Watershed-based Flash Flood Risk Assessment in Yulin Municipality, Guangxi, China

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Abstract. An analysis was performed on flash flood risk for the purpose of finding appropriate strategies and measures for flash flood management from area to area in Yulin region. This region suffered heavily from flash flood disasters in the past years and a project on Flash Flood Investigation and Assessment (FFIA) was conducted during the period of 2013-2016 focusing on acquiring basic information on flash flood prone area, historical flash flood events, riverside communities or towns. Based on the data from FFIA and risk triangle conception of on hazard, exposure and vulnerability, flash flood risk assessment was performed for each watershed entity in mountainous area, by steps of suitable risk index system development, appropriate risk assessment model construct, risk component computation and flash flood risk analysis. The main understandings include: 1) consideration on computed entity and weight set for risk factors made the results more creditable; 2) exposure level distributes evenly and the areas with high and medium flash flood vulnerability level concentrate in the lower of the Nanliu River and the Beiliu River; 3) referring to the main stream line of the Nanliu River and the Beiliu River, hazard level in the lower part is much higher than that in the upper part, and the areas with high and medium flash flood risk level concentrate on both mountainous and hilly areas along the line. Finally, suggestions on flash flood countermeasures were made at county level, including macro-scale rainfall monitoring, local rainfall and water stage monitoring and warning, community-based awareness and drill, appropriate local structural measures. This risk analysis was made special by considering on overlaying effect of risk tri-components and watershed-based entity.

1. Introduction

Yulin is a prefectural level region located in southeastern Guangxi Zhuang Autonomous Region of China. It covers an area of 12,838 km^2, where the Yulin Basin, hill areas and mountainous areas cover 17.6%, 49.4% and 33% of the total area, respectively (refer to Figure 1). Yulin Basin is bounded by Darong Mountain in north, Liuwan Mountain in west, Stone Mountains in east, and some low hills in south. There are 2 major rivers flow through Yulin area: the Nanliu River, originating at the Darong Mountain, flows through the Yulin Basin from northeast to southwest; the Beiliu River, originating at the Yunkai Mountain, flows northeast through the area. The area is subjected to subtropical monsoon climate with average annual precipitation about 1,650 mm; the monsoon season

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is centered from June to August, with frequent short-duration frontal rains, terrain rains and convectional rains (refer to Figure 2). Owing to aerial climate and geography conditions along with recent human activities, Yulin is a flash flood prone area. By 2016, the population in the hill and mountainous areas where potentially threatened by flash flood, reached 5.10 million, 74% of the total population of Yulin region.

Yulin has jurisdiction over seven counties: the Yuzhou District, the Fumian District, the Rongxian County, the Luchuan County, the Bobai County, the Xingye County and the Beiliu County. All of them suffer heavily from flash floods with Beiliu County ranked heaviest. In recent years, rapid developments have increasingly encroached mountain-hill areas, putting more lives and properties in potential threats of flash floods. Hence, flash flood management has become one of the most challenging tasks in flood management in Yulin.

According to international experiences, one of the effective strategies on flash flood mitigation is to practice risk management that can present guidance on countermeasures. The literature review reveals following seven understandings on flash flood risk analysis: (1) The concept of risk. Some literatures proposed that flood disaster system consists of surrounding environment, disastrous factors, exposures and disaster prevention capacity [1]. The current concept of flood risk involves the possible consequence among interactions of hazard, exposure and vulnerability, while the very early concept of risk was usually the sequence of losses and possibility [2, 3]. Erich J. Plate [4, 5] regarded that the regional flood risk should be determined by quantizing the hazard, exposure and vulnerability, while Merz and Thieken [6] regarded that the aim of flood hazard appraisal is to estimate the possible inundated area and intensity of various scenarios. (2) Detailed information needed in risk analysis. Apel H, et al [7] discussed how to choose methods or models and how detailed information one would need in risk analysis. (3) Development of risk index system. Usually, a 2- or 3-layer index framework was first developed with a number of factors. Some analyses, such as principal component analysis and sensitivity analysis, were performed on factor choice [8, 9]. (4) The basic computation entity for risk. Various grid resolutions were found in many studies; such as 1km×1km, 5km×5km, and so on, were widely used. However, the relation of hazard factors with grid resolution was little taken into account. (5) The process of the three components of risk. Many studies focused on each component; such as hazards estimate [10-12], exposure and vulnerability appraisal. Especially in recent years, attentions were increasingly paid to vulnerability or resilience and uncertainty at community level [13-15]; exposure and vulnerability were typically combined as one entity in most studies [16]. (6) The emphasis of risk analyses. In many studies, the emphasis was, to some extent, put on the technical approaches, such as hydrological and hydraulic techniques and tools [17-19], RS (Remote Sensing) and GIS (Geographic Information System) [20-22]. (7) The method for risk analysis. Typically, the risk analysis methods consist of three categories: the product of loss and possibility [2, 3], each component of risk [5], and the historical approaches [23-26].

This study performed flash flood risk assessment in assisting decision making on flash flood management strategies for various areas in Yulin region. This study emphasized on three aspects: (1) the risk conception of references [4, 5] is employed for it presents expression not only to the components of flash flood risk, but also to macro-thought of flood risk computation and guidance on flash flood management; (2) flash flood risk is regarded as the overlying effect of hazard, exposure and vulnerability; and (3) the basic computation entity for flash flood risk analysis is watershed, not grid, and the relationship among various hazard factors was taken into consideration.

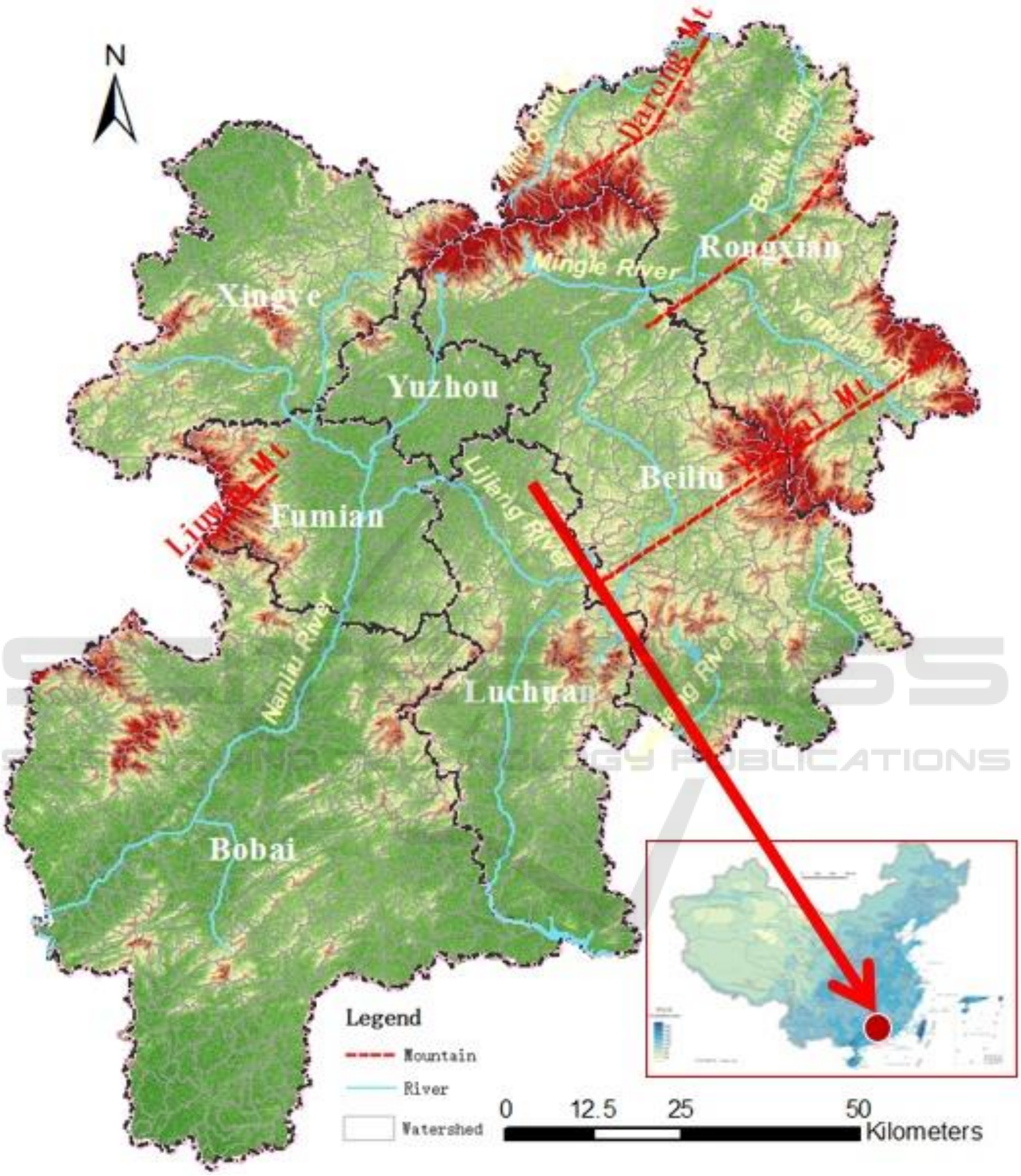

Figure 1. Landform and counties in Yulin.

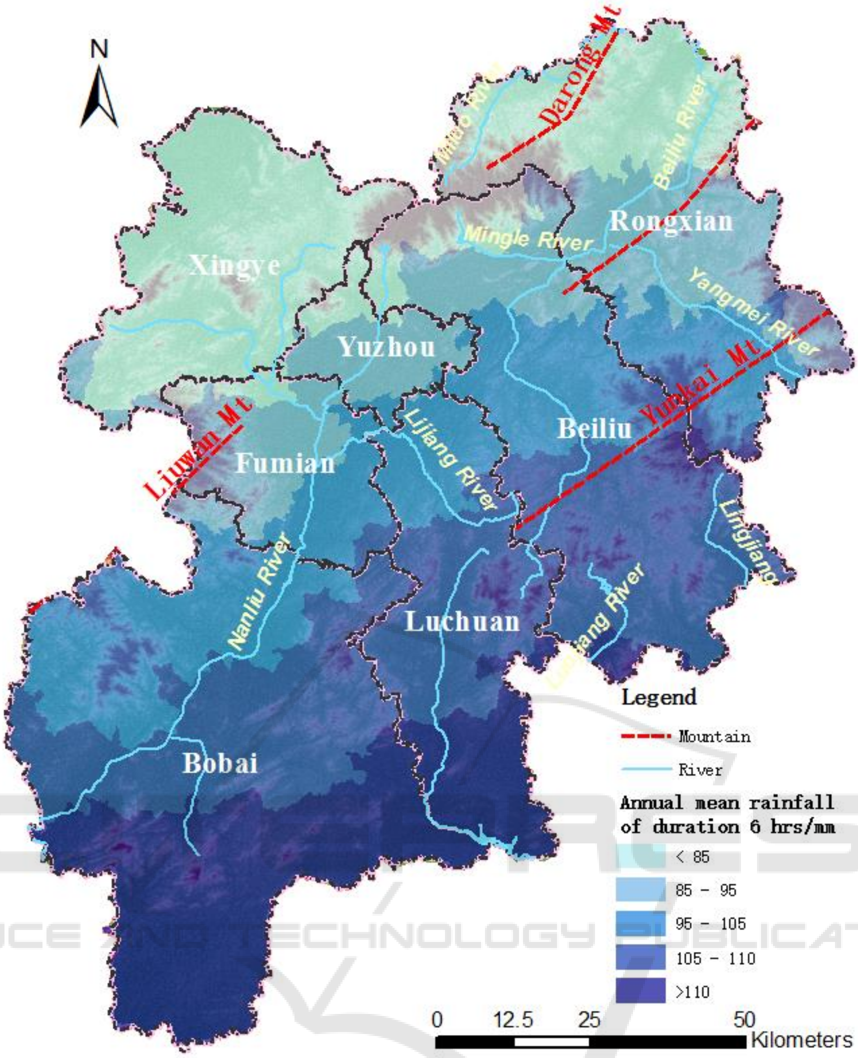

Figure 2. Rainstorm of 6 hr-duration in Yulin.

2. Data acquiring

In the past years, great efforts were made to mitigate flash flood hazards in Yulin. However, some fundamental information for effective flash flood management was still unavailable or unclear to flood management staff or decision makers. These include flash flood prone areas, vulnerable exposures, and capacity on monitoring and warning for flash flood. Hence, a municipality-wide project (hereinafter referred to as "the Project") was conducted from 2013 through 2016 to implement structural and non-structural measure interventions against flash floods in Yulin. Through the Project, fundamental data was collected regarding flash flood management. To achieve jurisdictional and technical high efficiency, the data was analyzed and summarized using both watershed and county as basic unit. The project included 1,106 watersheds ranging from of 0.5 km^2 to 318 km^2 with an average of 14 km^2. The following items were clarified for each watershed: (1) the basic geometrical and geographical attributes of the watershed, such as catchment area, water course system, length and slope of each water course, and land use/land cover; (2) flash flood prone area; (3) population distribution, house distribution, household asset, monitoring and warning device, and current flood control capacity of flood prone community; (4) water-related structures which potentially causing disasters, such as bridges, culverts, and weirs; (5) survey data on longitudinal and cross sections of river channel near riverside communities; and (6) historical flash flood events.

3. Approach

In this study, risk was regarded as the overlaying effect of hazard (H), exposure (E), and vulnerability (V). Hazard is mainly from physical factors, such as short-duration storms and steep landform within a watershed; exposure consists of socioeconomic factors, such as population and houses in flood prone areas; vulnerability relates primarily on susceptibility to flash flood, for example, the material and structure of houses, community capacity on flash flood monitoring and warning, and flash flood awareness of local people. As watershed is the basic entity for this study, the raw values of each factor were acquired and processed based on watershed scale.

3.1. Index system construction

The index system for risk assessment was developed from three aspects: hazard, exposure, and vulnerability. Each index should satisfy following conditions as much as possible: (1) utmost use of the data from the Project; (2) liable to be quantified; (3) the independence between factors, and (4) directly serving flash flood management.

Figure 3 presents the index system that consists of three layers: a general risk layer, a component layer and a factor layer. Layer 1 is the general risk (R) that is the overlaying effect of all components of risk; layer 2 includes three components of risk: hazard (R_h), exposure (R_e) and vulnerability (R_v), all of which resulted from factors of risk; and layer 3 is the corresponding factors to three components of risk.

In this study, much attention was attached to the characteristics of flash floods; such as short duration and high intensity rainstorm, steep slope of waterway with small drainage area, population and properties of located in flood prone area. When choosing factors at the third layer, the main considerations were as follows.

Hazard (R_h) refers to the degree of dangerous of a flash flood event. It is determined by combined effects of pregnant environment, the disastrous factors, and disaster prevention capacities. In this study, the rainstorms with durations of 6 hours (H_{r6}) and 3 hours (H_{r3}) were selected as rainfall feature, while flood peak modus (H_{lm}) and time of concentration (H_{lt}) as landform feature.

Exposure (R_e) considers population, houses and household assets located in flood areas. In this study, the population (E_p), houses (E_{hse}) and household assets (E_{asset}) were chosen as three indexes to represent exposure. The household assets were simply estimated as the magnification of the number of households in mountain and hill area in the process of FFIA to estimate the possible losses due to flash flood.

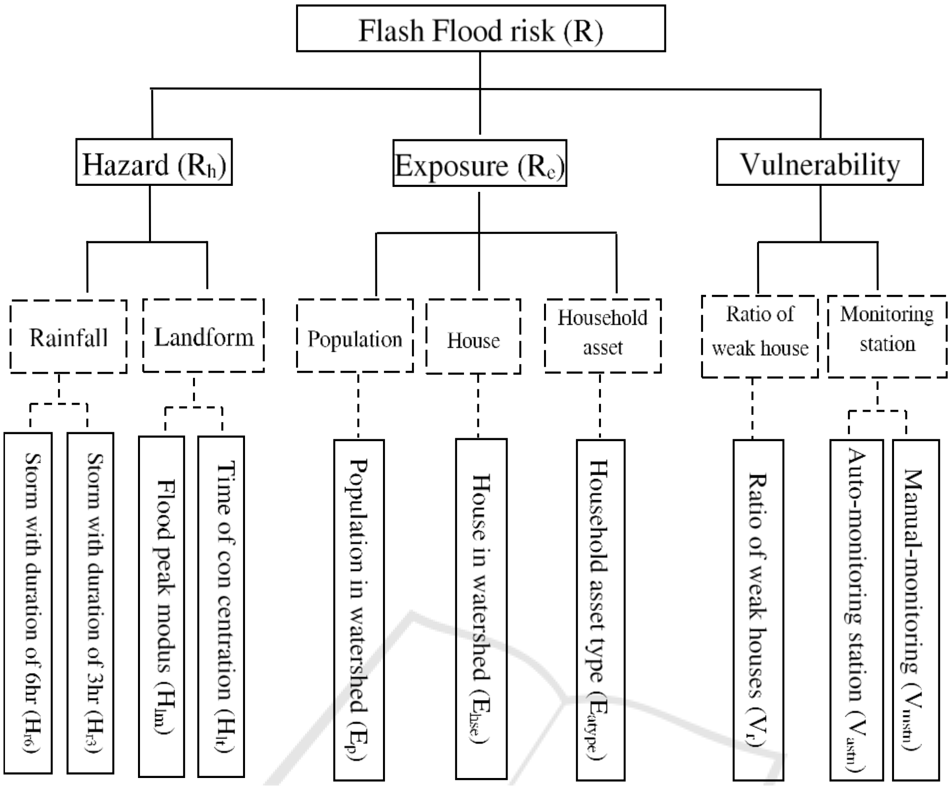

Figure 3. Flash flood risk index system.

Vulnerability (R_v) is the inner attribute of exposure and represents the fragility of exposures in same flash flood hazard. It is closely related to the capacity of exposure to response to flash flood. In this study, both the ratio of weak houses (V_r) and covering scope of single auto- or manual-monitoring stations (V_{astn} and V_{mstn}) are on half of vulnerability (R_v). In the process of FFIA, the houses in mountain and hill areas were classified into four types, with type III and IV being weak to flash flood.

3.2. Model descriptions

3.2.1. Risk model. The model to compute flood risk is as follows:

$$\text{Risk} = \text{H} \cap \text{E} \cap \text{V} \tag{1}$$

where, Risk is regional flood risk; H, E and V the elements of flood risk, hazard, exposure and vulnerability, respectively. They are computed as follow:

$$\text{H} = \sum_{i=1}^{m} W_i H_i = \sum_{i=1}^{m} w_i \left(\sum_{k=1}^{m'} w_{ik} H_{ik}\right) \tag{2}$$

$$\text{E} = \sum_{j=1}^{n} W_j E_j = \sum_{j=1}^{n} w_j \left(\sum_{k=1}^{n'} w_{jk} E_{jk}\right) \tag{3}$$

$$\text{V} = \sum_{k=1}^{l} W_k V_k = \sum_{k=1}^{l} w_k \left(\sum_{k'=1}^{l'} w_{kk'} V_{kk'}\right) \tag{4}$$

H_i,E_j, V_k —factors of layer 3 corresponding to components of layer 2; m,n, l - numbers of factors of layer 3 corresponding to components of layer 2; m', n', l' — numbers of factors of layer 3; i, j, k, k' — intermediate variables to summarize; W — weights of components of layer 2 and factors of layer 3.

3.2.2. Considerations on weights. The following three considerations were taken into account:

1) Components of layer 2: three factors - hazard, exposure and vulnerability were equally weighted with each bearing a weight of 1/3.

2) Factors of layer 3: for hazard, short-duration rainstorms bear more weight as these storms are likely trigger flash flood; for exposures, population bears more weight; and for vulnerability, monitoring stations carry more weight for their importance to emergency evacuation.

3) Weight value calibration: trial-and-error method were used to calibrate weight values for each factor by comparing with historical flash flood data.

3.2.3. Considerations on thresholds. Certain threshold considerations for risk level of the Layer 1 and all components of the Layer 2 are listed as follows.

1) Three threshold levels (high, medium, low) were signed to each component (hazard, exposure, vulnerability) in the risk level. A H-E-V Cube was developed with 27 sub-cubes (see Figure 5) to display the overlaying effect. The overlaying effect is also presented in Table 1.

2) To determine the thresholds of the Layer 2 components, the sample data was sort in a descending order. The values ranked at 1/3 and 2/3 were taken as the thresholds for high, medium, low level (refer to Figure 4).

Table 1. Overlaying effect of H-E-V and risk level.

Risk level	Number	H1E3V3, H2E3V3, H3E1V3, H3E2V3, H3E3V1, H3E3V2, H3E3V3
High	7	H1E2V2, H1E2V3, H1E3V2, H2E1V2, H2E1V3, H2E2V1, H2E2V2, H2E2V3, H2E3V1, H2E3V2, H3E1V2, H3E2V1, H3E2V2
Medium	13	H1E1V1, H1E1V2, H1E1V3, H1E2V1, H1E3V1, H2E1V1, H3E1V1

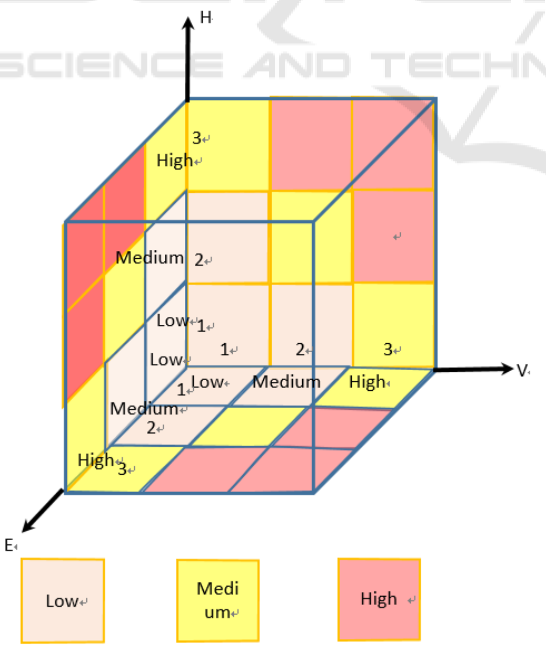

Figure 4. Threshold for hazard, exposure and vulnerability.

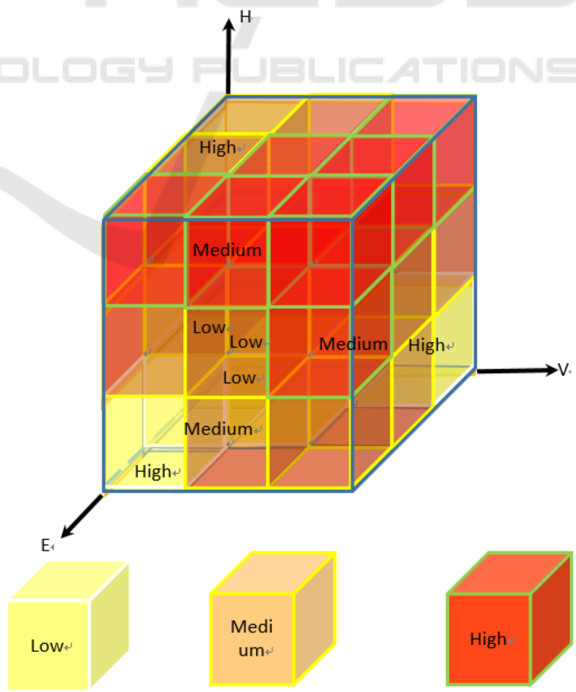

Figure 5. Overlaying effect of H-E-V Cube and risk level threshold.

4. Flash flood risk computation

4.1. Data process and analysis
Data collected for each watershed was processed and analyzed. There are 1,106 watersheds involved, and the sizes of watershed are less than 300 km^2.

The flood peak modus (H_{lm}) is defined as the ratio of peak discharge to the drainage area at the outlet of the watershed. The time of concentration (H_{lt}) for each watershed were determined as follows [27].
Mean concentration velocity at basin level (v_τ) is used to reflect the characteristics of slope concentration and channel concentration:

$$v_\tau = mJ^\alpha Q_m^\beta \tag{5}$$

Yield the time of concentration of a watershed as

$$\tau = 0.278\frac{L}{V_\tau} = 0.278\frac{L}{mJ^\alpha Q_m^\beta} \tag{6}$$

in which, τ- time of concentration, hr; L-the longest distance from the river mouth to the divide of watershed, km; J-the mean slope of L; m - experimental parameter for concentration related to the situations in the watershed, such as land use, soil type, vegetation cover, and average surface slope; Q_m - peak discharge, m^3/s; α, β- experimental exponent, 1/3 and 1/4 for triangular cross section in mountainous and hilly area.

Both flood peak modus (H_{lm}) and time of concentration (H_{lt}) involve the characteristics of runoff generation and surface volume in a watershed, from the point view of hydrology and hydraulics. This is quite different to many other gird-based researches on flash flood risk analysis in which many physical factors about the conditions in the watershed were taken into consideration only as divided index factors.

Table 2 presents some original values of sample data of flash flood risk index.

Table 2. Demo data of flood risk index for watershed.

No.	H_{r6} (mm)	H_{r3} (mm)	H_{lm} ($m^3/(s\cdot km^2)$)	H_{lt} (hr)	E_p	E_{hse}	E_{asset} (10^3 Yuan)	V_r	V_{astn} (km^2)	V_{mstn} (km^2)
1	114	89	0.20	1.33	1,143	211	1,688	0.10	14.86	7.43
2	120	92	0.12	2.17	13,368	2,883	23,064	0.29	9.55	14.33
3	102	84	0.21	1.33	2,502	771	6,168	0.57	28.00	9.33
4	94	78	0.16	1.67	1,516	279	2,232	0.56	21.74	10.87
5	90	76	0.19	1.33	8,175	2341	18,728	0.59	21.83	21.83
6	102	84	0.14	1.83	1,250	246	1,968	0.31	16.30	8.15
7	108	86	0.24	1.17	10,136	2176	17,408	0.05	6.73	6.73
8	110	87	0.18	1.33	3,197	560	4,480	0.18	10.20	10.20
9	110	87	0.14	1.83	5,532	949	7,592	0.12	19.22	19.22
10	114	89	0.20	1.33	1,143	211	1,688	0.10	14.86	7.43

4.2. Risk Analysis
The risk analysis was performed using following four steps.

Step 1, index normalization. As illustrated in Table 2, 10 indexes are quite different in magnitude and dimensions. It is necessary to make normalization before performing flash flood risk assessment. After normalization, the absolute value of indexes can be expressed into relative values in same magnitude and dimensionless. The following equation presents the algorithm of normalization:

$$x_i^* = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{7}$$

where, x_i is the values of original data, x_i^* the normalized value of original data, and x_{max} and x_{min} the maximum and minimum of a same index, respectively.

Step 2, weights determination. The initial weight values were estimated based on engineering experiences. For rainstorms with 6-h (H_{r6}) and 3-h (H_{r3}) durations, flood peak modus (H_{lm}) and time of concentration (H_{lt}) were set as 0.3, 0.2, 0.3, and 0.2, respectively; the exposure factors of population, number of houses and household assets were set as 0.4, 0.4 and 0.2, respectively; and the vulnerability factors for ratio of weak houses (type III and IV) was set to total houses; covering areas of single auto- or manual monitoring stations were set of 0.4, 0.3 and 0.3, respectively. The initial values were revised by trial-and-error method, using historical flash flood events records.

Pilot trial-and-error was performed using data of Beiliu County which had 36 historical flash flood events. Among these events, 14 are classified as high risk, 21 and 1 are classified as medium and low risk, respectively (refer to Figure 6).

Table 3 demonstrates the calibrated weight values of components and factors in the risk index system.

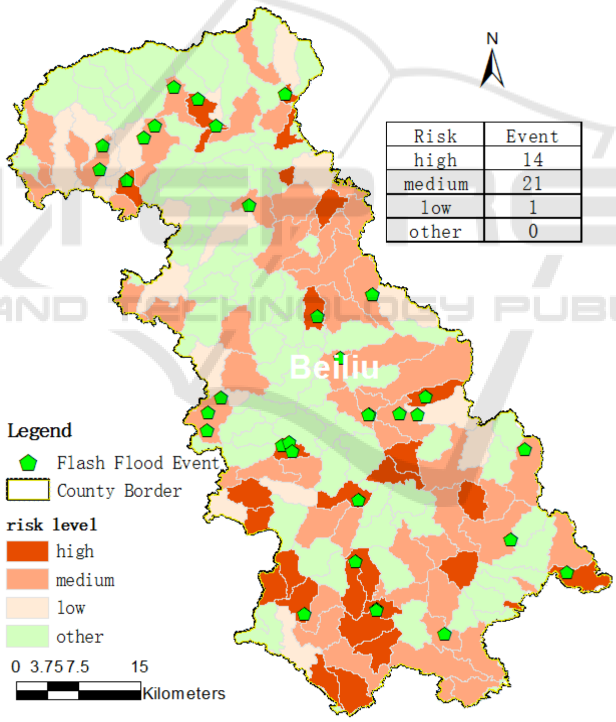

Figure 6. Pilot trial-and-error in Beiliu County.

Table 3. Weights of component and factors in the risk index system.

Component	Hazard				Exposure			Vulnerability		
Weight	1/3				1/3			1/3		
Factor	H_{r6}	H_{r3}	H_{lm}	H_{lt}	E_p	E_{hse}	E_{asset}	Vr	V_{astn}	V_{mstn}
Initial Weight	0.30	0.20	0.30	0.20	0.40	0.40	0.20	0.40	0.30	0.30
Calibrated Weight	0.20	0.10	0.40	0.30	0.55	0.35	0.10	0.30	0.35	0.35

Step 3, risk values computation. The contributions of H, E and V were computed using the model described in section 3.2. The values of flash flood risk were computed using formula (2), (3) and (4) as follows: first, obtaining the weighted values of each factor by multiplying each factor with its weight value; second, summarizing the values of components of layer 2 (hazard, exposure and vulnerability); third, multiplying the values of components of layer 2 and obtaining the values of flash flood risk in each computed entity.

Step 4, flash flood risk assessment and risk level classification. the contributions of H, E, and V were classified into three levels (high, medium, low); and a risk assessment was performed using the H-E-V Overlaying Cube to obtain the general risk levels for each watershed.

5. Results and discussions

This study completed flash flood risk analysis at watershed scale for Yulin. The primary results of flash flood hazard level, exposure level, vulnerability level and risk level are illustrated in Figure 7 through Figure 10. The major understandings from this analysis are as follows.

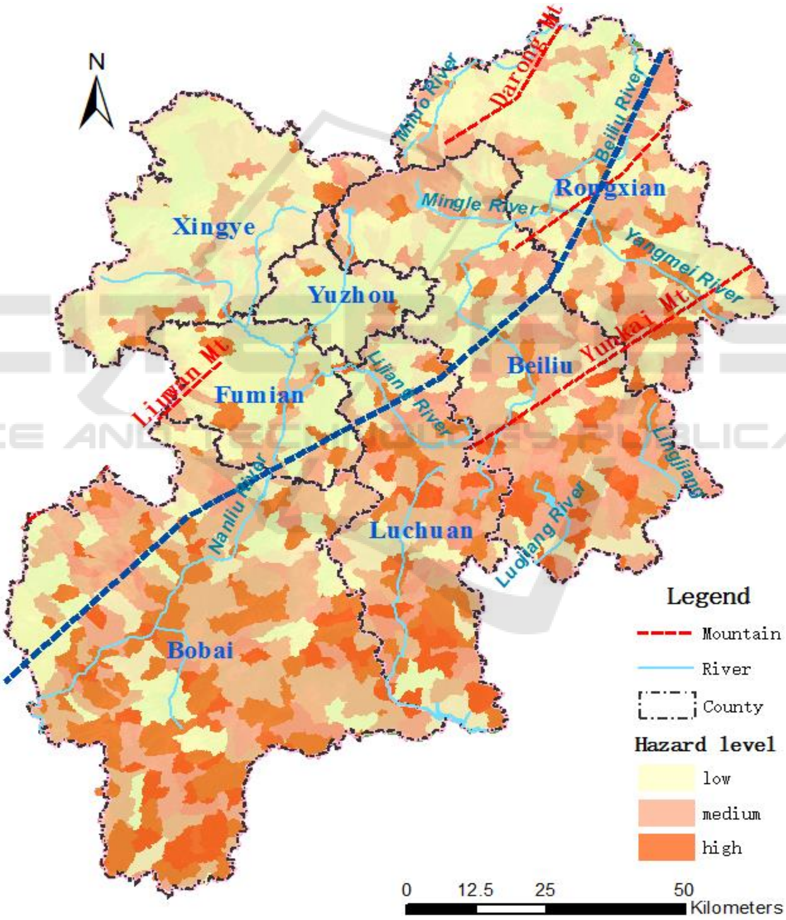

Figure 7. Flash flood hazard level.

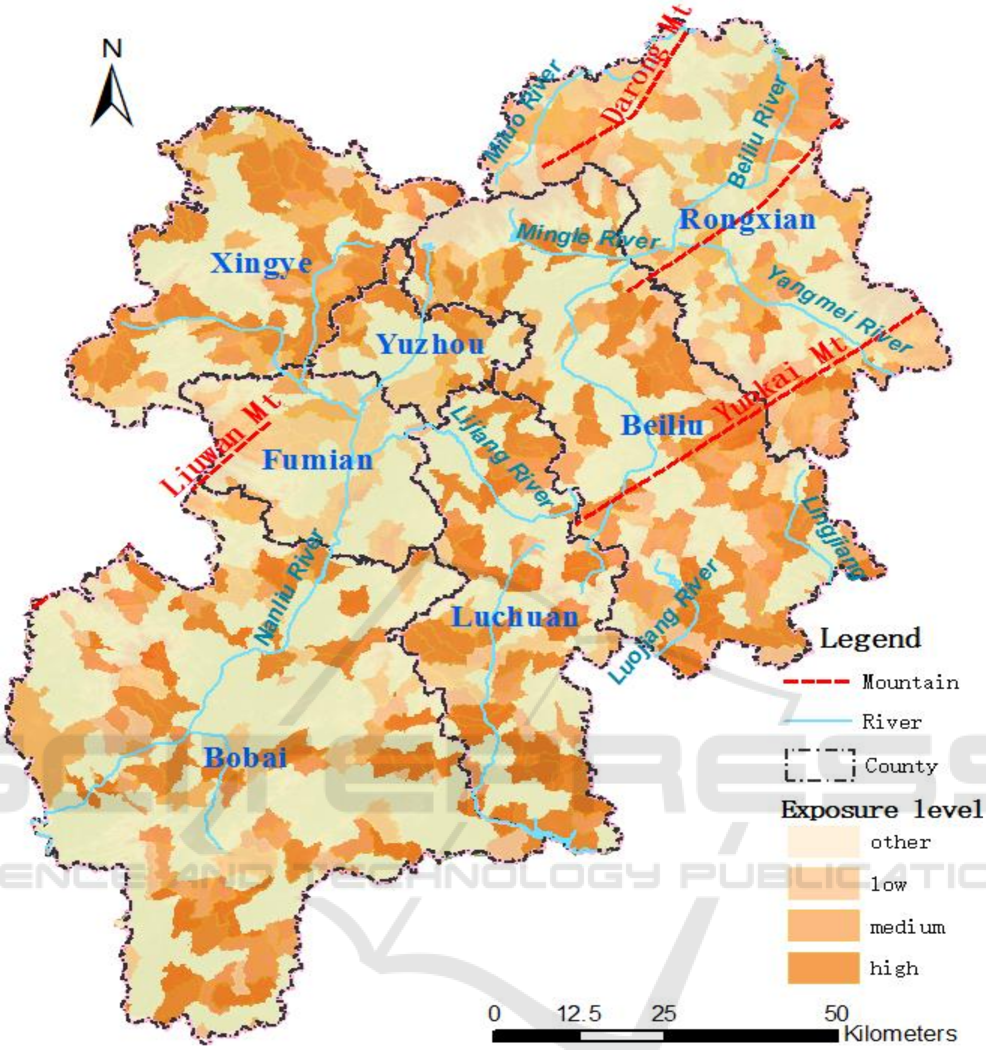

Figure 8. Flash flood exposure level.

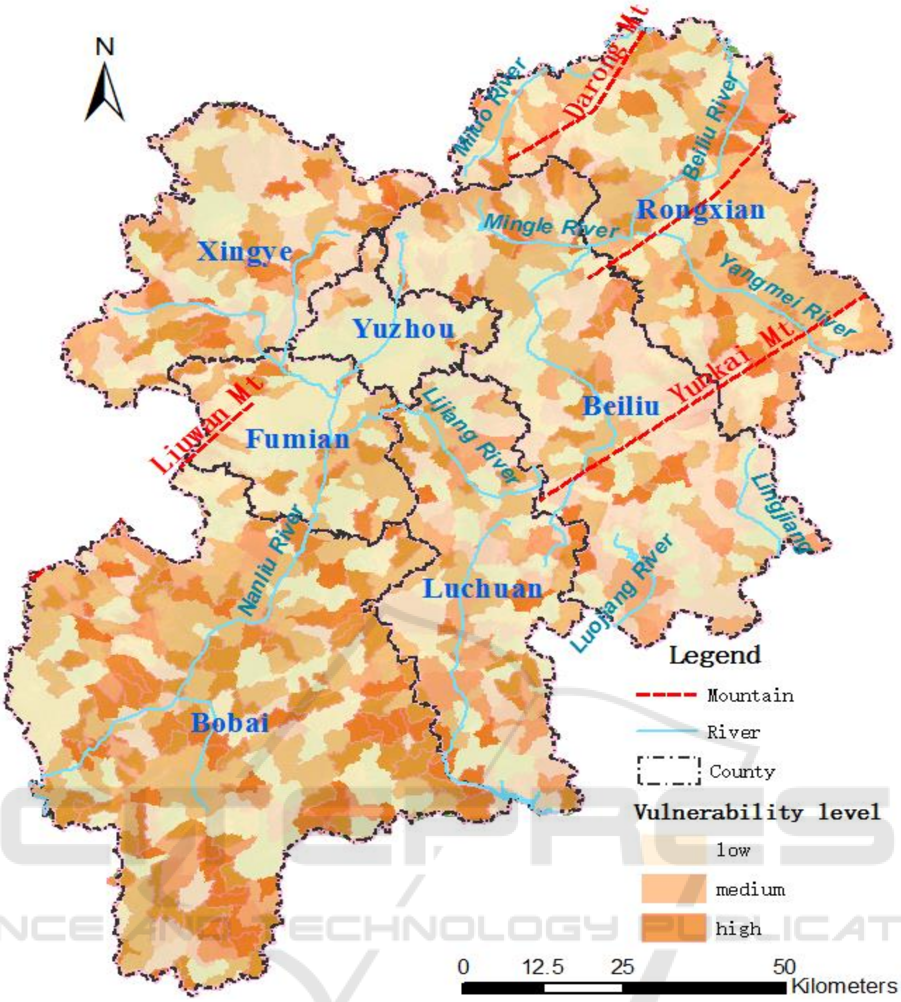

Figure 9. Flash flood vulnerability level.

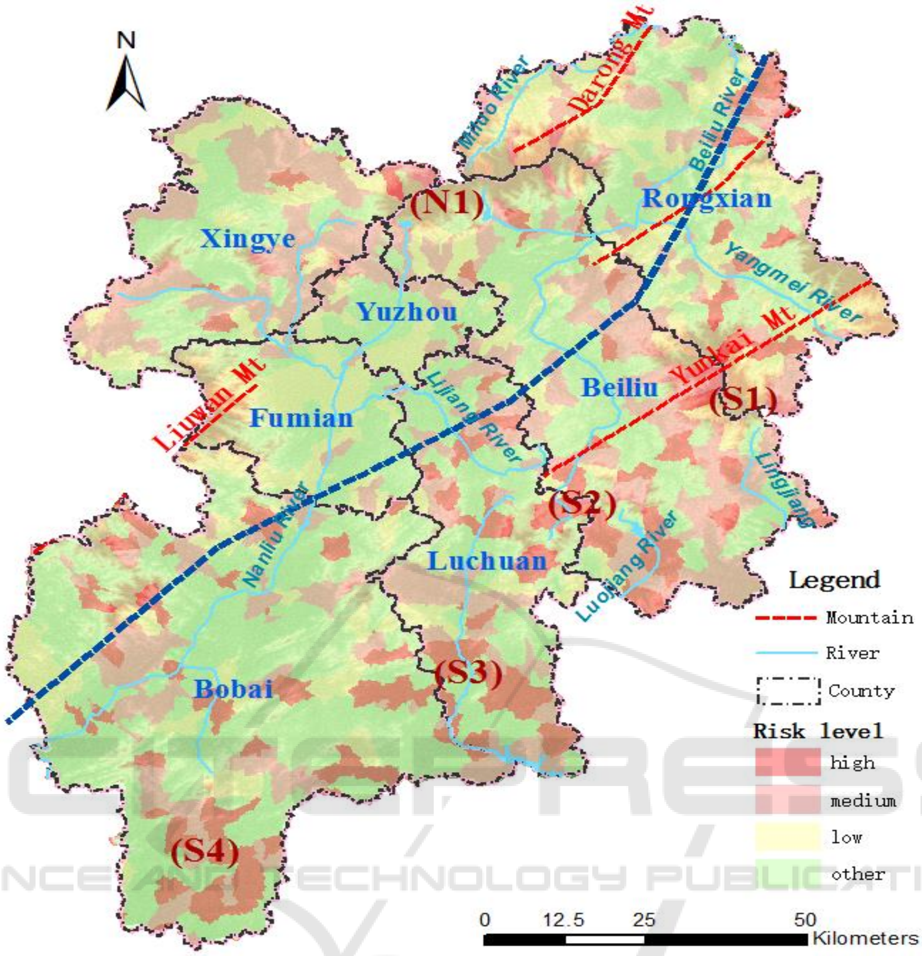

Figure 10. Flash flood risk level.

(I. Macro-scale rainfall monitoring; II. local rainfall and water stage monitoring and warning; III. appropriate local structural measures; IV. Community-based awareness and drill; special attention should be paid to measures underlined)

(1) The consideration on the computed entity and weight setting for risk factors were special and made the results more creditable in this study. On one hand, the basic entity for flash flood computation is watershed that the relationship among various hazard factors was taken into consideration. Flood peak modus and time of concentration were selected as factors relating watershed geographic delineation to hazard components. As illustrated, the calculation processes of the two parameters involve characteristics of each watershed, river system, land use, etc. therefore, hazard components were considered in terms of hydrology and hydraulics. On the other hand, weight setting was performed by trial-and-error method using the flash flood events records in Beiliu County. It makes the weights in this analysis more reliable. Consequently, the results are more creditable.

(2) Figure 7 presents the flash flood hazard level in Yulin. It shows that along the downstream area of Nanliu and Beiliu Rivers, the hazard levels are much higher than along the upstream areas. It also shows that both rainstorm and steep land slope are the key factors for hazard components. As illustrated in Figure 2, the 6-h duration rainstorm has higher intensity in southeast area. and the

Yunkai Mountain and some hill areas cover the south part of Rongxian, Beiliu, Luchan and Bobai (see Figure 1). The framework of hazard level plays important role in the distribution of flash flood risk.

(3) The flash flood exposure level is evenly distributed in Yulin along the main reaches of the Nanliu and Beiliu rivers (refer to Figure 8). Generally speaking, the areas of high exposure level are concentrative in Luchuan, Beiliu, and Xingye, which are located between the Nanliu River and Beiliu River, and decentralized in Bobai which is in the lower of the Nanliu River. It reveals that more attention should be paid to these areas in flash flood management in future.

(4) The areas of high and medium flash flood vulnerability level concentrate in the lower of the Nanliu River and the Beiliu River, including Bobai and Rongxian. There are other areas marked as high/medium vulnerability scattered in Xingye, Luchuan, and Beiliu. Areas with low vulnerability cover over half of Yuzhou and Fumian (refer to Figure 9). It indicates that more monitoring devices and capacity construction should be installed in these areas.

(5) The areas of high and medium flash flood risk level concentrate in both mountain-hill areas along the main reaches of Nanliu River and Beiliu River. In the lower area of these rivers, there are 4 high or medium risk level subareas locating in the county border areas of Beiliu and Rongxian (S1), Beiliu and Luchuan (S2), Luchuan and Bobai (S3), and the southwest of Bobai (S4). In addition, the high or medium risk level subareas are relatively continuous along the Darong Mountains and the Liuwan Mountains (refer to Figure 10), involving northwest Rongxian, north Beiliu, north Yuzhou, Xingye, west Fumian, and northwest Bobai (N1).

(6) As mentioned above, the purpose of this study is to support decision making on flash flood management strategy for Yulin region. And the strategy involves the management of hazard, exposure and vulnerability. A preliminary evaluation of flash flood hazard, exposure, vulnerability and risk has been performed and Table 4 present the results and general suggestions in each county of Yulin. Here one can see that the main countermeasures include macro-scale rainfall monitoring, local rainfall and water stage monitoring and warning, community-based awareness and drill, appropriate local structural measures. The suggestions in Table 4 made emphasis on countermeasures (the underlined) for each county.

Table 4. Suggestions on flash flood risk management to each county in Yulin

No.	Area	Hazard	Exposure	Vulnerability	Risk	Suggestions
1	Yuzhou	Stretched low	Stretched high in north and west	Stretched low	Stretched high or medium in north and west	<u>I</u>,II, III, and <u>IV</u>
2	Fumian	Stretched low in north and medium in south	Stretched medium in north and low in south	Stretched low in center and high in north and south	Stretched medium in north and west	<u>I</u>, II, III, and <u>IV</u>
3	Rongxian	Stretched low in north, stretched high or medium in south	Isolated medium and low	Stretched high	Stretched high or medium in north, middle and south	<u>I</u>, <u>II</u>, III, and <u>IV</u>
4	Luchuan	Stretched high or medium in middle and south	Stretched high	Isolated high in north, middle and south	Stretched high or medium	<u>I</u>, <u>II</u>, III, and <u>IV</u>
5	Bobai	Stretched high or medium	Isolated high and medium	Stretched high and medium	Isolated high or medium	<u>I</u>, <u>II</u>, III, and <u>IV</u>
6	Xingye	Stretched low, isolated medium or low	Stretched high in ambient and low in center	Isolated high and medium	Stretched medium in ambient	<u>I</u>, <u>II</u>, III, and <u>IV</u>
7	Beiliu	Stretched low and isolated high and medium in north, stretched high in south	Stretched high in both sides of the Beiliu River	Isolated high and medium, stretched low along the Beiliu River	Stretched high or medium in both sides of the Beiliu River	<u>I</u>, <u>II</u>, III, and <u>IV</u>

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