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Risk Assessment and Zoning of Flood Damage Caused by Heavy Rainfall in Yamaguchi Prefecture, Japan

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Abstract: This paper presents the methodology and procedure for risk assessment and zoning of flood damage caused by heavy rainfall based on the “macro-zonation concept” in which regional macro-information such as meteorological triggering factor, natural and socioeconomic factors contributing to flood damage generating, and historical flood damages etc. is considered. In this study, Yamaguchi Prefecture in Japan is selected and its flood damage risk caused by heavy rainfall is assessed and zoned based on statistical data related to maro information.

Keywords: flood damage, heavy rainfall, weighted comprehensive analysis, gray correlation analysis, AHP, risk assessment

1. INTRODUCTION

The flood damage caused by heavy rainfall is one of the most important natural disasters in Japan, and affects human life and social development. Moreover, the frequency of its occurrence and disaster risk are considered to increase recently with global warming. Therefore, the study on risk assessment and zoning of flood damage caused by heavy rainfall is very important to make strategies for preventing and mitigating flood damage caused by heavy rainfall.

Risk assessment of natural disasters is defined as the assessment on both the probability of natural disaster occurrence and the degree of danger caused by natural disasters (Zhang and Hayakawa, 1999). In Japan, previous studies on risk assessment of flood damage caused by heavy rainfall include those by Okimura and Sugimoto (1995), Suzuki et al. (1994) and Mizutani (1993) etc. They are based on limited factors contributing to flood damage. We assume that natural disasters result from the interaction of both physical impact (hazard) and human and environmental vulnerability (Mizutani, 1993; Carrara and Guzzetti, 1993). The factors which contribute to flood damage triggered by heavy rainfall include broad aspects related to meteorological triggering factor, natural factors in connection with the earth surface conditions and socioeconomic factors in connection with conditions of human being and society etc. However, these factors and their interrelation have not been fully considered in the previous studies.

From this point of view, the methodology and procedure for risk assessment and zoning of flood damage caused by heavy rainfall were developed, whereby flood damage caused by heavy rainfall is regarded as the result of interactions among natural conditions, social and economical conditions and some complex chronological changes on the macro-zonation basis, from the viewpoints of climatology, geography, disaster science and environmental science and so on. The main objectives of this paper are (1) to identify and quantify key factors related to flood damage, (2) to evaluate their contribution to damage, and (3) to develop a methodology to assess and zone flood damage risk caused by heavy rainfall.

2. MATERIALS AND METHODS

2.1 Study Area

Yamaguchi prefecture is located at the western tip of Honshu Island and bordered by Shimane and Hiroshima prefectures to the east. Its north and west sides face the Sea of Japan and its south looks toward the Seto-naikai (the Inland Sea) as shown in Fig. 1. The total land area of the prefecture is 6,110km², while the total population is 1.54 million. Yamaguchi prefecture is situated in the area where extratropical disturbances are active. Severe meteorological phenomena on various scales such as typhoon, the Baiu front in early summer, extratropical cyclones and the front in the seasons from autumn to spring sometimes bring about heavy rainfall. It causes many kinds of flood damages. Consequently, Yamaguchi is susceptible to flood damage caused by heavy rainfall.

Yamaguchi prefecture is administratively divided into 56 counties which comprises of 14 cities, 37 towns and 5 villages. In this paper, taking meteorological data available into account, 19 districts which only are installed AMeDAS (Automated Meteorological Data Acquisition System) are chosen as the study areas (Shade parts as shown in Fig.1).

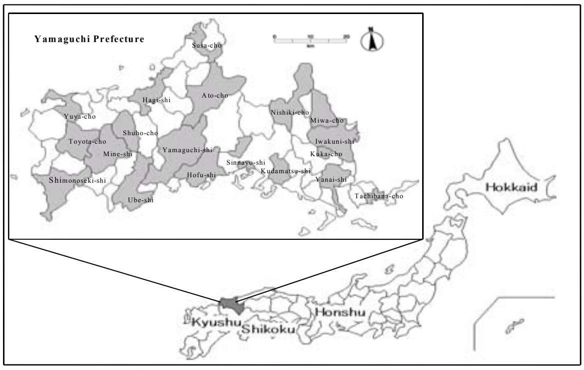

Fig. 1 Location of Yamaguchi prefecture in Japan and range of the study area in this paper

2.2 Statistical Data

In this paper, the statistical data of flood damage obtained from "the Disaster of Yamaguchi Prefecture" (Yamaguchi Prefectural Fire and Disaster Prevention Division), monthly and daily precipitation in AMeDAS observation points from "the Weather Monthly Report of Yamaguchi Prefecture" (Simonoseki Local Meteorological Observatory) and social and economic data from "the Statistical Yearbook of Yamaguchi Prefecture" (Yamaguchi Prefectural Statistical Division) from 1965 to 1994 were used for the analysis.

2.3 Analytic Methods

2.3.1 Weighted comprehensive analysis

This method assumes that the degree of the influence of each factor *j* on a particular object *i* to be assessed is discriminated as the quantification value of the indicator *j* is different, the total of the influences on this object can be expressed by Eq. (1) (Zhang and Wei, 1994).

$$CV_i = \sum_{j=1}^{m} QV_{ij} \; WC_j \tag{1}$$

where CV_i is the comprehensive value of the assessment object *i*, QV_{ij} is the quantification value of the indicator *j* with respect to the assessment object *i* ($QV_{ij} \geq 0$), WC_j is a weight on the indicator *j* ($0 \leq WC_j \leq 1$) and is computed by using *AHP*, and *m* is the number of assessment indicators.

2.3.2 *AHP* (Analytic Hierarchy Process)

The Analytic Hierarchy Process (*AHP*) (Satty, 1980) is a decision analysis method, which combines both quantitative and qualitative criteria in decision problems. Briefly, there are following five basic steps in applying the *AHP* in practice: (1) structure the decision hierarchy; (2) collect data by pairwise comparisons; (3) check consistency of material judgments; (4) apply the eigenvector method to compute weights; and (5) aggregate the weights to determine a ranking of decision alternatives.

2.3.3 Grey relation analysis

Grey system theory was originated by Deng (1982). The fundamental definition of "greyness" is information being incomplete or unknown, thus an element from an incomplete message is considered to be of gray element. "Grey relation" means the measurements of changing relations between two elements that occur in a system over time. The analysis method, which measures the relation among elements based on the degree of similarity or difference of development trends among these elements, is called "grey relation analysis".

Let *X* be a factor set of grey relation, $x_0 \in X$ represents the referential sequence, $x_i \in X$ represents the comparative sequence. $x_0(k)$ and $x_i(k)$ represent the respective numerals at point *k* for x_0 and x_i. If the average relation value $\gamma(x_0(k), x_i(k))$ is a real number, then it can be defined as (Deng, 1982)

$$\gamma(x_0, x_i) = \frac{1}{n}\sum_{k=1}^{n} \gamma(x_0(k), x_i(k)) \tag{2}$$

$\gamma(x_0, x_i)$ is designated as the grey relational grade in x_i correspondence to x_0. $\gamma(x_0(k), x_i(k))$ is the grey relational coefficient of the same at point *k*, which is given as follows:

$$\gamma(x_0(k), x_i(k)) = \frac{\min_{i\in I} \min_k |x_o(k) - x_i(k)| + \zeta \max_{i\in I} \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \zeta \max_k \max_k |x_0(k) - x_i(k)|} \tag{3}$$

where ξ is the distinguished coefficient ($\xi \in [0,1]$). The smaller the value of ξ is, the larger the distinguished ability is, and ξ=0.5 generally.

3. THE CONCEPT FRAMEWORK OF RISK ASSESSMENT OF FLOOD DAMAGE CAUSED BY HEAVY RAINFALL

The meaning included in flood damage risk can be classified into a potential threat (flood damage generating potential), and the direct damage caused by heavy rainfall. A flood damage caused by heavy rainfall is a phenomenon of composite nature in which the natural and social factor overlapped, the grade of the damage changes with the natural and social characteristics of an area, and the distribution of flood damage serves as a phenomenon of diversity. Therefore, the degree of flood damage risk caused by heavy rainfall is related not only to potential danger factors of flood damage, states and changes of flood damage, but also to socioeconomic development level and resistance capacity against the flood damage of the area. From this viewpoint, the conceptual framework for flood damage risk caused by heavy rainfall was created (Zhang et al., 1998; Zhang, 2000):

$$FDR = PD + S + C + SEPL + RC$$

It provides a rationale for the choice of indicators included in the risk assessment of the flood damage and the way in which they are combined, and also suggests that five main factors contribute to region's the flood damage risk: (1) Potential danger of flood damage caused by heavy rainfall (*PD*) represents the natural factors that cause flood damage, determines the value of hydrological abstraction and their spatial-temporal dynamics, velocity of overland flow in the area and, consequently, the situations and severity of flood damage; (2) The state of flood damage caused by heavy rainfall (*S)* represents the flood damage history and its extent; (3) The change of flood damage caused by heavy rainfall (*C*) shows how the flood damage changes with time; (4) The socioeconomic development level of the area (*SEDL*) describes the socioeconomic development level of the damaged area, and determines the vulnerability of the area to flood damage; and (5) Resistance capacity against flood damage caused by heavy rainfall of the area (*RC*) indicates both the capability of disaster prevention from flood damage and recovery capability from its impact. In this paper, we use the indicator of the ratio of amount of damages (in money term) to the *GDP* of the normal year before flood damage occurring to measure the resistance capacity against flood damage caused by heavy rainfall of the area. The larger the value of this indicator is, the lower is the resistance capacity against flood damage caused by heavy rainfall of the area, and also the higher is the degree of flood damage.

4. THE INDICATOR SELECTION AND QUANTIFICATION OF RISK ASSESSMENT OF FLOOD DAMAGE CAUSED BY HEAVY RAINFALL

The conceptual framework is operationalized by representing each of the five main factors with a set of scalar, measurable indicators. Table 1 shows the indicators and their evaluation formulas of risk assessment of flood damage caused by heavy rainfall. For more detailed descriptions of the factors, indicators, and data sources see Zhang (2000).

Table 1 Indicators of risk assessment of flood damage caused by heavy rainfall

Factor	Indicator	Evaluation formula	Code
Potential danger of flood damage generating caused by heavy rainfall (PD)	Average precipitation from April to October	Average of precipitation from April to October (mm)	I_1
	One-hour maximum rainfall	Maximum of one-hour rainfall (mm/hr)	I_2
	Geographical features index	Ratio of land area between 0m and 100m to total land area (%)	I_3
	Soil index	Ratio of sum of grey lowland soil area and yellow soil area to total soil area (%)	I_4
	Vegetation index	Ratio of vegetation (forest, grassland etc.) area to total land area (%)	I_5
The state of flood damage caused by heavy rainfall (S)	Flood damage index	FDI = Ip+Ih+Ie*	I_6
	Crop damage area	Crop damage area caused by heavy rainfall (ha)	I_7
The change of flood damage caused by heavy rainfall (C)	Heavy rainfall frequency	Ratio of rain days of 100mm and over to statistics years (%)	I_8
	Flood damage frequency	Ratio of number of damage times to statistics years (%)	I_9
The socioeconomic development level of the area (SEDL)	Population density	Ratio of total population to total land area (Personal/km^2)	I_{10}
	GDP per unit area	Ratio of GDP to total land area (100 million yen/km^2)	I_{11}
Resistance capacity against flood damage caused by heavy rainfall of the area (RC)	Resistance damage index	Ratio of amount of damages (money value) to GDP of the normal year before flood damage occurring (%)	I_{12}

* where *FDI* represents flood damage index and the larger the value of the index is, the severer the loss extent of flood damage caused by heavy rainfall is. *Ip*, *Ih* and *Ie* express the normalization index of persons damaged number (*p*), houses damaged number (*h*) and economic losses (*e*) respectively and are calculated as following (zhang et al; 1998):

For $p \geq 10^2$ (houses), $h \geq 10^3$ (persons) and $e \geq 10^2$ (100 million yen)

$$Ip = \log_{10} p - 1, \qquad Ih = \log_{10} h - 2, \qquad Ie = \log_{10} e - 1$$

For $p < 10^2$ (houses), $h < 10^3$ (persons) and $e < 10^2$ (100 million yen)

$$Ip = p/10^2, \qquad Ih = h/10^3, \qquad Ie = e/10^2$$

The indicators identified for use in risk assessment of the flood damage have a variety of units, e.g., yens, houses, and number of people. These indicators are scaled so that they are all unitless, and then they are combined. The theoretical foundation for indicator quantification is based on identifying and evaluating key factors related to the flood damage risk and their contribution to the flood damage. In the paper, in order to identify and evaluate key factors related to the flood damage risk and their contribution to the flood damage, the grey relation analysis and the regression analysis are used. In the grey relation analysis, since it is thought that the flood damage frequency (I_9) and the flood damage index (I_6) among 12 indicators are the main factors which contribute to the potential of flood damage and the extent of flood damage by the heavy rain, here I_6 and I_9 are considered as the referential sequence, shown as R_6 and R_9 respectively, and the other 10 indicators are made into the comparative sequence, shown as C_i (i=1, 2, 3, 4, 5, 7, 8, 10, 11, 12). $\gamma_{(6,i)}$ and $\gamma_{(9,i)}$ were designated as the grey relational grades in R_6 and R_9 correspondence to C_i respectively. Then, $\gamma_{(6,i)}$ and $\gamma_{(9,i)}$ are calculated respectively, and average grey relational grades γ_i (i=1, 2, 3, 4, 5, 7, 8, 10, 11, 12) of respective flood damage factors obtained from the mean value of respective grey relational grades based on Eq. (2) and Eq. (3) by using the average data sequence that each attribute of raw data is normalized by dividing each value by its respective mean values are shown in Table 2.

Table 2 Grey relation analysis of flood damage risk factors caused by heavy rainfall

Grey relational grades ($\gamma_{(6,i)}$) corresponding to the1st the referential sequence (Q_6)	Verification results at the threshold value of grey relational grades of 0.2	Grey relational grades ($\gamma_{(9,i)}$) corresponding to the 2nd the referential sequence (Q_9)	Verification results at the threshold value of grey relational grades of 0.2	Average grey relational grades (γ_i)
$\gamma_{(6,1)}$= 0.2976	Close	$\gamma_{(9,1)}$= 0.6578	Close	γ_1= 0.4777
$\gamma_{(6,2)}$ = 0.2979	Close	$\gamma_{(9,2)}$= 0.6372	Close	γ_2= 0.4676
$\gamma_{(6,3)}$= 0.3067	Close	$\gamma_{(9,3)}$= 0.4750	Close	γ_3= 0.3909
$\gamma_{(6,4)}$= 0.3088	Close	$\gamma_{(9,4)}$= 0.6395	Close	γ_4= 0.4742
$\gamma_{(6,5)}$= 0.2941	Close	$\gamma_{(9,5)}$= 0.5974	Close	γ_5= 0.4458
$\gamma_{(6,7)}$= 0.3917	Close	$\gamma_{(9,7)}$= 0.2076	Close	γ_7= 0.2997
$\gamma_{(6,8)}$= 0.2990	Close	$\gamma_{(9,8)}$= 0.6535	Close	γ_8=0.4763
$\gamma_{(6,10)}$= 0.2900	Close	$\gamma_{(9,10)}$= 0.3695	Close	γ_{10}= 0.3298
$\gamma_{(6,11)}$ = 0.2404	Close	$\gamma_{(9,11)}$= 0.3135	Close	γ_{11}= 0.2770
$\gamma_{(6,12)}$= 0.2148	Close	$\gamma_{(9,12)}$= 0.3635	Close	γ_{12}= 0.2892

As can be seen from the grey relation analysis results in Table 2, the ranking of the grey relational grade can be conducted from a higher grade to lower grade:

$$\gamma_6 = \gamma_9 > \gamma_1 > \gamma_8 > \gamma_4 > \gamma_2 > \gamma_5 > \gamma_3 > \gamma_{10} > \gamma_7 > \gamma_{12} > \gamma_{11}$$

In addition, the regression analysis of the flood damage index and the other factors is carried out to find out the concrete relationships between the respective factors related to the flood damage and the flood damage as shown in Fig. 2.

Fig. 2 shows that there are relatively good positive correlations between the indicator I_6 and I_1, I_2, I_3, I_4, I_7, I_8, I_9, I_{10}, I_{11} and I_{12}, i.e., the greater these indicators are, the larger the grades of flood damage caused by heavy rainfall are, however, there is a close negative correlation between the indicator I_6 and I_5, i.e., the smaller the vegetation index is, the larger grades of flood damage caused by heavy rainfall. Therefore it turns out that the used indices are the factors effective in risk assessment of flood damage caused by heavy rainfall. Moreover, the research method can be used as a practical approach for assessing flood damage risk caused by heavy rainfall since it is easy to calculate. Based on the results as shown in Table 2 and Fig. 2, risk assessment indicators of flood damage caused by heavy rainfall are quatificated in consideration of the maximum and the minimum value of the raw data of each assessment indictors by using the method of scaling value and point scoring method (Ohmura, 1983). The result is shown in Table 3.

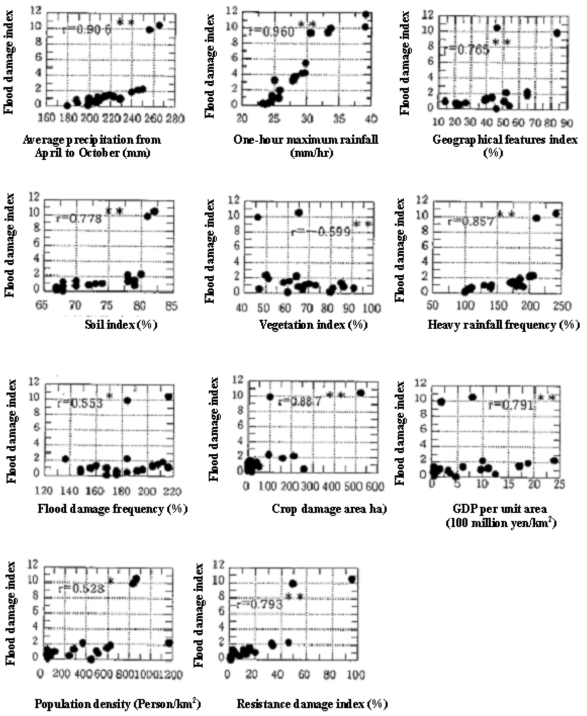

Fig. 2 Relationships between flood damage index and the other assessment indicators (* and ** represent insignificant at $p < 0.05$ and $p < 0.01$ significant level respectively)

Table 3 Criteria and values of quantification on risk assessment indicators of flood damage caused by heavy rainfall

Assessment indicator	Criteria	Rank	Evaluated score (QV)	Assessment indicator	Criteria	Rank	Evaluated score (QV)
Average precipitation from April to October	≥250	1	5	Heavy rainfall frequency	≥210	1	5
	230–249	2	4		180–209	2	4
	210–229	3	3		150–179	3	3
	190–209	4	2		120–149	4	2
	≤189	5	1		≤119	5	1
One-hour maximum rainfall	≥35	1	4	Flood damage index	≥3.0	1	4
	33–34	2	3		2.0–2.9	2	3
	31–32	3	2		1.0–19	3	2
	≤30	4	1		≤0.9	4	1
Geographical features index	≥60	1	5	Flood damage frequency	≥200	1	5
	45–59	2	4		180–199	2	4
	30–44	3	3		160–179	3	3
	15–29	4	2		140–159	4	2
	≤14	5	1		≤139	5	1
Soil index	≥80	1	4	Resistance damage index	≥49.5	1	4
	75–79	2	3		29.9–49.4	2	3
	70–74	3	2		9.9–29.8	3	2
	≤69	4	1		≤9.8	4	1
Vegetation index	≤50	1	5	Population density	≥800	1	5
	51–60	2	4		600–799	2	4
	61–70	3	3		400–599	3	3
	71–80	4	2		200–399	4	2
	≥81	5	1		≤199	5	1
Crop damage area	≥200	1	5	GDP per unit area	≥10.5	1	5
	150–199	2	4		7.5–10.4	2	4
	100–149	3	3		4.5–7.4	3	3
	50–99	4	2		1.5–4.4	4	2
	≤49	5	1		≤1.4	5	1

5. ESTABLISHMENT AND APPLICAYION OF RISK ASSESSMENT MODEL OF FLOOD DAMAGE CAUSED BY HEAVY RAINFALL

On the basis of the above-mentioned conceptual framework, the risk assessment model of flood damage caused by heavy rainfall can be described by using weighted comprehensive analysis and *AHP*, as follows:

$$FDRI_i = \sum_{j=1}^{m} QV_{ij}\ WC_j \tag{5}$$

where $FDRI_i$ is the flood damage risk index caused by heavy rainfall. This corresponds to the degree of the flood damage risk caused by heavy rainfall, that is, the higher *FDRI* is, the higher the degree of the flood damage risk is caused by heavy rainfall.

A weight is a numeric value assigned to an evaluation criterion that indicates its importance relative to other criteria in the decision situation. The larger the weight becomes, the more importance is given to the criterion. According to the formulated structure of risk assessment of flood damage caused by heavy rainfall, the weight of the objective hierarchy and attribute hierarchy can be analyzed. Weights are obtained by using *AHP*, then the average weights (Fig. 3) are derived after the consistency verification.

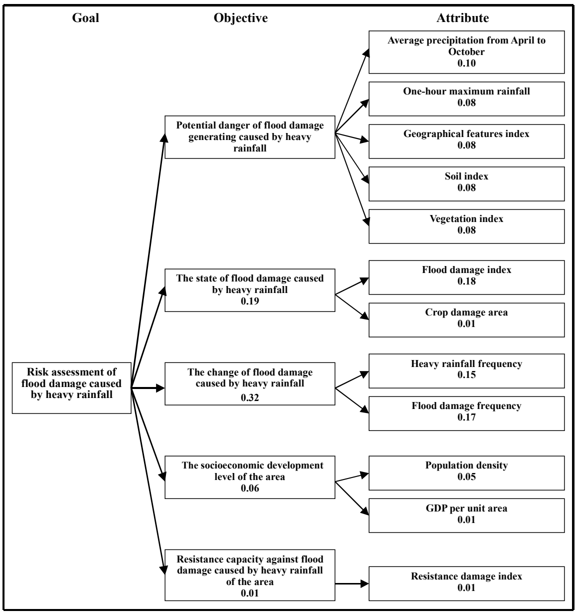

Fig. 3 The weights structure of the flood damage caused by heavy rainfall according to AHP
(The numbers are the weights of each hierarchy)

In order to assess the degree of flood damage risk caused by heavy rainfall, a criterion of risk assessment of flood damage caused by heavy rainfall is created according to the four-grade system (Ohmura, 1983) based on the computed results of the flood damage risk index caused by heavy rainfall, by using the data in Yamaguchi Prefecture from 1970 to 1994, and then, based on the criterion, the degree of flood damage risk caused by heavy rainfall in Yamaguchi Prefecture are assessed and zoned (Fig. 4). The degree of flood damage risk caused by heavy rainfall in Yamaguchi Prefecture shows that the places where flood damage risk caused by heavy rainfall is high are distributed centering on the area in the Seto Inland Sea. This explains much of the causes that heavy rain frequency is relatively larger, and heavy rain intensity, socioeconomic development level, and population density are also high there.

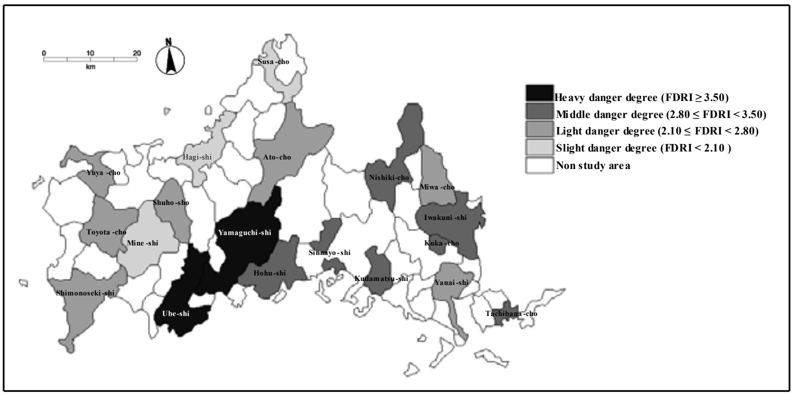

Fig. 4 Risk zoning of flood damage caused by heavy rainfall in Yamaguchi Prefecture

6. CONCLUDING REMARKS

Based on the "macro-zonation concept", the methods for risk assessment of flood damage caused by heavy rainfall are presented. The methods consider potential danger factors of flood damage generating, situations and changes of flood damage, region's socioeconomic development level and resistance capacity against the flood damage. Application of the proposed methods to Yamaguchi Prefecture of Japan has shown that they are useful in performing the risk assessment and zoning of flood damage caused by heavy rainfall. The process and result will help decision maker design the flood damage protection measures, and develop strategies for the flood damage prevention and mitigation activities.

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