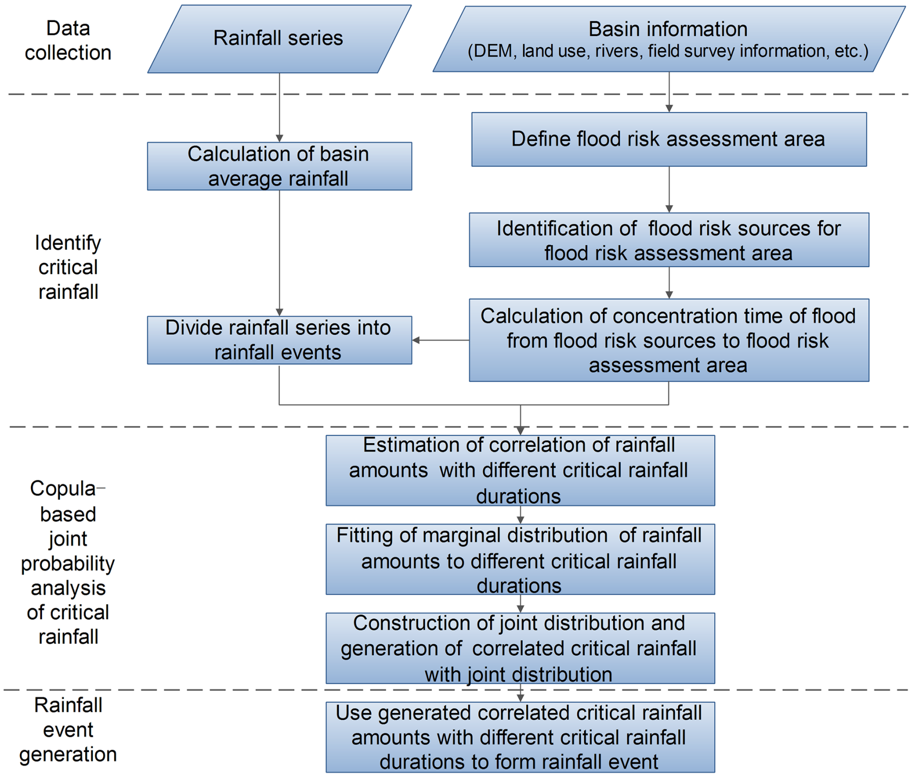

Figure 1. Rainfall design procedure for spatial flood risk assessment considering the joint effects of multiple flood sources.

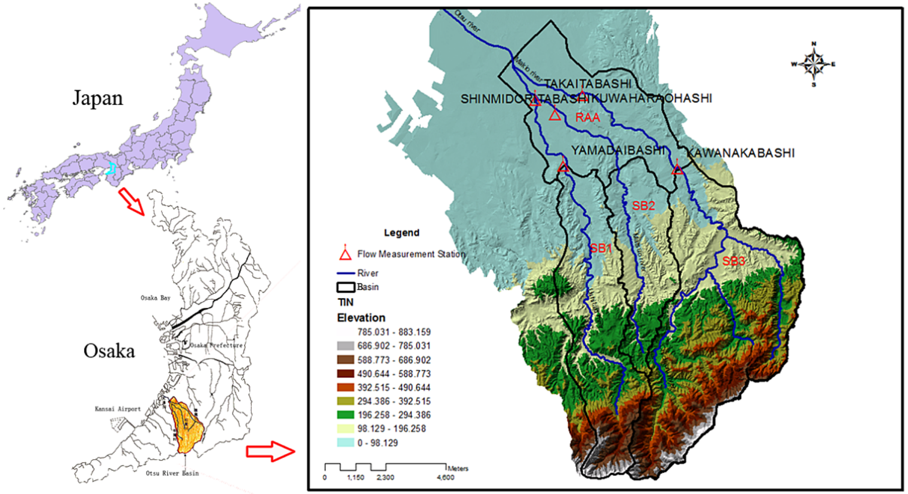

Figure 2. Map of the study area.

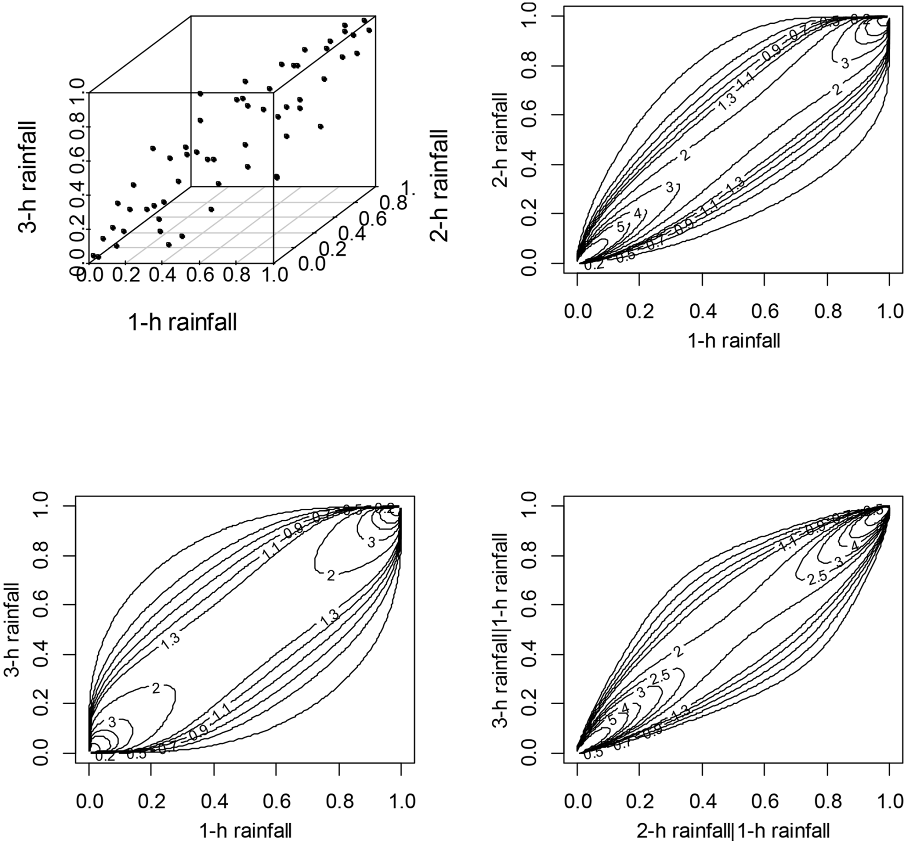

Figure 3. 3-D scatter plot of pseudo data and fitted copula densities for 1 h/2 h, 1 h/3 h, and conditional 2 h/3 h rainfall events.

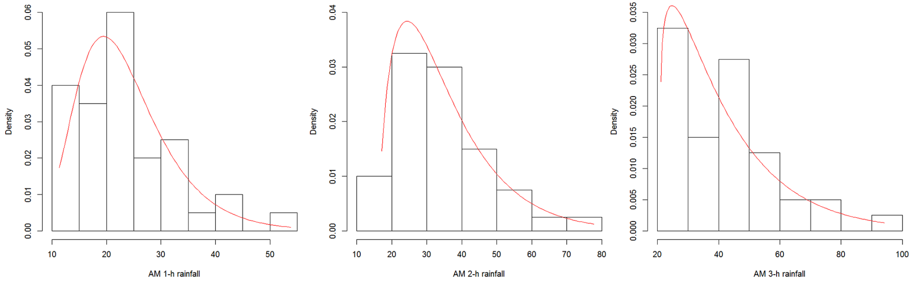

Figure 4. Marginal distribution of annual maximum 1, 2, and 3 h rainfall.

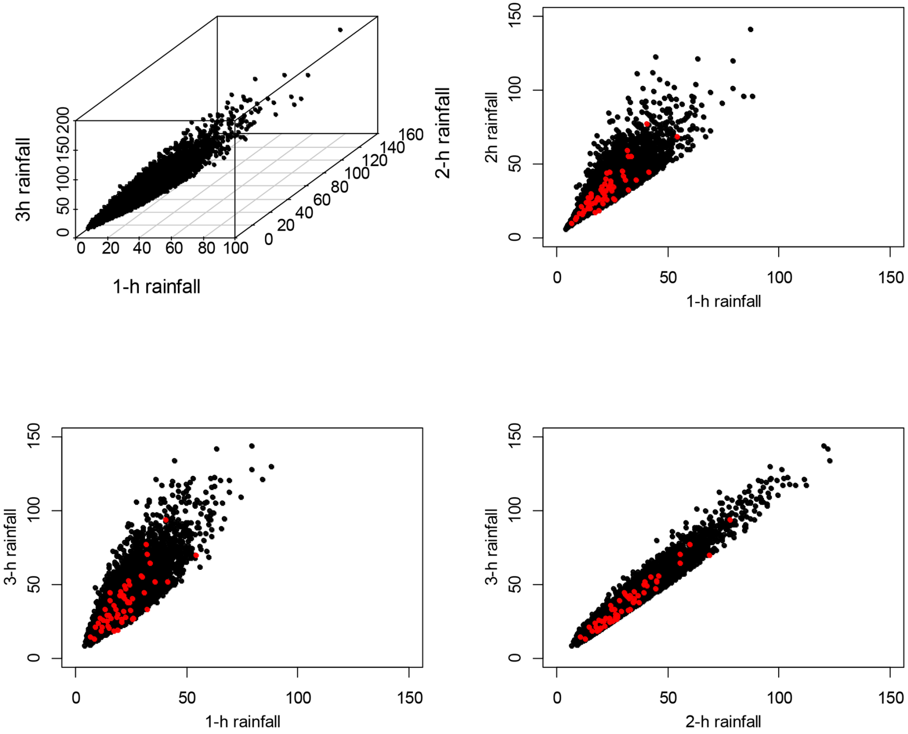

Figure 5. Plots of 10 000 random rainfall values generated by the copula model. Black dots are random values; red dots represent observed real rainfall data.

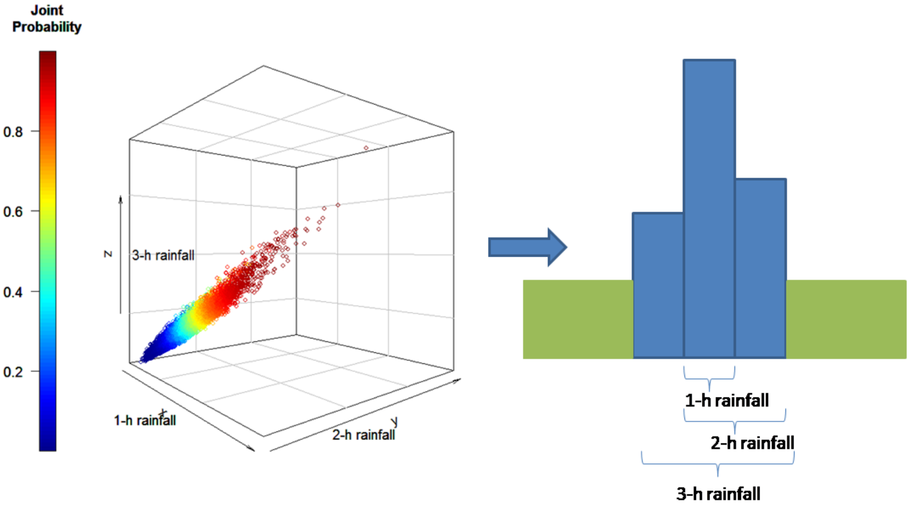

Figure 6. Generation of rainfall events from simulated correlated critical rainfall.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

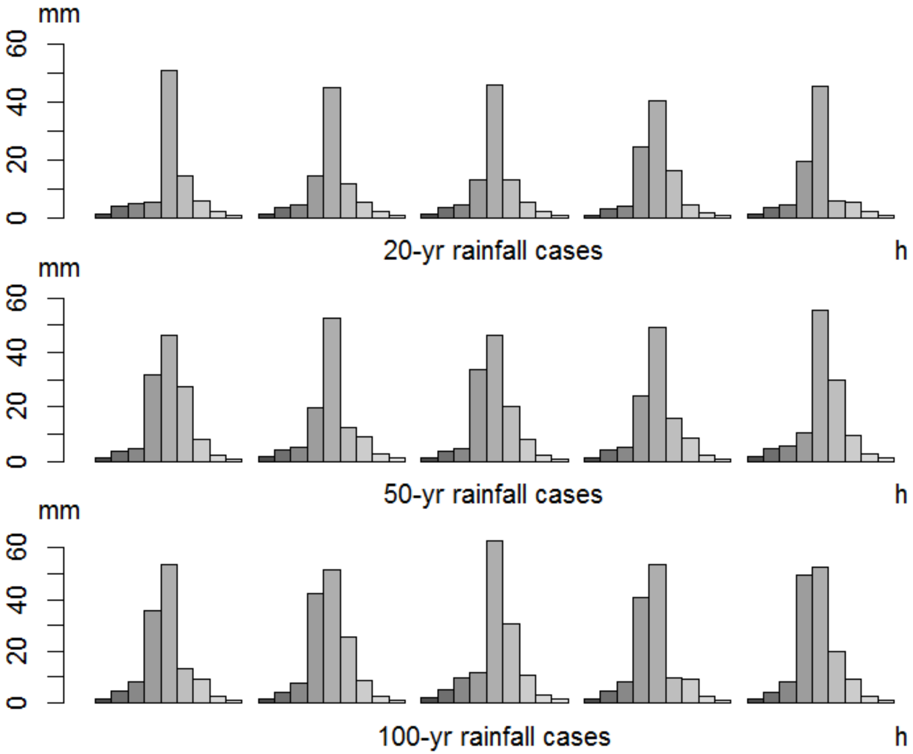

Figure 7. Five rainfall cases for 20, 50, and 100 yr return periods, respectively.

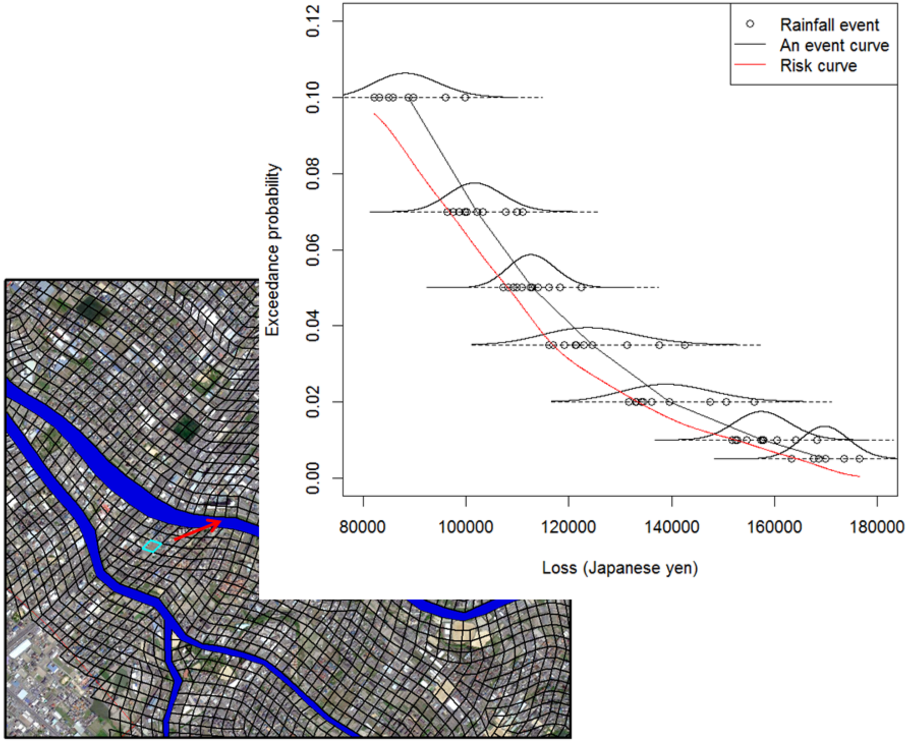

Figure 8. Location of mesh No. 6881 and its loss of rainfall events, event curve, and risk curve.