Risk evaluation of China's natural disaster systems: an approach based on triangular fuzzy numbers and stochastic simulation

Ju-Liang Jin · Yi-Ming Wei · Le-Le Zou · Li Liu · Juan Fu

Abstract To deal effectively with the evaluation problem of natural disaster risk system affected by many uncertain factors, a multivariate connection number expression is presented. This expression is based on the index samples and evaluation grade criterions of natural disaster risk system and is capable of describing the hierarchy property and fuzziness of membership relationship between index samples and evaluation grade criterions. In this proposed method, the fuzzy evaluation grade criterion problem is resolved by combining triangular fuzzy numbers with multivariate connection number theory, and triangular fuzzy numbers are used to express the discrepancy degree coefficients of connection number and evaluation index weights. Accordingly, a connection number-based evaluation method for the natural disaster system of China (named CN-TFN for short) is established using triangular fuzzy numbers and stochastic simulation. The application results show that the spatial distribution of natural disaster risk grades of China has the trend of aggrandizement from west to east of China. The economically developed and densely populated coastal areas are very likely to have a high level of natural disaster risk grade or above; thus, these areas are the key regions of the natural disaster risk management of China. The results also show that the CN-TFN is able to reflect practical conditions of the evaluation problem of natural disaster system and to provide more reliability information as compared to the existing evaluation methods. This is as a result of its

J.-L. Jin
Chengdu Institute of Plateau Meteorology, CMA, Chengdu 610072, China

J.-L. Jin · L. Liu · J. Fu
School of Civil Engineering, Hefei University of Technology, Hefei 230009, China

Y.-M. Wei
School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China

Y.-M. Wei (✉)
Center for Energy and Environmental Policy Research, Beijing Institute of Technology,
Beijing 100081, China
e-mail: wei@bit.edu.cn

L.-L. Zou
Institute of Policy and Management, Chinese Academy of Sciences, Beijing 100090, China

comprehensive usage of various information of subjective and objective uncertainties in the evaluation process of natural disaster risk system and its expression by confidence intervals. Due to the simplicity and generalization, the CN-TFM is applicable to comprehensive risk grade evaluation of various natural disaster systems.

1 Introduction

Natural disaster is a typical complex system (Wei et al. 2002; Bruijn et al. 2007), which possesses both complex natural and significant social attributes. Natural disaster risk is the combined result of the natural disaster hazard and vulnerability (Wei et al. 2002; Liu and Dai 2004). Randomness of the intensity and the time of the natural disaster occurrence, the uncertainty of natural disaster loss index, and the scarcity or roughness of subjective or objective data contribute collectively to the uncertainty of natural disaster system. Natural disaster risk evaluation is always the research frontier, and it has important significance in natural disaster comprehensive regionalization and the management of natural disaster risk (Wei et al. 2002; Bruijn et al. 2007; Liu and Dai 2004; Birkmannn 2006; Shang 2000). Due to a large number of random, fuzzy, unascertained uncertainty, there is obvious limitation in conventional uncertainty analysis theory for natural disaster risk system (Wei et al. 2002; Liu and Dai 2004; Shang 2000). However, based on natural disaster risk evaluation index system and its grade criterions, and utilizing intelligent uncertainty analysis theory, qualitative and quantitative meta-synthesis evaluation has become an important development direction. How to deal effectively with the fuzziness of membership relationship between index samples and evaluation grade criterions and how to estimate the uncertainty of the risk evaluation value rationally are current key research difficulties (Chen and Guo 2006; Zhao et al. 2007). Triangular fuzzy numbers are convenient to expressing and processing the random, fuzzy, and insufficient or inexact data, and some other distribution information (Ronald and Robert 1997a; Ronald and Robert 1997b), so it has been applied to risk evaluation (Li et al. 2007). The method of stochastic simulation with triangular fuzzy numbers can overcome the deficiencies that triangular fuzzy numbers operation is not precise enough, and the process is relatively complex and so on (Jin et al. 2008). Based on the above research, this paper put forward using multivariate connection number theory (Zhao 2000, 2007) to construct multivariate connection number expression. This expression was suggested to describe the fuzziness of membership relationship between index samples and evaluation grade criterions. A method of combining triangular fuzzy numbers with multivariate connection number theory was presented to deal with the fuzzy evaluation grade criterions problem, the discrepancy degree coefficients of connection number and evaluation index weights were expressed using triangular fuzzy numbers, and then a connection number-based evaluation method for natural disaster risk system (named CN-TFN for short) was established using stochastic simulation and triangular fuzzy numbers. This model can be used to construct the confidence interval of natural disaster risk evaluation results and to evaluate the natural disaster risk of the provinces, municipalities, and autonomous regions in China.

2 CN-TFN model

Establishment process of CN-TFN includes five steps:

Step 1: According to the disaster-forming environment, types, chains, vulnerability, and other characteristics of regional natural disasters, the natural disaster risk evaluation index system, and their evaluation grade criterions are established based on the principle of systematization and maneuverability (Liu and Dai 2004). The limits of these evaluation criterions indexes are denoted as $\{s_{kj} \mid k = 1 - K + 1, j = 1 - m\}$. For example, the first evaluation criteria interval is $[s_{1j}, s_{2j}]$, the others can be achieved by analogy. Note, the corresponding index sample value as $\{x_{ij} \mid i = 1 - n, j = 1 - m\}$, where K, n, and m are the numbers of evaluation grade criterions, evaluation samples, and evaluation indexes, respectively.

Step 2: To establish set pair H of natural disaster risk evaluation index samples and evaluation grade criterions, the relation structure of identity, discrepancy, and contrary to H and the connection number expression of H is created. The sake of simplicity without losing generality, five interval-valued is considered for the five-level system evaluation problem (the first level is extremely low risk, the second is low risk, the third is medium risk, the fourth is high risk, and the fifth is extremely high risk) (Liu and Dai 2004). In accordance with the hierarchical theory of identity, discrepancy, and contrary system (Zhao 2000, 2007), the identity, discrepancy, and contrary relation structure of the five-level system evaluation problem are established (Fig. 1).

Figure 1 shows (1) The first level represents the relationship between the identity, discrepancy, and contrary to H with three-element connection number, where the relationship between the evaluation index samples and the evaluation grade criterion is divided into three parts. The second level, refining the first one, corresponds with the five-level evaluation criterions (Wu et al. 2009). The third level aims at dealing with the fuzziness of the limit membership adjacent criterions grade of evaluation grade criterions, by further refining the relationship between the identity, discrepancy, and contrary on H to resolve the key issue of excessive particle size of measurement rules (Wu et al. 2009). (2) The evaluated index samples according to the first-grade criterion are divided into the identity, partial discrepancy in identity, partial identity in discrepancy by a certain percentage, respectively. The samples according to the second criterion are divided into partial discrepancy in identity, partial identity in discrepancy, entirety discrepancy by a certain
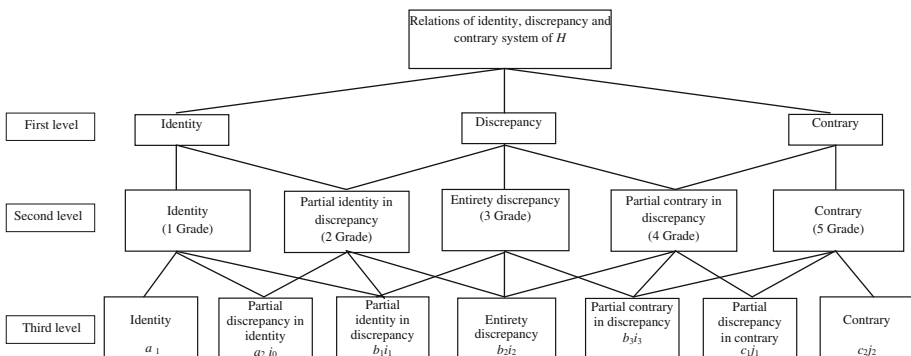
Fig. 1 Hierarchical structure of identity, discrepancy, and contrary relation of set pair for five-grade system evaluation problem

percentage, respectively. The samples according to the third evaluation criterion are divided into partial identity in discrepancy, entirety discrepancy, partial contrary in discrepancy by a certain percentage, respectively. The samples according to the fourth evaluation criterion are divided into entirety discrepancy, partial contrary in discrepancy, partial discrepancy in contrary by a certain percentage, respectively. The samples according to the fifth evaluation criterion are divided into partial contrary in discrepancy, partial discrepancy in contrary, contrary by a certain percentage, respectively. According to the above set pair analysis, seven-element connection number formula of five-grade evaluation problem can be constructed as follows:

$$u_{ij} = a_1 + a_2 i_0 + b_1 i_1 + b_2 i_2 + b_3 i_3 + c_1 j_1 + c_2 j_2 \tag{1}$$

where a_1, a_2, b_1, b_2, b_3, c_1 and c_2 are the identity, partial discrepancy in identity, partial identity in discrepancy, entirety discrepancy, partial contrary in discrepancy, partial discrepancy in contrary, contrary, respectively. The coefficient of partial discrepancy in identity, i_0, is taken as 1. i_1, i_2, i_3 are the coefficients of partial identity in discrepancy, entirety discrepancy, partial contrary in discrepancy, respectively. The triangular fuzzy numbers of $(0.0, 0.5, 1.0)$, $(-0.5, 0.0, 0.5)$, and $(-1.0, -0.5, 0.0)$ can be used to express continuous variation characteristics, respectively (Wu et al. 2009). j_1 and j_2, the coefficients of partial discrepancy in contrary and contrary, are both regarded as –1 (Wu et al. 2009). According to the size relationship between the number of evaluation index samples x_{ij} and the number of evaluation criterions grade limit s_{kj}, the connection number expression of Eq. 1 can be further expanded as follows:

$$
\begin{aligned}
&u_{ij} \\
&= \begin{cases}
0.5(x_{ij} - s_{2j})/(s_{1j} - s_{2j}) + 0.5 + 0.5(s_{1j} - x_{ij})/(s_{1j} - s_{2j})i_1 + 0i_2 + 0i_3 + 0j_1 + 0j_2, & x_{ij} \in 1\text{Grade} \\
0 + 0.5(x_{ij} - s_{3j})/(s_{2j} - s_{3j}) + 0.5i_1 + 0.5(s_{2j} - x_{ij})/(s_{2j} - s_{3j})i_2 + 0i_3 + 0j_1 + 0j_2, & x_{ij} \in 2\text{Grade} \\
0 + 0 + 0.5(x_{ij} - s_{4j})/(s_{3j} - s_{4j})i_1 + 0.5i_2 + 0.5(s_{3j} - x_{ij})/(s_{3j} - s_{4j})i_3 + 0j_1 + 0j_2, & x_{ij} \in 3\text{Grade} \\
0 + 0 + 0i_1 + 0.5(x_{ij} - s_{5j})/(s_{4j} - s_{5j})i_2 + 0.5i_3 + 0.5(s_{4j} - x_{ij})/(s_{4j} - s_{5j})j_1 + 0j_2, & x_{ij} \in 4\text{Grade} \\
0 + 0 + 0i_1 + 0i_2 + 0.5(x_{ij} - s_{6j})/(s_{5j} - s_{6j})i_3 + 0.5j_1 + 0.5(s_{5j} - x_{ij})/(s_{5j} - s_{6j})j_2, & x_{ij} \in 5\text{Grade}
\end{cases}
\end{aligned}
\tag{2}
$$

Step 3: In accordance with weights determination methods such as Delphi process, analytic hierarchy process, information entropy weighted process, projection pursuit, and so on (Jin and Wei 2008), the weight triangular fuzzy number of each evaluation index, (W_{j1}, W_{j2}, W_{j3}), $j = 1 - m$, can be determined.

Step 4: According to the stochastic simulation formula of triangular fuzzy number (a_1, a_2, a_3) (Jin et al. 2008),

$$
x = \begin{cases}
a_1 + [u(a_2 - a_1)(a_3 - a_1)]^{0.5}, & u \leq (a_2 - a_1)/(a_3 - a_1) \\
a_3 - [(1 - u)(a_3 - a_2)(a_3 - a_1)]^{0.5}, & u > (a_2 - a_1)/(a_3 - a_1)
\end{cases}
\tag{3}
$$

a large number of simulated samples series $x_1, x_2, \ldots, x_N$ of likely value variable x are obtained. In Eq. 3, u is uniform distribution random number in interval $[0, 1]$, N is the number of stochastic simulation tests. Eq. 3 is used to simulate the triangular fuzzy numbers of the coefficients of partial identity in discrepancy, entirety discrepancy, partial contrary in discrepancy in Eq. 2, and the triangular fuzzy numbers of the weights of evaluation indexes in step 3, and then to simulate the comprehensive connection number

between the samples i and the evaluation grade criterions, and the comprehensive risk evaluation number of five-grade system evaluation problem can be obtained as follows:

$$y_{il} = \sum_{j=1}^{m} w_{jl} u_{ijl} \tag{4}$$

$$z_{il} = 3 - 2y_{il} \tag{5}$$

where w_{jl} is the weight value of jth index in lth simulation test, u_{ijl} is the connection number of the evaluation index samples x_{ij} and evaluation criterion grades in lth simulation test, y_{il} is the comprehensive connection number between the simulation test samples i and the evaluation criterion grades, z_{il} is the comprehensive risk evaluation number of the evaluation sample i, $j = 1 - m$, $l = 1 - N$, $i = 1 - n$.

Step 5: Let the series of simulation $\{z_{il} \mid l = 1 - N\}$ be in a descending order. According to the mathematical expectation formula of the experience cumulative frequency (Jin 1993):

$$P_l = l/(N+1) \quad (l = 1 - N) \tag{6}$$

the confidence interval of the comprehensive risk evaluation grade number of evaluation sample i under the confidence level α can be constructed as follows:

$$\left[z_{i\mathrm{INT}((1-0.5(1-\alpha))(N+1))}, \, z_{i\mathrm{INT}(0.5(1-\alpha)(N+1))} \right] \tag{7}$$

where P_l is the experience cumulative frequency of z_{il}, whose serial number is l in descending order, INT() is integral function.

3 Case study

Now, we study the application of CN-TFN to natural disaster risk evaluation in each provincial, urban, and autonomous region of China. According to the natural disasters characteristics of each region, the indexes of natural hazard risk, economic vulnerability, and social vulnerability are chosen to construct natural disaster risk evaluation index system of China. The hazard risk index was structured by the risk degree of earthquake, geological, flood, and typhoon, which cause significant loss to human society. The economic vulnerability index was structured by annual average gross domestic product and annual average investment in fixed assets from 1990 to 2001. The social vulnerability index was structured by total number of regional population and regional area in 2001 (Liu and Dai 2004), as shown in Table 1 (Hong Kong and Macao Special Administrative Region and Taiwan Province are not included in because of no data available).

In Table 1, the hazard risk index can be obtained by synthesizing the four hazard degrees of earthquake, geological, flood, and typhoon in each administrative region (Liu and Dai 2004):

$$x_1 = \begin{cases} s/10, & s < 10 \\ 1, & s \geq 10 \end{cases} \tag{8}$$

where $s = z + d + h + t$; z, d, h, and t are the hazard risk degrees of earthquake, geological disaster, flood, and typhoon, respectively.

Table 1 The indexes samples of natural disaster in provinces, cities, and self-governing area of China

Region	Hazard risk degree of natural disaster				Hazard risk x_1	Annual average gross domestic product p (ten million yuan)	Annual average investment in fixed assets q (ten million yuan)	Economic Vulnerability x_2	Total population r (ten thousand people)	Area s (10^4km^2)	Social vulnerability x_3	Result of risk evaluation (grade)	
	Earthquake z	Geology disaster d	Flood h	TyPhoon t								CN-TFN	(Liu and Dai 2004)
Beijing	3	3	2	0	0.8	1,504	783	0.77	1,383	1.68	0.82	[3.66,4.19]	4
Tianjin	3	1	3	2	0.9	989	395	0.72	1,004	1.1	0.91	[3.95,4.41]	5
Hebei	3	2	3	2	0.9	3,035	1,039	0.83	6,699	19	0.35	[3.71,4.25]	4
Shanxi	3	2	1	1	0.6	1,095	336	0.73	3,272	16	0.21	[1.82,2.35]	3
Neimenggu	1	1	1	0	0.3	873	259	0.7	2,377	118	0.02	[1.42,1.83]	1
Liaoning	3	2	2	2	0.8	2,818	849	0.82	4,194	15	0.28	[2.94,3.56]	3
Jilin	1	1	2	1	0.5	1,168	348	0.73	2,691	19	0.14	[1.58,2.06]	2
Heilongjiang	1	1	2	1	0.5	2,084	535	0.79	3,811	45	0.09	[1.67,2.16]	2
Shanghai	1	1	2	2	0.6	2,675	1,320	0.83	1,614	0.6	1	[3.06,3.66]	3
Jiangsu	3	1	3	2	0.9	5,199	1,682	0.88	7,355	10	0.74	[4.40,4.75]	5
Zhejiang	1	2	3	3	0.8	3,571	1,376	0.85	4,613	10	0.46	[3.78,4.32]	4
Anhui	2	1	3	2	0.8	1,954	499	0.78	6,328	14	0.45	[3.58,4.13]	4
Fujian	3	2	3	3	1	2,269	676	0.8	3,440	12	0.29	[3.49,4.03]	4
Jiangxi	1	3	2	2	0.7	1,291	304	0.74	4,186	17	0.25	[2.22,2.80]	3
Shandong	3	1	3	2	0.9	5,156	1,451	0.88	9,041	15	0.6	[4.36,4.72]	4
Henan	2	1	3	1	0.7	3,113	859	0.83	9,555	17	0.56	[3.36,3.93]	3
Hubei	1	3	3	0	0.6	2,595	790	0.81	5,975	19	0.31	[2.38,2.98]	3
Hunan	1	3	3	2	0.8	2,271	1,250	0.82	6,596	21	0.31	[3.13,3.73]	4
Guangdong	2	3	3	3	1	4,993	2,071	0.89	7,783	18	0.42	[4.50,4.84]	5
Guangxi	1	3	2	3	0.8	1,407	389	0.75	4,788	24	0.2	[2.56,3.14]	3

Table 1 The indexes samples of natural disaster in provinces, cities, and self-governing area of China

Region	Hazard risk degree of natural disaster				Hazard risk x_1	Annual average gross domestic product p (ten million yuan)	Annual average investment in fixed assets q (ten million yuan)	Economic Vulnerability x_2	Total population r (ten thousand people)	Area s (10^4km^2)	Social vulnerability x_3	Result of risk evaluation (grade)	
	Earthquake z	Geology disaster d	Flood h	TyPhoon t								CN-TFN	(Liu and Dai 2004)
Hainan	3	2	3	3	1	337	163	0.62	796	3.4	0.23	[2.68,3.25]	4
Chongqing	1	3	2	0	0.5	1,520	533	0.76	3,097	8.24	0.38	[2.54,3.12]	2
Sichuan	3	3	2	0	0.8	2,955	882	0.83	8,640	48	0.18	[2.70,3.32]	3
Guizhou	1	3	1	0	0.5	648	208	0.68	3,799	18	0.21	[1.51,2.02]	2
Yunnan	3	3	1	0	0.7	1,250	421	0.74	4,287	39	0.11	[2.16,2.71]	3
Xizang	3	3	1	0	0.6	69	35	0.46	263	123	0.002	[1.31,1.72]	2
Shanxi	3	3	2	0	0.8	1,051	366	0.73	3,659	21	0.17	[2.50,3.08]	3
Gansu	3	3	1	0	0.6	633	212	0.67	2,575	45	0.06	[1.61,2.12]	2
Qinghai	3	2	1	0	0.5	170	80	0.55	523	72	0.007	[1.14,1.50]	2
Ningxia	3	2	1	0	0.5	171	82	0.55	563	6.6	0.09	[1.18,1.55]	2
Xinjiang	3	2	1	0	0.5	836	345	0.71	4,876	160	0.03	[1.49,1.95]	2

The economic vulnerability index can be obtained by synthesizing annual average gross domestic product p and annual average investment in fixed assets q in each administrative region (Liu and Dai 2004):

$$x_2 = \begin{cases} \ln(p+q)/10, & p+q < 10,000 \\ 1, & p+q \geq 10,000 \end{cases} \qquad (9)$$

In Table 1, p and q are annual average of each administrative region (Chongqing city is from 1998 to 2001, the other regions are from 1990 to 2001).

The social vulnerability index can be obtained by synthesizing the total number of regional population and regional area of each administrative region (Liu and Dai 2004):

$$x_3 = \begin{cases} r/(1,000s), & r/s < 1,000 \\ 1, & r/s \geq 1,000 \end{cases} \qquad (10)$$

where r and s are the total number of population (ten thousand persons) and area (10^4 km^2) of each administrative region, respectively.

The evaluation grade criterions of hazard risk index, economic vulnerability index, and social vulnerability index can be determined by anomaly percentage (Wang et al. 2009):

$$p = \frac{\text{index value} - \text{average value}}{\text{average value}} \times 100\% \qquad (11)$$

where average value is the national average of a certain index. According to Table 1, the risk grades of each index are divided into five grades: $p < -20\%$ corresponding to extremely low-risk grade, $-20\% \leq p < -10\%$ corresponding to low-risk grade, $-10\% \leq p < 10\%$ corresponding to intermediate-risk grade, $10\% \leq p < 20\%$ corresponding to high-risk grade, and $p \geq 20\%$ corresponding to extremely high-risk grade, as shown in Table 2.

Taking account that the role of the hazard risk index is slightly larger, and the role of economic vulnerability and social vulnerability indexes are smaller, the weights triangular fuzzy numbers of the three indexes are taken as (0.3, 0.4, 0.5), (0.2, 0.3, 0.4), and (0.2, 0.3, 0.4), respectively. Through 10,000 times of stochastic simulation, the stable confidence interval of natural disaster risk evaluation grade values is obtained, corresponding to each province, city, and autonomous region of China under the confidence level 95%, as shown in Table 1. For comparative analysis, Table 1 lists the corresponding evaluation grade values of (Liu and Dai 2004).

Table 1 shows that:

1. The evaluation results of the two methods are generally consistent, although some provincial, urban, and autonomous regions have little difference. Taking example for Hainan, the value of hazard risk index is in extremely high-risk grade, the value of

Table 2 Grading criterion of risk evaluation of natural disaster

Grade criterion of risk evaluation	1 Grade extremely low risk	2 Grade low risk	3 Grade intermediate risk	4 Grade high risk	5 Grade extremely high risk
x_1	<0.565	0.565–0.636	0.636–0.777	0.777–0.848	>0.848
x_2	<0.600	0.600–0.675	0.675–0.825	0.825–0.900	>0.900
x_3	<0.255	0.255–0.287	0.287–0.351	0.351–0.382	>0.382

economic vulnerability index is in the low-risk grade, and the value of social vulnerability index is in low-risk grade. The risk evaluation result of Hainan of CN-TFN shows that the risk of natural disaster has 95% possibility in the [2.68, 3.25] grade, but the risk index value 0.66 belongs to high-risk grade in (Liu and Dai 2004) close to the minimum grade of high risk. Thus, the result of the risk evaluation of (Liu and Dai 2004) is a high estimate. The risk evaluation results of Tianjin, Jiangxi, Qinghai, and Ningxia are similar as well.

2. The risk evaluation result of CN-TFN, expressed by confidence interval, provides more information on the reliability of the evaluation results than the result of conventional methods such as (Liu and Dai 2004), and the risk evaluation result of CN-TFN is more consistent with the actual situation. However, the result of conventional methods is just a certain real number and is not able to reflect the objective actual circumstances of natural disaster risk analysis, which is affected by a number of the combined impacts of uncertainties. For example, the natural disaster risk evaluation result of CN-TFN in Jiangsu has 95% possibility in the [4.40, 4.75] grade, representing a very serious situation of natural disaster, while 0.81 of the risk index value belongs to extremely high-risk grade in (Liu and Dai 2004), which is close to the maximum grade of high risk. Shandong and Guangdong are also similar.

3. The spatial distribution of Chinese natural disaster risk grades has gradually aggravation trend from west to east. In coastal areas, the economically developed areas and densely populated areas, natural disaster will lead to heavy casualties and property losses, and in these areas, the natural disaster risk grades have large possibility in high-risk grade and above grade, so they are key areas of Chinese natural disaster risk management.

4. Determining the hazard risk index can have a further consideration to the drought risk index and other factors causing significant loss to human society regularly. And, determining the economic and social vulnerability indexes can have a further consideration to the infrastructure, the quality of the population, and other factors. Therefore, the result of natural disaster risk assessment is more consistent with the actual situation in the studied region.

4 Conclusions

1. Multi-element connection number for expressing the relationship between index samples and evaluation grade criterions of natural disaster risk system was suggested to describe hierarchy property and fuzziness of relationship between index samples and evaluation grade criterions. In the proposed approach, a method of combining triangular fuzzy numbers with multi-element connection number theory was presented to deal with the fuzzy evaluation grade criterions problem, and the discrepancy degree coefficients of connection number and evaluation index weights were expressed using triangular fuzzy numbers. Accordingly, a connection number-based evaluation method for the natural disaster system of China, named CN-TFN for short, was established using stochastic simulation and triangular fuzzy numbers.

2. The spatial distribution of natural disaster risk grades of China has the aggrandizement trend from west to east of China. The natural disaster risk grades of the economically developed and densely populated coastal areas are very likely to have a high-risk grade and above; thus, these areas are the key regions of natural disaster risk management of

China. Various information on subjective and objective uncertainties between index samples and evaluation grade criterions can be comprehensively utilized using CN-TFN, and its comprehensive evaluation results expressed by confidence intervals can provide more reliability information than those of the common evaluation methods only providing a certain real number as evaluation result. CN-TFN is able to reflect practical conditions of the evaluation problem of natural disaster risk system, and the evaluation results of CN-TFN is more consistent with the actual situation. Overall, the concept of CN-TFN is distinct, its result is rigorous, its method is visual, simple, and general. CN-TFN can accord with the actual situation of different grades evaluation criterions and can promote the development of set pair analysis theory and variable fuzzy sets theory. Therefore, CN-TFN has the value of popularization and application in the issue of natural disaster risk assessment where the grades evaluation criterions are known.

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