

ASSESSING VULNERABILITY TO REGIONAL FLOOD HAZARD THROUGH SPATIAL MULTI-CRITERIA ANALYSIS IN THE HUAIHE RIVER BASIN, CHINA

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The identification of regional vulnerability to flood hazard and the components related to vulnerability is crucial for emergency preparedness, immediate response, mitigation planning, and long-term recovery from disasters. This research attempts to employ demographic and socio-economic data as well as other hazard information in studying the vulnerability to flood hazard with quantitative measures. Firstly the perspective of vulnerability to regional flood hazard is reviewed according to previous literature. On the basis of the conceptual framework of flood hazard vulnerability analysis, this paper develops a quantitative methodology to characterize the vulnerability of regional flood hazards, which employs spatial multi-criteria analysis approach based on entropy weight determining and scenario analysis of the flood event occurred in 2003. The utility of this approach in an assessment of the vulnerability is illustrated in the Huaihe River Basin, China.

Key Words: Flood hazard, vulnerability, entropy, multi-criteria analysis, geographical information systems

1. INTRODUCTION

Floods are known as frequent and most devastating events worldwide. Asia continent is much affected by floods and the countries like China, India, and Bangladesh are extremely vulnerable¹. The impacts of hazardous events are often exacerbated by the interactions with other hazards or by occurring in areas with a high density population and social vulnerability. The identification of regional vulnerability to hazard and the components contributing to vulnerability is crucial for emergency preparedness, immediate response, mitigation planning, and long-term recovery from disasters. Thus the need for a spatially oriented vulnerability assessment is highlighted. For example, Birkmann² stressed the need for a paradigm shift from the quantification and analysis of the hazard to the identification, assessment and ranking of vulnerability. In this

regard, vulnerability has emerged as the most critical research field in disaster studies. This new emphasis on vulnerability marks a shift away from traditional scientific assessments, which limit analysis to the stressors (e.g. climate change, hurricanes) and the corresponding impacts, towards an examination of the system being stressed and its ability to respond³. The advantage of the vulnerability based approach is that it allows a broad array of potential risk factors to be explored⁴. This is conducive to diagnosing the various factors and interactions that contribute to vulnerability.

Although vulnerability is a key issue in understanding disaster risk, quantitative assessment of vulnerability is often less advanced than hazard mapping and impact analysis. To identify spatio-temporal distribution of vulnerability, to improve understanding of the underlying processes, and to prioritize strategies to reduce vulnerability, the index approach as a quantitative measure is

potentially useful. Some previous studies illustrate the composite index approach to measure vulnerability^{5,6)}.

While the index approach aggregates a broad range of potential factors that may contribute to vulnerability, the relative importance of indicator generally has not been considered in part due to a lack of knowledge regarding their relationships and contributions of factors. The components are summed and rescaled to estimate vulnerability. Actually to create an integrated index of vulnerability with the application of index approach, it is significant to deal with the weight determining of indicator.

Large scale flooding due to heavy rainfall and drainage congestion has been regularly experienced in the Huaihe River basin, China. The summer dominant rainfall, special topographic and socio-economic conditions make the region highly vulnerable to flooding. Taking the Huaihe River basin as case study, the main objective of this research is to put forth a methodology for assessing vulnerability to regional flood hazard.

2. METHODOLOGY

(1) The perspective of vulnerability

Vulnerability is a concept that evolved out of the social science and was introduced as a response to the purely hazard-oriented perception of disaster risk in the 1970s. In the literature of vulnerability, although there are different views on vulnerability from different experts and examples of methods for vulnerability analysis that have been developed by institutions and researchers, vulnerability is often viewed as an intrinsic characteristic of a system or element^{2,7,8)}.

In recent years, many interdisciplinary researches have begun to explore the vulnerability for addressing vulnerable people and regions. The concept of vulnerability has been continuously broadened towards a more comprehensive framework encompassing exposure, susceptibility, coping capacity and adaptive capacity or resilience, as well as focusing on different contexts, such as physical, social, economic, environmental and institutional vulnerability.

This research of vulnerability assessment traces its roots to Cutter⁹⁾ who introduced a conceptual model of locality's vulnerability to hazards. It is hypothesized that the social and biophysical elements interpenetrate and shape the overall vulnerability, which is represented by the combination of biophysical and social vulnerability (Fig. 1). Biophysical vulnerability relies upon hydro-geological conditions, and social vulnerability depends on socio-economic characteristics. It should be noted that eco-environmental vulnerability is not taken into

consideration in this study. However the previous studies always laid emphasis on social vulnerability.

To employ the indicator-based approach, vulnerability is conceptualized as a function of exposure to a stressor, susceptibility to associated impacts, and the ability of a system to adapt to the stressor's impacts^{7,10)}. In other words, three determinants of vulnerability can be identified, which are exposure, susceptibility and resilience. According to analysis of the actual conditions in the Huaihe River basin, China, for the whole basin as a management zone, the national disaster mitigation policy can be thought as the same, and the households have similar awareness because the frequent flood disaster occurs. Noticeably it is necessary to consider data availability for indicator selection in developing country. Therefore both actual conditions and data availability in the Huaihe River basin form a fundamental assumption that ten kinds of indicators are the most significant factors of vulnerability to regional flood hazard (Fig. 1), which are population density, land use, GDP per capita, dependents and inequality, income of farmer, income of employment, social expenditures, household savings, hospital beds of 10k people, and institutional preparedness.

Although flood prevention standard indicates the level of flood prevention, in China to some extent it also can be used to reflect the level of institutional preparedness. Thus flood prevention standard is selected to represent the institutional preparedness. Because in the Huaihe River basin the agriculture is dominant, the percentage of farmland is to reflect the land use. Furthermore, enrollment rate is selected to represent the dependents and inequality.

(2) Vulnerability assessment methodology

The study objective is to develop a quantitative approach for assessing vulnerability that enables combining some variables influencing vulnerability. In which, mathematical quantification of heterogeneous indicators enables the representation of their interrelations, and different indicators can be incorporated in one assessment context.

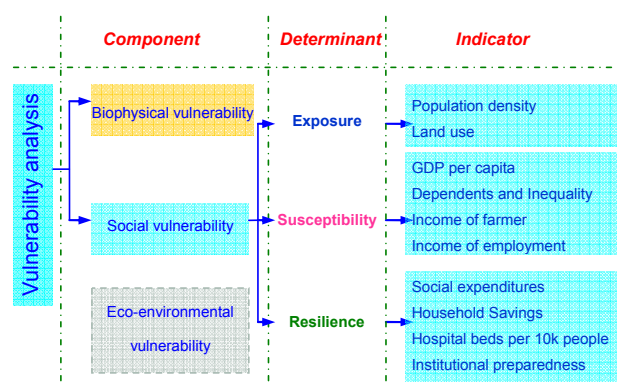


Fig. 1 The conceptual framework of vulnerability analysis for regional flood hazard.

As mentioned in the introduction, composite index approach is selected to measure vulnerability, which is based on the conceptual framework developed in this study.

Constructing a vulnerability index from a suite of indicators raises several problems in the aggregation of these selected indicators, including weight determining and model structure. In this paper, multi-criteria analysis method is employed for the construction of model, and entropy-based weight determining approach is used to supply objective indicator weights. More details are illustrated in Section 4.

3. DESCRIPTIONS OF STUDY AREA AND DATA AVAILABILITY

The Huaihe River basin (HRB)¹¹ is situated in eastern China, which is one of the seven major river basins in China (Fig. 2). Geographically, it is located between the latitude 31°N-36°N and longitude 112°E -121°E, covering an area of 270,000km². This study area is composed of four provinces, which are Jiangsu, Shandong, Anhui and Henan. HRB is composed of two water systems, one is the Huaihe River to the south of the old Yellow River and the other is the Yishusi River to the north. The Huaihe River originates from the Tongbo Mountain, and flows into the Yangtze River with the length of approximately 1000 km. The elevation usually is from 2 m to 200 m.

Climatologically, it lies in the warm semi-humid monsoon region. Precipitation mainly occurs in the period from May to October. Because of anomalies of the Meiyu front during the rainy season influenced by the South Asian monsoon, and the unique topography, the basin has been known for its frequent disasters. Moreover, this region is populous with the population density of 623 capita per km² in 2003, at the same time the total population reached 168 million, accounting for 13% of the nation's population. And there is 17% of the country's cultivated land¹².

Obviously it is significant to study vulnerability to flooding for preparedness strategy making and governance. This paper takes a typical flood event occurred in the year 2003 as a case, the relevant data such as demographical census, socio-economic data in the year 2003 are collected or generated from the census yearbooks of Jiangsu, Shandong, Anhui and Henan Provinces. In this study, 186 counties and cities have been selected as assessment units. The land use data is generated by the MODIS Vegetation Index composite imagery data obtained in 2003. Meanwhile for larger area, the biographical vulnerability is identified by remote sensing data processing according to scenario analysis of flood event occurred in 2003 (Fig. 3)¹³.

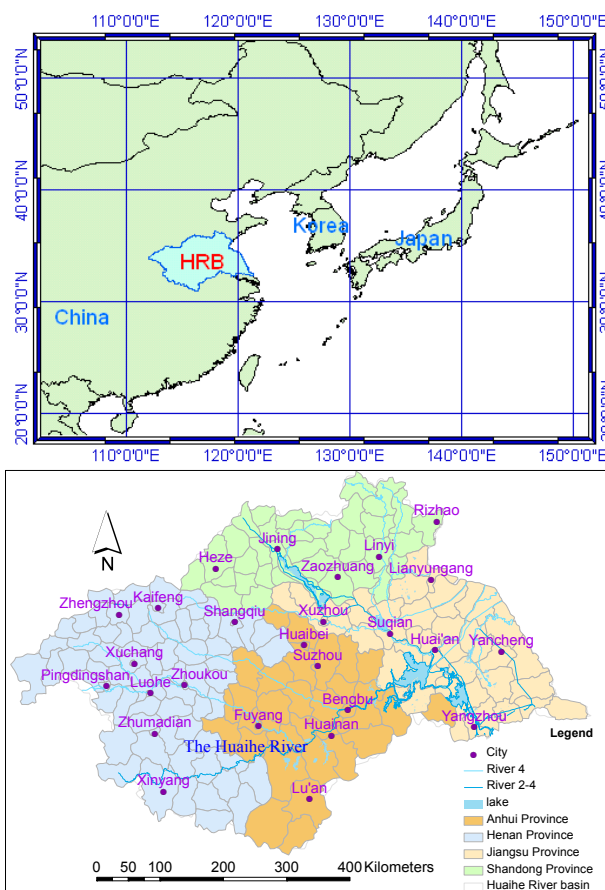


Fig. 2 The Huaihe River basin, China. The upper map shows its location in China. In the bottom figure, main rivers, lakes and districts are shown.

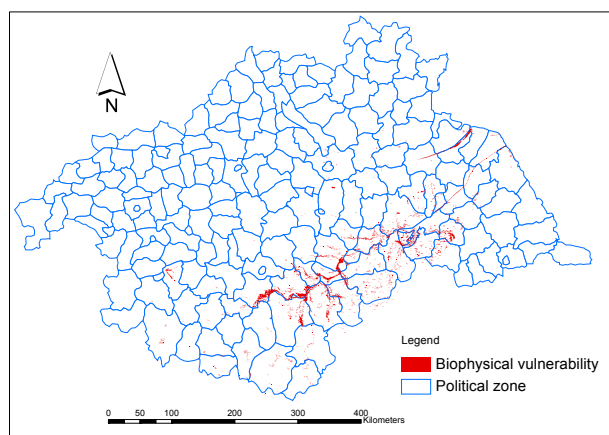


Fig. 3 The biophysical vulnerability to flood hazard in the Huaihe River basin, China, 2003.

4. VULNERABILITY ASSESSMENT THROUGH SPATIAL MULTI-CRITERIA ANALYSIS

In this section social vulnerability metric by translating a framework of vulnerability analysis into a mathematical expression is presented. A numerical weighting scheme is applied. Multi-criteria analysis model¹⁴ is receiving increasing attention in dealing with complex

problems. It was introduced to GIS science in a variety of applications using different calculation methods. In essence, a multi-criteria method creates summary evaluation scores for each decision alternative based on their combined performance in the multiple criteria. Suppose there are n indicators ($n=10$, see Fig. 1) and m assessment units ($m=186$, see Fig. 3), the original indicator data X is expressed as following Eq. (1).

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

For dealing with quantitative measure of social vulnerability, the method used is an additive model, in which a vulnerability index is calculated based on a set of indicators (Eq. (2)).

$$VI(i) = \sum_{j=1}^n w_j \times V(x_{ij}) \quad (2)$$

where $VI(i)$ is the vulnerability index of the units i . n denotes the number of indicator, w_j is the relative weight of the indicator j . The weights have to be non-negative and sum up to 1. x_{ij} is the value of the indicator j for the units i (x_{i1} - Population density, x_{i2} - Percentage of farmland, x_{i3} - GDP per capita, x_{i4} - Enrollment rate, x_{i5} - Income of farmer, x_{i6} - Income of employment, x_{i7} - Social expenditures, x_{i8} - Household savings, x_{i9} - Hospital beds of 10k people, and x_{i10} - Institutional preparedness). $V(x_{ij})$ stands for the representation of indicator normalization for x_{ij} .

(1) Measuring key indicators for vulnerability assessment

To make spatial multi-criteria analysis possible, each vulnerability indicator is to be measured by its impact and converted into a normalized range from 0 (very low impact) to 1 (very high impact). The indicators may have different measurement scales (nominal, ordinal, interval and ratio). For standardizing indicators, a set of equations can be utilized to convert the original data to a range between 0 and 1. In terms of literature analysis, the contribution of individual indicator to vulnerability is better to be represented by a nonlinear function referring to risk analysis¹⁵. In this study, S-shaped transform function¹⁶ is selected to convert the quantitative indicator according to the feature of vulnerability (Eq. (3)). Other percentage indicators are used directly. Moreover flood prevention standard (T_i) is selected to measure the institutional preparedness. Subjectively it is represented by flood prevention capacity of main river or city in assessment unit i . The function $x_{i10} = 1 - (T_i / 100)$ is designed to quantify it while $0 \leq T_i \leq 100$, or else $x_{i10} = 0$ while $T_i > 100$. For example when T_i is

25-year return period, it is specified as 0.75.

$$V(x) = \frac{1}{1 + e^{(a \times (-x+b))}} \quad (3)$$

where a is used to determine the gradient of curve, and estimated by the fitting of independent variable (x) and dependent ($V(x)$) according to S-shaped regression function (Eq. (3)). b is specified by a mean (or median) value of indicator. This function just shows the indicator is positive in relation to vulnerability. Additionally, the unfavorable indicator can be converted by reverse S-shaped function (Eq. (4)).

$$V(x) = 1 - \frac{1}{1 + e^{(a \times (-x+b))}} \quad (4)$$

For example, the original data of GDP per capita in the Huaihe River basin, 2003 is shown in Fig. 4. In order to estimate the parameter a , some empirical information is considered because there is no a prior information about the relationship of indicator value and normalized value. It is assumed that the normalized value is higher while larger than 0.8 and it is lower while less than 0.2. Thus after sorting GDP per capita from minimum to maximum, the corresponding indicator value is obtained while the order in the sorted data series over total number m in study area is 0.8, 0.5 and 0.2 respectively. After fitting analysis¹⁶, the parameter a is estimated (Fig. 5). GDP per capita is converted by Eq. 4 (Fig. 6). To illustrate the assessment processes, some examples are listed in Table 1.

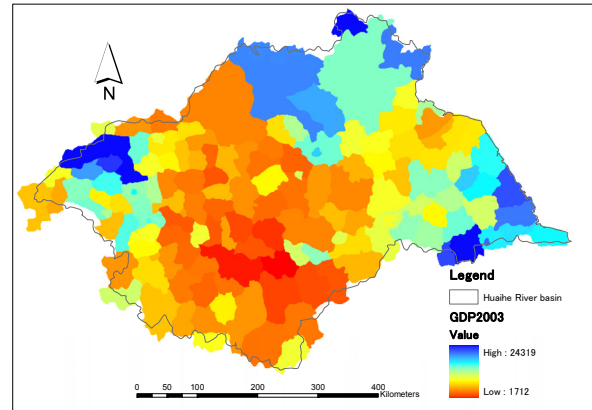


Fig. 4 The example of original data (GDP per capita in 2003).

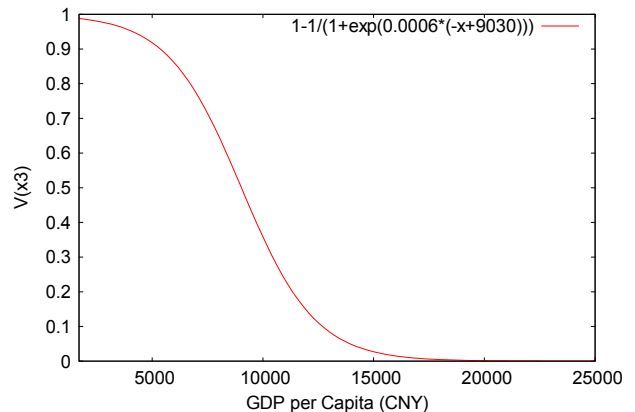


Fig. 5 The normalization function for GDP per capita in 2003.

Table 1 The data used in the multi-criteria analysis (Examples from three assessment units)

Indicator*	$x_{\bullet 1}$	$x_{\bullet 2}$	$x_{\bullet 3}$	$x_{\bullet 4}$	$x_{\bullet 5}$	$x_{\bullet 6}$	$x_{\bullet 7}$	$x_{\bullet 8}$	$x_{\bullet 9}$	$x_{\bullet 10}$	
Unit No.											
1	$x_{1\bullet}$	344.2	61	24319	0.99450	2900	12123	649.01	4112.5	26.0	0.5
	$s_{1\bullet}$	0.46	0.61	0.00	0.00550	0.44	0.11	0.45	0.18	0.38	0.5
2	$x_{2\bullet}$	460.7	62	8264	0.99630	2713	9885	451.91	3682.0	26.0	0.5
	$s_{2\bullet}$	0.48	0.62	0.26	0.00370	0.47	0.32	0.42	0.34	0.38	0.5
3	$x_{3\bullet}$	584.0	67	11211	0.99900	3260	9885	318.64	2834.4	26.0	0.5
	$s_{3\bullet}$	0.49	0.67	0.06	0.00100	0.39	0.32	0.40	0.74	0.38	0.5
Weight	0.01677	0.03379	0.24105	0.06418	0.02677	0.11250	0.03432	0.11251	0.14773	0.21038	

* $x_{\bullet 1}$ —Population density (Capita/km²), $x_{\bullet 2}$ —Percentage of farmland (%), $x_{\bullet 3}$ —GDP per capita (CNY), $x_{\bullet 4}$ —Enrollment rate (%), $x_{\bullet 5}$ —Income of farmer (CNY), $x_{\bullet 6}$ —Income of employment (CNY), $x_{\bullet 7}$ —Social expenditures (CNY/Capita), $x_{\bullet 8}$ —Household savings (CNY), $x_{\bullet 9}$ —Hospital beds of 10k people, and $x_{\bullet 10}$ —Institutional preparedness

(2) Entropy-based weighting determining

There are some approaches to determine weight of individual indicator composing of subjective and objective methods. In previous researches about vulnerability assessment, the relative importance of indicator is assumed as the same. To deal with this problem, the study attempts to employ objective method for judging their relative importance, which is based on entropy¹⁷⁾ described as follows.

a) Normalization of the original data matrix

The normalized matrix (\bar{S}) is shown as Eq. (5).

$$S = (s_{ij})_{m \times n}, \quad i = 1, \dots, m, \quad j = 1, \dots, n \quad (5)$$

where s_{ij} is the normalized data of the units i at the indicator j ($m=186, n=10$), which is computed by the method mentioned in subsection (1) of Section 4.

b) The definition of entropy value

According to the normalization result, the ratio (r_{ij}) of the normalized value s_{ij} to the sum of them for the indicator j is shown as Eq. (6).

$$r_{ij} = s_{ij} / \sum_{i=1}^m s_{ij}, \quad i = 1, \dots, m, \quad j = 1, \dots, n \quad (6)$$

The entropy measurement e for the indicator j is computed by Eq. (7).

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m r_{ij} \ln r_{ij}, \quad j = 1, \dots, n \quad (7)$$

c) The entropy-based weight determining

The objective weight w for the indicator j is defined as Eq. (8).

$$w_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)}, \quad j = 1, \dots, n \quad (8)$$

where $0 \leq w_j \leq 1$ and $\sum_{j=1}^n w_j = 1$.

With the application of entropy-based weight determining, the indicator weights used in the multi-criteria analysis model can be calculated, which are listed in **Table 1**. The results about weighting determining indicate that GDP per capital and institutional preparedness in study area are most important, and the economic indicators play much more role in this assessment.

(3) Results and analysis

After the selection of the indicators, their normalizations and the definition of indicator weights (**Table 1**), the social vulnerability index (SVI) is computed by Eq. (2). The social vulnerability index map is generated by ArcGIS environment (**Fig. 7**), in which the social vulnerability index values range from 0.19 to 0.71. The greater value shows the more vulnerable to flooding. This comprehensive quantitative index can be used to characterize the social vulnerability of regional flood hazard in the Huaihe River basin.

According to spatial distribution of social vulnerability index in the Huaihe River basin, the vulnerable area is located in the center and southwestern part. The most vulnerable region is located in the southeastern of Henan Province and the northern of Anhui Province. From the city of Bengbu to the upstream along the main trunk of the Huaihe River, it is found that social vulnerability is

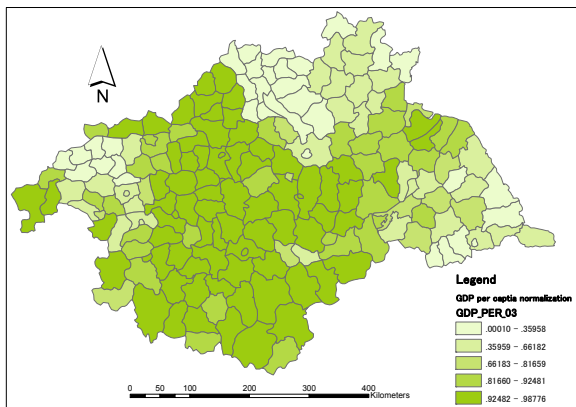


Fig. 6 The normalized value for GDP per capita in 2003.

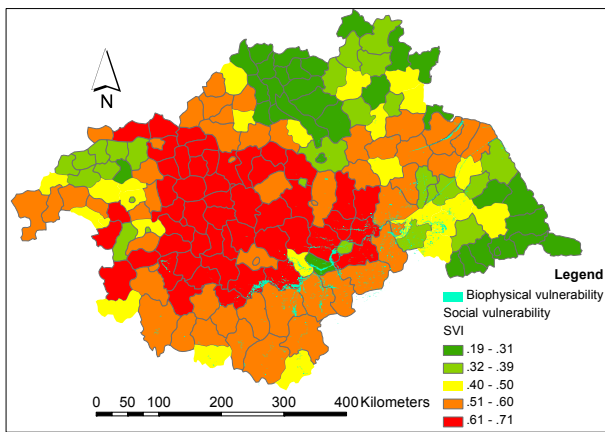


Fig. 7 The distribution of vulnerability to flood hazard in the Huaihe River basin, 2003.

relatively higher. Moreover, social vulnerability index is lower in the eastern part and around Zhengzhou city because the economic activities are more active and institutional preparedness is well, which result in the resilience is stronger. It indicates greater socio-economic differences among political zones in developing country cause spatially heterogeneous. Because of temporal variability of indicator value, the resultant vulnerability index is not static. It is necessary to be updated regularly.

After overlay analysis of social vulnerability and biophysical vulnerability, it is identified that from Bengbu city to the upstream along main trunk of the Huaihe River, the integrated vulnerability to regional flood hazard is much higher (**Fig. 7**). It is helpful to prioritize strategies to reduce regional vulnerability to flooding.

5. CONCLUSIONS

This study proposed a methodology for assessing vulnerability to flood hazard in the Huaihe River basin, China, in which biophysical vulnerability and social vulnerability are considered. The analysis result shows that the proposed method is applicable to regional flood hazard analysis. In terms of quantitative information of vulnerability, the vulnerable area can be identified for basin flood management. However it is important to check the effectiveness of vulnerability index for the decision makers. The objective entropy-based weight determining approach is very significant to vulnerability assessment while a lack of a priori knowledge. The analysis shows that the approach is applicable to better understand the vulnerability.

However in the further study, the sensitivity of assessment model and the integrated approach of social and biophysical vulnerability index should be analyzed in detail.

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