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Flash flood vulnerability assessment for small catchments with a material flow approach

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Abstract Flash flood often causes serious losses in small catchments of China. Nevertheless, the flash flood vulnerability assessment is relatively limited in China. This paper presented a material flow assessment framework to evaluate the flash flood vulnerability for small catchments in Wuzhishan County of Hainan province, China. The framework was developed into three parts: selection of typical villages and small catchments, calculation of exposure, sensitivity and adaptive capacity with material flow analysis, and multiple evaluation of vulnerability with the proposed material flow indices. In this framework, all material flows of exposure, sensitivity, and adaptive capacity were measured by water's mass. Then, the relationship between the three elements of vulnerability was established through material flow indices. Results of the three elements of vulnerability and four material flow indices in each small catchment were exhibited via GIS. The evaluation results suggested that catchments with lower exposure, sensitivity, and adaptive capacity did not necessarily lead to lower vulnerability, as the inherent relationship among them might aggravate the vulnerability of catchments to flash flood. Some suggestions were put forward for the prevention of flash flood based on the vulnerability assessment. Finally, the advantages and disadvantages of the approach were discussed.

Keywords Flash flood · Vulnerability · Assessment framework · Small catchments · Material flow analysis · Material flow indices

1 Introduction

Flash flood is one of the most difficult natural disasters to deal with and it is frequently responsible for loss of life and severe damage to infrastructure (Llasatbotija et al. 2007; Gascón et al. 2016; Hapuarachchi et al. 2011; Yucel 2015; Rahman et al. 2016). Flash

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flood is usually understood as a high-intensity rainfall event [intensive rainfall up to 12 h (Gaume et al. 2009)] leading to high peak discharges (IAHS-UNESCO-WMO 1974), where the size of the catchment area is in most of the cases less than 1000 km^2 (Kara-giorgos et al. 2016). In China, there are 29 provinces, 274 cities, and 1836 counties with flash flood prevention tasks. The whole areas prone to flash flood cover 4.63 million km^2, and the number of population threatened by flash flood has increased to 560 million. In recent years, the number of casualties caused by flash flood accounting for the total number of deaths of natural disasters is still rising. As in 2005 and 2006, flash flood disasters caused 1400 and 1632 deaths, accounting for 84 and 72% in the total number of deaths of natural disasters, respectively. In 2010, the amount of deaths and missing population reached 3887 due to flash flood, and the proportion reached 92%. So it is urgent to make great efforts to minimize the loss of flash flood in China. Flash flood vulnerability assessment will help the local government to take steps to effectively reduce the overall damages to one region.

Researchers began to pay attention to the function vulnerability in the process of dis-asters in the 1980s and vulnerability has in recent years become a central focus of the global environmental change and sustainability science research communities (Füssel 2007; GLP 2005; McCarthy et al. 2001). Vulnerability referred to the degree of adverse response of the system or a part of the system in the event of disaster (Timmerman 1981), mainly including exposure, sensitivity, and adaptive capacity (Adger 2006). Many scholars used the integrated system of nature and society to understand the vulnerability. They viewed that the concept of vulnerability was a comprehensive study on the human and natural environment. Then, the concept of coupling system vulnerability, which was characterized by the integration of society, economy, humanity, nature, organization and environment, was proposed gradually (Roberts and Yang 2003; Newell et al. 2005; Bradley and Smith 2004; Füssel 2007). At the same time, the evaluation methods and indicators of vulnerability were constantly updated and improved (Brooks et al. 2005). Ouma and Tateishi (2014) used AHP to assign the weight of the decision-making parameters and drew the flood vulnerability diagram. Szlafsztein and Sterr (2007) proposed a compre-hensive vulnerability index (CVI) containing 16 related natural and socioeconomic con-ditions. Metzger et al. (2006) gathered 12 social and economic indicators, including awareness, ability, and action. Then they were combined into an index of adaptive capacity. In these studies, the relationships between indicators representing exposure, sensitivity, and adaptive capacity for assessing vulnerability were often assumed inde-pendent. Then they were weighted and ranked separately. Finally they would be combined and aggregated to derive an overall measure of vulnerability.

From the perspective of industrial ecology, this paper suggested using a common unit (material flow) to highlight the fact that the three constituents of vulnerability are insep-arable entities. At present, material flow analysis is mainly applied to economic and environmental system. The method takes the mass as the measure of materials. According to the law of conservation of mass, total mass of economic system input is equal to the mass of material storage, output product, and waste material. In the early 1990s, Austria, Japan, and Germany firstly applied the material flow analysis on their natural resources of national economic system. In 2001, the bureau of statistics in European Union developed a national level guide to the material flow analysis, which was used to analyze the material flow in the 15 countries of the EU (Matthews 2000). The material flow analysis on the material balance in Japan has provided the theoretical basis for the development of circular society. Binder et al. (2004) used the material flow analysis to carry out a quantitative analysis of the flow process of wood in Appenzell Ausserrhoden (AR) area of Switzerland.

In this study, we incorporated material flow analysis for flash flood vulnerability assessment. There were two challenges for this: One is taking into account the interactive characteristics among the three components of vulnerability, and the other is evaluating these three components with comparable material flow units.

On the basis of material flow concepts, this paper developed a material flow assessment framework for small catchments and used it to evaluate the flash flood vulnerability of Wuzhishan county in China. The paper was organized as follows. Firstly, the material flow assessment framework was proposed, which included selection of typical villages and determination of small catchments, evaluation of exposure, sensitivity and adaptive capacity, and multiple evaluation of vulnerability with material flow indices. Secondly, the framework was applied to the study area to reveal the internal relation of exposure, sensitivity, and adaptive capacity. Then material flow indices were applied to assess flash flood vulnerability for small catchments and the spatial heterogeneity of flash flood vulnerability was exhibited via GIS. In the end, the advantages and limitations of the material flow approach were discussed.

2 Material flow assessment framework

From a view of a material flow account, there is a unified relationship between exposure, sensitivity and adaptive capacity in the assessment of flash flood vulnerability in small catchments. An important principle for the regional material flow analysis account is that the measurement unit should be consistent. Measurement unit of one material that does not meet the definition of a material flow account (by mass unit) should be converted into mass units. However, if the mass of water and other materials are calculated, respectively, the total mass of water will cover the others' mass, which will affect the accuracy of the whole material flow evaluation. So in this paper all material flow was unified into mass of water based on the equivalent relationship, taking into account the particularity of the research object.

The proposed material flow assessment framework for flash flood vulnerability is shown in Fig. 1. First, typical villages were selected on account of combination of multiple factors associated with flash flood such as historical records, geographical position, and orographic conditions. Moreover, the field investigation contributed a lot to the list of typical villages. Then typical small catchments could be selected according to the typical villages. Secondly, the concepts of three factors of vulnerability as exposure, sensitivity, and adaptive capacity were redefined from the material flow accounts point. The material flow values of the three components of vulnerability were explained as follows: Exposure is the total material flow values of flash flood in the study area; sensitivity is the amount of existing material flow that may be affected by flash flood; adaptive capacity is the total input material flow to the system that may reduce or prevent the danger. Then the three elements of vulnerability in different typical small catchments were calculated by means of material flow analysis. Next, the material flow indices were proposed in the assessment framework, including potential disaster frequency (PDF), potential disaster loss (PDL), defensive capability (DC), and vulnerability (VU), which revealed the internal relationship among exposure, sensitivity and adaptive capacity. Finally, these material flow indices gave out the multiple evaluation results for the flash flood vulnerability in every small catchment.
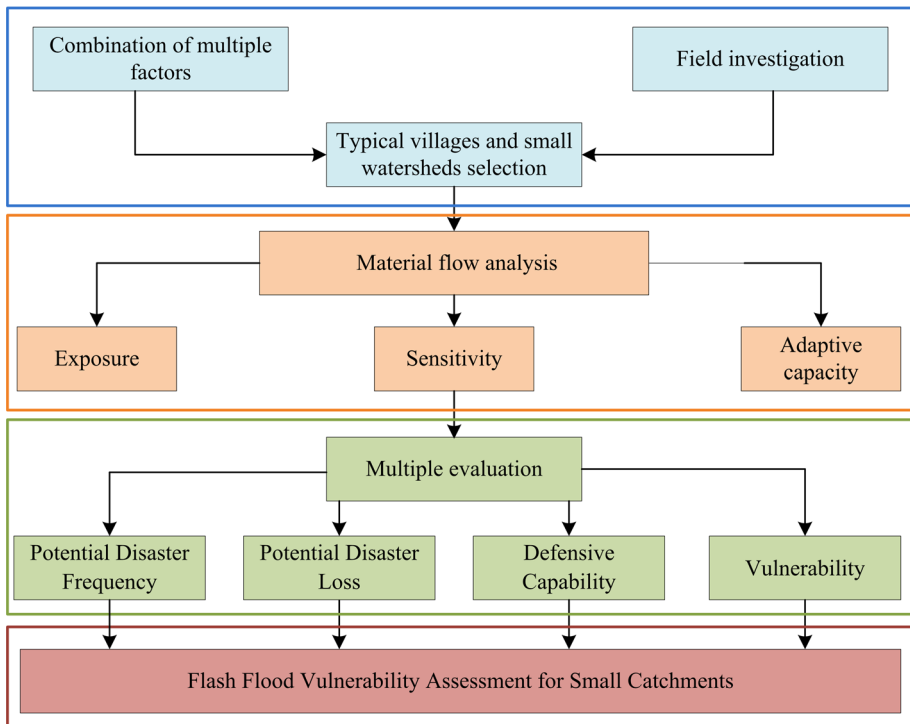
Fig. 1 Material flow assessment framework

2.1 Selection of typical villages and determination of small catchments

Mountainous area is vulnerable to flash flood and many villages have records of flash flood. Some useful information of flash flood can be obtained through field investigation. The fact raises the possibility to assess the regional flash flood vulnerability. In the research, we defined some villages affected by flash flood as typical villages. Typical villages can be selected and listed according to various ways as inquiry, expert consultation, analysis of major flood tracking methods, and investigation of the highest flood level or the highest possible flooding level.

Based on the typical villages list, the corresponding small catchments can be determined by carrying out an intersection operation between the layer of small catchments divided by official sector and the layer of typical villages selected via GIS. The characteristic values of the selected small catchments are the sum of the related indicators values of the typical villages.

2.2 Evaluation of exposure, sensitivity, and adaptive capacity

2.2.1 Exposure

Exposure can be seen as the degree to which an area is in contact with a perturbation (Adger 2006; Chang and Huang 2015; Kasperson et al. 2012). In a flash flood disaster, the accumulated rainfall is regarded as the exposure of an area. The flash flood prone area can

be characterized with high exposure because they are exposed to higher accumulated rainfall.

In this frame, we take the total mass of accumulated rainfall of all typical villages in one small catchment as the exposure of the small catchment. The calculation formula is as follows:

$$EX_i = \frac{\rho}{1000} \sum_{j=1}^{n} (H_j \times S_j) \tag{1}$$

where EX_i is the exposure of the ith small catchment (t), n is the number of typical villages in the ith small catchment (dimensionless), H_j is the accumulated rainfall of recorded flash floods in the jth typical village (mm), S_j is the area of the jth typical village (m^2), and ρ is the water density (t/m^3), respectively.

2.2.2 Sensitivity

The concept of sensitivity varies across authors. This paper adopted the view of Gallopín (2006). He pointed out that sensitivity was the degree to which the system is modified or affected by an internal or external disturbance or set of disturbances. The magnitude of the effects of a flash flood on the system depends not only on the intensity of flooding, but also on the characteristics of area being flooded.

Sensitivity could be characterized by the material flow values of the accumulated assets of the typical villages in each small catchment. The calculation formula is as follows:

$$SE_i = \sum_{j=1}^{n} \sum_{k=1}^{m} f(k) \tag{2}$$

$$f(k) = \frac{g(k)}{g_0} \times \rho \tag{3}$$

where SE_i is the sensitivity of the ith small catchment (t), n is the number of typical villages in the ith small catchment (dimensionless), m is the total number of sensitivity evaluation factors in one typical village (dimensionless), $f(k)$ is the material flow values of a single sensitive factor in each typical village (t), $g(k)$ is the monetary value of a single sensitive factor (yuan), g_0 is the monetary value of agricultural compensation water (yuan/m^3), and ρ is the water density(t/m^3).

2.2.3 Adaptive capacity

Adaptive capacity refers to the ability of different species to adapt to different environments. Gunderson (2000) defines adaptive capacity as system robustness to changes in resilience. Adaptive capacity of human systems also can be defined as the capacity of any human system from the individual to humankind to increase the quality of life in a given environment or range of environments (Gallopín et al. 1989).

In this research, adaptive capacity was developed into two parts, including self-regulation ability and recovery capability. Self-regulation ability was the material flow values converted from the investment of engineering measures and the non-engineering measures to reduce the flash flood damages. Recovery capability was characterized by the material flow values of disposable income of the villagers in typical villages. They can be calculated by using Eqs. (4)–(8):

$$AC_i = SR_i + RC_i \tag{4}$$

$$SR_i = \sum_{j=1}^{n} \left[\sum_{k=1}^{m} p(k) + \sum_{l=1}^{h} q(l) \right] \tag{5}$$

$$p(k) = \frac{e(k)}{g_0} \times \rho \tag{6}$$

$$q(l) = \frac{n(l)}{g_0} \times \rho \tag{7}$$

$$RC_i = \sum_{j=1}^{n} \frac{r(j)}{g_0} \times \rho \tag{8}$$

where AC_i is the adaptive capacity of the ith small catchment (t), SR_i is the self-regulation ability of the ith small catchment (t), RC_i is the recovery capability of the ith small catchment (t), n is the number of typical village in each small catchment (dimensionless), m is the number of engineering measures in single typical village (dimensionless), $p(k)$ is the material flow values of a single engineering measure (t), h is the number of non-engineering measures in one typical village, $q(l)$ is the material flow values of a single non-engineering measure(t), $e(k)$ is the monetary values of one engineering measure(yuan), $n(l)$ is the monetary values of a non-engineering measure (yuan), g_0 is the monetary value of agricultural compensation water (yuan/m^3), $r(i)$ is the disposable income of one typical village (yuan), and ρ is the water density(t/m^3).

2.3 Multiple evaluation of vulnerability with material flow indices

The above process produced a harmony of exposure, sensitivity, and adaptive capacity through the establishment of a common measurement unit—material flow value. Developing indices relating exposure, sensitivities and the associated adaptive capacities of the ecological economic system is important for the interpretation of vulnerability to flash flood. The relevant definitions of material flow indices for vulnerability in small catchments were given as follows:

1. *Potential disaster frequency (PDF)* It was the material flow values that caused the danger on per unit existing material flow values of the accumulated assets in one small catchment area. The lager the PDF value was, the larger the potential disaster frequency would be. The calculation formula is:

$$PDF_i = \frac{EX_i}{SE_i} \tag{9}$$

The PDF established relation of exposure and sensitivity. We could get the relative frequency of potential disaster in different small catchments through the PDF value.

2. *Potential disaster loss* (PDL) The index meant the ratio of material flow values of the accumulated assets of the typical villages to material flow values of adaptive capacity. It can be calculated by using Eq. (9)

$$PDL_i = \frac{SE_i}{AC_i} \tag{10}$$

The PDL index revealed the mutual influence of sensitivity and adaptive capacity. Through the assessment of PDL, we could draw the different magnitude of the potential disaster loss in small catchments. In response to the economic development, it is necessary to improve the adaptive capacity of one small catchment. Otherwise, it would cause a greater loss of life and property.

3. *Defensive capability* (DC) It meant the total security investment on per unit material flow values that cause the danger. The lager the value was, the larger the defensive capability would be. The calculation formula is:

$$DC_i = \frac{AC_i}{EX_i} \tag{11}$$

Defense ability expressed the relationship between exposure and adaptive capacity. Through the assessment of DC, we could assess the input strength of engineering measures and non-engineering measures in different small catchments for prevention to flash flood. Also, it would give a quantitative judgment on the ability of local residents to protect their own lives and property safety. Further, the results were able to provide the government or related policy makers some planning reference on financial input and engineering construction for reducing disaster losses.

4. *Vulnerability* (VU) It was the sum of two parts, including existing material flow values of the accumulated assets of the typical villages and the material flow values that cause the danger on the per unit investment to reduce the loss of flash flood disasters. The calculation formula is:

$$VU_i = \frac{EX_i + SE_i}{AC_i} \tag{12}$$

Vulnerability was an index which established relation of exposure, sensitivity and adaptive capacity. If the VU of one small catchment was relatively larger, it was more essential to increase the attention to the prevention of flash flood in the small catchment. Together with the development of economy, increasing the construction of disaster prevention facilities and improving the early warning or forecast for rainfall, would reduce the overall vulnerability of the region effectively.

We can see from the above discussion, the material flow is a kind of general measuring unit and it can be used to link the exposure, sensitivity and adaptive capacity. Figure 2 brings to light the relationship among the three factors of vulnerability.

3 Case study

3.1 Study area

The study area, Wuzhishan County, is in the center of Hainan Island, China. It is located between latitudes 18°38′ and 19°02′N, and longitudes 109°19′ and 109°44′E (Fig. 3). The county is surrounded by hills, classified as the typical hill area. Wuzhi Mountain is seated in the center of Wuzhishan County, which owns a maximum altitude of 1867 meters and brings a large area of mountainous districts to the county. Wuzhishan County belongs to a tropical monsoon climate. It has a relatively larger frequency of flash flood disasters owing
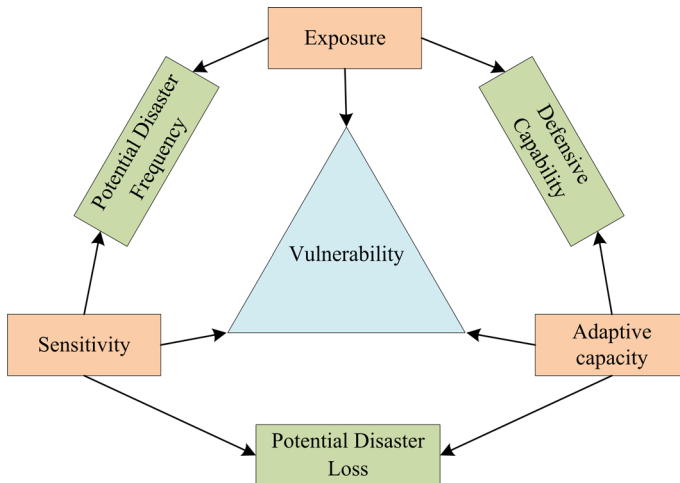
Fig. 2 Intrinsic relationship of the three factors of vulnerability

to the effect of topography, geomorphology, typhoons and rainfall together. So it is urgent to apply some flash flood measures including engineering measures and non-engineering measures. The main engineering measures may contain road culverts, bridges and other facilities that drain off water. The mainly non-engineering measures may include automatic rainfall stations, radio stations, simple rainfall stations and simple water level stations. Meanwhile, it is also essential to do some flash flood vulnerability assessment for the area, which may provide some reference for the application of flash flood measures.

3.2 Selection of typical villages and small catchments

A detailed typical villages list was proposed according to various methods, including expert visiting, field investigation, basic data analysis, communion with water management staff, analysis of major flood tracking methods, and investigation of the highest flood level or the highest possible flooding level. Photographs of field investigation are shown in Fig. 4. Through field investigation and the collection of water resources data, we determined the list of recorded flash floods. Figure 5 shows the spatial and temporal distribution of the recorded flash floods.

Through expert visiting and related records of the collation of hydrological data, we preliminary identified the villages list with frequent flash floods. And then the final typical villages list was obtained further field investigation. The final typical villages are shown in Fig. 6.

Then the small catchments list could be obtained through the ArcGIS 10.1 to carry out an intersection operation between the layer of small catchment divided by official sector and the layer of selected typical villages. Figure 7 shows the distribution of selected small catchments [Tongshen River (TS), Maoxin River (MX), Changhua River (CH), Maoqing River (MQ), Yayi River (YY) and Shuiman River (SM)].
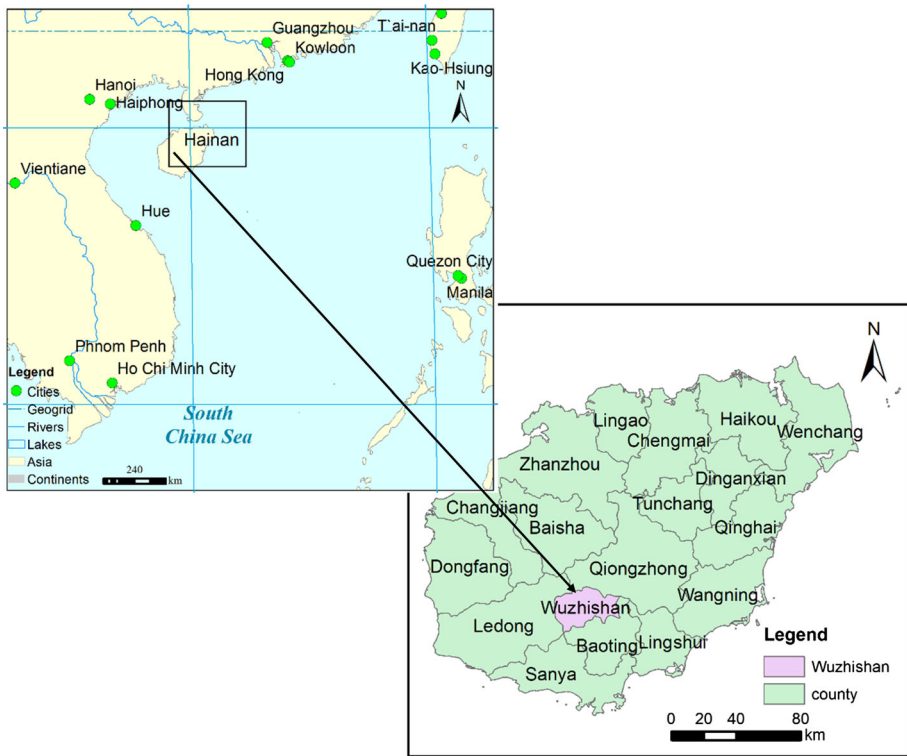
Fig. 3 Location map of the study area

3.3 Input data and calculation

1. *Exposure* The area of typical villages was from the relevant towns' census data. The data of accumulated rainfall of recorded flash floods come from the official hydrological data. Then we obtained the exposure of different catchments based on Eq. (1).

2. *Sensitivity* in this study, we selected the material flow values of family property in typical villages as the characterization value of sensitivity. This paper selected some indices that could reflect the household property (including major productive fixed assets, durable consumer goods, etc.), referring to "Rural Household Survey Program"—2012 annual sampling survey report, which was from statistical departments of the provinces. Then we collected the owned property of typical families. Further, according to the statistical department 2012 commodity price guide, we converted them to the material flow values of the sensitivity in one small catchment referring to Eqs. (2) and (3).

3. *Adaptive capacity* It was developed into two parts, including self-regulating ability and recovery capability. The main engineering measures were: road culverts, bridges and water gates. The author considered the mainly non-engineering measures, including automatic rainfall stations, radio stations, simple rainfall stations, and simple water level stations. These data were from census data of water resources and field investigation. The disposable income of typical villages was from the "Statistical
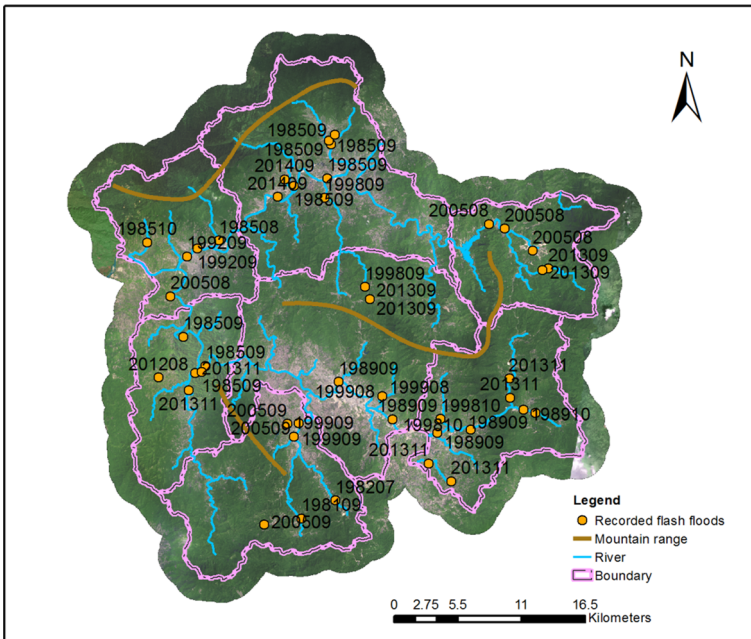
Fig. 4 Photographs of field research

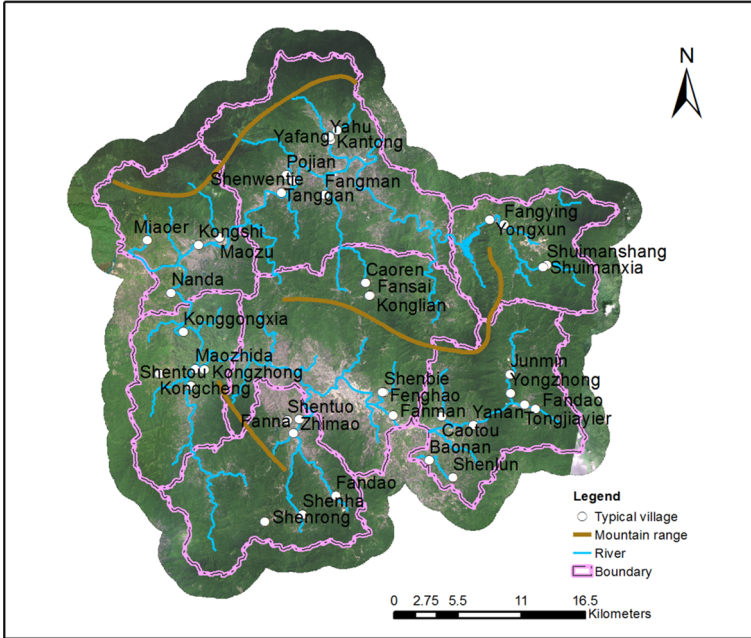**Fig. 5** Spatial and temporal distribution of recorded flash floods

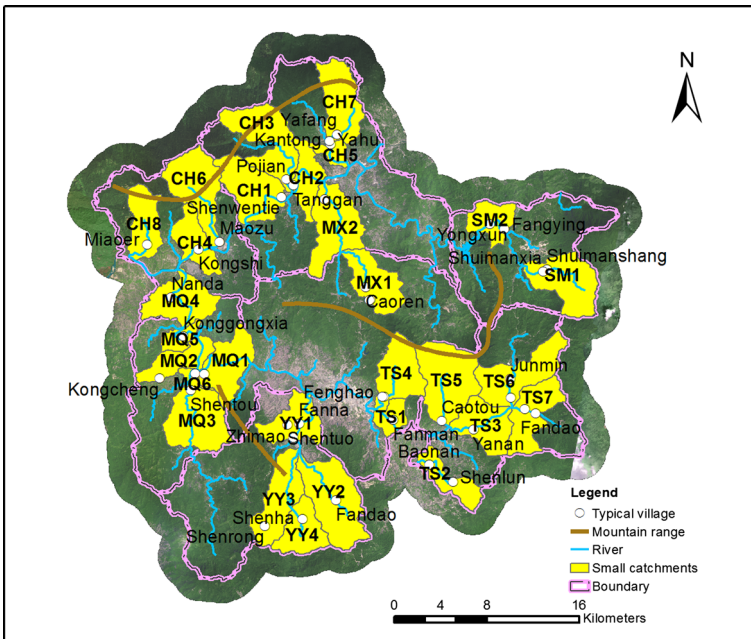**Fig. 6** Typical villages distribution map

Fig. 7 Selected small catchments distribution map

Yearbook of Wuzhishan County." Finally, we converted these data into the corresponding material flow values according to Eqs. (4)–(8).

3.4 Results of material flow evaluation of exposure, sensitivity, and adaptive capacity

Figure 8 shows the distribution of material flow values for accumulated rainfall of recorded flash floods by Eq. (1). CH6, MX1, and TS6 own the larger material flow values and MQ3, MQ4, and MQ6 possess the smaller material flow values. The material flow values of all catchments are distributed in the interval of 276210 t − 12343810 t, which represent exposure of small catchments. The spatial distribution map to exposure is highly influenced by mountain ranges inside and the characteristics of small catchments. Small catchments with higher exposure are mainly located at the foot of hills or the river valley as the CH6, MX1 and TS6, where have a larger accumulated rainfall. The larger the exposure value is, the greater the amount of accumulated rainfall will be. When the flash flood disasters occur, they will bring a greater flood control pressure.

Figure 9 shows the sensitivity information of small catchments with material flow values. It has a close relationship between the sensitivity values and the economic power. The higher the economic storage capacity is, the higher the values of sensitivity will be, since it may have a higher economic loss when a flash flood is happened. From the sensitivity spatial distribution, we can see TS2, TS3, TS6, and TS7 have lager values of material flow, as these districts have relatively developed economic conditions. On the contrary, if the economy is relatively backward in some places such as YY2, YY3, YY4, MQ4, and MQ6, their sensitivity values are relatively lower.
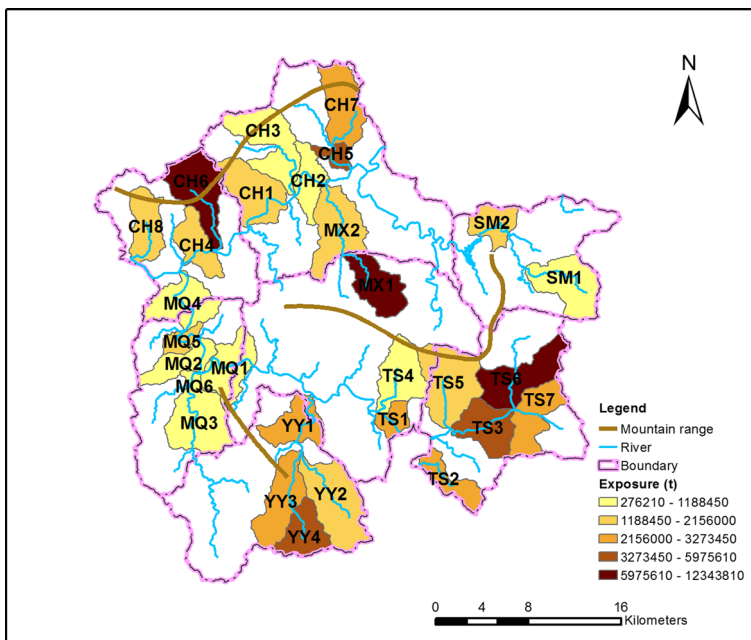

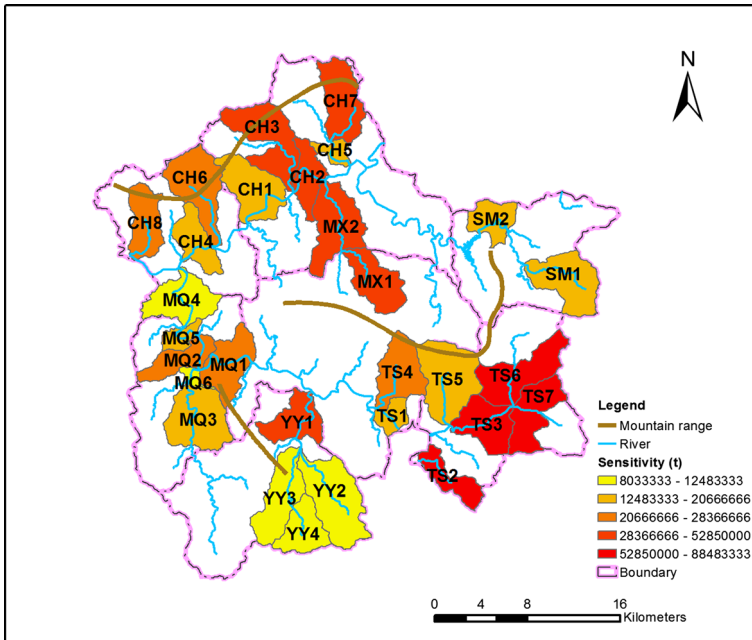**Fig. 8** Material flow values of exposure

Fig. 9 Material flow values of sensitivity

The adaptive capacity is mainly to reflect the self-regulation ability and recovery capability when it has a flash flood. The results of self-regulation ability are shown in Fig. 10, which including the material flow values of engineering and non-engineering measures. The small catchments such as MX2, MQ5, YY1, YY2, and TS7 have a stronger resistance to flash flood, because these districts invest larger amounts of their budgets to control flash floods. We can also see the distribution of material flow values of the recovery capability from Fig. 10. It shows the material flow values of disposable income in each small catchment. The number of disposable income is lager, the recovery capability is higher. TS3 has the largest recovery capability among them. The material flow values of self-regulation ability and recovery capability added together represent the total adaptive capacity. As Fig. 10 shows, CH1, SM2, MQ3, MQ4, TS1, YY2, YY3, and YY4 have a lower adaptive capacity, required to strengthen their own capacity to defense flash floods.

3.5 Results of multiple evaluation of vulnerability with material flow indices

As is stated above, material flow indices including PDF, PDL, DC, and VU will be calculated according to Eqs. (9)–(12) to give the multiple evaluation results of vulnerability in small catchments.

Potential disaster frequency (PDF) is the ratio of exposure to sensitivity. Figure 11 shows the space distribution of material flow values of potential disaster frequency in different small catchments. The larger the value is, the higher the potential disaster frequency will be. From Fig. 11 we can get the relative potential disaster frequency in different small catchments, and we can see clearly CH6 and YY4 have a lager value of PDF. It indicates that villagers need to cultivate their own sense of disaster prevention, especially in the time of frequent occurrence of flash floods. At the same time of
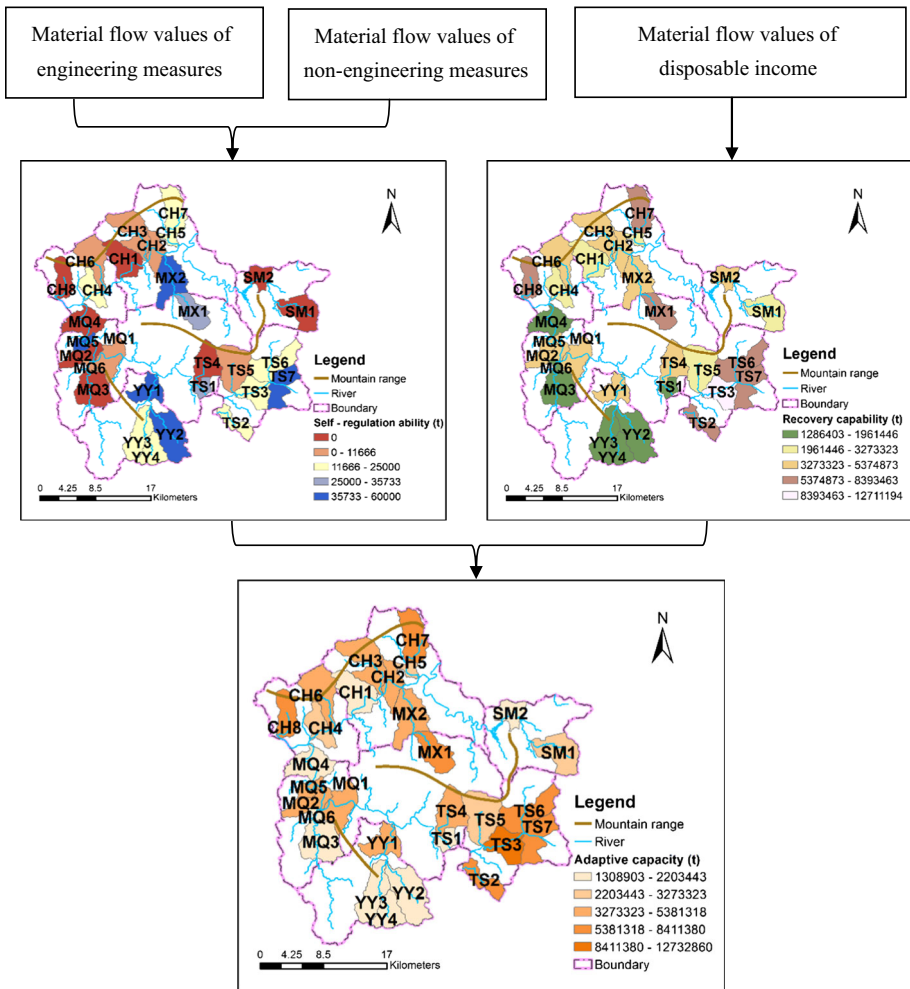
Fig. 10 Material flow values of self-regulation ability, recovery capability and adaptive capacity

developing their economy, they should do a good job in advance, so as to reduce loss to minimum.

Potential disaster loss (PDL) means existing material flow values of the accumulated assets of the typical villages on per unit material flow values of adaptive capacity, which unifies the comprehensive influence of sensitivity and adaptive capacity together in a small catchment. Through the assessment of PDL, we can draw the different magnitude of the potential disaster loss in small catchments. Since the small catchments including CH2, CH3, CH7, SM2, TS1, TS5, TS6, TS7, MQ3, YY1, and YY3 have a lager PDL value as Fig. 12 shows, it need to increase the economic investment of flash flood control facilities in these areas. Otherwise, the small catchments will have a greater loss of life and property.

Defensive capability (DC) is the ratio of adaptive capacity to exposure. It reveals the relationship between exposure and adaptive capacity in these small catchments. The indicator is a good combination of socioeconomic and environmental factors. Higher the
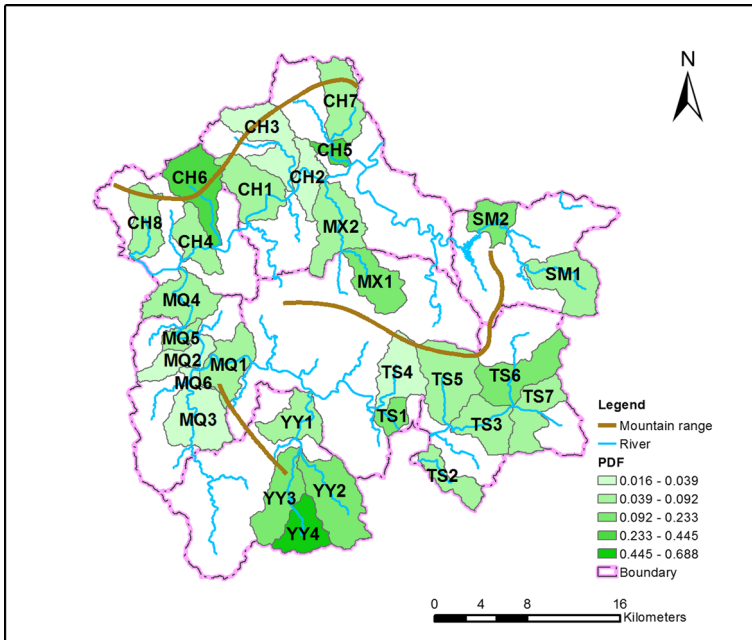
Fig. 11 Distribution map of potential disaster frequency

DC value is, stronger ability to resist flash floods will be. The small catchments as CH6, MX1, TS1, YY3, and YY4 have a lower DC value for the reasons that they own a higher exposure value and a relatively small value of adaptive capacity. The distribution map of DC for all the catchments is shown in Fig. 13.

Through the indicator which combines the socioeconomic and environmental factors, we can assess the input strength of engineering measures and non-engineering measures in different small catchments. It is able to give a quantitative judgment on the ability of local residents to protect their own lives and property safety. Moreover, the results can provide the government or related policy makers some planning reference on financial input for reduce disaster losses for different small catchments.

Vulnerability (VU) reveals the inter-relationships among the exposure, sensitivity, and adaptive capacity further, instead of simply summing up the results of exposure, sensitivity, and adaptive capacity. It is the sum of the amount of the exposure and the sensitivity on the per unit adaptive capacity, which embodies, comprehensively, the frangibility of the small catchments. Figure 14 shows the distribution of vulnerability in the all small catchments.

The VU of small catchments such as TS1 and YY3 is relatively larger. That means it is essential to increase the attention to prevention and control of flash flood disaster in the two small catchments. Increasing the construction of disaster prevention facilities and improving the early warning or forecast of rainfall will help the local government to reduce the overall vulnerability of the region.

Table 1 shows the detailed data of materials flow indices including PDF, PDL, DC, and VU from which we can see every index value of different small catchments. Then we calculate the average value of each index for all small catchments. The average value of PDF, PDL, DC and VU is 0.10, 6.85, 2.43, and 7.67, respectively. Then the average value
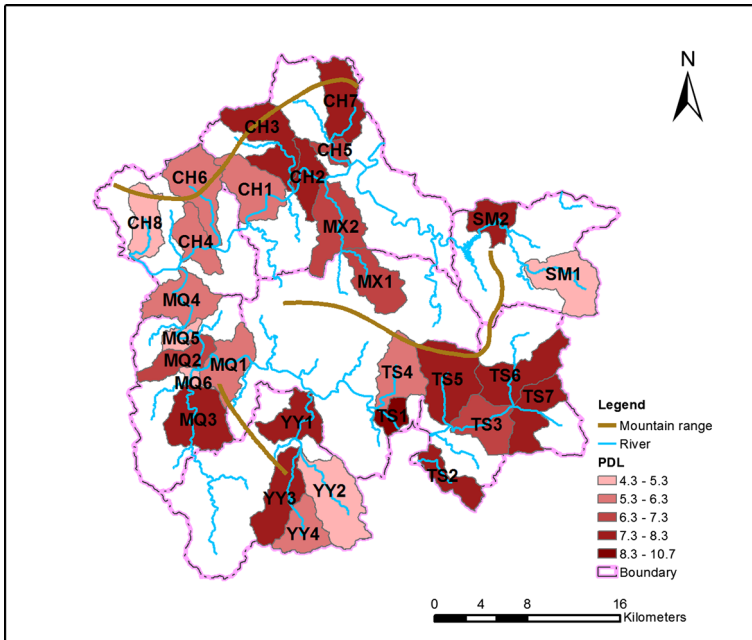
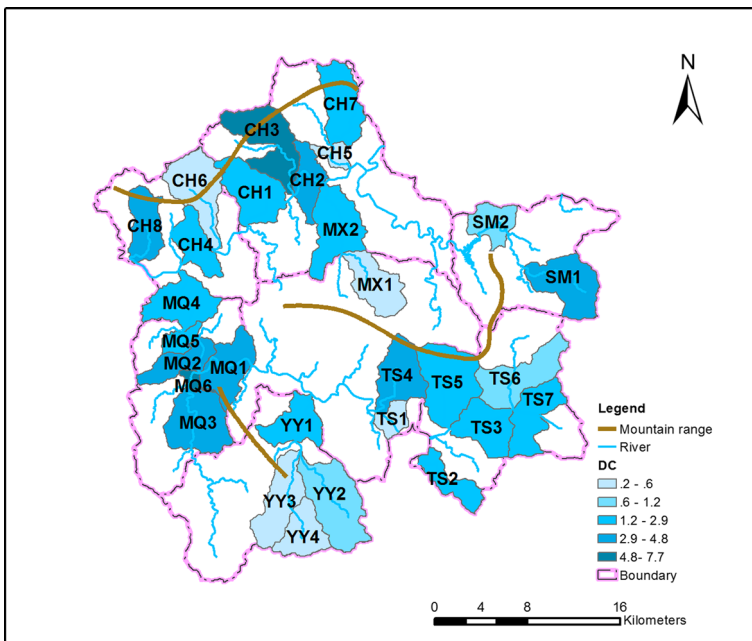**Fig. 12** Distribution map of potential disaster loss

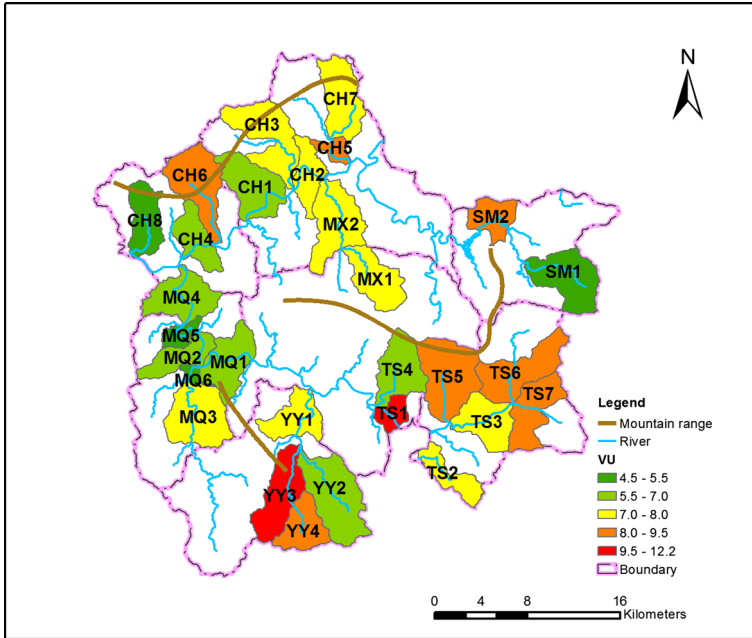**Fig. 13** Distribution map of defensive capability

Fig. 14 Vulnerability to flash flood

is taken as a reference to compare the size of every capacity among all the small catchments. As Fig. 15 shows, we can clearly see the relative size of various capacities to flash floods in small catchments. It can provide a more obvious result to the local government or policy makers, which can strengthen the attention of them to different capacities of small catchments. And then they can take some relevant measures to avoid the loss furthest.

4 Discussion

Figure 16 shows the evaluation results of exposure, sensitivity, adaptive capacity, PDF, PDL, DC, and VU in all small catchments with the material flow approach. If we simply look at the value of exposure, sensitivity, and adaptive capacity, the TS1 owns a relatively smaller value among them. According to a traditional algorithm or intuitive understanding, the TS1 may face a less dangerous environment. But from the view of PDL, which means material flow values of the accumulated assets of one small catchment on per unit material flow value of adaptive capacity, it has the maximum value. Because of consideration of the inherent relationship between the sensitivity and adaptive capacity, it indicates that TS1 has a larger potential disaster loss. Similarly, as taking into account the internal relationship of exposure, sensitivity, and adaptive capacity, TS1 has the maximum number of VU, which means the loss on the unit investment is larger. As the same principle, if we only refer to the adaptive capacity value, CH3 is not prominent, or even worse among all the small catchments. But, it has the largest defensive capability to flash flood, considering the interaction between exposure and adaptive capacity.

Table 1 Values of material flow indices

| Indices	Catchments									
	TS1	TS2	TS3	TS4	TS5	TS6	TS7	MX1	MX2	CH1
PDF	0.15	0.06	0.06	0.03	0.07	0.13	0.05	0.23	0.06	0.09
PDL	10.61	7.68	6.95	6.13	8.39	7.64	8.15	6.50	7.30	6.34
DC	0.64	2.25	2.33	4.83	1.76	1.00	2.39	0.66	2.27	1.75
VU	12.16	8.12	7.38	6.34	8.96	8.64	8.57	8.02	7.74	6.91
	CH2	CH3	CH4	CH5	CH6	CH7	CH8	MQ1	MQ2	MQ3
PDF	0.03	0.02	0.09	0.30	0.45	0.06	0.07	0.05	0.03	0.04
PDL	7.64	7.78	5.57	7.04	6.16	7.48	4.34	6.07	6.84	7.54
DC	4.11	7.65	1.95	0.48	0.36	2.22	3.15	3.11	4.45	3.38
VU	7.88	7.91	6.08	9.14	8.91	7.93	4.66	6.39	7.06	7.84
	MQ4	MQ5	MQ6	YY1	YY2	YY3	YY4	SM1	SM2	
PDF	0.05	0.08	0.03	0.08	0.15	0.21	0.69	0.05	0.12	
PDL	6.36	4.46	5.18	7.47	5.24	8.66	5.54	5.30	8.43	
DC	2.96	2.79	5.61	1.70	1.24	0.54	0.26	3.68	1.02	
VU	6.70	4.82	5.36	8.06	6.04	10.50	9.36	5.57	9.41	
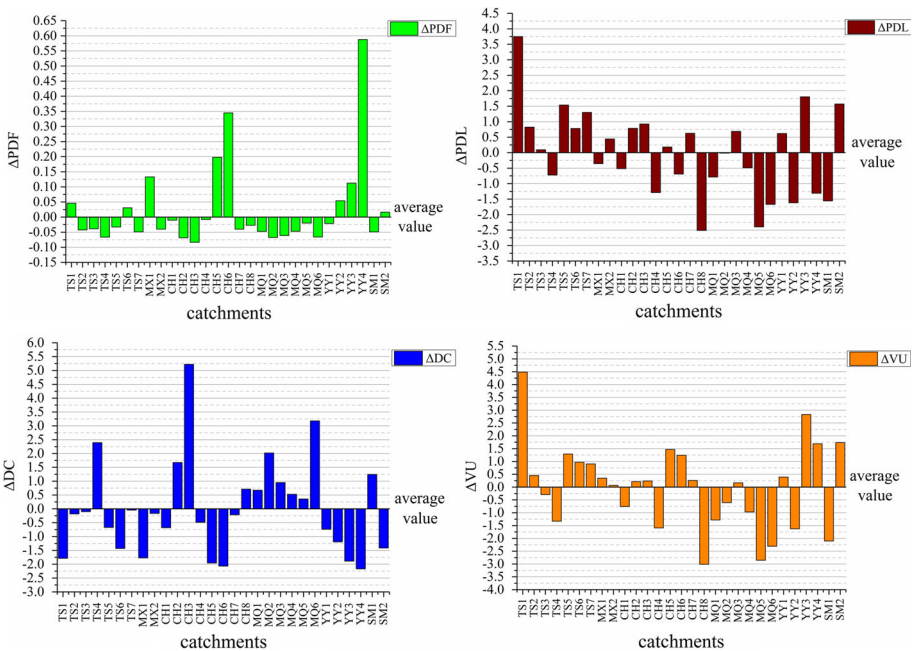
Fig. 15 Relative size of various capacities to flash floods in small catchments
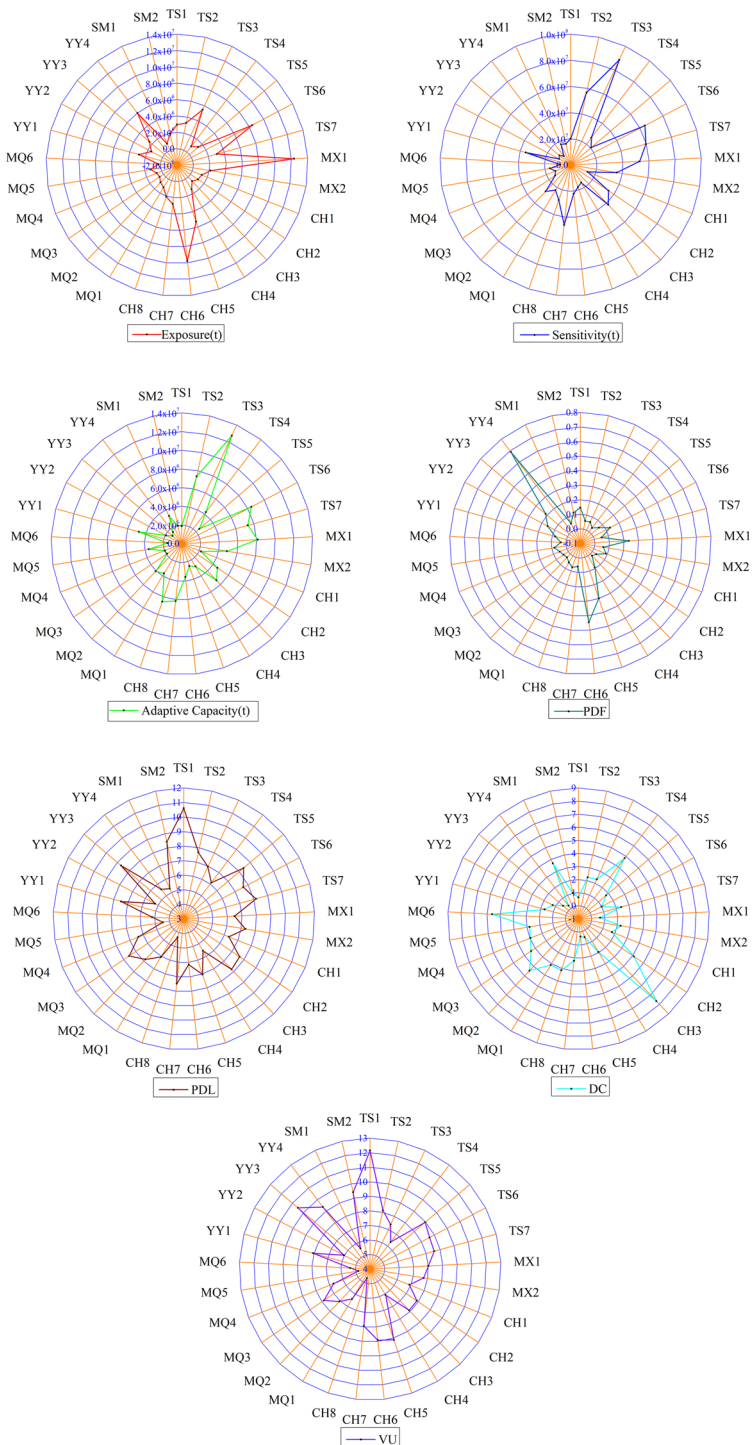
Fig. 16 Evaluation results for all small catchments

We can see from the above discussion, the value of exposure, sensitivity and adaptive capacity only cannot meet requirements of vulnerability assessment, and may even cause assessment errors sometimes. The concept of material flow provides a method of industrial ecology. It describes and evaluates the interaction characteristics of exposure, sensitivity and adaptive ability, using common mass units. It allows the three components to be integrated into the vulnerability assessment indices.

Material flow indices are preferable to link the three factors together, and reveal the mutual influence among them. Besides, the established material flow indicators in this study can also be used in other disaster vulnerability assessment.

Moreover, the method of material flow analysis is unique in that all material flows are unified into water's mass based on the equivalent relationship. It is an improved material flow calculation method for special research objects. Meanwhile, it effectively avoids the complexity weight calculation and the standardization of data in previous studies.

Overall, by means of material flow analysis, we can give a clear contrast among the PDF, PDL, DC, and VU of different small catchments. It can capture the social and the biophysical characteristics of fragile. The results are able to give a judgment of the relative strength of the corresponding ability, which will provide a reference and guidance to the government or related policy makers for flash floods control planning.

Of course, there are some limitations of using material flow analysis to assess vulnerability. This evaluation method just gives the evaluation results of the relative size in different small catchments and does not give exact threshold intervals to determine security or not. The magnitude of the calculated results may be different because of the difference in the calculation of the reference term. Making a threshold criterion will be a research direction in the future.

5 Conclusions

This paper is devoted to using material flow analysis to develop an evaluation framework for assessing small catchments vulnerability to flash flood. (1) This framework selected the typical villages and small catchments for flash flood, so that the evaluation results were more representative. (2) All material flows were transformed into water's mass, which was an improvement in material flow analysis for special objects. (3) In this framework, we carried out the multiple evaluations of flash flood vulnerability with proposed material flow indices which considered the internal relations of exposure, sensitivity, and adaptive capacity. (4) The evaluation framework was applied to small catchments in Wuzhishan County of Hainan province for flash flood vulnerability assessment, and the assessment results could provide guidance and direction to decision-makers on the prevention of flash floods in different small catchments. (5) Material flow analysis is a feasible method to assess the flash flood vulnerability and the framework can be applied to other research areas. (6) Making a threshold criterion to determine security or not will be a research direction in the future.

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