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Study on Vulnerability Evaluation Method of Lightning Disaster based on Projection Pursuit Dynamic Clustering Model

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Abstract. Vulnerability evaluation of lightning disaster is an important part of lightning disaster research and it is a typical multi-factor comprehensive evaluation problem based on index system. Multi-factor evaluation methods such as hierarchical zoning method, cluster analysis, analytic hierarchy process, principal component analysis and fuzzy evaluation are all applied to the vulnerability evaluation of lightning disaster. However, these methods need to determine the weights of each index artificially in the process of comprehensive evaluation, which leads to the subjective differences of evaluation results. Therefore, a comprehensive evaluation model of lightning disaster vulnerability is established by using projection pursuit dynamic clustering method. The case studies show that the method does not need to be given the weight of each index in advance, but evaluates comprehensively according to the characteristics of the sample data. The results are objective and easy to operate, which provides a new method for the objective evaluation of lightning disasters vulnerability.

Introduction

Lightning disaster is one of the ten most serious natural disasters published by the International Decade for Disaster Reduction (IDNDR) of the United Nations. It is called "a great public hazard in the electronic age" [1]. Lightning is also a common meteorological disaster in China which resulting in fatalities, injures and huge economic losses [2]. According to conservative estimates, the direct economic losses caused by lightning disasters in China amount to hundreds of millions of yuan every year, but the indirect economic losses caused by them are difficult to estimate, and the social impact is becoming more and more serious [3]. The occurrence of disasters is determined by the types of disaster factors, the risk of disaster environment and the vulnerability of disaster bearing bodies [4]. Wisner defined vulnerability as the characteristic of a person or a group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard [5]. Vulnerability is one of the important factors determining the degree of disaster impact [6]. Therefore, based on the characteristics of lightning disaster vulnerability, the comprehensive evaluation index system of lightning disaster vulnerability is constructed, and the objective evaluation of lightning disaster vulnerability can provide a decision basis for reducing the loss and influence of lightning disasters, and it is helpful to take targeted measures for lightning protection and disaster reduction, which is of great social and practical significance.

The comprehensive evaluation of lightning disaster vulnerability has been widely concerned by scholars at home and abroad, and it is a typical complex nonlinear classification problem under the influence of multiple factors. The commonly used methods to solve these problems include expert

scoring, analytic hierarchy process, grey correlation analysis, fuzzy evaluation, artificial neural network and matter-element analysis, etc. For example, Luo et al [7] used the grey correlation method to carry out the regional division of the lightning disaster vulnerability in Chongqing area; Gao et al [8] used cluster analysis method to carry out the risk zoning of lightning disaster vulnerability in Hainan Island; Wu et al [9] carried out the division of lightning disaster vulnerability in Guizhou Province by principal component analysis, and so on. However, the above evaluation methods used in the evaluation of lightning disaster vulnerability need to determine the weight of evaluation indexes according to experience in the evaluation process, and the evaluation results have a certain degree of artificial arbitrariness. Therefore, a new method to evaluate the vulnerability of lightning disasters objectively is urgently needed. In view of the above problems, a comprehensive evaluation of lightning disaster vulnerability based on projection pursuit dynamic clustering theory is proposed for the first time in this paper. This method has no artificial determination of parameters in the whole evaluation process, so the evaluation results are objective and clear, and the method is easy to operate and provides a new method for the comprehensive evaluation of lightning disaster vulnerability.

This paper first introduces the basic principle of the projection pursuit dynamic clustering method and the process of establishing the comprehensive evaluation model of lightning disaster vulnerability, and then through the analysis of two cases, the scientificity and practicality of the model is discussed. Finally, the conclusion is drawn and the prospect is given.

Comprehensive Evaluation Model of Lightning Disaster Vulnerability

Modeling Principle. Projection pursuit model is to project the high dimensional data into the low dimensional space, and by analyzing the projection characteristic of the low dimensional space, the characteristic of high dimensional data are studied [10]. It is a statistical method for dealing with multi-factor and complex problems [11]. Projection pursuit dynamic clustering model is based on the principle of projection pursuit, and the dynamic clustering method is used to construct projection index. Projection pursuit dynamic clustering method has been successfully applied in multi-factor comprehensive evaluation. For example, projection pursuit dynamic clustering method has been applied to analyze climate zoning in reference [12], and satisfactory results have been obtained. In reference [13], a projection pursuit dynamic clustering method was established to solve the problem of regional partition of water resources in China, and so on. The lightning disaster is determined by many factors. The evaluation of lightning disaster vulnerability is not to consider the effect of each factor, but to analyze the interaction between the various factors, so as to get the comprehensive evaluation results reflecting the factors. Therefore, this paper applies projection pursuit dynamic clustering method to the lighting disaster vulnerability evaluation for the first time, and a comprehensive evaluation model is established.

Modeling Process. Assume that the j-th vulnerability evaluation indicator value of the i-th evaluation sample is x_{ij}^{0} (i=1,…, n; j=1,…, m; n is the number of evaluation samples and m is the number of vulnerability evaluation indicators, such as per capita GDP, population density, etc.). The steps of establishing the comprehensive evaluation model of lightning disaster vulnerability are as follows:

Step 1 normalization of evaluation indicators value

Since the dimensions of each indicator are different or the range of values varies greatly, it is necessary to normalize the indicators value before modeling. For an indicator that is bigger and better, the formula is shown in Eq.1,

$$x_{ij} = \frac{x_{ij}^0 - x_{jmax}^0}{x_{jmax}^0 - x_{j\min}^0}. \tag{1}$$

For the smaller and superior indicator, the formula is shown in Eq.2,

$$x_{ij} = \frac{x_{jmax}^0 - x_{ij}^0}{x_{jmax}^0 - x_{j\min}^0}. \tag{2}$$

Where x_{jmax}^0 and $x_{j\min}^0$ represent the maximum and minimum sample values of the j-th vulnerability evaluation indicators, respectively.

Step 2 Linear projection

Linear projection is to observe the data from different angles and find the best projection direction which can fully excavate the characteristic of the data. Suppose $\vec{a}$ is an m-dimensional unit vector, the comprehensive evaluation index reflecting the vulnerability of the i-th sample can be expressed as:

$$z_i = \sum_{j=1}^{m} a_j x_{ij} (i = 1, \mathbf{L}, n). \tag{3}$$

Step 3 Construction of objective function $Q(\vec{a})$

The set of comprehensive evaluation index value sequences of the whole sample is represented as $\Omega = \{z_1, z_2, \mathbf{L}, z_n\}$, and we use dynamic cluster method to divide them into K types. Steps are as follows:

①Randomly select K points to be K nucleation, denoted as $L^0 = \left(A_1^0, A_2^0, \mathbf{L}, A_K^0\right)$;

②Divide points in Ω into K types based on L^0, denoted as $P^0 = \left(P_1^0, P_2^0, \mathbf{L}, P_K^0\right)$;

Among them, $P_i^0 = \left\{z \in \Omega \mid d\left(A_i^0 - z\right) \le d\left(A_j^0 - z\right), \forall j = 1, 2, \mathbf{L}, K, j \ne i\right\}$, and $d\left(A_i^0 - z\right)$ is the absolute distance between point A_i^0 and any point in set Ω.

③Start off by P^0 to calculate new nucleation $L^1, L^1 = \left(A_1^1, A_2^1, \mathbf{L}, A_K^1\right)$;

Among them, $A_i^1 = \frac{1}{n_i} \sum_{z_i \in P_i^0} z_i$, and n_i is the number of sample points in P_i^0.

④ Repeat above steps, and get a sorting result sequence $V^m = \left(L^m, P^m\right)$ (m=1, 2, …),

$D\left(A_i^m, P_i^m\right) = \sum_{z_i \in P_i^m} \left| z_i - A_i^m \right|$, $u_m = \sum_{i=1}^{K} D\left(A_i^m, P_i^m\right)$. Then the algorithm terminal condition is $\frac{u_{m+1} - u_m}{u_{m+1}} < e$, in which e is a small enough allowable value of error. Theories prove that this algorithm is convergent [14].

⑤Define $d(z_i, z_j)$ as any absolute distance between two comprehensive evaluation indexes. And polymerization degrees of samples within the class can be shown as:

$$d(\vec{a}) = \sum_{K=1}^{N} d_h(\vec{a}) \quad . \tag{4}$$

Among them, $d_h(\vec{a}) = \sum_{z_i, z_K \in \Theta_h} s(z_i, z_K)$, and the smaller $d(\vec{a})$ is, the higher the polymerization degrees of samples within the class are.

The discrete degrees between the samples can be expressed by using the degree of intra-class dispersion $s(\vec{a})$ as:

$$s(\vec{a}) = \sum_{i,K \in n; i \neq K} s(z_i, z_K) . \tag{5}$$

The bigger $s(\vec{a})$ is, the higher the discrete degrees between the samples are.

Finally, define objective function $Q(\vec{a})$ as the difference between the degrees of project dispersion and polymerization degrees of samples within the class, i.e. :

$$Q(\vec{a}) = s(\vec{a}) - d(\vec{a}) . \tag{6}$$

The higher the degrees of project dispersion or the smaller the polymerization degrees of samples within the class are, the bigger the objective function $Q(\vec{a})$ is. When $Q(\vec{a})$ becomes maximum, clustering purpose that the samples between the classes are scattered as far as possible and those with the class are centralized as much as possible can be reached.

Step 4 Optimization of projection direction

The analysis shows that the corresponding projection direction is the optimal projection direction when $Q(\vec{a})$ gets the maximum. Therefore, the problem of finding the optimal projection can be transformed into an optimization problem

$$\begin{cases} \max Q(\vec{a}) \\ \|\vec{a}=1\| \end{cases} . \tag{7}$$

Immune evolutionary algorithm can be used to solve the above problem [15]. In this paper, MATLAB software is used to optimize the solution.

Step 5 Comprehensive evaluation

According to the optimized $\vec{a}$, we can calculate the comprehensive evaluation index z_i, which reflects the impact of each evaluation indicator, so as to comprehensively evaluate the vulnerability of lightning disaster.

Case Studies

Comprehensive Evaluation of Lightning Disaster Vulnerability in Sichuan Province. According to the lightning location data of 2005~2012, and the lightning disaster data of 2000~2012 in Sichuan Province, with reference [16], the statistical data of average annual lightning disaster in Sichuan Province is shown in Table 1.

Table 1 The statistical data of average annual lightning disaster in Sichuan Province

City	Per capita GDP [yuan / person]	Population density [person /km^2]	Annual lightning density [frequency/ km^2]	Lightning casualties [person]	Lightning economic loss [ten thousand yuan]	Number of Lightning disaster [frequency]
Chengdu	57624	1181	4.738788	94	4582.60	115
Zigong	32787	678	4.443164	4	1014.30	149
Panzhihua	60391	176	3.978972	20	299.35	19
Luzhou	24317	354	2.785142	12	540.96	68
Deyang	35945	589	4.819839	6	240.90	27
Mianyang	29080	232	3.439179	18	1241.60	50
Guangyuan	18672	158	3.034179	7	86.40	25
Suining	20908	654	6.908440	5	1472.60	44
Neijiang	26341	744	6.330502	7	299.50	37
Leshan	31942	250	4.367641	12	836.50	39
Nanchong	18757	525	4.545774	6	168.73	26
Meishan	26168	424	5.783368	4	539.50	27
Yibin	27865	343	3.349493	20	334.60	28
Guangan	23410	536	2.292284	12	370.30	44
Dazhou	20685	343	2.426584	7	277.40	30
Yaan	26157	102	1.841436	17	739.36	51
Bazhong	11823	276	2.271954	6	330.30	22
Ziyang	27283	449	5.901837	4	170.80	31
Aba Tibetan and Qiang Autonomous Prefecture	22525	11	0.305860	20	112.18	26
Ganzi Tibetan	15753	7	0.299126	74	914.16	66

Autonomous Prefecture						
Liangshan Yi Autonomous Prefecture	24668	76	1.589028	127	852.40	63

Taking per capita GDP, population density, annual lightning density, lightning casualties, lightning economic loss, and number of lightning disasters as evaluation indicators of lightning disaster vulnerability, a comprehensive evaluation model is established and solved with MATLAB software. The greater the comprehensive evaluation index is, the lower the vulnerability of lightning disaster is, and the optimal projection direction is (0.0023, 0.6252, 0.6652, 0.0179, 0.3055, 0.2701). Then the comprehensive evaluation index value is divided into 5 levels, and the numbers 1-5 are used to represent the extremely low, low, middle, high and very high vulnerability areas respectively. The comprehensive index value and the classification results are shown in Table 2.

Table 2 Comprehensive evaluation results of lightning disaster vulnerability in Sichuan Province

City	Comprehensive evaluation index	Comprehensive evaluation index classification results	City	Comprehensive evaluation index	Comprehensive evaluation index classification results
Chengdu	0.3063	5	Meishan	0.8172	4
Zigong	0.7401	4	Yibin	1.1466	3
Panzhihua	1.1979	3	Guangan	1.1494	3
Luzhou	1.1661	3	Dazhou	1.2467	3
Deyang	0.863	4	Yaan	1.4077	2
Mianyang	1.1363	3	Bazhong	1.2944	3
Guangyuan	1.286	3	Ziyang	0.8075	4
Suining	0.507	5	Aba Tibetan and Qiang Autonomous Prefecture	1.6737	2
Neijiang	0.5931	5	Ganzi Tibetan Autonomous Prefecture	1.6051	2
Leshan	1.0513	3	Liangshan Yi Autonomous Prefecture	1.4352	2
Nanchong	0.9174	4			

According to Table 2, it can be seen that Chengdu, Suining and Neijiang are extremely vulnerable areas. Zigong, Deyang, Nanchong, Meishan and Ziyang belong to high vulnerable areas. Due to the large population density and rapid economic development in these areas, severe losses will be caused by lightning disasters. Therefore, in the work of lightning protection and disaster reduction, we should focus on these areas with high vulnerability, and take the targeted measures to reduce the impact of lightning disasters. The results of this evaluation are basically consistent with

the results of the literature [16].

Vulnerability Evaluation of Lightning Disaster in Jilin Province. Refer to literature [17], the density of lightning, the frequency of lightning disaster, the modulus of life loss, and the modulus of economic loss are selected as the evaluation indicators of lightning disaster vulnerability and the value of them is shown in Table 3.

Table 3 the indicator of lightning disaster vulnerability in Jilin Province

City	The density of lightning [frequency/year·km^2]	The frequency of lightning disaster [frequency/year]	The modulus of life loss [person/km^2]	The modulus of economic loss [ten thousand yuan/km^2]
Changchun	3.47	7.2	372	1960
Jilin	3.58	4.9	162	839
Siping	3.2	7.6	240	710
Liaoyuan	3.4	3.2	229	975
Tonghua	3.47	8.7	153	500
Baishan	3.25	7.3	74	311
Songyuan	3.13	5.9	142	674
Baicheng	2.79	3.5	79	206
Yanbian	2.49	2.7	48	132

We use MATLAB software to calculate the comprehensive evaluation index of the lightning disasters vulnerability in each region, and divide the index into 4 levels, which are represented by the number 1-4, representing the low vulnerable areas, the middle vulnerable areas, the high vulnerable areas and the extremely high vulnerable areas. According to the calculation results, the vulnerability regionalization of lightning disaster in various regions of Jilin province is shown in Table 4.

Table 4 vulnerability regionalization of lightning disaster in Jilin Province

City	Comprehensive evaluation index	Comprehensive evaluation index classification results	Classification results in the literature
Changchun	0.1784	4	4
Jilin	0.9125	3	3
Siping	0.7977	3	3
Liaoyuan	1.0065	2	2
Tonghua	0.7563	3	4
Baishan	1.15	2	2
Songyuan	1.1304	2	1
Baicheng	1.7125	1	1
Yanbian	1.9956	1	1

It can be seen form Table 4 that regionalization results obtained from the comprehensive evaluation model of lightning disaster vulnerability is basically the same as those obtained in literature [17]. It shows that it is scientific and feasible to establish projection pursuit dynamic clustering model for comprehensive evaluation of lightning disaster vulnerability.

Conclusion and Discussion

Based on projection pursuit theory and dynamic clustering method, a projection pursuit dynamic clustering model for comprehensive evaluation of lightning disaster vulnerability is established in this paper. The analysis of examples shows that the projection pursuit dynamic clustering evaluation model of the lightning disaster vulnerability can be more objective to determine the influence degree of various factors on the lightning disaster. The evaluation results are scientific and reasonable, and the operation is simple and convenient, which provides a new method for the study of the lightning disaster vulnerability.

On the other hand, the current evaluation indicator system of lightning disaster vulnerability does not conclude the factors of lightning disaster response and management ability. How to incorporate the factors of lightning protection and mitigation measures into the evaluation indicator system of lightning disaster vulnerability, and then reflect the effectiveness of lightning protection measures and provide intelligent scheme for the design of lightning protection and disaster reduction engineering, which will be an important part of lightning disaster vulnerability evaluation research.

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