Flash flood vulnerability assessment at village level using a currency flow approach in Baoting County of Hainan province, China

Jiangchuan Liu[1], Lihong Zhang[2], Weichao Yang [1,3,4]*, Xuefeng Jiang[5], Kui Xu[4]*, Changhong Liu[3]

[1]Jilin Province Water Engineering Safety and Disaster Prevention Engineering Laboratory, Changchun Institute of Technology, Changchun, 130012, China.

[2]Beifang Investigation,Design & Research CO.LTD, Tianjin, 300222, China.

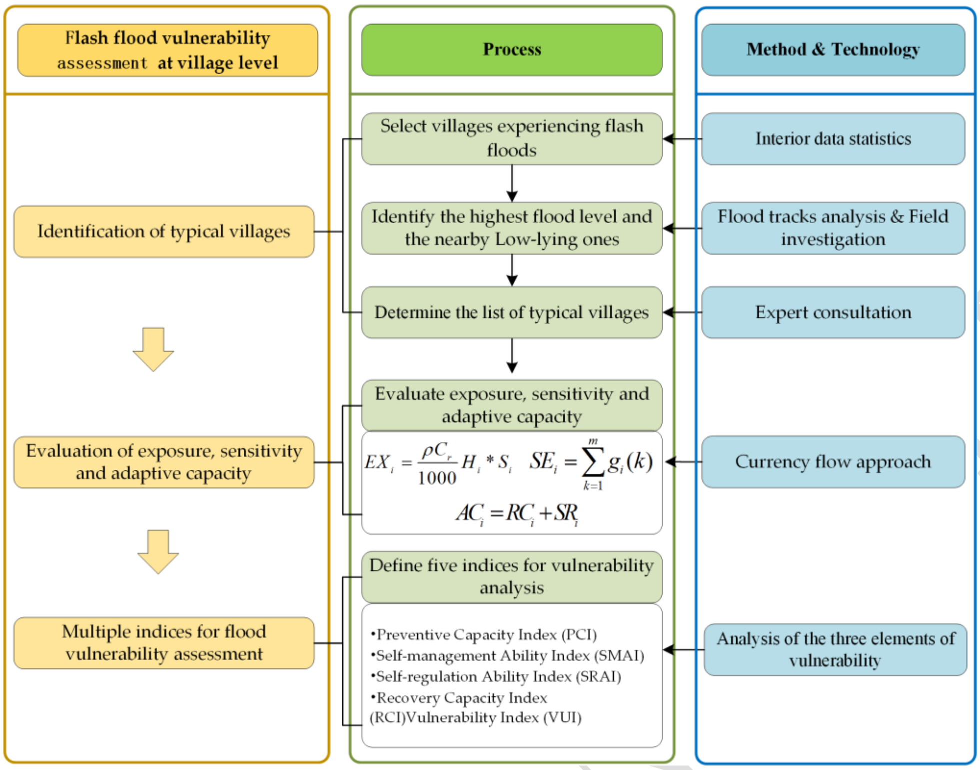
[3]Tianjin Key Laboratory of Soft Soil Characteristics & Engineering Environment, Tianjin Chengjian University, Tianjin, 300384, China.

[4]School of Civil Engineering, Tianjin University, Tianjin, 300072, China.

[5]College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100124, China.

*Correspondence: yangweichao@tju.edu.cn (Weichao Yang) and jackykui@126.com (Kui Xu)

Graphical abstract



Abstract: In recent years, flash floods have caused significant losses in most areas of the world. However, the assessment of flash flood vulnerability is lacking and weak, especially for the rural areas at village level in China. This work introduces a novel currency flow approach to analyze the flash flood vulnerability for typical villages of Baoting County in Hainan province, China. The typical villages are selected and identified by expert consultation and field investigation of flood events. The three elements of flood vulnerability like exposure, sensitivity and adaptive capacity are measured in monetary form with a currency flow approach. The multiple indices are developed to analyze flash flood vulnerability in terms of the relationships of the three elements. Results show that most identified typical villages of Baoting County have the relatively large values of Vulnerability Index (VUI). The numerical results in the study area for VUI, SMAI, SRAI and PCI fall within the ranges of 0.86-8.58, 1.6-21.79, 0.13-1.76, 0.008-0.26 and 0.11-1.26. It is essential to increase the investment in engineering and non-engineering measures especially in villages of Sidui (SD), Yidui(YD) and Shenjin(SJ), for more resilient to the effects of flash floods. The *NSE* result of the standardized numerical value of transferred population in the historical process of flash flood disasters and the standardized numerical value of flash flood vulnerability assessment ranking results is is 0.747, indicating that the accuracy of the currency flow approach is high. The currency flow approach proposed in this work reveals the relationships between exposure, sensitivity and adaptive capacity, identifying village and element of vulnerability that need strengthened against flash flood. The work findings will have a promising application prospect in flash flood management.

Keywords: Flash flood; Vulnerability; Multiple indices; Rural areas; Flood management

1. Introduction

Flash flood is usually defined as a sudden flooding caused by a high-intensity rainfall event within minutes or up to several hours (Yang et al., 2015). It is frequently transpiring natural hazards and cause serious loss of life and economic damage to infrastructures (Gascón et al., 2016; Karagiorgos et al., 2016; Lian et al., 2017; Mahmood et al., 2017; Costache et al., 2020; Alkaabi et al., 2025; Sarker et al., 2025; Zhang et al., 2025). Worldwide, Especially in countries from the Global South, it has been reported that 44% of disasters are associated with floods, causing 31% of the world's economic losses (WMO, 2021). Also in China, the whole areas and population threatened by flash flood have run up to 4.63 million km² and 560 million respectively (Zhitong, 2016). Flash flood tends to affect rural areas in China due to the backward economic development, few early warning systems and weak flood risk awareness. Moreover, China starts late on flash flood management compared to developed countries, and the study on flash flood management should be strengthened. Recent years, some researches are carried out to assess the flash flood risk at basin or region scales in China (Guo et al., 2014; Hu, 2016; Hou et al., 2024; Li et al., 2024). In recent years, floods prediction is more and more accurate and greatly reduce the loss of human life and property (Arun et al., 2024; Babu T et al., 2024; Karthik.S et al., 2025). However, limited researches are developed to analyze the flash flood vulnerability for villages which may be the places most in need of attentions. Thus, to improve adaption policies and effective management to reduce flash flood risk, it is crucial to quantify the vulnerability of rural areas affected by flash floods.

Vulnerability is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt in the latest IPCC (Intergovernmental Panel on Climate Change) assessment report (IPCC, 2022). Vulnerability is widely understood to differ within communities and across societies, regions and countries, also changing through time. The latest UNDRR (United Nations Office for Disaster Risk Reduction) report indicates that reduced vulnerability to flash and riverine floods, improved public health, enhanced conservation of natural resources and community participation are good projects represented a long-term commitment to benefit future generations (Reduction, 2025). Also, Vulnerability is generally defined as a function of exposure, sensitivity, and adaptive capacity, in which exposure is the degree of the system subjected to a hazard; sensitivity is the perturbation of a hazard has on the system; and adaptive capacity is the ability of the system to adjust to and cope with the effects of the hazard (Frazier et al., 2014; Chang and Huang, 2015; Lian et al., 2017; Hoque et al., 2019; Sarker et al., 2025). In this study, we adopted the vulnerability definition as a function of exposure, sensitivity, and adaptive capacity. The exposure and sensitivity of the system are generally considered to be influenced by the inter-action of environment and society, and adaptive capacity is affected by cultural, political and socio-economic forces (Smit and Wandel, 2006).

Flash flood vulnerability assessment is the key link in disaster prevention and mitigation. In recent years, a growing number of approaches have been developed to assess vulnerability, as new data and technologies become available. The vulnerability index system-based method is widely used in flood vulnerability studies. Wood et al., (2010) adjusted the index of social vulnerability in term of principal component analysis to carry out at the geographical census-block level. Szlafsztein and Sterr, (2007) classified, weighted and combined sixteen differently socio-economic and natural variables to form a single indicator--a composite vulnerability index (CVI), which provided a receivable measurement of differences among communities and regions. Karagiorgos et al., (2016) developed an integrated vulnerability method to evaluate the exposure of residential buildings to flash floods in Greece, which created an index system including parameters for assessing physical and social vulnerability. Geographic Information System (GIS) approaches have been gradually employed to assess flood vulnerability for involving geographic characteristics of study areas in recent years (Vujović et al. 2025). An involved GIS analysis and analytical hierarchy process (AHP) techniques were applied for flood vulnerability and risk mapping in urban areas by Ouma and Tateishi (2014). Montgomery et al. (2013) examined differences in environmental justice implications between coastal and inland flood hazard zones with GIS-based interpolation methods.

Shatanawi et al. (2024) applied a geospatial integrated approach using GIS, remote sensing, hydro-morphological analysis, and rainfall-runoff modeling for better flood hazard assessment.

In addition, some new vulnerability evaluation models have been developed. Milanesi et al., (2015) presented a conceptual model to evaluate human vulnerability to floods, focusing on people's stability in rapid flows designed for various floods in which life might be threatened. Fekete et al. (2010) introduced scale as a basic tool to improve the assessments of conceptual structure vulnerability and argued that scale and vulnerability assessments are seriously intertwined. Huang et al. (2012) developed an assessment model of multidimensional flood vulnerability based on the data envelopment analysis method. Rana and Routray (2018) proposed a Multidimensional Model for Vulnerability Assessment of Urban Flooding, which can be replicated irrespective of spatial scales and can be modified for other disasters by streamlining hazard specific indicators. Tavakoli et al. (2025) introduced an integrated flood assessment approach (IFAA) for sustainable management of flood risks by integrating the analytical hierarchy process-weighted linear combination (AHP-WLC) and fuzzy-ordered weighted averaging (FOWA) methods.

The above approaches for vulnerability assessment is quite effective in specific situations. However, these studies often assume that the relationships of the three elements for vulnerability (exposure, sensitivity, and adaptive capacity) are independent, and commonly sum them up to obtain an aggregate score for vulnerability assessment. There often exists subjective factors as index weights and the inner relationships between them are ignored in general during the process of these studies on vulnerability assessment. To overcome shortcomings of the above studies, this work suggests using a common unit (currency flow) to point out that the three elements of vulnerability are unified entities. In the field of economics, currency flow is applied to calculate the exchange rate, depending on the gap between cumulative capital inflows and the cumulative current account deficit (Müller-Plantenberg 2017). Here, we try to introduce the currency flow to quantify the exposure, sensitivity, and adaptive capacity. The results can not only reveal the relationships of the three elements for vulnerability, but also clearly identify which village and which element of vulnerability should be strengthen against flash floods in rural areas.

The Materials and Methods are introduced in Section 2. The results are shown in Section 3. Section 4 gives the discussions on the advantages of using the currency flow approach. The last section is conclusion.

2. Materials and Methods

2.1 study area

The case study area, Baoting County is located in the southern part of Hainan province, China with latitudes between 18°23′ and 18°53′N and longitudes between 109°21′ and 109°48′E (Figure 1). The majority of land in this county is mixed with hilly areas of 1058.5 km^2 (about 91.2%) and valley terraces of 102.1 km^2 (about 8.8%). The altitude range of Baoting County spans from 100 meters to 1,317.1 meters. The terrain is with a decreasing trend from northwest to southeast. The county has 9 townships, administer 62 village (neighborhood) committee, and 462 natural villages. The population is of about 167,605 in 2016, with urban population of 56,722 (33.8%) and rural population of 110,883 (66.2%). And the minority nationalities account for 59.3% of the population. The economic development of Baoting County is relatively low, and it is one of the most backward in Hainan province.

Given the maritime tropical monsoon climate, the mean annual temperatures of Baoting County range from 20.7 °C to 24.5 °C, and the annual precipitation is approximately between 1,800 and 2,300 mm. Heavy rains often abruptly happen with extreme rainfall during typhoons. Statistically, Baoting County has been struck by typhoons 3.9 times on average a year, the main sources of heavy rains. The rural areas in this county are particularly vulnerable to flash floods due to more frequent and intense extreme weather events. So it is urgent for the government to take measures to reduce the flood risk. In recent years, some measures including structural and non-structural measures are implemented to reduce the vulnerability to flash floods. The main structural measures contain pump facilities, bridges, road culverts and so on. And the main non-structural measures mainly include simple or automatic rainfall stations and simple water level stations. For Baoting County, it is necessary to analyze flash flood vulnerability after the implement measures, which can provide necessary basis for the future flood mitigation plans.

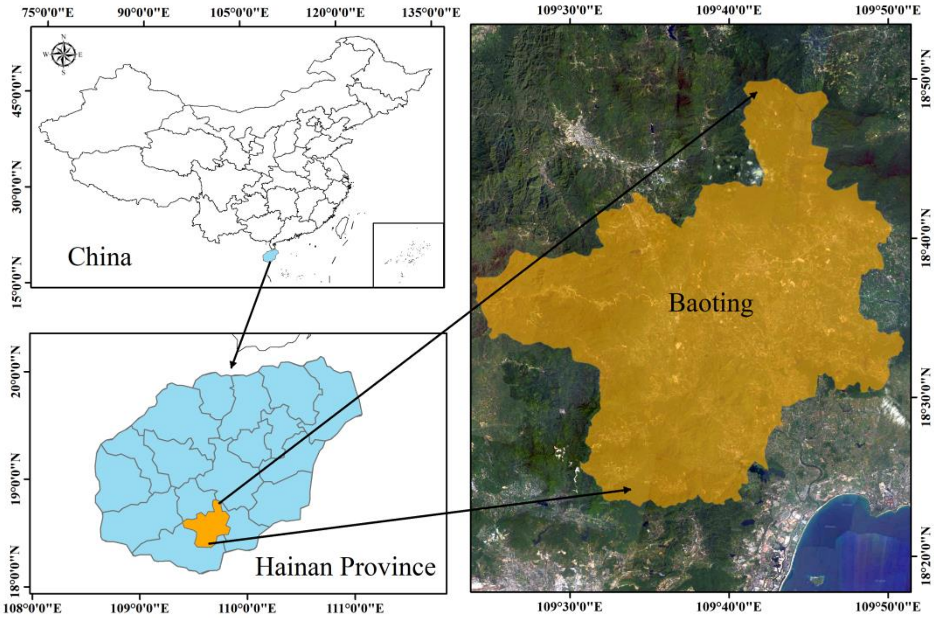


Figure 1. Location map of the study area

2.2 Data collection

(1) Exposure data

Here we selected the maximum accumulated rainfall during flash flood events as the exposure indicator. The area of typical villages was from the relevant towns' census data. The data of the maximum accumulated rainfall during flash flood events come from the official hydrological report.

(2) Sensitivity data

This study selected house assets and farm property as sensitivity indices. The data is from "Rural Household Survey Program"—annual sampling survey report, which was from statistical departments of the provinces.

(3) Adaptive capacity data

Our work selected the total disposable incomes and the investment of structural and non-structural measures against flash floods of a typical village as the adaptive capacity indicators.

These data were from census data of water resources and field investigation. The disposable income of typical villages was from the "Statistical Yearbook of Baoting County" Finally.

All data sources of vulnerability indicators are shown in **Table 1.**

Class	Indicator and relevant data	Data Sources
Exposure	The maximum accumulated rainfall	The official hydrological report
	The area of typical villages	The towns' census database
Sensitivity	house assets	Rural Household Survey Program
	farm property	Rural Household Survey Program
Adaptive capacity	The total disposable incomes	Statistical Yearbook of Baoting County
	The investment of structural and non-structural measures against flash floods	Census data of water resources and field investigation

Table 1. Data Sources of vulnerability indicators

2.3 Methodology

This study is devoted to proposing a novel flash flood vulnerability assessment approach based on the currency flow calculation. The methodology framework is shown in figure 1. First, typical villages potentially threatened by flash flood are identified as study objects by field investigation, flood tracks analysis, and expert consultation. Secondly, from the viewpoint of system theory, the three elements (exposure, sensitivity, and adaptive capacity) for vulnerability assessment are evaluated by currency flow. Finally, multiple indices are proposed and do a more comprehensive vulnerability assessment, considering the relationships of the three elements (exposure, sensitivity, and adaptive capacity), which are connected with currency flows between nature and human society. The methodology framework is shown as Figure 2.

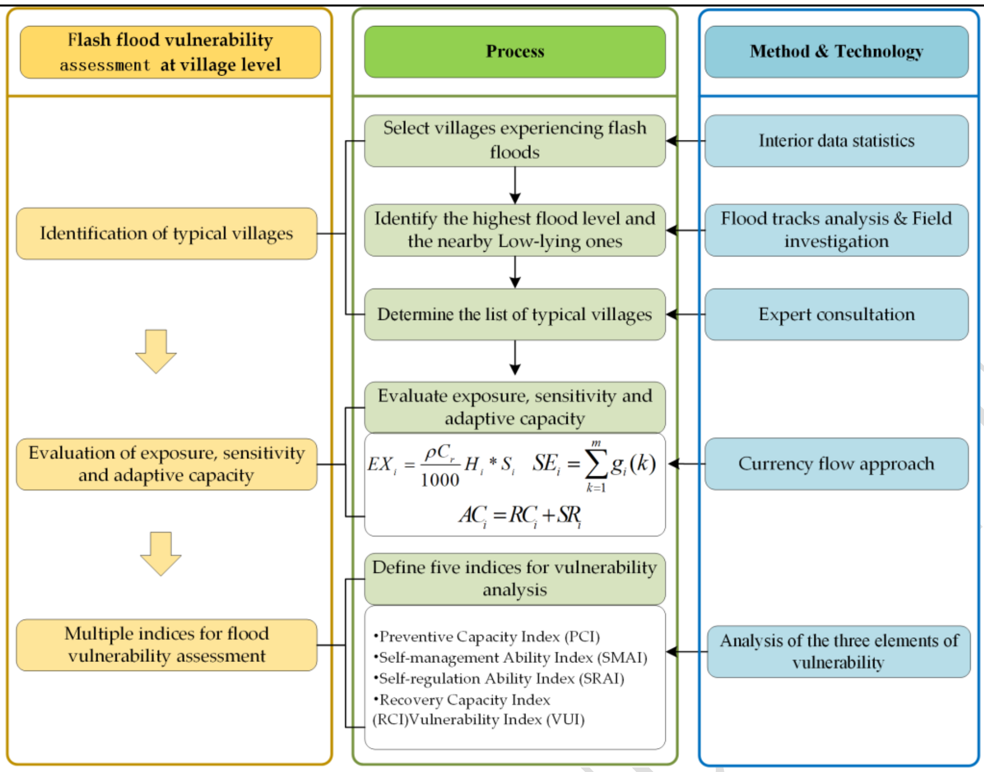


Figure 2. Methodology framework

2.3.1 Identification of typical villages

The typical villages who are potentially threatened by flash flood are identified as study objects. They can be selected and identified by various ways, mainly including expert consultation and field investigation of the flood events. Firstly, the villages experiencing flash floods are selected based on the historic flash floods records from the the official hydrological report. Secondly, field investigation methods like inquiry, expert consultation, analysis of major flood tracking methods, and investigation of the highest flood level are carried out to clearly identify the highest flood water level for these recorded villages. Then the neighboring villages whose elevation is not more than 1m above the highest flood water level are also selected and contained in the list of the typical villages. Finally, the list of typical villages is ultimately identified synthesizing field investigation, major flood tracks analysis, and expert consultation.

2.3.2 Evaluation of exposure, sensitivity and adaptive capacity

To directly illustrate how much the exposure, sensitivity and adaptive capacity are, we evaluate them with a currency flow approach. In this approach, the three elements of vulnerability are redefined in term of the currency flow. The currency flow values of these elements are interpreted as bellow: exposure is the total currency flow value of a flash flood for a typical village; sensitivity is considered as the sum value of currency flow that may be threatened by a flash flood; adaptive capacity can be taken as the total input currency flow of the system which is provided to reduce flash flood risk. Then these elements of vulnerability can be evaluated for different typical villages in term of the currency flow approach.

(1) Exposure

Exposure can be reviewed as the extent duration, and/or degree where a system is in subject to, or contact with a perturbation (Adger, 2006; Huang et al. 2011; Chang and Huang, 2015). Exposure is the nexus between the perturbation and system, rather than an attribute of the system itself. Accumulated rainfall is supposed to be the exposure of the system to a flash flood event. In this study, we take the maximum accumulated rainfall during flash flood events as the exposure of a village. The exposure for a village can be expressed in the monetary form as Equation (1):

$$EX_i = \frac{\rho C_r}{1000} H_i * S_i \tag{1}$$

Where, EX_i is the exposure of the ith typical village in RMB (yuan), whose value is greater than or equal to 0; H_i is the maximum accumulated rainfall during historical flash floods for the ith typical village(mm); S_i is the area of the ith typical village (m^2); ρ is the water density (kg/m^3); and C_r is price per unit of the rainfall in the ith typical village (yuan/kg).

(2) Sensitivity

Sensitivity is regarded as the extent or degree to which the system is modified or affected, either beneficially or adversely, by related climate (Gallopín, 2006). It depends on biophysical factors, social factors or a combination of both. In a flash flood event, sensitivity can be viewed as the likely influence of the system to such an event. Due to the limitation of data collection in the villages of Baoting County, we choose accumulated assets (including house assets and farm property) as the sensitivity indicators of the typical village to flash flood. The calculation formula in the monetary form is as Equation (2):

$$SE_i = \sum_{k=1}^{m} g_i(k) \quad (2)$$

Where, SE_i is the sensitivity of the ith typical village in RMB (yuan), whose value is greater than or equal to 0; m is sensitivity indicators' number in a typical village; $g_i(k)$ is the monetary value of the kth sensitivity indicator for ith village (yuan).

(3) Adaptive capacity

Adaptive capacity is reviewed as the system's ability to reduce the risk due to environment change, to cope with the consequences, or to take advantage of opportunities (Smit and Wandel, 2006). Adaptive capacity in this work consists of two parts, recovery capacity and self-regulation ability. Recovery capability is represented by the monetary values of total disposable incomes of a typical village. Self-regulation ability is the monetary values of the investment of structural and non-structural measures against flash floods. They can be expressed by Equations (3) to (5):

$$AC_i = RC_i + SR_i \quad (3)$$

$$RC_i = d_i * n \quad (4)$$

$$SR_i = \sum_{k=1}^{m} p_i(k) + \sum_{l=1}^{h} q_i(l) \quad (5)$$

Where, AC_i is the adaptive capacity for the ith typical village in RMB (yuan), whose value is greater than or equal to 0; RC_i is the recovery capacity of the ith typical village in RMB (yuan), whose value is greater than or equal to 0; SR_i is the self-regulation ability in the ith typical village in RMB (yuan), whose value is greater than or equal to 0; m is the number of structural measures (culverts, bridges), as they play an important role in the rapid drainage of flash floods of the ith typical village; $p_i(k)$ is the investment of the kth structural measure for the ith typical village (yuan); h is the number of non-structural measures for the ith typical village; $q_i(l)$ is the investment of the ith non-structural measure for the ith typical village (yuan); n is the number of total population for the ith typical village; and d_i is the resident's per capita disposable income in the ith typical village (yuan).

2.3.3 Multiple indices for flood vulnerability assessment

It is important to develop the relationships between exposure, sensitivity and adaptive capacity of a system for understanding of vulnerability to flash flood events. In the above work, a harmony of the three elements of vulnerability is established through a unified measurement, currency flow value. In this context, five indices to assess and manage vulnerability are developed in this study for the typical villages and presented through the ArcGIS (Arc Geographic Information System, version 10.8). The relevant indices for vulnerability analysis are defined as follows.

(1) Preventive Capacity Index (PCI): it is the ratio of currency flow value of adaptive ability to that of the maximum accumulated rainfall in a typical village, whose value is greater than 0. The PCI illustrates the total security input on per currency flow value that causes the danger in a typical village through the relation between adaptive ability and exposure. The lager PCI value means the better preventive capacity to adapt to the climate change for the typical village. The expression of PCI is shown as Equation (6):

$$PCI_i = \frac{AC_i}{EX_i} \tag{6}$$

Where, PCI_i is Preventive Capacity Index value of the ith typical village; AC_i is the adaptive capacity for the ith typical village in RMB (yuan); and EX_i is the exposure of the ith typical village in RMB (yuan).

(2) Self-management Ability Index (SMAI): it is the ratio of currency flow value of adaptive ability to that of accumulated assets in a typical village, whose value is greater than 0. The SMAI illustrates the total security investment on per currency flow value of accumulated assets through the relation between adaptive ability and sensitivity. The lager SMAI value means the better preventive capacity to adapt to the economic development for the typical village. The expression of SMAI is shown as Equation (7):

$$SMAI_i = \frac{AC_i}{SE_i} \tag{7}$$

Where, $SMAI_i$ is the Self-management Ability Index value of the ith typical village; AC_i is the adaptive capacity for the ith typical village in RMB (yuan); and SE_i is the sensitivity of the ith typical village in RMB (yuan).

(3) Self-regulation Ability Index (SRAI): it is the ratio of currency flow value of self-regulation ability to that of the exposure to flash flood in a typical village, whose value is greater than 0. The SRAI illustrates the total physical security investment (including structural and non-structural measures) on per currency flow value of the maximum accumulated rainfall. This index can reflect the level of the physical investment adapting to the exposure of flash flood. The lager SRAI value means the higher physical input to adapt to climate change for the typical village. The expression of SRAI is shown as Equation (8):

$$SRAI_i = \frac{SR_i}{EX_i} \quad (8)$$

Where, SRAIi is the Self-regulation Ability Index value of the ith typical village; SR_i is the self-regulation ability in the ith typical village in RMB (yuan); and EX_i is the exposure of the ith typical village in RMB (yuan).

(4) Recovery Capacity Index (RCI): it is the ratio of currency flow value of recovery capacity to that of the exposure and sensitivity to flash flood in a typical village, whose value is greater than 0. The RCI illustrates the total disposable incomes on per currency flow value of the maximum accumulated rainfall and accumulated assets. This index can reflect the level of the recovery ability adapting to the exposure and sensitivity of flash flood. The lager RCI value means the higher recovery ability from the flash flood for the typical village. The expression of RCI is shown as Equation (9):

$$RCI_i = \frac{RC_i}{EX_i + SE_i} \quad (9)$$

Where, RCI_i is the Recovery Capacity Index value of the ith typical village; RC_i is the recovery capacity of the ith typical village in RMB (yuan); EX_i is the exposure of the ith typical village in RMB (yuan); and SE_i is the sensitivity of the ith typical village in RMB (yuan).

(5) Vulnerability Index (VUI): it is the ratio of currency flow value of exposure and sensitivity to that of adaptivity capacity in a typical village, whose value is greater than 0. The VUI is employed to illustrate the vulnerability of a typical village in a flash flood event. The lager VUI value means the higher vulnerability to the flash flood. The expression of VUI is shown as Equation (10):

$$VUI_i = \frac{EX_i + SE_i}{AC_i} \tag{10}$$

Where, VUIi is the Vulnerability Index value of the *i*th typical village; EX_i is the exposure of the *i*th typical village in RMB (yuan); SE_i is the sensitivity of the *i*th typical village in RMB (yuan); and AC_i is the adaptive capacity for the *i*th typical village in RMB (yuan).

2.3.4 Accuracy assessment of the Methodology

The Nash-Sutcliffe Efficiency (NSE) is introduced to verify the quality of flash flood vulnerability assessment methodology. The expression of *NSE* is shown as Equation (11):

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_0^T - Q_m^T)^2}{\sum_{t=1}^{T}(Q_0^T - \overline{Q_0})^2} \tag{11}$$

Where, Q_0^t is the standardized numerical value of transferred population in the historical process of flash flood disasters in the *t*th village; Q_m^t is the standardized numerical value of flash flood vulnerability assessment ranking results in the *t*th village; and $\overline{Q_0}$ is the total average of standardized numerical value of transferred population.

The value of *NSE* is from minus infinity to 1. The closer the parameter is to 1, the better the assessment result will be. It is generally believed that a value exceeding 0.5 for this parameter indicates good assessment result.

3. Results

3.1 Results of typical villages

The typical villages who are potentially threatened by flash flood are identified as study objects in this paper. They are selected and identified by various ways, mainly including expert consultation and field investigation of the flood events. Firstly, the villages experiencing flash floods have been selected based on the historic flash floods records (The time, location, maximum flood level, and maximum rainfall amount of the flash floods occurred) from the local statistical yearbook and field investigation. There are 33 villages which have been recorded due to flash floods in whole county. Secondly, a field investigation is carried out to clearly identify and collect the highest flood water level for these recorded villages, as shown in Figure 3. Then the neighboring villages whose elevation is not more than 1m above the highest flood water level are also selected and contained in the list of the typical villages based on the suggestions from the local government (Figure 4). Finally, the list of typical villages is ultimately identified synthesizing field investigation, major flood tracks analysis, and expert consultation. There are 56 typical villages selected to be evaluated the vulnerability to flash flood (Figure 5).

Figure 3. Field investigation of villages' elevation and highest flood water level

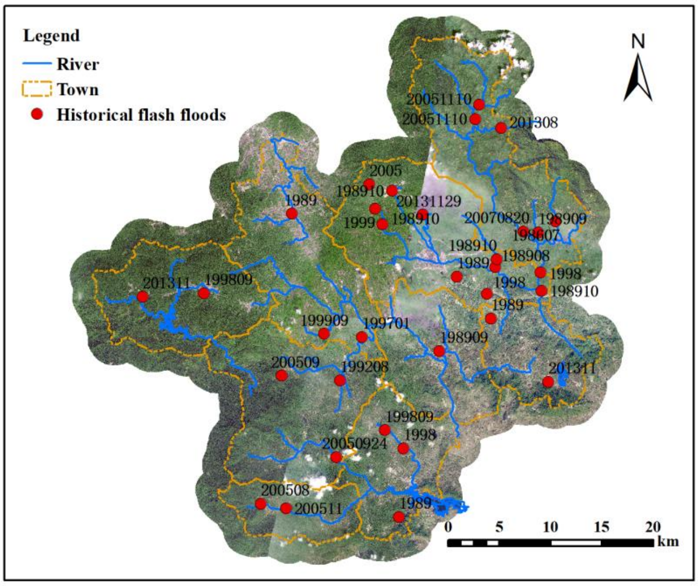


Figure 4. Spatial distribution of recorded maximum floods (Occurrence time is marked and one red point means one record of a flash flood)

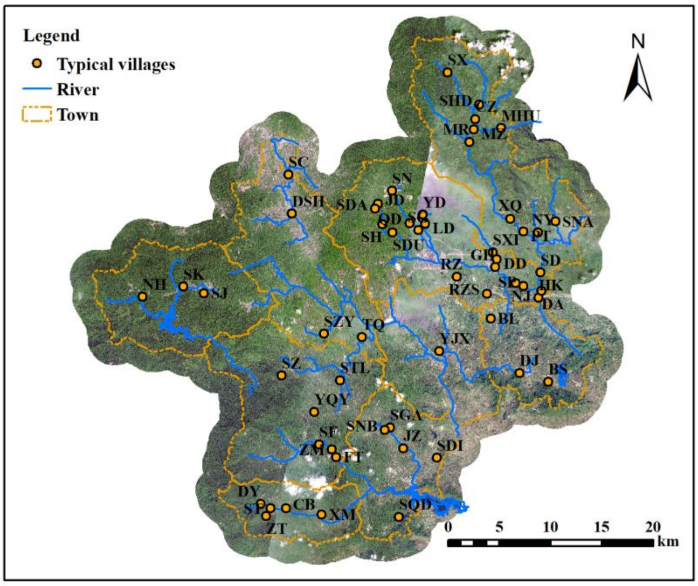


Figure 5. Spatial distribution of identified typical villages (all abbreviations represent names of different villages)

3.2 Assessment of exposure, sensitivity, and adaptive capacity in currency flow approach

Using the currency flow approach, exposure, sensitivity and adaptive capacity for the villages can be calculated according to Equations (1) to (5). The data for exposure calculation including the area of every typical villages and the accumulated maximum rainfalls of recorded flash floods (or maximum rain events) are collected from local Statistical Yearbook and Hydrographic Office. The data for sensitivity calculation including durable consumer goods, major productive fixed assets, and farm property are also collected from local Statistical Yearbook. For calculating adaptive capacity, the data about structural and non-structural measures consisting of road culverts, bridges, radio stations, rainfall stations, simple water level stations are collected from Hydrographic Office and field investigation. And the data about the disposable income and population of typical villages are from local Statistical Yearbook.

Figure 6 shows the distribution of villages' exposure in the form of currency flow values, which represents the maximum accumulated rainfall for the villages. The exposure values of whole county range from 86,310 to 990,360 yuan. The villages with maximum exposure including MZ, MR and CZ are distributed in the northeast part of the county.

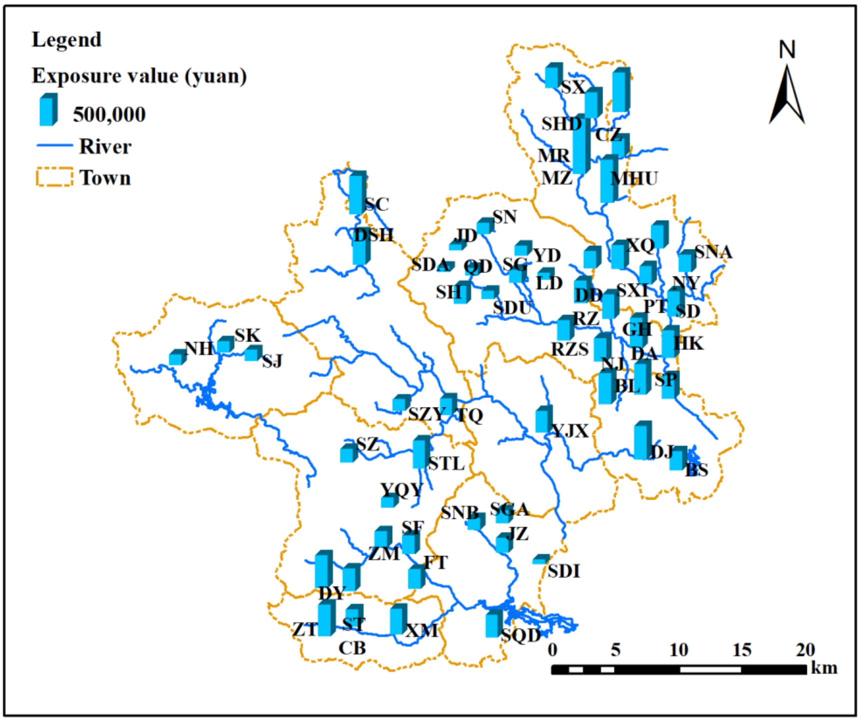


Figure 6. Distribution of typical villages' exposure by currency flow value

Figure 7 shows the distribution of villages' sensitivity in the form of currency flow values, which represents the accumulated assets in typical villages. The sensitivity of all villages ranges from 510,000 to 9,890,000 yuan. Higher values of sensitivity represent higher economic storage capacity, as well as a greater economic loss when flash flood events occurred. The villages with maximum sensitivity include YD, XM and MHU, which are distributed in the north and south end of the county.

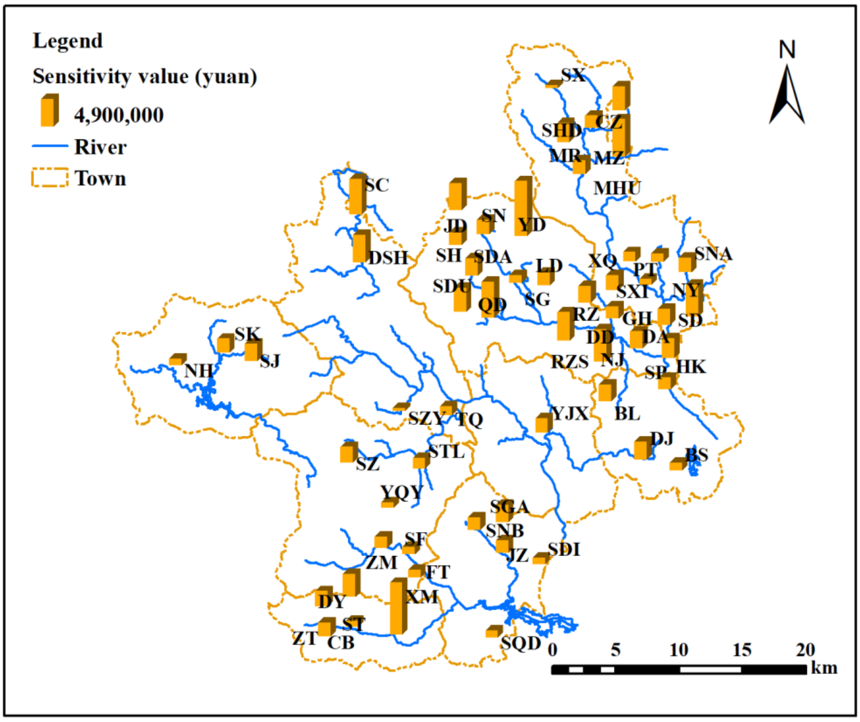


Figure 7. Distribution of typical villages' sensitivity by currency flow value

Figure 8 shows the distribution of villages' adaptive capacity in the form of currency flow values, which represents self-regulation ability and recovery capacity of typical villages. The adaptive capacity values of all villages range from 674,328 to 5,380,668 yuan. The values of adaptive capacity vary greatly for the villages of this county. Higher values of adaptive capacity represent higher investment of structural and non-structural measures against flash floods, or higher disposable income for recovering from flash floods. The villages with maximum adaptive capacity include DSH, SC and XM, which are distributed in the north and south end of the county. The village SX with minimum adaptive capacity is in the northeast part of the county.

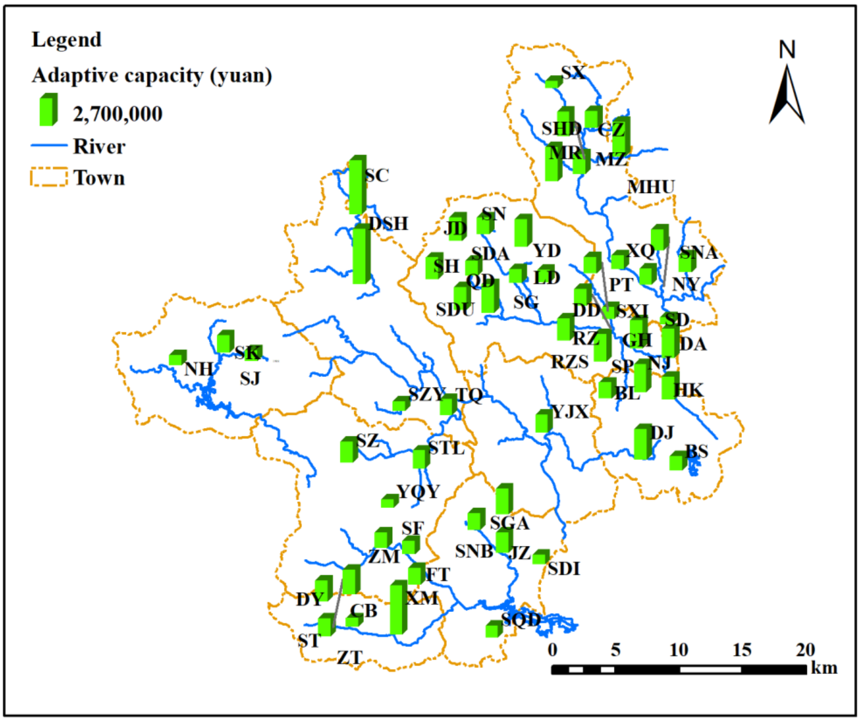


Figure 8. Distribution of typical villages' sensitivity by currency flow value

3.3 Multiple indices for flood vulnerability analysis

According to Equations (6) to (10), the multiple indices including PCI, SMAI, SRAI, RCI, VUI for flood analysis can be calculated. Figure 9 shows the values of VUI for all typical villages in Baoting County. VUI reveals the correlations between exposure, sensitivity, and adaptive capacity of a system. It is the ratio that the sum of exposure and sensitivity to adaptive capacity, rather than the sum of the three indices. The larger value of VUI means the higher vulnerability of a village to the flash flood. When the value of VUI in a village exceeds 1, it means the adaptive capacity cannot cover the exposure and sensitivity, which also implies that the vulnerability of this village is relatively high. Figure 9 illustrates that there are 53 out of 56 typical villages whose VUI exceeds 1, and another 3 villages with VUI values close to 1. The results of the VUI values may prove that the typical villages are identified correctly to some extent, and also illustrate that the index, VUI developed in this work can correctly reflect the vulnerability to flash flood for a village.

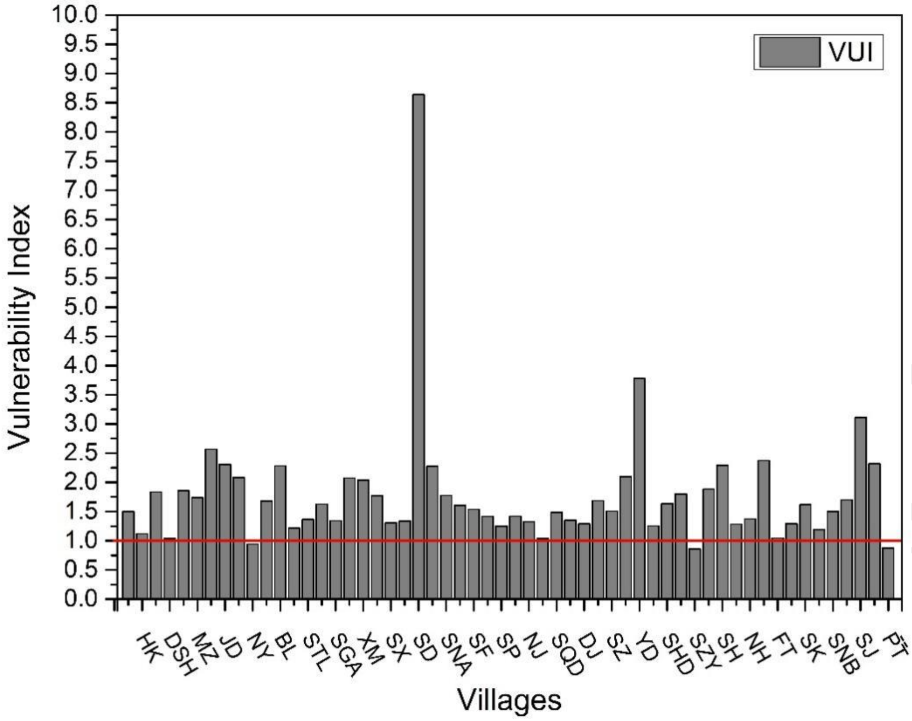


Figure 9. Bar chart of VUI values for all typical villages

Figure 10 shows the vulnerability distribution of typical villages. The VUI values of all villages range from 0.86 to 8.58. Most of them are concentrated in the range of 1.0 to 2.4. The village SD with maximum VUI is located in the east end of the county.

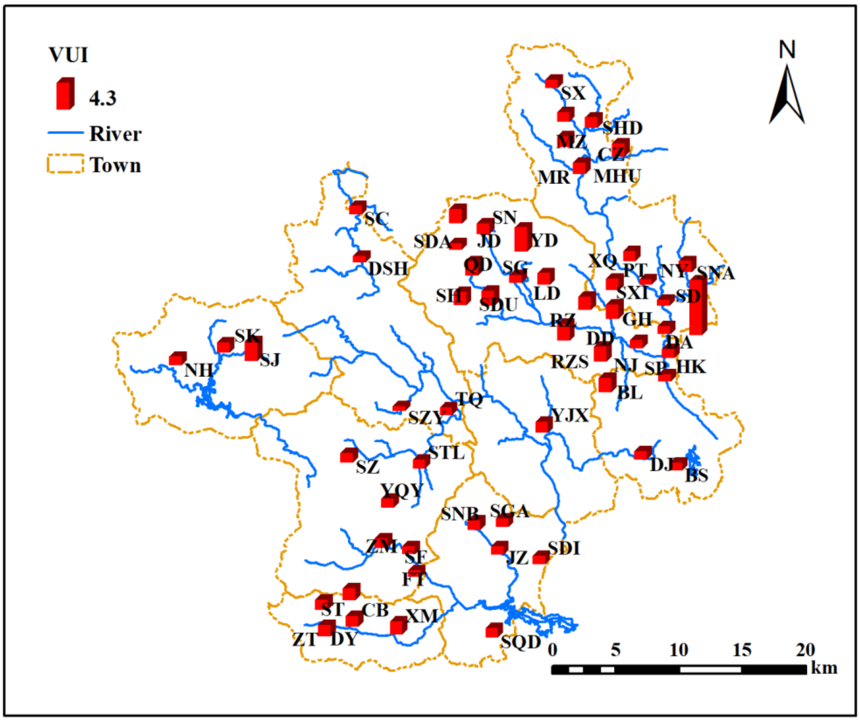


Figure 10. VUI distribution of typical villages

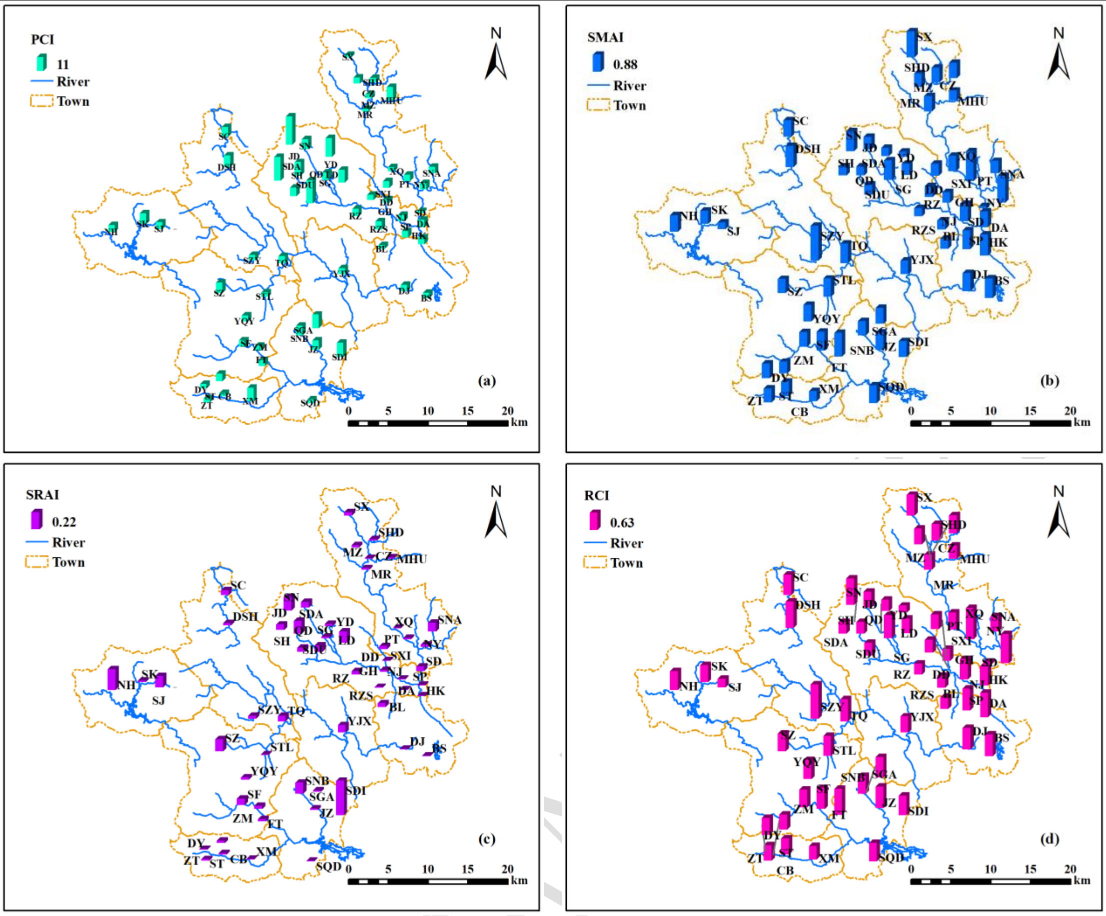


Figure 11. Multiple indices distribution of typical villages for flood vulnerability assessment:(a) PCI; (b) SMAI; (c) SRAI; and (d)RCI.

Figure 11(a) shows the space distribution of PCI, which reveals the relation between adaptive ability and exposure, as well as the combination of social economy and environment. The PCI values of all villages range from 1.6 to 21.79. The values of PCI vary greatly for the villages of this county. Higher values of PCI represent that relatively higher investment of measures and disposable incomes can be against the flash floods. The villages with maximum PCI include SDA, JD and QD, which are distributed in the north center of the county. While the villages, as SD, SX have minimum PCI values due to their smaller adaptive capacity. For these villages, the public investment on flood defenses should be prioritized.

Figure 11(b) shows the space distribution of SMAI, which reveals the relation between adaptive ability and sensitivity. The SMAI values of all villages range from 0.13 to 1.76. Higher values of SMAI means higher investment of measures or disposable incomes to protect the property of a village in flash floods. The SMAI value of SD village is 0.13, smaller than that of other villages. Its smaller adaptive capacity accounts for the minimum SMAI. While for village YD, it has second smallest SMAI value of 0.27 due to its biggest sensitivity value.

Figure 11(c) shows the space distribution of SRAI, which reveals the relation between self-regulation ability and exposure. The SRAI values of most typical villages are under 0.10. Lower values of SMAI means lower investment of measures against flash floods. For the typical villages in Baoting County, the investment of structural and non-structural measures of flood defenses should be strengthened.

Figure 11(d) shows the space distribution of RCI, which reveals the relation between recovery capacity, exposure and sensitivity. The RCI values of all typical villages range from 0.11 to 1.26. Lower values of RCI represents relatively lower disposable incomes or relatively higher exposure and sensitivity. The typical village SD owns the minimum RCI value because of its the minimum disposable incomes.

4. Discussion

4.1 Rationality analysis of currency flow approach

In order to verify the rationality of the currency flow approach for vulnerability assessment proposed in this work, the statistical results of the actual number of transferred population in the historical process of flash flood disasters in the villages are compared with the flash flood vulnerability assessment results, as shown in Figure 12. The results show that the SD village has the largest number of transferred people, where also has the largest vulnerability. The RZ, YD, SH and SJ villages are in a high position in the vulnerability and the actual number of transferred population. It is easy to see that the distribution of the above two types of results is basically the same, announcing the rationality of currency flow approach for vulnerability developed in this study.

Furthermore, The NSE of the standardized numerical value of transferred population in the historical process of flash flood disasters and the standardized numerical value of flash flood vulnerability assessment ranking results is calculated based on the Eq. (11). The NSE result is 0.747, which is more than 0.5, indicating that the accuracy of the currency flow approach is high.

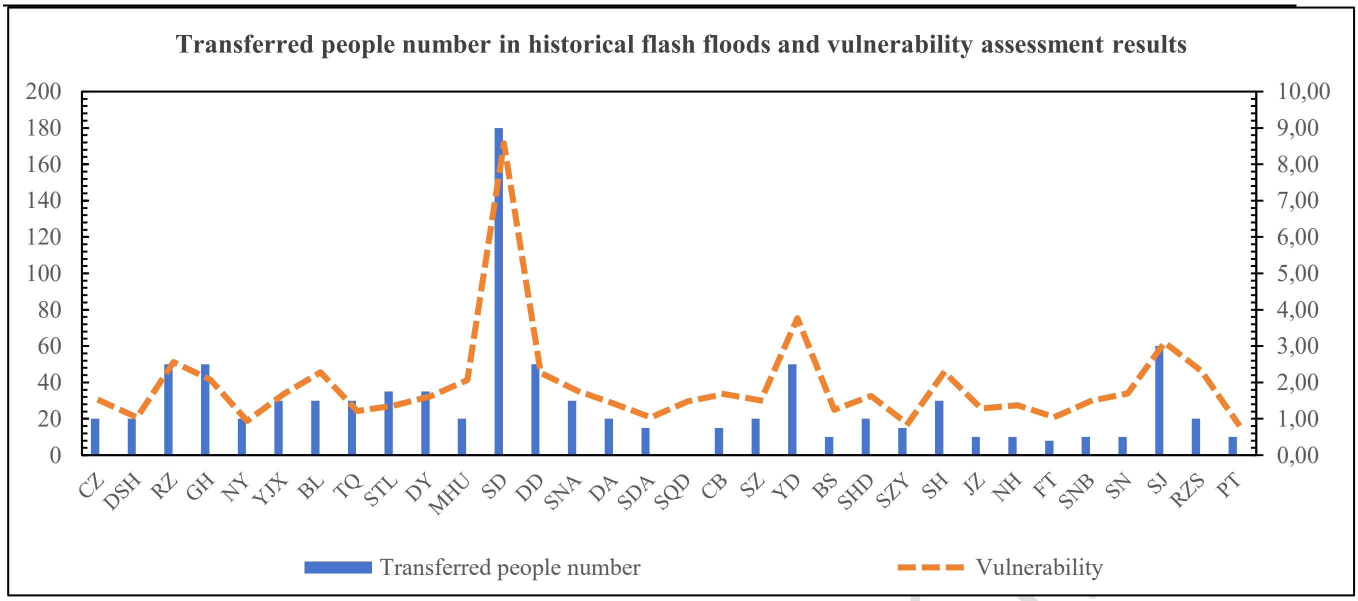


Figure 12. Rationality verification of currency flow approach for vulnerability

4.2 Advantages analysis of currency flow approach

From the viewpoint of system theory, vulnerability assessment is involved with the system's exposure, sensitivity and adaptive capacity to a hazard. In the previous studies, exposure, sensitivity, and adaptive capacity are evaluated as three independent elements for vulnerability assessment. The three elements are ranked and weighted separately, and added together to derive the vulnerability. This work develops a currency flow approach to assess exposure, sensitivity and adaptive capacity with unified measurement, monetary flow value. It can avoid the weight calculation of each element and the standardization of study data in previous work. Also, it can clearly reveal the relationships between the three elements and further investigate the vulnerability from multiple indices, avoiding incomplete evaluation. As shown in Figure 13, the village SJ has relatively smaller exposure ranking 47 out of 56 typical villages (47/56), not larger sensitivity ranking 21/56, and smaller adaptive capacity ranking 55 /56. In the traditional method accumulating the three elements to assess vulnerability, the result would tell that the village SJ has less danger. While in this work, we can see the village SJ has relatively higher vulnerability ranking 3/56 due to its terrible SMAI (Figure 14). Village SJ has the third lowest SMAI of whole typical villages, which represents the adaptive capacity on per unit currency flow of sensitivity in this village is very small. It means that the adaptive capacity cannot effectively protect the property, and the potential loss would be huge. In a word, revealing the relations between the three elements (exposure, sensitivity and adaptive capacity) to completely assess vulnerability is one of advantages using currency flow approach.

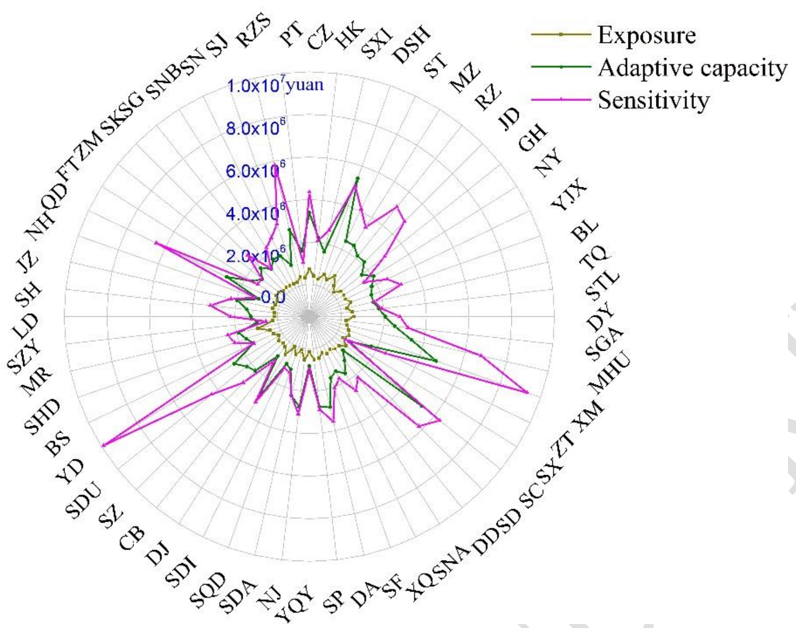


Figure 13. Radar chart of exposure, sensitivity and adaptive capacity in currency form

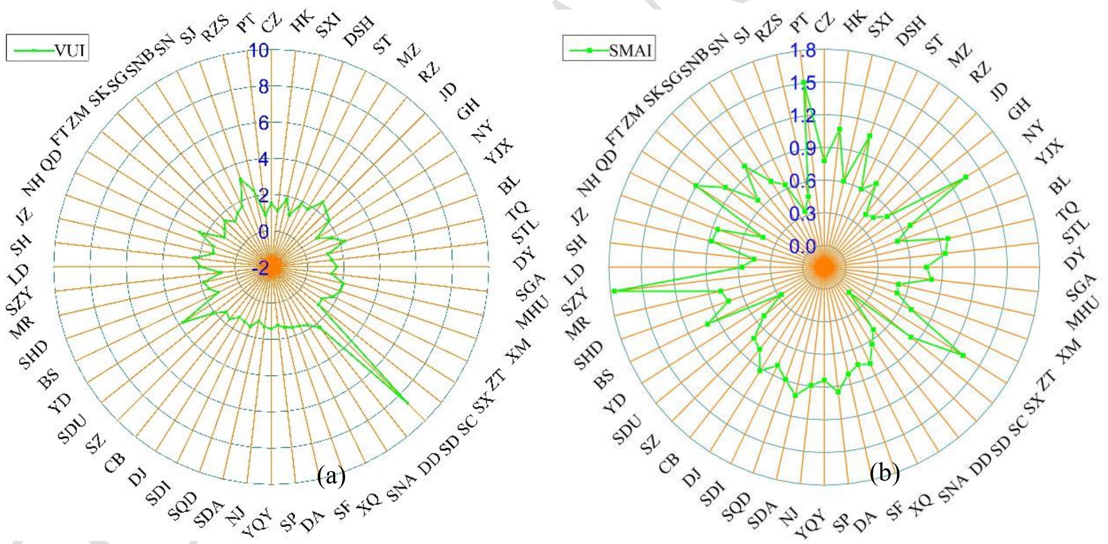


Figure 14. Radar chart of VUI and SMAI for all typical villages: (a) VUI chart; (b) SMAI chart.

Another advantage using the currency flow approach is that we can clearly identify where is not enough investment, which can give the government a precise input direction. For a village, for example, for village SD with minimum VUI because of the minimum RC, the government should effectively improve local economic development and increase local disposable incomes. For village YD with second smallest VUI due to the minimum SR, the government should strengthen the investment in structural and non-structural measures against flash flood. And for village SJ with the third smallest VUI due to the third lowest SMAI, the government should strengthen adaptive capacity, including both SR and RC in the future input. For all villages of the whole county, we can see that the SRAI values of almost 84% of the villages are smaller than 0.1, and the maximum SRAI is only 0.43 (Figure 15). It means that the investments of the villages in the whole county should be strengthened in structural and non-structural measures against flash flood by the government.

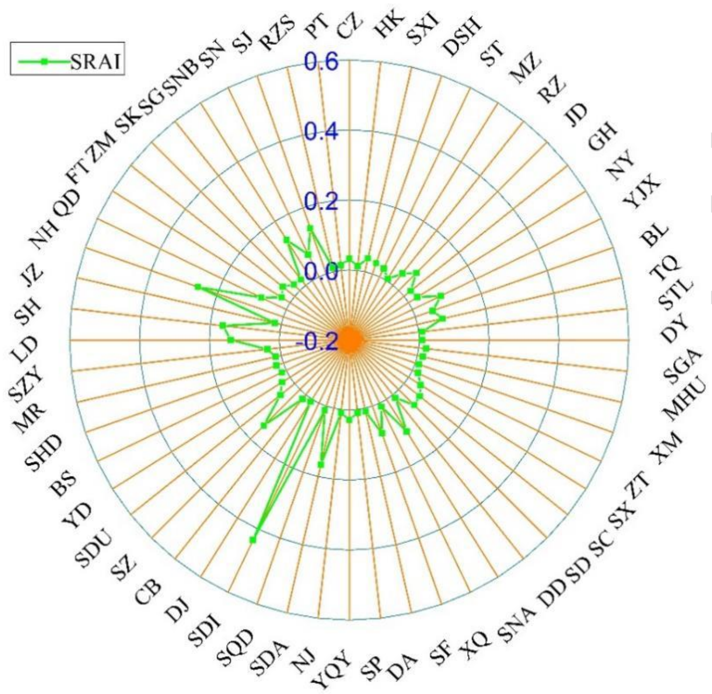


Figure 15. Radar chart of SRAI for all typical villages

Moreover, it is accessible to identify prioritization of investment assignment for the government by using currency flow approach. The data of exposure, sensitivity and adaptive capacity are from the local government departments and on-site investigations, which ensures the accuracy and scientific nature of the vulnerability assessment results. Figure 16 gives the classification of typical villages in term of VUI values. Typical villages of the county are divided into four classes. The first-class villages with VUI values ranging from 2.57 to 8.58 contain 3 villages (5% of the total villages). The 3 villages, SD, YD and SJ, have the largest VUI. So their assignment prioritization should be make sure if the investment is limited. The remaining villages (95% of the total villages) are divided into three categories. The second-class villages with VUI values ranging from 1.85 to 2.56 contain 13 villages. The sum of VUI values of these 13 villages is the 1/3 of that of the remaining 53 villages. The third-class villages with VUI values ranging from 1.48 to 1.84 contain 17 villages.

The sum of VUI values of the third-class villages is also the 1/3 of the remaining 53 villages. The fourth-class villages with VUI values ranging from 0.86 to 1.47 contain 23 villages. In the same way, the sum of VUI values of these villages is almost the 1/3 of the remaining 53 villages.

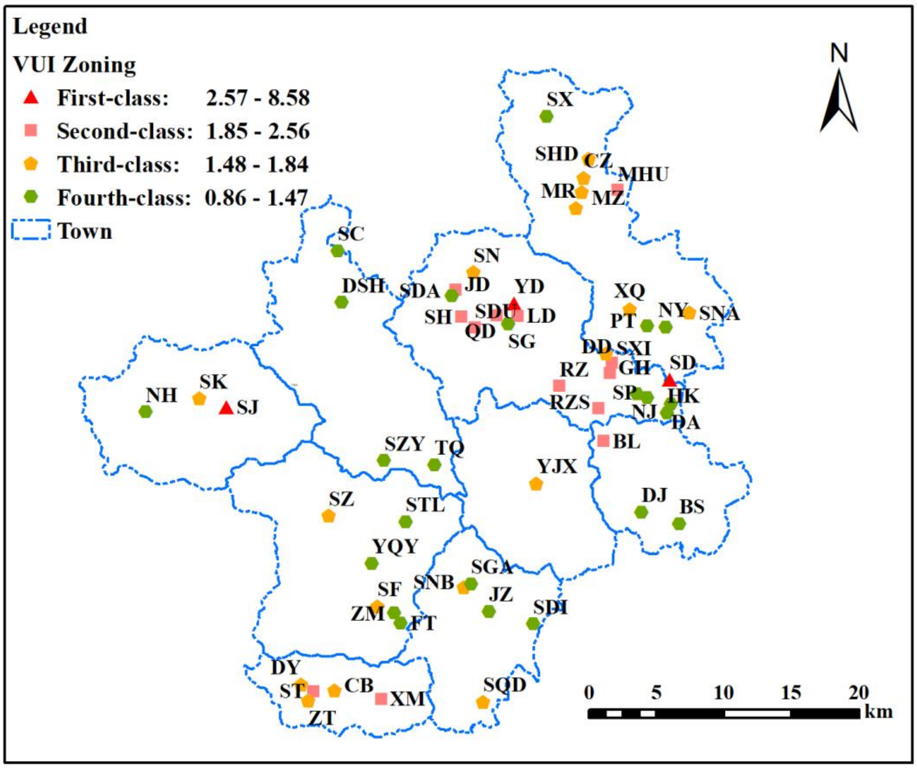


Figure 16. Classification of typical villages in term of VUI

Finally, the proposed currency flow approach for flash flood vulnerability assessment holds significant potential for both future research and real-time implementation due to its quantifiable, scalable, and element-wise diagnostic nature. For research, its monetary quantification of exposure, sensitivity, and adaptive capacity provides a standardized foundation for integration with emerging technologies like AI-driven predictive models, Digital Twin platforms, and real-time IoT sensor data streams. For practical application, the framework generates clear, monetized indices that can be operationalized within intelligent decision-support systems on cloud or edge computing platforms, offering decision-makers actionable intelligence for optimized budget allocation, prioritized interventions, and adaptive management by simulating how changes in specific vulnerability elements impact overall risk under various flood scenarios.

4.3 Limitation and future work

Certainly, the application of currency flow approach for flash flood vulnerability assessment exhibits several inherent limitations. Primarily, as it is very difficult to collect the basic data in rural villages, this study provides a relatively simple generalization of the quantification of exposure, sensitivity and adaptability. Although the vulnerability assessment results have been verified and also offer good disaster prevention and mitigation suggestions, further in-depth research is needed to develop a more comprehensive assessment of vulnerability in the future. Secondly, this approach provides only comparative evaluations of relative magnitudes across villages, while failing to establish precise threshold intervals for definitive security classification. Furthermore, the quantitative outcomes may demonstrate variability due to discrepancies in reference term computation methodologies. Consequently, the development of standardized threshold criteria emerges as a critical avenue for future research endeavors in this domain, being expected to improve the accuracy of the method.

5. Conclusions

This study is devoted to employing a currency flow methodology to construct an evaluation framework for village-level flash flood vulnerability assessment. The novel framework can avoid the weight calculation of each vulnerability element and the standardization of study data in previous work. The multiple indices proposed like PCI, SMAI, SRAI, RCI and VUI can clearly reveal the relationships among exposure, sensitivity and adaptive capacity, which further investigate the vulnerability and avoids incomplete evaluation. The framework was applied to villages in Baoting County of Hainan province in China for flash flood vulnerability assessment, providing guidance to decision-makers on the investment of flash floods prevention. The numerical results in the study area for VUI, SMAI, SRAI and PCI fall within the ranges of 0.86-8.58, 1.6-21.79, 0.13-1.76, 0.008-0.26 and 0.11-1.26. It is essential to increase the investment in engineering and non-engineering measures especially in villages of Sidui (SD), Yidui(YD) and Shenjin(SJ), for more resilient to the effects of flash floods. Nevertheless, the approach provides only comparative evaluations of relative magnitudes across villages, while failing to establish precise threshold intervals for definitive security classification. The development of standardized threshold criteria in multiple indices emerges as a critical avenue for future research endeavors in vulnerability assessment domain. Based on the vulnerability threshold, it can provide a more scientific basis for the government to allocate investment for the prevention of flash floods in different villages. In conclusion, the novel vulnerability assessment approach can support local institutions in the formulation of emergency and recovery plans, awareness campaigns, and disaster risk reduction investment strategies, appropriate to each vulnerability dimension.

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