

Integrated risk assessment of flood disaster based on improved set pair analysis and the variable fuzzy set theory in central Liaoning Province, China

Enliang Guo · Jiquan Zhang · Xuehui Ren · Qi Zhang ·
Zhongyi Sun

Received: 25 March 2014 / Accepted: 5 May 2014 / Published online: 21 May 2014
© Springer Science+Business Media Dordrecht 2014

Abstract This study presents the methodology and procedure for risk assessment of flood disasters in central Liaoning Province, which was supported by geographical information systems (GIS) and technology of natural disaster risk assessment. On the basis of the standard formulation of natural disaster risk and flood disaster risk index, of which weights were developed using combined weights of entropy, the relative membership degree functions of variable fuzzy set (VFS) theory were calculated using improved set pair analysis, while level values were calculated using VFSs, including hazard levels, exposure levels, vulnerability levels and restorability levels, and the flood risk level for each assessment unit was obtained using the natural disaster index method. Consequently, integrated flood risk map was carried out by GIS spatial analysis technique. The results show that the southwestern and central parts of the study area possess higher risk, while the northwestern and southeastern parts possess lower risk. The results got by the assessment model fits the area of historical flood data; this study offer new insights and possibility to carry out an efficient way for flood disaster prevention and mitigation. The study also provides scientific reference in flood risk management for local and national governmental agencies.

Keywords Flood disaster · Risk assessment · Improved set pair analysis · Variable fuzzy set theory · Central Liaoning Province

E. Guo · J. Zhang (✉) · Q. Zhang · Z. Sun
School of Environment, Northeast Normal University, Changchun 130024, People's Republic of China
e-mail: zhangjq022@nenu.edu.cn

X. Ren
School of Urban and Environment, Liaoning Normal University, Dalian 116000,
People's Republic of China

1 Introduction

Flood disaster poses one of the greatest overall and most widely distributed natural risks in highly developed and/or densely populated regions throughout the world. Flood disaster accounts for about a third of all natural disasters in terms of the frequency of occurrence, the fatalities and economic losses (Chang et al. 2009). Moreover, The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reveals that flood disaster and the losses generated by them will continue to grow in frequency and severity in the future (2007). China is one of the countries most afflicted with serious flood disaster in the world (Yang et al. 2013). According to statistical analysis, it is shown that the damage area of flood disasters had reached 9.35×10^4 km² in each year from 1951 to 2000 (Wen and Ding 2008). The study area is located in center of Liaoning Province, which has the highly developed economic and densely population; therefore, the flood disaster will bring the huge impact to the economy once it happened. For example, a flood disaster with serious damage occurred in 1995, during the flooding, some 3.2 million residents have been affected, and at least 100 fatalities have been registered across the affected region. The direct economic loss from weeks of large-scale flooding is estimated at 3.9 billion yuan (Wen et al. 2005). The most affected by the flood disasters were local people's life, infrastructure, agriculture, economic structure, supply and tourist; finally, they restrict the development of local economy. Consequently, it is important to assess the risk of flood disaster in order to make strategies to mitigate flood hazard and reducing the losses from it.

Flood disaster risk assessment is the fundamental procedure for the flood risk management; it is not only the effective decision-making of flood control and mitigation, but also it has been a hot and difficult issue of international studies. Flood disaster risk assessment in the international can be divided into qualitative assessment and quantitative assessment; quantitative assessment assesses a potential risk by means of several well-weighted indicators, and it can be conducted in two ways: the probabilistic risk assessment method (Unami et al. 2010) and the comprehensive risk index method (Zhang et al. 2012). The probability risk assessment method assesses the possible risk level by analyzing quantitative historical data; the presentation is usually selected that many impact factors such as mortality and economic loss. For example, Van Dyck and Willems (2013) develop a probabilistic model to estimate the rate of flood-induced losses for a set of properties distributed over a large geographical region; Li et al. (2013) put forward a composite method based on artificial neural network and information diffusion method for flood analysis, which used the affected area, the number of deaths, collapsing houses and other historical disaster data; Ji et al. (2013) built a classification and regression tree model for the flood risk assessment with the available data of Hunan Province. Comprehensive risk index method usually uses a synthetic value through considering all kinds of indicators to assess the risk level. For example, Stefanidis and Stathis (2013) proposed method factors in order to assess flood hazard, which used the coupling of the analytical hierarchy process and geographical information systems based on either natural or anthropogenic. Zhang et al. (2010) used the natural disasters risk index, based on administrative regions, grids and spatial scale of settlement to assess the risk of storm flood in middle and lower reaches of the second the Songhua River area.

It is well known that flood disaster has a significant seasonality, regional and repeatability characteristics. So it is very important to timely and accurately monitor flood disaster and to assess the flood disaster risk in the flood-prone area. Remote sensing technology has been introduced as a basis method for monitoring floods by analyzing the

flood depth, submerged area. There are a number of international scholars who conducted a series of studies. For example, Taubenböck et al. (2011) have used remotely sensed data for flood risk assessment in urbanized areas; Rakwatin et al. (2013) have been used synthetic aperture radar (SAR) imagery, optical satellite imagery to map the area flooded and to estimate water volume in near real time to support decision-making for flood relief operations. Duan et al. (2012) developed an improved model of regional flood disaster risk assessment based on remote sensing data to assess flood risk.

However, there is an unavoidable fact that the geographic, remote sensing and statistical information used to present risk factors, which have multiplicity, complexity, uncertainty and inaccuracy characteristics. All of them make flood risk assessment into a worldwide problem of multi-principle and multi-level fuzzy synthetically evaluation (Zou et al. 2012). Therefore, uncertainty theory has been introduced into the flood risk assessment by many researchers, for example, Monte Carlo method (Neal et al. 2013; Ruiz-Villanueva et al. 2013), neural networks (Li 2011), fuzzy comprehensive evaluation (Sun et al. 2014), set pair analysis (Su et al. 2013; Song et al. 2013) and variable fuzzy set (VFS) theory (Su et al. 2013). Researchers have achieved some achievements based on those methods. However, all of them are not good at deal with the problem of fuzzy and uncertainty information in the disasters system. For example, the neural network has not greater generalization ability and reliability because it is easy to over convergence during its learning process. Fuzzy comprehensive evaluation cannot well solve the information duplication problem caused by related assessment indices. Variable fuzzy set theory and its computation processes are complicated and tedious, and its establishment of relative membership function depends on physical analysis and expert's instinct or experience according to different problems. Taking into consideration on these disadvantages or deficiencies of the approaches aforementioned, many other theories, methods and evolutionary algorithms are combined for various improvements; meanwhile, this is a trend that connects different advantages of approaches with each other to form new approaches. In the paper, we use improved set pair analysis method to calculate the relative membership degree, in order to counteract the defects of maximum membership degree law of VFSs. The level value is calculated using VFSs to solve the problem of level judgment distortion, and it has the advantages of simple calculation and intuitionist course, clear physical meaning and reasonable results. Therefore, it can be seen as organic combination of the two theories.

The occurrence of flood disasters is due to both natural and human factors. Traditional studies are often limited to the hazard formation or monitoring, whereas economic and management factors of flood disaster risks are less taken into account. Therefore, in this study, flood disaster is regarded as a multiple system with natural, social and economic components. Integrated risk of flood disaster is defined as a composite function of hazard (H), exposure (E), vulnerability (V), and emergency response and recovery capability (abbr. Restorability) (R) based on the standard formulation of natural disaster risk. The study took central Liaoning Province as a case study area based on GIS (geographic information system). The current study was to evaluate risk of flood disaster taking county as a basic unit. In the support of technique of natural disaster risk assessment, entropy combination weighted method, optimal partition method(OPM), improved set pair analysis and the VFS theory, which from the viewpoints of climatology, geography, disaster science and environmental science. The objectives of the study are to (1) establish a conceptual framework of flood disaster risk and the primary risk assessment indicator system; (2) calculate the weights for each indicator by entropy combination weighted method; (3) develop the improved set pair analysis and the VFS theory model, get access to the flood

hazard levels, flood exposure levels, flood vulnerability levels and flood restorability levels for the unit areas; (4) finally obtain the flood risk level for each assessment unit using the natural disaster index method and carry out the integrated flood risk map for flood risk management. The results obtained in this study specifically offer new insights and possibility to carry out an efficient way for flood disaster prevention and mitigation. It also provides scientific reference in flood risk management for local and national governmental agencies as they are responsible in disaster resource allocation, planning decisions and efforts in public education.

2 General description of the study area

A part of Liaoning Province in northeast China situated between $40^{\circ}01'–43^{\circ}29'N$ and $122^{\circ}11'–125^{\circ}46'E$. The central Liaoning Province is one of the important economic zones in Northeast China; it is one of the four famous Chinese urban agglomerations. It is administratively divided into seven cities (Fig. 1), including a sub-provincial city: Shenyang and six prefecture-level cities: Anshan, Fushun, Benxi, Yingkou, Liaoyang and Tieling. Detailed speaking, those cities include 21 counties in the study area. It covers an area of $6.28 \times 10^4 \text{ km}^2$, nearly account for 44 % of total province. And its population is 22.50 million people. The study area is a crossing river with complex underlying surface characteristics and vagaries of weather and climate characteristics. Therefore, flood disaster happened much more frequently with widely range in recent years. Major precipitation occurs in June–September, which accounts for more than 60 % of the total annual rainfall. Because of the distribution of the annual rainfall is considerably uneven both in time and space, the average annual rainfall precipitation is 500–900 mm (Figs. 2, 3). Thus, flood disaster in central Liaoning Province has become one of the most important factors that restrict the development of the social and economic.

Flood disaster is related not only to climatic factors, but also to conditions of the earth's surface such as landform and geomorphology. The eastern is a hilly area, where mostly are low mountains and hills; the central and western are Liaohe alluvial plain, according to the Liaoning Province meteorological disasters ceremony. The total damage area reaches up to $3.99 \times 10^4 \text{ km}^2$, and the total damage area reaches up to $2.76 \times 10^4 \text{ km}^2$ from 1950 to 1990 in central Liaoning Province, they account for more than 67.2 and 67.0 % in Liaoning Province, respectively. In terms of the affected area of those cities, Shenyang accounts for 24.1 % of the total affected area, and it ranks first in the province (Fig. 3).

3 Materials and methods

3.1 Data sources

The meteorological data were obtained from the China Meteorological Data Sharing Service Network during 1960–2009 from 15 meteorological stations, of which five stations are around the central Liaoning Province. Social and economic data were collected from Statistical Yearbook of Liaoning Province (2006–2011) and Chinese macro data mining analysis system website. The LUCC data are provided by Cold and Arid Regions Science Data Center at Lanzhou (<http://westdc.westgis.ac.cn>) and Database of Global Change Parameters, Chinese Academy of Sciences. (<http://globalchange.nsdc.cn>). Digital elevation

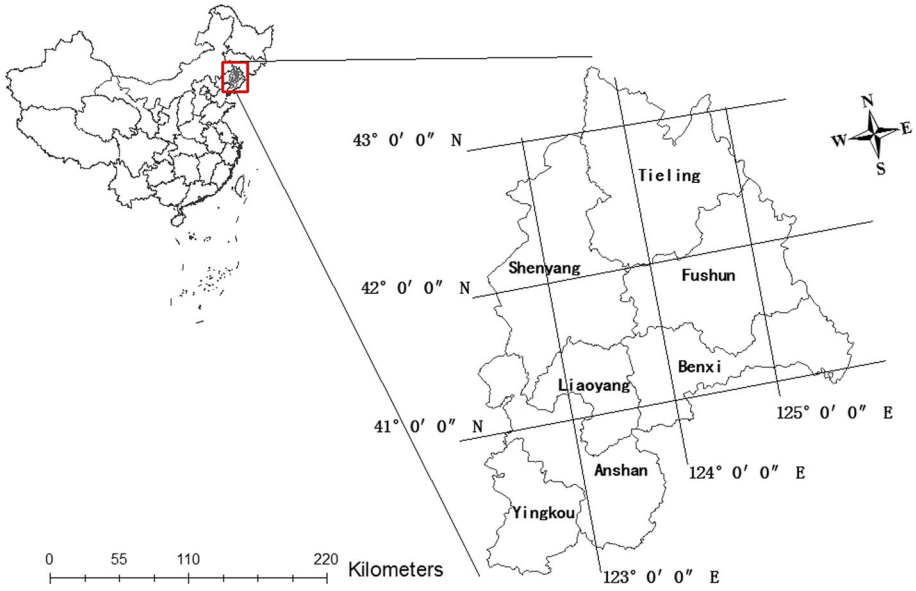


Fig. 1 Diagram of the study area

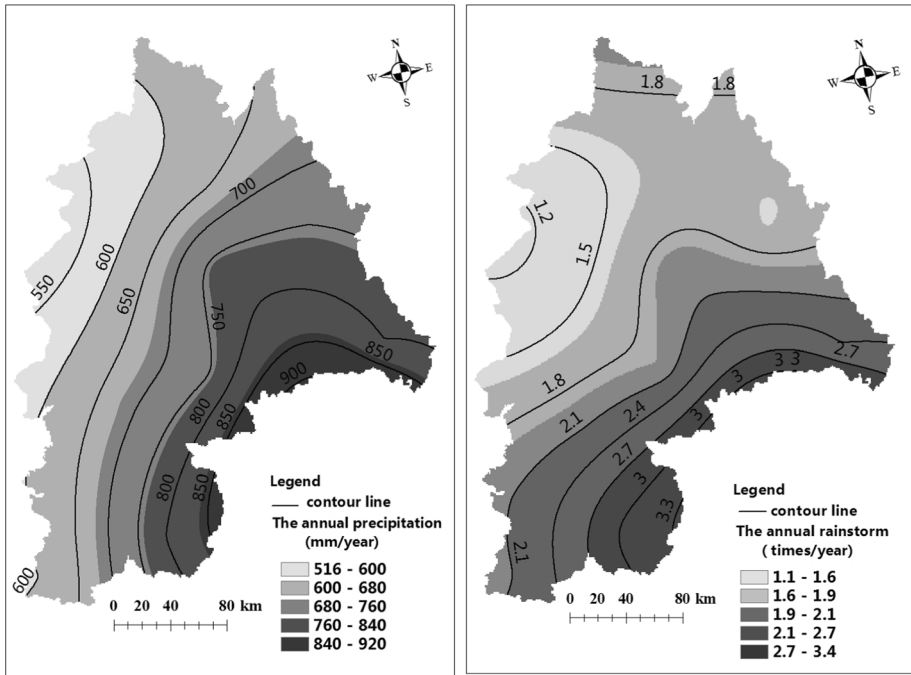


Fig. 2 Annual rainfall and storm frequency spatial distribution in central Liaoning Province

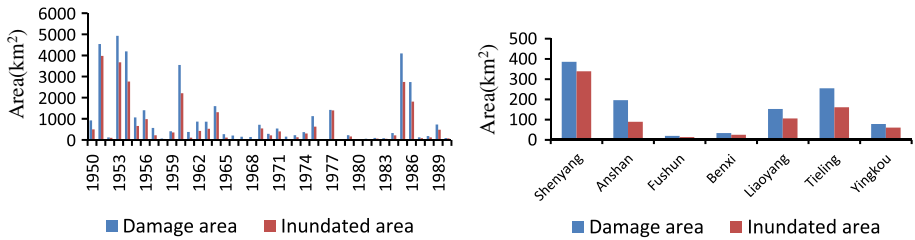


Fig. 3 Damage area and Inundated area from 1950 to 1990 in central Liaoning Province

model data are selected STRM system of digital elevation model data (90 m resolution). The procedure of flood risk assessment in this paper is described in Fig. 4.

3.2 Research methods

3.2.1 The principle of natural disaster risk

Natural disaster means that a natural variable exceeds a certain level and results in some damage to human and social economies; natural disaster risk is defined as the hazard-related potential adverse effects and total economic loss expected in a region as a composite functions of *H*, *E*, *V* and *R*. The natural disaster risk can be expressed as the following:

$$\begin{aligned} \text{Natural disaster risk} &= f(\text{Hazard}; \text{exposure}; \text{vulnerability}; \text{Restorability}) \\ &= H \cap E \cap V \cap R \end{aligned} \tag{1}$$

where *H*, *E*, *V* and *R* are hazard, exposure, vulnerability, and Emergency response and recovery capability (abbr. Restorability), respectively.

3.2.2 Improved set pair analysis

Set pair analysis was proposed by Zhao (Zhao 1989) and applied to many fields such as system engineering, hydrology and multi-attribute assessment. A set pair is formed by putting together the certainty and uncertainty sets. It is depicting the relationship between them from three aspects as identity, discrepant and contrary, which can be given as follows: $\mu_{(A-B)} = a + bi + cj$. This is called the three-element connection degree. However, in practice, this depiction has not been able to meet the requirements of accuracy for many studies; two sets may have more than one kind of discrepancy degree. According to the developability principle of original connection degree, we can obtain five-element connection degree, which can be shown in Eq. (2):

$$\mu_{(A-B)} = a + bi + cj = a + b_1i_1 + b_2i_2 + b_3j_3 + cj \tag{2}$$

where $\mu_{(A-B)}$ is the connection degree of the set pair; *i* is the uncertainty coefficient of discrepancy degree; *j* is the coefficient of the contrary degree; *a*, *b* and *c* are the identical degree, discrepancy degree and contrary degree, respectively; *b*₁, *b*₂ and *b*₃ are the numbers of different kinds of discrepancy characteristics; and $a + b_1 + b_2 + b_3 + c = 1$, $i \in [-1, 1]$, $j = -1$.

There are *m* assessment area, with the property description area of the *n*th indicators, *x*_{*ij*} is the *j*th indicator of the *i*th area ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$). The flood evaluation level is

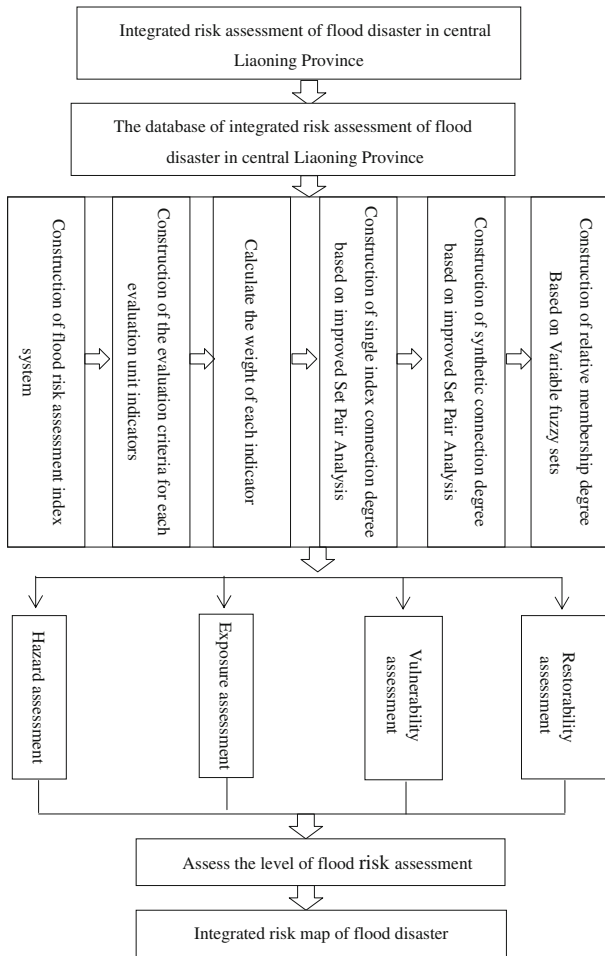


Fig. 4 Flow chart of flood disaster risk assessment

divided into k levels ($k = 1, 2, \dots, k$) in this article to make $k = 5$. The flood evaluation level is made into a set ($A_k = [S_{k1}, \dots, S_{kj}, \dots, S_{kn}]$) and made the indicator values of four flood factors into a set ($B_i = [x_{i1}, \dots, x_{ij}, \dots, x_{in}]$). Then, putting together set A_k and set B_i to form a set pair $H(A_k, B_i)$. Finally, it can calculate the connection degree between the evaluation unit and level of hazard, exposure, vulnerability and restorability, respectively.

When x_{ij} is a negative index, the computational equations of u_{ijk} are as follows:

$$u_{ij1} = \begin{cases} 1, x_{ij} \leq S_{1j} \\ 1 - 2(x_{ij} - S_{1j}) / (S_{2j} - S_{1j}), S_{1j} < x_{ij} \leq S_{2j} \\ -1, x_{ij} > S_{2j} \end{cases} \quad (3)$$

$$u_{ij2} = \begin{cases} 1 - 2(S_{1j} - x_{ij})/S_{1j}, x_{ij} \leq S_{1j} \\ 1, S_{1j} < x_{ij} \leq S_{2j} \\ 1 - 2(x_{ij} - S_{2j})/(S_{3j} - S_{2j}), S_{2j} < x_{ij} \leq S_{3j} \\ -1, x_{ij} > S_{3j} \end{cases} \tag{4}$$

$$u_{ij3} = \begin{cases} -1, x_{ij} \leq S_{1j} \\ 1 - 2(S_{2j} - x_{ij})/(S_{2j} - S_{1j}), S_{1j} < x_{ij} \leq S_{2j} \\ 1, S_{2j} < x_{ij} \leq S_{3j} \\ 1 - 2(x_{ij} - S_{3j})/(S_{4j} - S_{3j}), S_{3j} < x_{ij} \leq S_{4j} \\ -1, x_{ij} > S_{4j} \end{cases} \tag{5}$$

$$u_{ij4} = \begin{cases} -1, x_{ij} \leq S_{2j} \\ 1 - 2(S_{3j} - x_{ij})/(S_{3j} - S_{2j}), S_{2j} < x_{ij} \leq S_{3j} \\ 1, S_{3j} < x_{ij} \leq S_{4j} \\ 1 - 2(x_{ij} - S_{4j})/(S_{5j} - S_{4j}), S_{4j} < x_{ij} \leq S_{5j} \end{cases} \tag{6}$$

$$u_{ij5} = \begin{cases} 1, x_{ij} \leq S_{3j} \\ 1 - 2(S_{4j} - x_{ij})/(S_{4j} - S_{3j}), S_{3j} < x_{ij} \leq S_{4j} \\ -1, S_{4j} < x_{ij} \leq S_{5j} \end{cases} \tag{7}$$

When x_{ij} is a positive index, the corresponding computational equations of u_{ijk} are as follows:

$$u_{ij1} = \begin{cases} 1, x_{ij} \geq S_{1j} \\ 1 - 2(S_{1j} - x_{ij})/(S_{1j} - S_{2j}), S_{1j} > x_{ij} \geq S_{2j} \\ -1, x_{ij} < S_{2j} \end{cases} \tag{8}$$

$$u_{ij2} = \begin{cases} 1 - 2(x_{ij} - S_{1j})/S_{1j}, x_{ij} \geq S_{1j} \\ 1, S_{1j} > x_{ij} \geq S_{2j} \\ 1 - 2(S_{2j} - x_{ij})/(S_{2j} - S_{3j}), S_{2j} > x_{ij} \geq S_{3j} \\ -1, x_{ij} < S_{3j} \end{cases} \tag{9}$$

$$u_{ij3} = \begin{cases} -1, x_{ij} \geq S_{1j} \\ 1 - 2(x_{ij} - S_{2j})/(S_{1j} - S_{2j}), S_{1j} > x_{ij} \geq S_{2j} \\ 1, S_{2j} > x_{ij} \geq S_{3j} \\ 1 - 2(S_{3j} - x_{ij})/(S_{3j} - S_{4j}), S_{3j} > x_{ij} \geq S_{4j} \\ -1, x_{ij} < S_{4j} \end{cases} \tag{10}$$

$$u_{ij4} = \begin{cases} -1, x_{ij} \geq S_{2j} \\ 1 - 2(x_{ij} - S_{3j})/(S_{2j} - S_{3j}), S_{2j} > x_{ij} \geq S_{3j} \\ 1, S_{3j} > x_{ij} \geq S_{4j} \\ 1 - 2(S_{4j} - x_{ij})/(S_{4j} - S_{5j}), S_{4j} > x_{ij} \geq S_{5j} \end{cases} \tag{11}$$

$$u_{ij5} = \begin{cases} 1, x_{ij} \geq S_{3j} \\ 1 - 2(x_{ij} - S_{4j})/(S_{3j} - S_{4j}), S_{3j} > x_{ij} \geq S_{4j} \\ -1, S_{4j} > x_{ij} \geq S_{5j} \end{cases} \tag{12}$$

where $S_{1j} - S_{5j}$ are extremum of the standard from level 1–5. $i = 1, 2, \dots, m$, $j = 1, 2, \dots, n$. u_{ijk} is the single index connection degree that represents the correlation between x_{ij} and the level k ; it can be seen as a ‘‘compact ladder type’’ function structure for make best use of the information of the set pair x_{ij} and s_{kj} .

3.2.3 Variable fuzzy set theory

Fuzzy set theory, which deals with uncertainties information in the system (Zhang and Lu 2009), has become an appropriate method for establishing risk management (Zhang et al. 2009). But it cannot adapt to the requirement of fuzzy hydrology in mathematics. Variable fuzzy set theory, which based on engineering fuzzy set theory, is a new way to ascertain the membership degree and function of a fuzzy subset in the domain of interest. In this paper, after the calculations of u_{ijk} , we can get access to the synthetic connection degree \bar{u}_{ik} using VFS theory:

$$\bar{u}_{ik} = \sum_{i=1}^m w_j \cdot u_{ijk} \tag{13}$$

Obviously, the more indicator x_{ij} differs from the level k , the closer for \bar{u}_{ik} to -1 , and the more impossible the indicator x_{ij} belongs to the level k ; on the contrary, the larger the identity between the indicator x_{ij} and level k , the closer for \bar{u}_{ik} to 1 , and the more impossible the indicator x_{ij} belongs to level k . So it is a type of relative membership degree of the VFS theory. The corresponding relative membership degree \bar{u}_{ik} between the indicator x_{ij} and level k can be calculated as:

$$v_k = (1 + \bar{u}_{ik})/2 \tag{14}$$

$$v'_{ik} = v_{ik} / \sum_{k=1}^k v_{ik} \tag{15}$$

In this way, we can calculate the level of hazard, exposure, vulnerability, and emergency response and recovery capability, respectively. And the level value H can be calculated as:

$$H = \sum_{k=1}^n kv'_{ik} \tag{16}$$

3.2.4 Entropy combination weighted method

The AHP is an appropriate method for deriving the weight assigned to each indicator and has been applied to assessments of natural disasters. It has been tested in handling regional complicated problems of different standards and indices. Entropy weight is a kind of objective weight methods. Entropy combination weighted method using minimum relative entropy principle and by combining entropy weight and AHP can reduce the influence of subjective and objective (Sun et al. 2013).

$$W_j = \frac{\sqrt{W_{1j} * W_{2j}}}{\sum \sqrt{W_{1j} * W_{2j}}} \tag{17}$$

where W_j is the combination weight of j index, W_{1j} is the subjective weight of j index, and W_{2j} is the objective weight of j index.

3.2.5 Optimal partition method (OPM)

OPM was described by Fisher (1958), who described an algorithm for calculating optimal partitions of one-dimensional data sets. The goal of OPM described in the one-dimensional

case is the minimization of the same objective sum of squares distance (Zhang et al. 2014). It was used to partition level standards and the threshold of flood risk level in this study.

4 Risk assessment model of integrated risk of flood disaster

As mentioned earlier, flood disaster is regarded as the multiple systems with natural, social and economic components. It is about water-related potential adverse effects and total economic loss expected in a region which are the composite function of H , E , V and R based on the standard formulation of natural disaster risk (Liu et al. 2011). The multi-attribute risk assessment model of flood disaster was employed on improved set pair analysis and the VFS theory in this study.

4.1 Conceptual framework of integrated risk of flood disaster

Based on the principle of flood formation and the theory of natural disaster risk, a conceptual frame for flood disaster risk was established (Fig. 5). The conceptual framework provides a rationale for the choice of indicators and the way in which they are combined. The four main factors (H , E , V and R) are disaggregated into more specific sub-factors, in order to simplicity, and there is no interaction among the factors were included. Hence, the risk of flood disaster is the result of the combined action of these four factors.

4.2 Establishment of the risk assessment indicator of flood disaster

Based on the analysis of geographical features in central Liaoning Province, and by considering the purpose, comparability, the principle of scientific maneuverable, the indicators were chosen from hazard, exposure, vulnerability and restorability and the risk assessment indicator system of flood disaster was established in central Liaoning Province (Table 1). The entire indicator system is divided into object hierarchy layer, rule hierarchy layer and realm hierarchy layer.

Hazards describe the extreme climatic loadings and severity of threats and harms to society. Therefore, hazard is mainly affected by meteorology and topography, vegetation and hydrology condition. The extreme precipitation is the main cause of flood disaster; richer precipitation may cause flood disaster. The frequency of extreme precipitation event was measured by the 99th percentile method based on the daily precipitation data. Afterward, the frequency of extreme precipitation event was distributed by Kriging interpolation method in space. Finally, the mean frequency of extreme precipitation of each city and county can be calculated by ArcGIS 10.0, which has a function that calculates the average of all cells in the value raster that belong to the same zone. The Dem lower and landform change less, the easier flood disaster appears. Elevation standard deviation was represented landform change. The higher the drainage density the easier flood disaster appears. Vegetation coverage is also important for flood disaster, because they can store water resources to reduce the buffering, hence, vegetation coverage lower, the smaller capacity of buffering, the higher flood hazard is.

Exposure mainly describes social, economic and ecosystem that impacted by flood disaster. The people, architecture and social economy are the main objects affected flood disaster. Population density was selected to describe the life exposure; the assets density and economic density were chosen to describe the socioeconomic exposure. In the areas

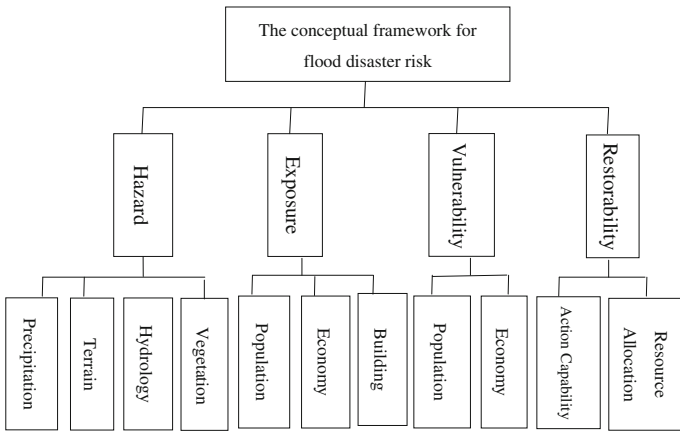


Fig. 5 Conceptual framework of integrated risk of flood disaster

with high population, the assets density and economic density, the potential losses of flood disaster are higher.

Vulnerability describes the extent of damage and losses in population and ecosystems. It represents the degree when the disaster was happened. Life vulnerability describes the individuals and groups more likely to be injured, killed or displaced by flood disaster. Proportion of male and female was selected to represent the life vulnerability degree. He higher education level is, the higher capacity of resist flood disaster, eventually the lower people daily lives were disrupted by flood disasters. Therefore, it is selected to describe industry vulnerability. The affordability of waterlogged farmland is weaker; flood disaster for waterlogged farmland will bring a greater impact.

Restorability describes the capacity of recover from the impacts in a short time period. When disaster happens, the higher density of road network is, the faster relief supplies will be allocated, and the smaller losses will be. The economic resources usually are reflected by GDP per capita. Richer region could quickly reach the pre-disaster area, and it is impossible that the loss of disaster will be reduced. The per capita medical person was selected to describe the capacity of recover from flood disaster.

4.3 Determine the evaluation level standards and indicator weights

There are indicators to determine the thresholds of evaluation standards using OPM. The lower function error is, the best classification is, and *F* value must be passing the *F* reliability test. Figure 6 is shown the error function and *F* test plot. All of them meet the 0.05 reliability test; therefore, in this paper, indicators of flood disaster risk assessment were divided into five levels, respectively. The evaluation level standards are described in Table 2.

Indicator weights were determined by combining entropy weight and AHP, according to the contribution of every factor, they will have a quantitative weight. For AHP, the judgment matrix is built that according to the final cumulative scores and by comparing the total score of every factor. Based on the judgment matrix, we can calculate the weight of the factors and test the consistency using yaahp5.0 software. Stochastic consistency ratio of the judgment matrix is CR = 0.0945, 0.0176, 0.0694 and 0.0519. According to AHP, if

Table 1 Flood risk assessment indicator system

Object hierarchy	Rule hierarchy	Realm hierarchy	Indicator hierarchy	Rule hierarchy	Realm hierarchy	Indicator hierarchy		
Flood risk assessment	Hazard	Precipitation	Annual precipitation (mm/year)	Vulnerability	Population	Proportion of male and female (%)		
			Extreme precipitation event frequency (times/year)			Education level (%)		
			Elevation			Altitude (°)	Economy	Proportion of industrial electricity (%)
			Terrain			Elevation standard deviation (m)		Waterlogged farmland (km ²)
			River network			Drainage density (km/km ²)		
		Vegetation	Vegetation coverage rate (%)					
		Exposure	Population		Population density (people/km ²)	Restorability	Action ability	Density of road network (km/km ²)
			Architecture		The assets density		Resource allocation	The per capita medical person (people)
			Economy		Economy density (thousand yuan/km ²)			The per capita GDP (thousand yuan/people)

Fig. 6 Error function and *F* test plot

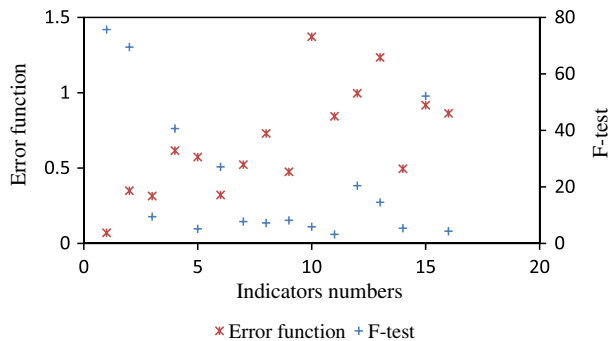


Table 2 Flood disaster risk assessment indicator weights and level standards

Four factors of flood disaster	Level standards	Wight	Level 1	Level 2	Level 3	Level 4	Level 5
Hazard (0.3955)	Annual precipitation	0.1818	(0.615]	(615,696]	(615,748]	(748,800]	(800,850]
	Extreme precipitation event frequency	0.1672	(0.2,771]	(2,773,3,111]	(3,113,3,5]	(3,5,3,95]	(3,95,4,46]
	Altitude	0.0885	[515,480)	[480,350)	[350,200)	[200,77)	[77,0)
	Elevation standard deviation	0.2130	(0,371]	(37,76]	(76,117]	(117,155]	(155,190]
	Drainage density	0.1503	(0,0,071]	(0,07,0,09]	(0,09,0,13]	(0,13,0,23]	(0,23,0,5]
Exposure (0.1745)	Vegetation coverage rate	0.1162	[0,84,0,67)	[0,67,0,44)	[0,44,0,26)	[0,26,0,13)	[0,13,0)
	Population density	0.2907	(0,0,02]	(0,02,0,03]	(0,03,0,06]	(0,06,0,14]	(0,14,0,32]
	The assets density	0.2928	(0,159]	(159,461]	(461,1,274]	(1,274,3,459]	(3,459,9,337]
	Economy density	0.4165	(0,285]	(285,743]	(743,2,093]	(2,093,6,064]	(6,064,1,7750]
	Proportion of male and female	0.2823	[1,06,1,05)	[1,05,1,04)	[1,04,1,03)	[1,04,1,03)	[1,01,0)
Vulnerability (0.2070)	Education level	0.3969	[45,99,39,88)	[39,88,34,55)	[34,55,29,89)	[29,89,25,81)	[25,81,0)
	Proportion of industrial electricity	0.1608	(0,0,40]	(0,40,0,52]	(0,52,0,65]	(0,65,0,79]	(0,79,0,93]
	Waterlogged farmland	0.1600	(0,31,92]	(31,92,80,43]	(80,43,1,71,48]	(1,71,48,342,37]	(42,37,663,111]
	Density of road network	0.1402	(0,0,56]	(0,56,0,60]	(0,60,0,89]	(0,89,2,79]	(2,79,15,34]
	The per capita medical person	0.3990	(0,21,67]	(21,67,27,48]	(27,48,30,71]	(30,71,36,52]	(36,52,46,93]
Restorability (0.2230)	The per capita GDP	0.4607	(0,22,684]	(22,684,27,422]	(27,422,35,549]	(35,549,49,491]	(49,491,73,406]

$CR < 0.10$, the judgment matrix has satisfactory consistency; otherwise, the judgment matrix must be adjusted. Our results indicate that judgment matrix of the flood disaster has a satisfactory consistency. Then, based on Eq. (17), we can determine the indicator weights (Table 2).

4.4 Establishment of the risk assessment model

According to the principles of natural disaster risk formation and the standards of evaluation indicators, the combined weights of entropy are applied to determine weights for each indicator. Improved set pair analysis and the VFSs theory are used to calculate the flood hazard levels, flood exposure levels, flood vulnerability levels and flood restorability levels. Eventually, we constructed flood risk assessment model in central Liaoning Province.

$$FDRA = \frac{H^{w_h} \times E^{w_e} \times V^{w_v}}{1 + R^{w_r}} \quad (18)$$

where w_h , w_e , w_v and w_r are weight of hazard, exposure, vulnerability and restorability, respectively. They mean the relatively important of factors for natural disaster risk.

5 Integrated risk assessment of flood disaster

5.1 The risk assessment of flood disaster in central Liaoning Province

It takes county as the basic assessment unit and supposes each indicator in the county is distributed evenly; we can calculate the average value of the indicators in the county. Then, we can calculate the flood hazard levels, flood exposure levels, flood vulnerability levels and flood restorability levels using improved set pair analysis and VFSs theory. The corresponding evaluation level will be divided into five levels, they are, respectively, defined as very low, low, middle, high and very high. Level standard is described in Table 3.

When assess flood disaster risk, the formation mechanism of flood disaster risks must be followed. With the help of GIS, the choropleth maps of hazard, exposure, vulnerability and restorability are drawn, respectively. The spatial distribution of hazard levels is shown in Fig. 7a. From the region, we know that the major area are above the middle level. More than middle level areas accounted for 67.9 % of the total number of the area. Very high level area is Benxi. Middle and high hazard levels of flood disaster account for 17.9 and 46.4 %, respectively. Very low and low hazard levels of flood disaster are both comprised 28.6 % of the total area. Overall, the spatial structure of flood hazard level in central Liaoning Province is obviously increasing from southeast to northwest. High hazard areas are mainly located in the hilly region of southeast and east, middle hazard areas are mainly located in the southeastern and northeastern regions of hilly region, and low hazard areas are mainly located in the northwest of the alluvial plains.

The spatial distribution of exposure levels is shown in Fig. 7b. High and very high exposure are mainly located in the high economic level and densely populated urban areas, they account for 21.4 and 7.1 % of the total area, respectively. Middle exposure zone accounts for 14.3 %. Very low and low exposure levels of flood disaster account for 39.3 and 17.9 % of the total area, respectively. Overall, the exposure levels of flood disaster are

Table 3 Level standard

Level	I	II	III	IV	V
Level range	[1,2)	[2,2.5)	[2.5,3.5)	[3.5,4)	[4,5)

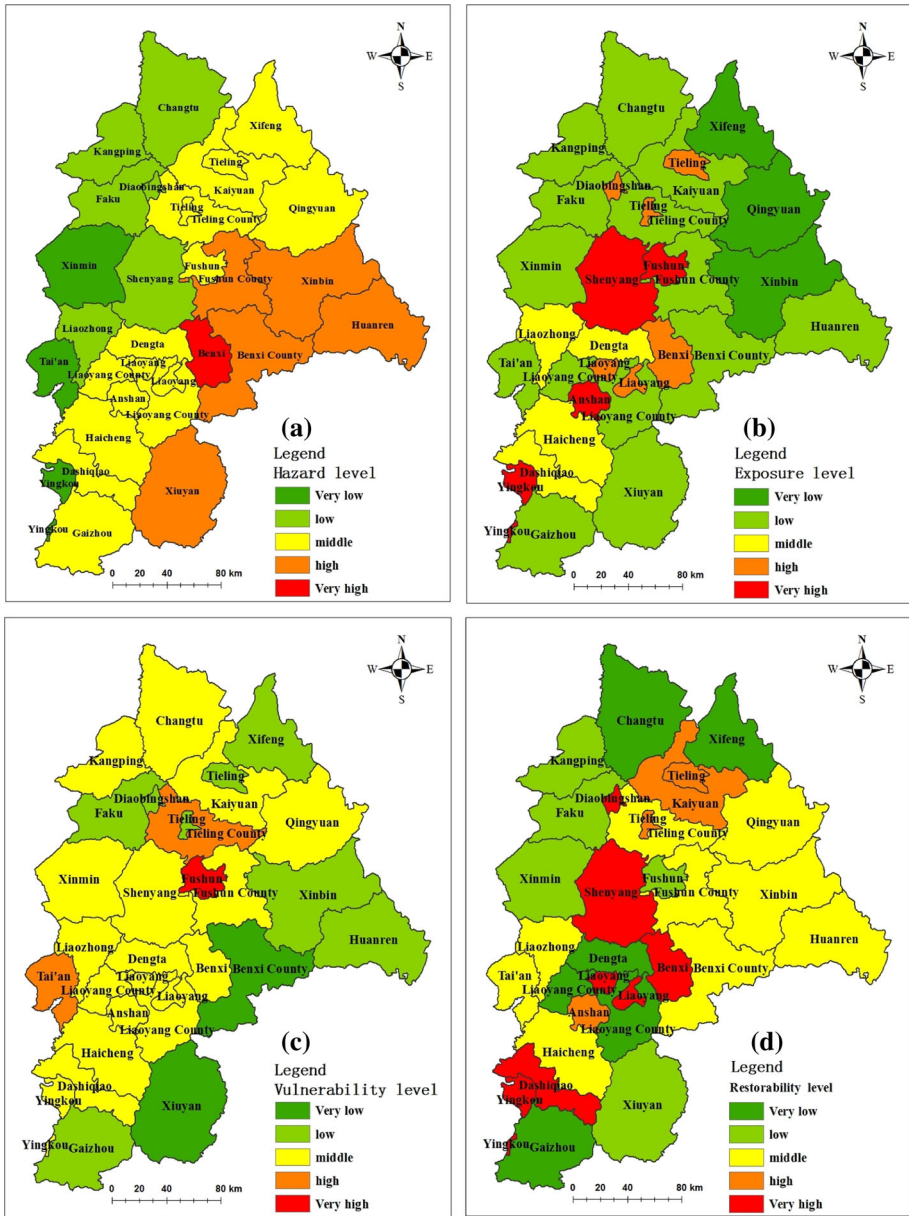


Fig. 7 Maps of hazard level (a), exposure level (b), vulnerability level (c) and restorability level (d) in central Liaoning Province

Table 4 Optimal partition points and F test for FRDA

Item	Variable number (n)	First partition point (T1)	Second Partition point (T2)	Third partition point (T3)	Fourth partition point (T4)	$F(4, n - k - 1)$	$F_{0.05}(4, n - k - 1)$
FRDA	28	0.78	0.9	1.07	1.21	89.973	2.8

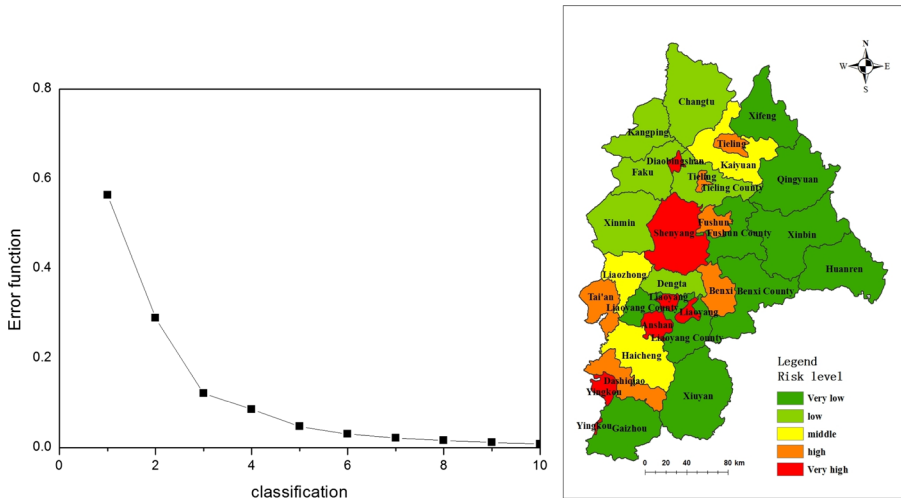


Fig. 8 Map of error function and classification number of optimal partition and flood risk level in central Liaoning Province

obviously increasing from central city area to the surrounding counties on the spatial distribution; however, the zone of very low exposure is mainly in the north and east areas.

The spatial distribution of vulnerability levels is shown in Fig. 7c. There are mainly in the above middle level. Middle vulnerability area accounted 14.3 %. High vulnerability areas only include Tieling, Tieling county and Tai’an. Very high vulnerability area only includes Fushun, whereas the low vulnerability area accounted for 25 % and the very low vulnerability areas include Benxi and Xiuyan. Overall, low vulnerability areas are located in the southeast and northwest, and middle and above middle vulnerability areas are mainly located in the central and northwestern.

Shown in Fig. 7d is the spatial distribution of restorability levels. It can be seen that mainly high restorability areas located in the municipal district and county-level cities in economically developed regions, they are comprised about 32 %. middle and under middle levels areas account for 32 and 36 %, respectively. From the spatial distribution, the high restorability areas located in the central region, the middle restorability areas are mainly located in the eastern and southwestern, and very low and low restorability areas mainly located in southcentral and northern.

After the analysis of each factor on the flood disaster risk in central Liaoning Province, the four factors forming risk are considered together. Then, to calculate eigenvalues of flood disaster risk, the result was classified into the following five levels: very low risk:

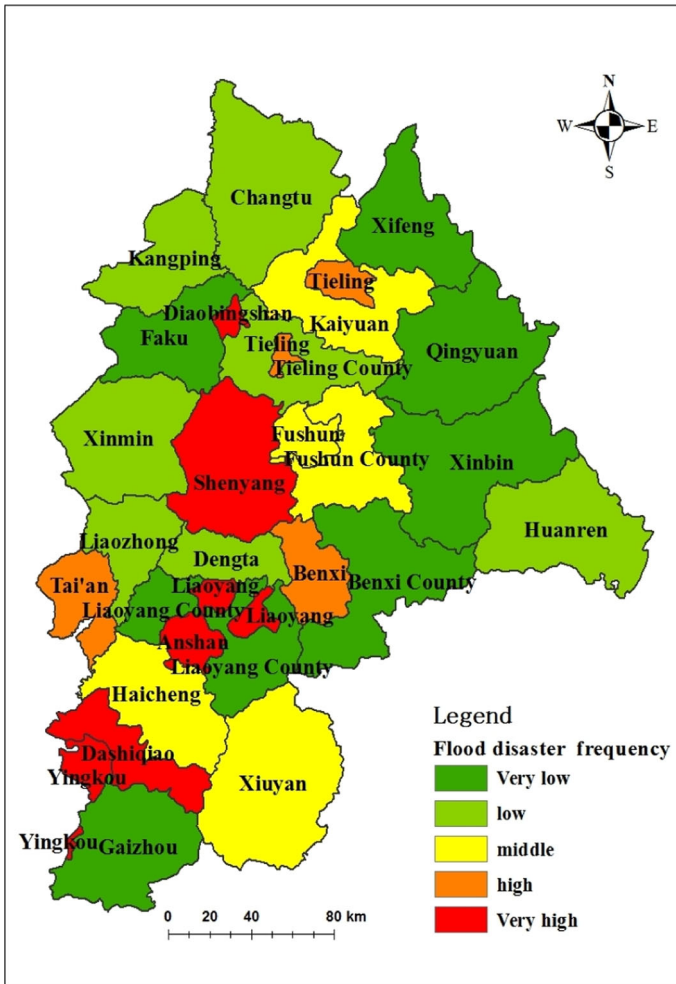


Fig. 9 Frequency of flood disaster happened in central Liaoning Province from 1977 to 2006

FDRA value < 0.78 , low risk: $0.78 \leq$ FDRA value < 0.9 , middle risk: $0.9 \leq$ FDRA value < 1.07 , high risk: $1.07 \leq$ FDRA value < 1.21 and very high risk: $1.21 \leq$ FDRA value < 1.38 . The thresholds of flood level using OPM were based on the characteristics of risk eigenvalues. The result through the 0.05 reliability test is shown in Table 4; therefore, five classifications are the best choice in this research.

Finally, the map of flood risk assessment in central Liaoning Province based on GIS is shown in Fig. 8. The results show that Yingkou, Shenyang, Diaobingshan, Anshan and Fushun belong to the very high risk level. Tieling, Fushun, Benxi. Those cities have high development economic and densely population in this study. Tai'an and Dashiqiao belong to the high risk level. Liaozhong, Haicheng and Kaiyuan belong to the middle risk level. Other areas are under the middle risk level. Overall, the southwestern and central parts of the study area possess higher risk, while the northwestern and southeastern parts possess lower risk.

5.2 Precision verification

In order to verify the applicability of flood risk assessment methods and models that proposed in the study, we calculate the frequency of flood disaster from 1977 to 2006 in central Liaoning Province, which were obtained from China meteorological disasters ceremony (Liaoning volume) and the China Meteorological Disasters Yearbook. The frequency of flood disaster is shown in Fig. 9. Through comparative analysis, we found that this fits the results got by the assessment model. So, this assessment model is reliable.

6 Discussions and conclusions

Flood risk analysis is the fundamental procedure for climate adaptation assessment. To assess the risk level of flood disaster risk, it is necessary to analyze hazards, exposures, vulnerabilities and restorability. However, flood disaster risk as a natural and societal phenomenon is neither precise nor certain. In this paper, we analyze the concept of fuzzy risk in relation to environment and socioeconomic using a new model. This study presents the methodology and procedure for risk assessment of flood disasters in central Liaoning Province. On the basis of the standard formulation of natural disaster risk and integrated risk factors of flood disaster, including hazard, exposure, vulnerability and restorability, combined weights of entropy, improved set pair analysis and the VFS theory. Finally, integrated flood risk maps were carried out by GIS spatial analysis technique. All in all, the results show that the southwestern and central parts of the study area possess higher risk, while the northwestern and southeastern parts possess lower risk in central Liaoning Province. The high risk levels are mainly located in the highly developed economic and densely population areas. Although there is high rainfall and many rainstorms occur in southeastern area, the area is the developing region. The northwestern area not only has less rainfall than other region, but also is the developing region. The computational results demonstrate that the model presented in this study to assess flood disaster risk is reasonable, reliable and applicable. Therefore, the methodology can be applied to the study of other nature disaster risks. The results obtained from this study can intend to support local and national government agencies when they make flood disaster resource allocation, high-level planning decisions, to process the sustainable development, and so on.

Acknowledgments This study was supported by the National Key Technology R&D Program of China under Grant No. 2013BAK05B01, the National Grand Fundamental Research 973 Program of China under Grant No. 2010CB951102, the National Key Technology R&D Program of China under Grant No. 2011BAD32B00-04 and the National Natural Science Foundation of China under Grant No. 41371495. The authors are grateful to the anonymous reviewers for their insightful and helpful comments to improve the manuscript.

References

- Chang HJ, Franczyk J et al (2009) What is responsible for increasing flood risks? The case of Gangwon Province, Korea. *Nat Hazards* 48(3):339–354
- Duan GY, Zhao WJ et al (2012) Improved model of regional flood disaster risk assessment based on remote sensing data. *J Nat Disasters* 21(04):57–61 (in Chinese)
- Fisher WD (1958) On grouping for maximum homogeneity. *J Am Stat As* 53(284):789–798
- Intergovernmental Panel On Change (IPCC) (2007) *Climate change 2007: impacts, adaptation and vulnerability*. Cambridge University Press, London

- Ji Z, Li N et al (2013) Comprehensive assessment of flood risk using the classification and regression tree method. *Stoch Env Res Risk Assess* 27(8):1815–1828
- Li Q (2011) A study on a new method for the analysis of flood risk assessment based on artificial neural network. *Adv Comput Sci Environ Ecoinform Educ Pt 5*(218):262–266
- Li Q, Jiang XW et al (2013) Analysis and modelling of flood risk assessment using information diffusion and artificial neural network. *Water SA*39(5):643–648
- Liu XP, Zhang JQ et al (2011) Grid-based multi-attribute risk assessment of snow disasters in the Grasslands of Xilingol, Inner Mongolia. *Hum Ecol Risk Assess* 17(3SI):712–731
- Neal J, Keef C et al (2013) Probabilistic flood risk mapping including spatial dependence. *Hydrol Process* 27(9SI):1349–1363
- Rakwatin P, Sansena T et al (2013) Using multi-temporal remote-sensing data to estimate 2011 flood area and volume over Chao Phraya River basin, Thailand. *Remote Sens Lett* 4(3):243–250
- Ruiz-Villanueva V, Diez-Herrero A et al (2013) Characterisation of flash floods in small ungauged mountain basins of Central Spain using an integrated approach. *Catena* 110:32–43
- Song ZH, Lai CG et al (2013) Evaluation model of flood risk based on set pair analysis. *Water Resour Power* 31(04):34–37 (in Chinese)
- Stefanidis S, Stathis D (2013) Assessment of flood hazard based on natural and anthropogenic factors using analytic hierarchy process (AHP). *Nat Hazards* 68(2):569–585
- Su H, Qin P et al (2013) A method for evaluating sea dike safety. *Water Resour Manag* 27:5157–5170. doi:10.1007/s11269-013-0459-0
- Sun ZY, Zhang JQ et al (2013) Drought and waterlogging combination disaster risk zoning in Anhui Province based on gridding GIS. *J Catastrophol* 28 (01):74–78+87 (in Chinese)
- Sun Z, Zhang J et al (2014) Integrated risk zoning of drought and waterlogging disasters based on fuzzy comprehensive evaluation in Anhui Province, China. *Nat Hazards* 71(3):1639–1657
- Taubenböck H, Wurm M et al (2011) Flood risks in urbanized areas: multi-sensoral approaches using remotely sensed data for risk assessment. *Nat Hazards Earth Syst Sci* 11(2):431–444
- Unami K, Abagale FK et al (2010) A stochastic differential equation model for assessing drought and flood risks. *Stoch Env Res Risk Assess* 24(5):725–733
- Van Dyck J, Willems P (2013) Probabilistic flood risk assessment over large geographical regions. *Water Resour Res* 49(6):3330–3344
- Wen KG, Li B et al (2005) Chinese meteorological disasters ceremony (Liaoning volume). China Meteorological Press, Beijing (in Chinese)
- Wen KG, Ding YH (2008) Chinese meteorological disasters ceremony (comprehensive volume). China Meteorological Press, Beijing (in Chinese)
- Yang XL, Ding JH et al (2013) Application of a triangular fuzzy AHP approach for flood risk evaluation and response measures analysis. *Nat Hazards* 68(2):657–674
- Zhang G, Lu J (2009) A linguistic intelligent user guide for method selection in multi-objective decision support systems. *Inf Sci* 179(14):2299–2308
- Zhang G, Ma J et al (2009) Emergency management evaluation by a fuzzy multi-criteria group decision support system. *Stoch Env Res Risk Assess* 23(4):517–527
- Zhang JQ, Jiang XY et al (2010) Evaluation of flood disaster risk indicators based on multi-scale multi-space. *J Catastrophol* 25(S1):382 (in Chinese)
- Zhang JQ, Liu XP et al (2012) Introduction of integrated disaster risk management. Peking University Press, Beijing (in Chinese)
- Zhang Q, Zhang J et al (2014) Risk early warning of maize drought disaster in Northwestern Liaoning Province. *Nat Hazards, China*. doi:10.1007/s11069-013-1030-2
- Zhao S (1989) Set pair and set pair analysis—a new concept and systematic analysis method. In: Proceedings of the National conference on system theory and regional planning, pp 87–91 (in Chinese)
- Zou Q, Zhou JZ et al (2012) Flood disaster risk analysis based on variable fuzzy sets theory. *Trans Chin Soc Agric Eng* 05:126–132 (in Chinese)