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Original paper

A Methodology for Spatial Flood Risk Assessment Taking Account of the Spatial–Temporal Characteristics of Rainfall

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Abstract This study focuses on the challenges of assessing the spatial distribution of flood risk in a city threatened by multiple flood sources and proposes a methodology for estimating the probability distribution of flood damages. In the proposed methodology, a copula method is used to capture the spatial dependence structure to analyze the behavior of rainfall that may cause floods in different sub-basins. An integrated model is developed to simulate the rainfall–runoff–inundation process of flood events, and a case study is conducted in the Maruyama River basin, Japan that shows the feasibility of this methodology. Through this case study, the significance of spatial correlation in spatial flood risk assessment is examined.

Key words: Spatial flood risk assessment, rainfall spatial–temporal characteristics, Maruyama River basin

1. INTRODUCTION

Flood risk management is an important strategy used in river and basin management. Although accurate assessment of flood risk is crucial, such a task is difficult in many areas, particularly for cities with water systems that include one main river and several smaller bodies of water. A city's flood risk refers to the expected losses by flooding from all possible sources. The term "once in *n* years' flood," often used to describe the hazards of flood risk, generally refers to risk from only one river. Therefore, such a distinction may not be appropriate for determining flood risk for cities affected by more than one river. If a specific river is expected to flood once in a particular number of years, city officials face challenges in adapting such a description to other rivers for determining the potential hazards of flood risk for the city. In some cases, secondary rivers cause flooding rather than the main river; therefore, flood risk assessment should include all possible flood sources.

This paper presents a methodological framework for evaluating the flood risk distribution in an area that includes multiple flood sources. Section 2 introduces the methodology used for determining the

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spatial flood risk assessment at an area threatened by multiple flood sources that includes a copula-based approach for rainfall generation with spatial dependence and an integrated hydrological model for flood and inundation simulation. Section 3 presents a case study of the Maruyama River basin in Japan, and section 4 includes a discussion and conclusions.

2. METHODOLOGY

The methodology used to assess spatial flood risk in an area with multiple sources is formulated on the basis of two main components. The first is a copula-based spatial dependence structure used to analyze the joint probabilities of rainfall in river basins, and the other is an integrated model used to simulate the rainfall–runoff–inundation process of a flood event. The procedure for this methodology is shown in figure 1. The sub-basins in the study area are divided on the basis of hydrological analysis that included digital-elevation-model (DEM) data processing and the extraction of contour lines and other geographical data. Rain gauge data are used to determine rainfall characteristics for each sub-basin, which are analyzed to estimate the rainfall duration for which flooding is likely to peak. The spatial-dependent structure of rainfall amount according to duration among sub-basins is estimated by copula function, and a theoretical rainfall dataset that considers the rainfall characteristics and spatial dependent structure is generated for driving the integrated distributed rainfall–runoff–inundation hydraulic model used to assess flood risk. Finally, flood risk is calculated by adopting the loss data or fragility curve. Because the copula method and the integrated rainfall–runoff–inundation model are not commonly used in spatial flood risk assessment, these two factors are discussed in detail.

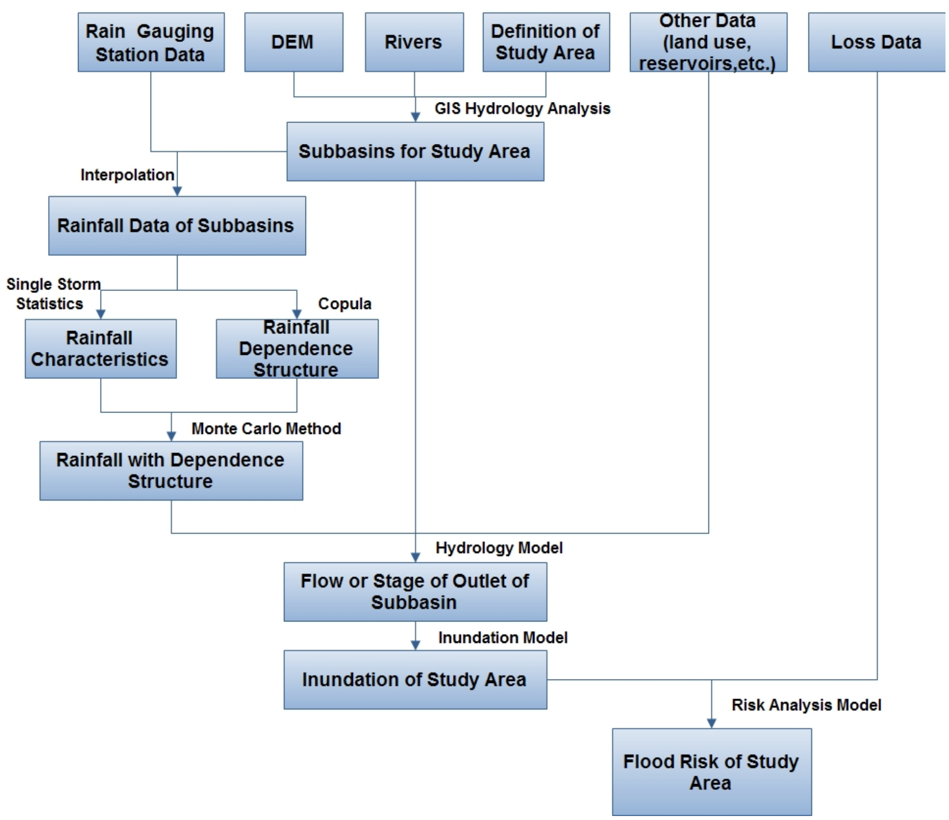

Fig. 1. Procedure for spatial flood risk assessment.

2.1 Copula method

In order to assess flood risk from multiple sources such as main rivers, secondary rivers, and local rainfall, their joint behavior should be examined. That is, the spatial dependence structure of flood risk sources should be captured. Spatial interpolation is widely used to determine spatial rainfall distribution based on rain gauge location and employs Thiessen polygons and inverse distance interpolation. However, scholars have recently demonstrated that Kriging interpolation is preferred for such analysis because it considers both location information and observation data. Although interpolation methods are appropriate for analyzing rainfall distribution in specific areas, they do not address statistical probability issues such as the expected rainfall at station B on the basis of measured rainfall at station A. An additional method for determining the spatial dependence of rainfall is to examine the joint distribution through one of two methods. In the first, the spatial dependence structure is analyzed directly by using the river gauging station data to build a joint distribution function. This method is straightforward and explicit but includes two major weaknesses. For many areas, continuous river gauging station data at each tributary is not available. In addition, this method ignores the influence of local rainfall. The second method adopts rainfall data for estimating the spatial dependence structure of rivers. In this paper, a copula method based on rainfall data is adopted to estimate the spatial dependence structure. The basic theory of this method is that copulas are functions that join or "couple" multivariate distribution functions to their one-dimensional (1D) marginal distribution functions (Nelsen2006). Given two continuous random variables X and Y with marginal distribution F and G and joint distribution H in the bivariate case, there is a copula $C:[0,1]^2 \rightarrow [0,1]$ such that for all $x,y \in$ R, $H(x,y) = C(F(x),G(y))$. Conversely, if C is a copula and F and G are distribution functions, then the function Q is a joint distribution with marginal F and G. The copula method allows for scale-free measurement and construction of families of joint distributions (Nelsen, 2006). This method is applied primarily to actuarial and financial fields and is used particularly for calculating values at risk (VaR) (Bouyé et al 2000). Copulas have been applied in the hydrological research of Salvadori et al. (2004), Zhang et al.(2006), and Ghosh (2010) Basic information on copula theory and practice in hydrology has been reported by hydrologists Salvadori et al. (2007) and Genest and Favre (2007) in research on the pairwise dependence between the depth, volume, and peak duration of flow or duration intensity of rainfall. Moreover, the copula method has been used by Serinaldi (2009) to address non-Gaussian temporal structures in the development of a multisite daily rainfall generator.

The general steps used in the copula method include fitting data to the marginal distribution, converting the data to [0, 1] data by the quantile function, and fitting the [0, 1] data to the proper copula function. Generation of a random copula value is also very useful in practice. First, random independent values u and t are generated. Then, let $v = C_u^{-1}(t)$, where $C_u = \partial C(u,v)/\partial u$, so that ($u$, v) are copula random values.

In this paper, our purpose is to assess flood risk at locations affected by rivers and to determine flood risk from multiple sources; therefore, we simply focus on the amount of rainfall generated considering the spatial correlation

2.2 Integrated rainfall–runoff–inundation model

In addition to the analysis of the spatial dependence structure of rainfall, an integrated rainfall–runoff–inundation model is required. Although individual inundation models with runoff input are often used in flood risk analysis, such models cannot assess flood risk from multiple sources because they are ineffective for considering the relationships between mountain and city areas and upstream and downstream regions. Thus, an integrated rainfall–runoff–inundation model is developed in this paper. Most similar hydraulic models are based directly on a DEM; however, such approaches present weaknesses in city-centered flood risk simulation. If the DEM resolution is too low, the simulation result will not accurately reflect the conditions, and finer resolutions require extremely lengthy simulation times. Thus, a balanced concept is proposed such that DEM-based hydrological analysis is conducted to generate reasonable calculation meshes prior to simulation. A mesh-based kinematic wave model is then adopted to simulate runoff in river basins, a simplified shallow-water equation is adopted to simulate inundation in the city area, and the two parts are integrated. In this paper, we simply describe the theoretical basis of this model.

2.2.1 Runoff model

In the runoff model, hydrological analysis is used to separate the runoff area into catchments according to topography; the ridges of mountains form the edges of catchments. For each catchment, contour lines and catchment edges are used to construct the calculation mesh. Although this model appears to be a two-dimensional (2D) representation, no discharge is produced because the catchment edges are ridges. Therefore, the contour lines and catchments edges ensure a 1D overland flow on the slope area for a reasonable resolution. The runoff model in our simulation is based on a kinematic wave model. Assuming that the bed slope and friction slope terms of the Saint Venant equation are dominant, the following 1D governing equations are applied for the slope area (Toda 2005):

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=r_e \text{, and} \quad (1)$$

$$q=\sqrt{\sin\theta_s}/N*h^m, \quad (2)$$

where t is the time independent variable, x is the longitudinal direction, h is the water depth, q is the water discharge per unit width in the slope area, r_e is the effective rainfall, θ_s is the angle of slope, and N is the equivalent roughness; m is defined as m = 5/3.

For the river flow, the following equations are applied:

$$\frac{\partial h}{\partial t}+\frac{\partial q_*}{\partial x}=\frac{q_s}{B} \text{, and} \quad (3)$$

$$q_s=\sqrt{\sin\theta_1}/n*h^m, \quad (4)$$

where q_* is the water discharge per unit width in a river, q_s is the lateral inflow discharge per unit width from the slope, B is the river width, θ_1 is the angle of the river bed, and n is the Manning roughness coefficient; m is defined as m = 5/3. Equations are easily discretized by using the control volume method.

2.2.2 Inundation model

The inundation flow model is more complex than runoff model because it should consider a 2D model to represent flow on flat ground. The most commonly used governing equations are those for shallow water. The governing equations for 2D unsteady flow are:

the continuity equation

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=\text{q}; \quad (5)$$

and the momentum equations

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$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (uM)}{\partial y}+gh\frac{\partial H}{\partial x}+\frac{gn^2u\sqrt{u^2+v^2}}{h^{\frac{1}{3}}}=0 \text{, and} \tag{6}$$

$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (uN)}{\partial y}+gh\frac{\partial H}{\partial y}+\frac{gn^2v\sqrt{u^2+v^2}}{h^{\frac{1}{3}}}=0 \text{,} \tag{7}$$

where h is the water depth, H is the water level, q is a source term representing rainfall in this model, M and N are the discharges per unit width in the x- and y-directions, u and v are the components of the flow velocity in x- and y-directions, n is the coefficient of roughness, and g is acceleration due to gravity.

It is not necessary, however, to solve the full equation for inundation. Here, we adopt a simplified strategy developed by the China Institute of Water Resources and Hydropower Research whereby the flux is calculated by various simplified equations according to the type of passage. The three main passage types considered include river passage, defined as that between river meshes; land passage, between land meshes; and special passage, between land meshes and river meshes. In addition, water obstructions such as railways and dykes could be treated as special passages.

For river passages, the acceleration, gravity, and resistance terms in the momentum equation are reserved:

$$\frac{\partial M}{\partial t}+gh\frac{\partial H}{\partial x}+\frac{gn^2u\sqrt{u^2+v^2}}{h^{\frac{1}{3}}}=0 \text{, and} \tag{8}$$

$$\frac{\partial N}{\partial t}+gh\frac{\partial H}{\partial y}+\frac{gn^2v\sqrt{u^2+v^2}}{h^{\frac{1}{3}}}=0 \cdot \tag{9}$$

A discrete equation is achieved by using the control volume method:

$$Q^{t+\Delta t}=Q^t-gH\frac{|Z_1{}^t-Z_2{}^t|}{L}\Delta t-gn^2\frac{|Q^t|Q^t}{H^{7/3}}\Delta t \cdot \tag{10}$$

For river passages, the gravity and resistance terms in the momentum equation are reserved:

$$gh\frac{\partial H}{\partial x}+\frac{gn^2u\sqrt{u^2+v^2}}{h^{\frac{1}{3}}}=0 \text{, and} \tag{11}$$

$$gh\frac{\partial H}{\partial y}+\frac{gn^2v\sqrt{u^2+v^2}}{h^{\frac{1}{3}}}=0 \cdot \tag{12}$$

A discrete equation is achieved by using control volume method:

$$Q^{t+\Delta t}=\frac{1}{n}H^{5/3}(\frac{|Z_1{}^t-Z_2{}^t|}{L})^{1/2} . \tag{13}$$

Owing to complex ground conditions, some surface features are defined as water hindrances. To calculate flow from such ground surfaces, the following weir flow equation is used:

$$Q_j=m\sigma_s\sqrt{2g}H_{\mathrm{j}}^{3/2} , \tag{14}$$

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where Q_j is the discharge per unit width, m is the discharge coefficient, σ_s is the submergence coefficient, and H_j is water depth at the weir crest. Details for the inundation model have been reported by Cheng (2009), Li (2002) and Tan (1998),.

2.2.3 GIS-based data processing and visualization

Geographic information system (GIS) technology plays an important role in data management and processing (Wan 2001). In this study, all works were conducted through the GIS platform with the exception of the calculation program. The geographical data were expressed as layers; other related data were expressed as attributes. By applying spatial analysis and other GIS functions, the connectivity matrix and parameters used in simulation were easily extracted. As shown in Fig. 2, the ArcGIS platform was used to develop a data processing procedure for flood and inundation simulation on irregular meshes (Jiang 2011).

Spatial and attribute information were integrated through the data management function, and the analysis of urban hydrology and existing conditions formed the basis for mesh generation and passage conversion. Through spatial analysis and statistics, the parameters were extracted from geographic maps and images as attributes for the meshes and passages, which allowed for the generation of text files for the calculation module. ARCGIS substantially reduced the amount of work required for programming. The outputs of calculation were combined into mesh and passage layers for ARCGIS analysis.

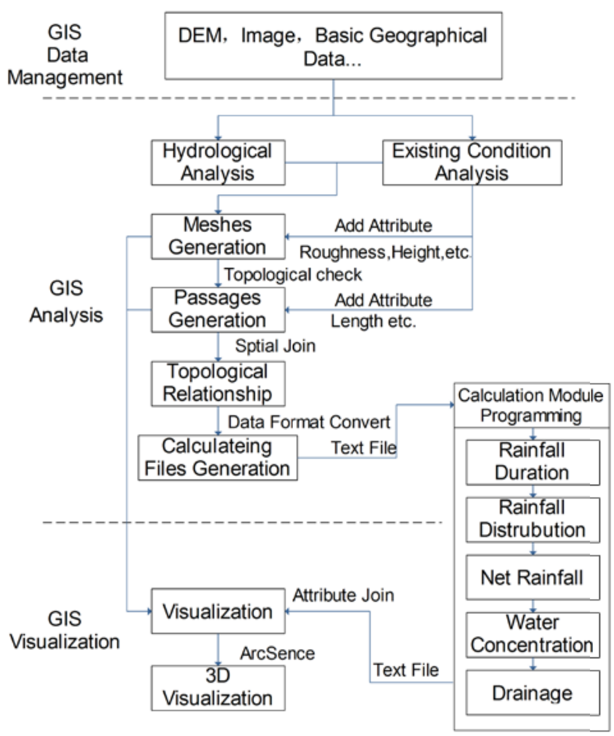

Fig. 2. Data processing procedure for simulation on irregular meshes created through Geography Information Systems (GIS) technology.

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3. CASE STUDY

3.1 Study area

In this paper, the study area is located in the southern part of the Maruyama River basin and consists of two subbasins of the Maruyama River (Fig. 5). The area assessed for flood risk is situated downstream of the study area where the two rivers converge. The left-hand image in the figure presents an overall view of the Maruyama River basin with a mask of study area. The bottom right-hand image shows an enlargement of the study area including terrain and the locations of two subbasins. The larger subbasin on the left-hand side is labeled sub-basin 1; the smaller one on the right-hand side is subbasin 2. The top right-hand image shows further detail of the flood risk assessment area with a yellow mask overlapping the terrain and river layers. The entire study area is approximately 218 km^2 with an average elevation of 370 m; the area for flood risk assessment is 8.2 km^2 with an average elevation of 81 m. Two rain gauging stations known as Wadayama and Nii and one flow gauging station known as Kyouguchi are located in the study area.

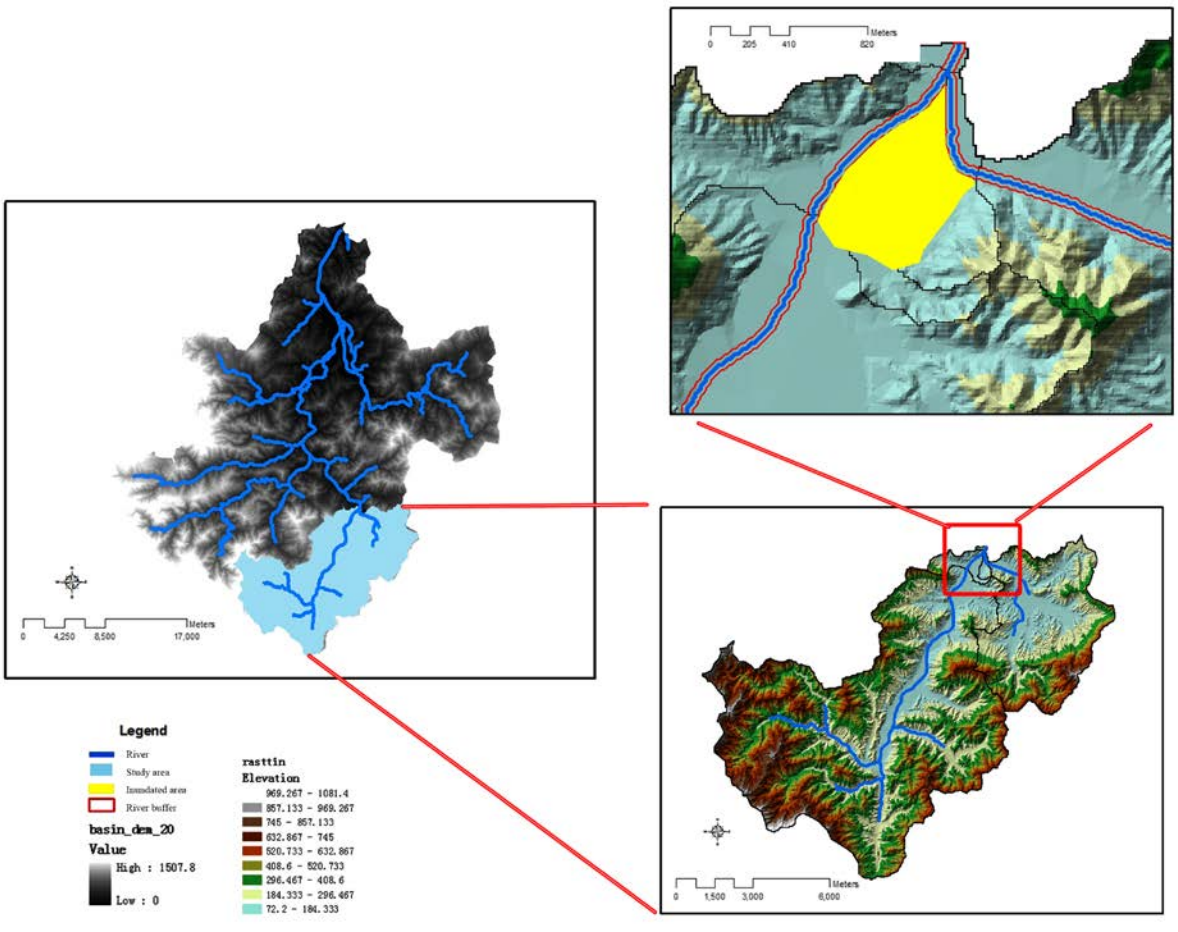

Fig. 3. Map of the study area.

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3.2 Data applied in the case study

Table 1 summarizes the data applied in the case study and their resources. Rainfall data were used for rainfall analysis, which formed the basis for spatial rainfall generation. Flow and stage data were used mainly for calibration in the runoff simulation. DEM and river system data provided basic geographical information such as sub-basin division and watershed area definition for hydrological analysis and served as the foundations for passage generation in the runoff modeling. Land-use data provided roughness information for the runoff and inundation simulations and served as a reference for mesh generation in the inundation modeling. Mesh and passage data served as the basic data for the flood and inundation simulation.

Table 1. Data applied in the case study.

Data	Resources
Rainfall data	Water information system, Ministry of Land, Infrastructure, and Transport. http://www1.river.go.jp/
Flow and stage data	Water information system, Ministry of Land, Infrastructure, and Transport. http://www1.river.go.jp/
DEM	Geospatial Information Authority of Japan. http://www.gsi.go.jp/
River system	Geographical information system, Ministry of Land, Infrastructure, and Transport. http://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-W05.html
Land use	Geographical information system, Ministry of Land, Infrastructure, and Transport. http://nlftp.mlit.go.jp/ksj/jpgis/datalist/KsjTmplt-L03-a.html
Meshes and passages for runoff model	Passages are derived from contour lines extracted from the DEM. Meshes are converted from passages.
Meshes and passages for inundation model	Meshes are drawn manually on the GIS considering the DEM, land use, and river orientation. Passages are converted from meshes.

3.3 Rainfall analysis

3.3.1 Estimation of the rainfall duration based on the time-to-arrival of flood

Because the sizes of the river basins differ, the flood reaching time from the two rivers also differs. In the study region, the areas of subbasins 1 and 2 are 168 km^2 and 50 km^2, respectively. A 2-h rainfall event may be sufficient to cause flooding of the smaller subbasin 2 into the city; however, the larger subbasin 1

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may require a longer duration. In this study, the time-to-arrival of flood is adopted to estimate the rainfall duration for each subbasin. The time-to-arrival of flood t is defined as the sum of the runoff duration t_1 and the routing duration t_2. Model-based flood simulation is one method for calculating the time-to-arrival of flood; however, the variety in rainfall type and amount results in inaccuracies. Thus, representative time-to-arrival of flood for subbasins are required. Because of the complex conditions of subbasins, representative time-to-arrival of flood could not be estimated by simple simulation. Thus, the empirical formulas (15) and (16) are adopted to estimate the representative time-to-arrival of flood:

$$t_1 = \sqrt{A} / \sqrt{2} * T \,, \tag{15}$$

where t1 is the runoff duration from slope to river, A is the area of the subbasin located at the upper stream of the river, and T is the empirical runoff duration for a 2-km2 area. T is 30 min for mountain areas and 20 min for steep slopes.

$$t_2 = \frac{1}{3600} * \frac{L}{W} \,, \tag{16}$$

where t2 is the routing duration from the upper river stream to the outlet, L is the distance from the upper river stream to the outlet, and W is the empirical flood speed. W is 3.5 m/s for slopes larger than 1/100, 3.0 m/s for slopes between 1/100 and 1/200, and 2.1 m/s for slopes smaller than 1/200.

The parameters for the two subbasins and calculations resulting from formula (15) and (16) are summarized in table 2.

Table 2. Parameters and calculation results for the flood reaching time.

	A (km^2)	*T* (*h*)	t_1 (*h*)	*L* (*m*)	*W* (*m/s*)	t_2 (*h*)	*t* (*h*)
Subbasin 1	10.5	0.5	1.1	24430	3.5	1.9	3
Subbasin 2	11.6	0.5	1.2	6400	3.5	0.5	1.7

3.3.2 Copula-based rainfall generation

The basic concept of the copula method has been previously introduced. In this section, we adopt this method for generating the rainfall amount. As was previously calculated in table 2, approximately 3 h and 2 h of rainfall can result in flooding of subbasins 1 and 2, respectively. The focus of this study is rainfall causing floods in inundation areas; thus, we estimate the correlations of rainfall duration in both subbasins. The paired value is from 2 h and 3 h of accumulated rainfall. Although a large amount of zero data was detected, we consider that at least one rain gauging station had non-zero data.

We follow the procedure of copula analysis introduced in section 2. We first fit the rainfall data of each subbasin to the marginal distribution. A generalized extreme value distribution more accurately reflects the characteristics of the data compared with other distributions, particularly for tail values. Thus, the rainfall data in subbasins 1 and 2 are described by generalized extreme value distribution with parameters of 0.59, 1.88, and 1.58 and 0.54, 1.84, and 1.72, respectively. Four types of copula functions including Gumbel, Gaussian, Clayton, and t copulas are then chosen to fit the marginal distribution. The root mean square error (RMSE) and Akaike information criterion (AIC) tests indicate that Gumbel copula is the best function for describing the joint distribution of rainfall from two basins (table 3).

Table 3. Fitness test by root mean square error (RMSE) and Akaike information criterion (AIC).

	RMSE	AIC
Gumbel Copula	0.012	-1912
Gaussian Copula	0.024	-1726
Clayton Copula	0.038	-1541
t Copula	0.022	-1790

Figures 4 and 5 plot the Gumbel copula with a parameter of 2.126. Figure 4 shows the *cumulative distribution function* (CDF) for the standard copula with marginal distribution values of [0, 1]. As previously mentioned, a standard marginal distribution value of [0, 1] could be obtained from quantile conversion, and vice versa. Therefore, the joint distribution for 2 h and 3 h of rainfall at two rain gauging station are obtained from a standard copula, as indicated in Fig. 5.

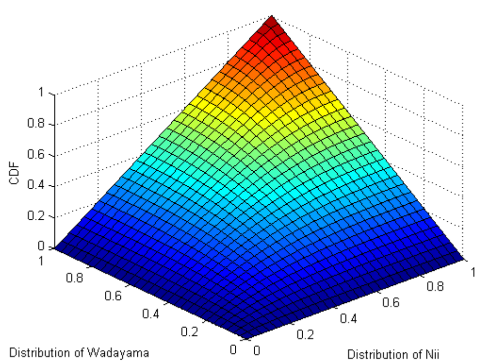

Fig. 4. Copula cumulative distribution function (CDF) with marginal distribution.

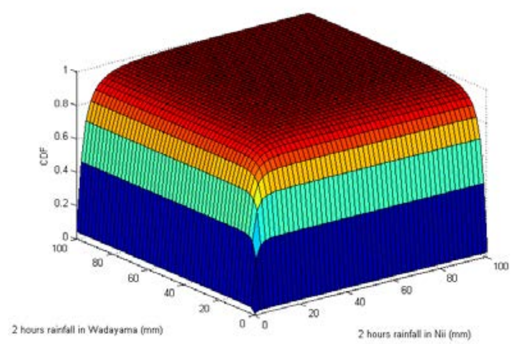

Fig. 5. Joint distribution for 2–3-h rainfall events.

On the basis of the copula function, random values of rainfall including spatial correlations are generated for flood and inundation simulation. Figures 6 and 7 plot the observed and generated rainfall for the two subbasins, which demonstrates that the copula function effectively captures the general spatial correlations of the index rainfall.

3.4 Flood and inundation simulation

The simulation model is an integrated model that includes runoff and inundation parts. As previously mentioned in section 3, the runoff values are developed on the basis of a contour line distribution, and inundation is based on an irregular mesh distribution. Figure 8 shows the basic working mechanism and combination of these two parts.

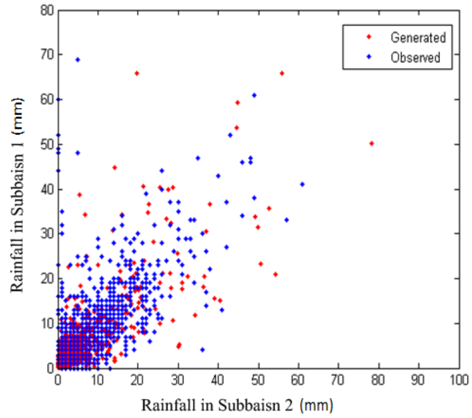

Fig. 6. Observed and generated rainfall (1000 samples).

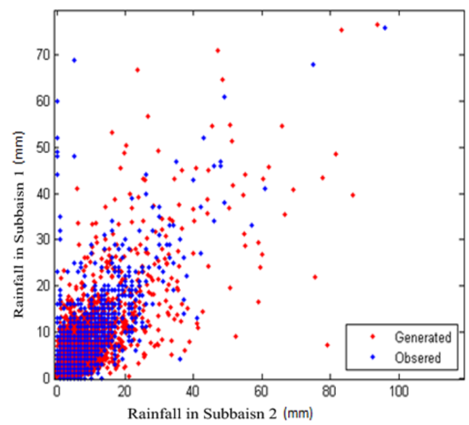

Fig. 7. Observed and generated rainfall (5000 samples).

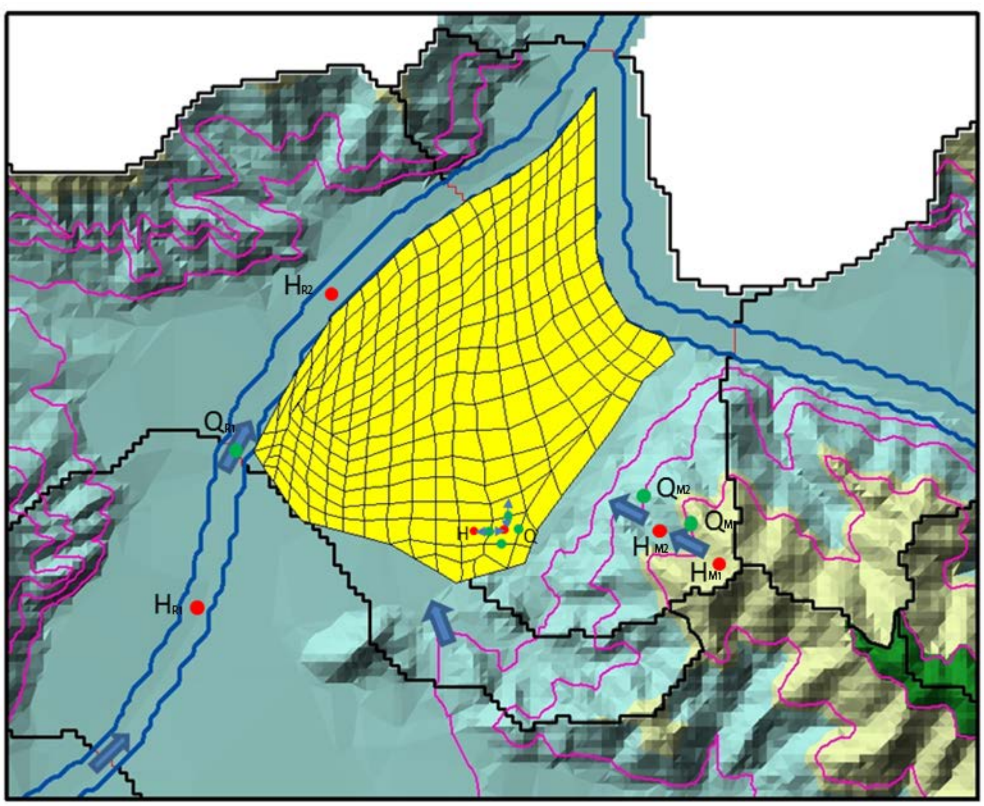

Fig. 8. Model combination and position of the unknown value set.

As shown in Fig. 8, the water depth and flow are calculated at the center and edge of the mesh, respectively. The runoff model calculates the rainfall that flows from the ground surface into the river. In the inundation model, dyke overflow and flow from the mountains in addition to rainfall runoff are treated as input information.

Before conducting flood simulations, the runoff model was validated by rainfall and river flow observation data. In our runoff model, a rainfall event that occurred from 18:00 to 4:00 on August 30–31, 2004 was used for input data. Rainfall and flow gauge data are summarized in table 4. The model was validated by comparing the observed flooding at the outlet and the simulation results.

Table 4. Rainfall and flow gauge data used for the runoff model.

Time	Rainfall in Subbasin 1 (mm)	Rainfall in Subbasin 2 (mm)	Q (m^3/s)
8/30/2004 18:00	5	2	1.53
8/30/2004 19:00	2	1	2.64
8/30/2004 20:00	13	15	5.74
8/30/2004 21:00	25	34	31.54
8/30/2004 22:00	36	15	214.27
8/30/2004 23:00	16	28	398.81
8/30/2004 24:00	17	29	1023.63
8/31/2004 1:00	2	5	913.05
8/31/2004 2:00	1	2	739
8/31/2004 3:00	0	0	593.49
8/31/2004 4:00	0	0	472.96

Figure 9 shows a comparison of the observed and simulated discharge, which demonstrates the accuracy of the runoff model, particularly for the flood peak occurrence time and flood volume.

To explain the importance of the spatial correlation of rainfall in the flood inundation simulation and to describe the model mechanism, the following example adopts spatial rainfall generated by the copula function. Rainfall amounts of 88 mm generated over 3 h in subbasin 1 and 68 mm over 2 h in subbasin 2 are adopted to drive our model. Dyke information is then applied for inundation simulation. Figure 10 illustrates a 4-h flood process caused by the rainfall. To compare different scenarios, two cases are simulated: the case considering only the main river without spatial correlation and the case considering both rivers with spatial correlation. Maximum inundation maps plotted in Figs. 11 and 12 indicate different inundation conditions; details are discussed in the following section.

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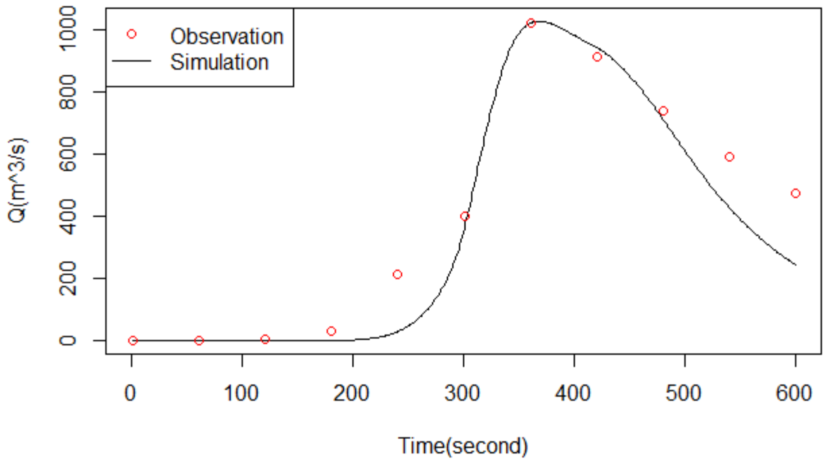

Fig. 9. Comparison of the observed and simulated discharge.

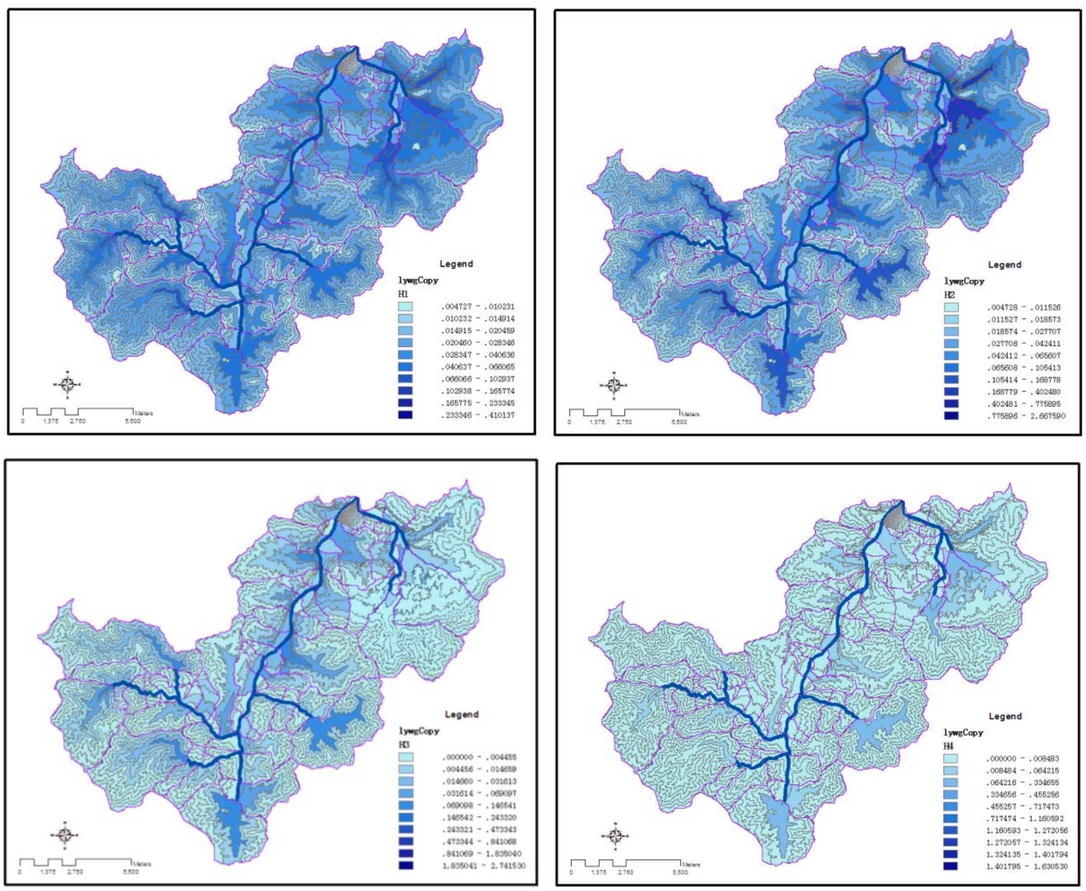

Fig. 10. Distribution of the water depth over 4 h, which includes rainfall amounts of 88 mm over 3 h in subbasin 1 and 68 mm over 2 h in subbasin 2. The upper left-hand illustration covers the first hour; upper right-hand, the second hour; bottom left-hand, the third hour; and bottom right-hand, the fourth hour.

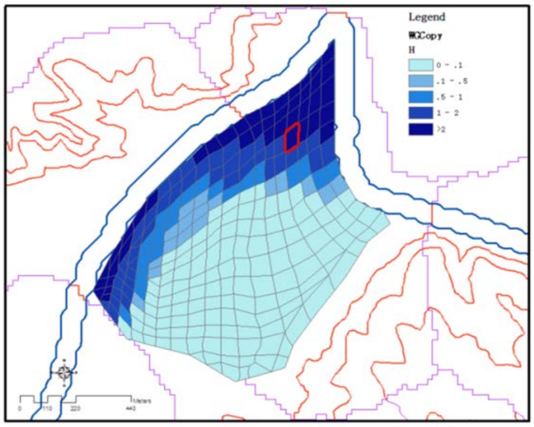

Fig. 11. Maximum inundation due to rainfall (88, 0 mm) without spatial correlation.

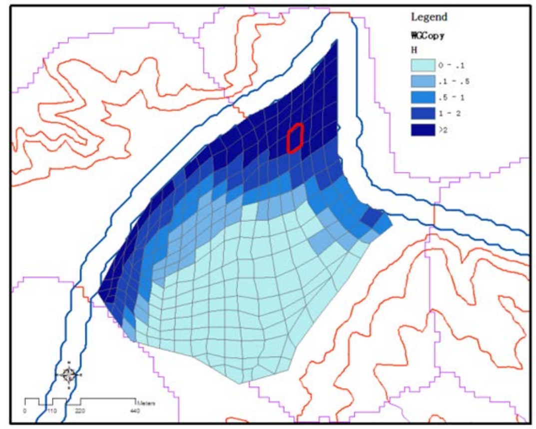

Fig. 12. Maximum inundation due to rainfall (88, 68 mm) with spatial correlation

3.5 Risk analysis

In this section, flood risk is analyzed for a specific area. Mesh no. 54 is used as an example to assess flood risk by inundation simulation and to assign a fragility curve. According to land-use maps, mesh no. 54 is essentially a residential area; the DEM indicates a slope of less than 1/1000. Thus, the damage rate for a group A house is applied, as determined by the damage rate table developed by the River Management Committee of Japan (1997) (table 5).

Table 5. Damage rate for a group A house.

Depth / Type	Water depth				
	<50 cm	50–99 cm	100–199 cm	200–299 cm	>300 cm
Group A house	0.053	0.072	0.109	0.152	0.220

The definition of risk is defined as the loss times the probability of loss; for flood risk, loss = property × damage rate, and probability of loss = probability of water depth. Therefore, the flood risk = property × damage rate × probability of water depth. In this case study, the mesh property is unknown; therefore, a curve of damage rate and probability of water depth is presented to demonstrate risk.

According to the rainfall generation method, if a threshold of probability is known, a rainfall pair corresponding to a probability larger than the threshold can be generated. We adopted a Monte Carlo algorithm and applied each rainfall pair to the flood and inundation simulation. The average water depth of a mesh was then applied to water depth corresponding to the threshold probability. Owing to the time constraints of flood and inundation simulation, we generated only 5000 random rainfall pairs.

Table 6. Inundation depth corresponding to the probability.

Threshold of probability	Number of rainfall pairs	Average water depth of mesh no. 54 (from the main river)	Average water depth of mesh no. 54 (from the two rivers)
0.99	21	0.02 m	0.02 m
0.995	12	1.37 m	1.52 m
0.999	5	1.93 m	2.36 m

From the information in table 6 and the damage rate table, data for flood and inundation risk at mesh no. 54, indicated by the red border in Figs. 11 and 12, can be determined (Fig. 13).

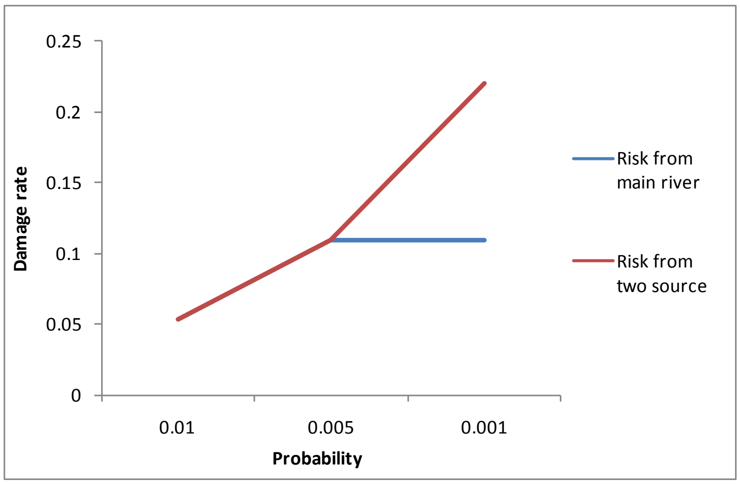

Fig. 13. Flood inundation risk at mesh no. 54.

Figure 13 illustrates the difference between risk from the main river, which does not consider rainfall spatial correlation, and that from multiple sources considering rainfall spatial correlation. As the probability decreases, trends become more apparent, which demonstrates the importance of studying the spatial correlation of rainfall.

4. DISCUSSION AND CONCLUSION

Flood risk assessment is an important topic that includes many aspects such as atmospheric sciences, hydrology, geography, and economy. Although proper assessment requires integrated research, isolated regions often focus on only one or two of these fields. For example, a heavy rainfall event that occurred in Beijing on July 21, 2012, caused 78 deaths and ￥579 millionin economic losses. Meteorological officials blamed poor infrastructure, and infrastructure officials attributed the losses to the extreme weather. Regardless, heavy rainfall disasters should be analyzed comprehensively to include multiple departments, disciplines, and sources.

Based on the analysis of spatial–temporal characteristics of rainfall and simulation of flood inundation, this paper presented a methodological framework for evaluating the flood risk distribution from various sources in a particular region. The case study in the Maruyama River basin demonstrated the feasibility of this methodology. However, several issues remain.

Owing to the short time series of rainfall data, we did not analyze rainfall according to once in n years. Rather, we analyzed the hourly rainfall during a 10-year period in two subbasins to capture the spatial correlation. Thus, in the joint distribution, a probability of 0.99 does not indicate once in 100 years. In addition, it should be noted that the generated rainfall amounts beyond the threshold of 0.995 do not indicate rainfall once in 200 years. To determine once in n years' rainfall, the same procedure could be adopted with recoded data. However, a possible difficulty may be the fit of marginal distribution after the selection of pair values. This topic will be studied in future research.

An additional issue is uncertainty. The methodology presented in this paper includes three main parts: rainfall analysis; hydrological models, including runoff and inundation models; and risk analysis. Each of these parts may contain individual uncertainty, and their accumulation may influence the final result. Although the copula functions have been tested by statistical methods and the runoff model was adjusted by observed flow data, the inundation model and risk analysis process have not been tested by actual observed data. This issue will also be addressed in future research.

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