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Seismic Risk Assessment and Analysis of Influencing Factors in the Sichuan–Yunnan Region

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Abstract: Investigating the distribution characteristics of earthquake disaster risks in the Sichuan–Yunnan region is of great importance for enhancing government emergency response capabilities and achieving sustainable regional development. This study, based on disaster systems theory, constructs a seismic risk evaluation index system for the Sichuan–Yunnan region and employs the entropy method to determine the comprehensive risk index for earthquake disasters across 37 prefecture-level cities. The findings reveal the following: (1) High-risk areas for disaster-causing factors are located in the Hengduan Mountain region and the North–South Mountain Range Valley Region; medium-risk areas are distributed along the northwestern edge of the Sichuan Basin; low-risk areas are situated in the eastern part of the Sichuan Basin and the Yunnan Plateau. (2) High-risk disaster-prone environments are found in the Hengduan Mountain region; medium-risk areas are present on the Yunnan Plateau and the western part of the North–South Mountain Range Valley Region; low-risk areas are in the Sichuan Basin. (3) High-vulnerability areas include the central Sichuan Basin and Kunming on the Yunnan Plateau; medium-vulnerability areas are located in the eastern and western parts of the Sichuan Basin; low-vulnerability areas are in the less developed parts of the Yunnan Plateau, the North–South Mountain Range Valley Region, and the Hengduan Mountain region. (4) High-risk seismic disaster areas are concentrated in the developed regions of the Sichuan Basin and the Yunnan Plateau; medium-risk areas are concentrated in the western part of the North–South Mountain Range Valley Region; low-risk areas are sporadically distributed in the eastern parts of the Sichuan–Yunnan region. (5) The vulnerability of the population, economy, and lifeline systems significantly explain the variation in seismic risk levels, all exceeding 0.70; the synergistic effects of disaster-causing factor danger, disaster-prone environment stability, and disaster-prone environment sensitivity are the most pronounced, with explanatory power exceeding 0.85 after factor interaction.

Keywords: seismic risk; risk assessment; Sichuan–Yunnan region

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1. Introduction

The 2020 Global Risk Report identifies the risks posed by extreme weather events and major natural disasters in the coming decade. With rapid urbanization, populations and economies are swiftly concentrating in urban areas, significantly increasing the vulnerability of disaster-bearing bodies. Once disasters occur, they can easily result in extensive casualties and property losses [1]. Since the beginning of the 21st century, a series of significant disasters have occurred globally, including the 9/11 terrorist attacks in the United States, the 2008 snow disaster in southern China, the 2019 COVID-19 pandemic, and the Great East Japan Earthquake. The diversity, unpredictability, and destructiveness of these disasters have had profound impacts on nations and humanity. Adopting proactive and effective comprehensive disaster risk management, fully understanding the patterns and processes of disasters, preventing losses to cities and humans when disasters occur, and determining effective actions and measures to respond to and manage various emergencies and secondary disasters have become a focal point for scholars worldwide [2,3].

As the "top disasters", earthquakes are characterized by their suddenness, severity, multiple secondary disasters, and their potential to have serious impacts on socio-economic sustainable development. China, although not the country with the most earthquakes, suffers some of the most devastating seismic disasters in the world [4]. Situated between two of the world's major seismic belts—the Pacific Ring of Fire and the Eurasian Seismic Belt—China has a long history of catastrophic earthquakes. Since records began, there have been four mega-earthquakes globally with death tolls exceeding 200,000, three of which occurred in China: the 1556 Shaanxi Huaxian earthquake (Ms8.5) which claimed 830,000 lives, the 1920 Ningxia Haiyuan earthquake (Ms8.6) which resulted in 230,000 deaths, and the 1976 Tangshan earthquake (Ms7.8) which killed 240,000 people. The Sichuan–Yunnan region, in particular, is a hotspot for seismic activity. Since the 20th century, China has experienced 70 earthquakes of magnitude 7.0 or greater, 21 of which occurred in this region, accounting for 30% of the total. These earthquakes have led to significant loss of life and property damage. For instance, the 2008 Wenchuan earthquake (magnitude 8.0) resulted in approximately 374,600 injuries, 87,100 fatalities, and a direct economic loss of CNY 845.1 billion. This event also triggered rare secondary disasters such as collapses, landslides, mudflows, and barrier lakes.

Additionally, the Sichuan–Yunnan region is located in the southwestern part of China. According to the most recent data, the combined year-end permanent population of these two provinces accounts for 9.25% of China's total population, with an average urbanization level below the national average. This region has a large population with a significant proportion of ethnic minorities, generally lower levels of education, and weak disaster self-rescue awareness. Ethnic minority areas often have buildings with poor seismic resistance. In contrast, economically developed areas such as Chengdu and Kunming have high population densities and urban building concentrations, leading to severe localized disaster impacts. Consequently, the overall vulnerability of the Sichuan and Yunnan provinces makes them key focus areas for national earthquake disaster prevention and reduction efforts. Therefore, focusing on the spatiotemporal patterns of seismic disasters in the Sichuan–Yunnan region, predicting future trends, assessing the seismic disaster risk levels and their controlling influencing factors in different areas, integrating regional seismic prevention, mitigation, and disaster relief resources, and effectively formulating regional earthquake emergency response measures are of great practical significance for improving the seismic fortification level of the region and achieving regional sustainable development.

In 2022, the 20th National Congress of Communist Party of China stated the need to enhance the capacity to prevent, mitigate, and respond to disasters and major emergencies, and to strengthen the development of national regional emergency response capabilities [5]. The Sichuan–Yunnan region is a seismic-prone area in China; the accurate identification of seismic disaster risk levels in this region and the determination of key areas for prevention and control are urgently required. Therefore, focusing on the key areas of national policy attention, this study selects the Sichuan–Yunnan region as the research area. Based on regional disaster system theory, the study measures the seismic disaster risk levels in various regions of Sichuan–Yunnan, discusses the influencing factors of seismic disaster risk levels, and aims to provide a scientific basis for decision-making on earthquake disaster risk prevention measures in the Sichuan–Yunnan region, thereby achieving regional sustainable development.

2. Literature Review

The beginning of systematic analyses of the relationship between resource development and natural disasters from the perspective of human behavior can be traced back to Gilbert White's 1945 publication "Human Adjustment to Floods" [6]. In this work, White analyzed the relationship between resource development and natural disasters from the perspective of human behavior and analyzed disaster cases from various countries around the world. In 1978, Burton et al.'s co-authored book *The Environment as Hazard* emphasized that natural disasters are products of the interaction between causative factors and humans [7]. Various human adjustments can be fundamental ways to mitigate disasters. In 1994, Blaikie et al.'s book *At Risk: Natural Hazards, People's Vulnerability, and Disasters* systematically summarized the relationship between regional resource development and natural disasters from the perspective of the comprehensive effects of causative factors, disaster-prone environments, and disaster-bearing bodies [8]. The viewpoints in their work are fundamentally similar to the regional disaster system theory proposed by Chinese scholar Shi Peijun. Shi believes that disasters are a surface variation system of the Earth's surface formed by the joint action of disaster-prone environments, causative factors, disaster-bearing bodies, and disaster situations, and disaster reduction is a social practice of disaster studies [9]. The above works basically cover the core viewpoints of the current international regional disaster system theory. Scholars from various countries have conducted research from different perspectives, aiming to provide a reliable basis for formulating regional disaster reduction strategies and achieving regional sustainable development.

In terms of research perspective, scholars have conducted related studies based on the time points of pre-disaster, during disaster, and post-disaster. Zhang et al. used the Standardized Precipitation Evapotranspiration Index (SPEI) to analyze the temporal and spatial trends in drought occurrence in the inland river basin of Inner Mongolia, providing a theoretical basis for effective drought countermeasures in Inner Mongolia [10]. Wan et al., using urban heavy rainfall disasters as an example, conducted data mining of public opinion big data and found that the timely release of information by the government during disasters is conducive to guiding the public's negative emotions [11]. Xue et al., by developing a structural performance response function for roads, found that if corresponding defensive measures are taken against debris flow, road resilience can be improved to 85.76% [12]. Eleni analyzed the post-disaster epidemic spread paths and influencing factors of developed countries' natural disasters and found that factors such as disease endemicity, environmental factors, health infrastructure, poverty, inequality, and political stability can lead to rapid post-disaster epidemic spread [13]. The aforementioned studies conducted detailed research on the different phases of single-disaster risk management, which is crucial for understanding the characteristics of each phase in a disaster′s evolution. However, sufficient research on the mechanisms that cause disasters before, during, and after they occur is lacking.

In terms of quantitative research, scholars have evaluated the three functions of natural disasters separately. In 1972, Duke first proposed the concept of lifeline systems in the losses caused by the San Fernando earthquake in the United States, indicating that human understanding of disasters has entered a new stage [14]. Tang et al. believe that it is necessary to strengthen the seismic risk assessment of urban pipeline systems (natural gas, water supply, drainage). However, due to the complexity of the pipeline system itself and the differences in the fields involved, research on this content has always been difficult [15,16]. Liu analyzed the spatial changes in seismic disaster house vulnerability in rural areas of Baoji through a spatial data analysis using ArcGIS (version 10.6) [17]. Wang et al. investigated the seismic hazard in the middle segment of Tanlu Fault Zone based on the seismic tectonic environment, deep-seated tectonic background, long-term sliding characteristics of active faults, and historical and modern seismic activities [18]. The studies analyzed the three functional systems of earthquake disaster risks. The significance of this research in evaluating the earthquake disaster risks in the Sichuan–Yunnan region lies in the provision of a decision-making basis for disaster risk management. Disaster risk management is a dynamic process that includes disaster prevention and mitigation before the event, emergency response during the disaster, and recovery and reconstruction afterward. Therefore, this study opts for a comprehensive evaluation approach, analyzing disaster risks across all stages.

In the research process, scholars have applied various methods in disaster risk research. Erkan, based on interval type-2 fuzzy sets, comprehensively considered factors such as distribution center capacity, available distribution logistics personnel, and available electricity to formulate site selection criteria for post-disaster rescue sites for landslides and flood disasters [19]. Martinez et al. evaluated the vulnerability of housing's seismic capacity during earthquakes using a dual-probability model [20]. Li et al. used the DEFNODE model to invert the negative fault rate of the GPS horizontal velocity field data in the middle segment of Honghe Fault Zone from 2009 to 2015 and calculated that the sliding loss rate in the middle segment of Honghe Fault Zone is relatively high, the stability of the seismic disaster-prone environment is poor, and the risk of a major earthquake is relatively high [21]. Ruggieri, based on a mechanical analysis and using Bisceglie city in Southern Italy's Puglia region as a case study, assessed the vulnerability of urban reinforced-concrete buildings. This approach, aimed at enhancing the resilience of urban structures, provides a theoretical basis for reducing losses in urban areas from earthquake risks [22,23]. The results of this quantitative method are of typical significance and offer a scientific basis for analyzing earthquake disaster risks from a geomechanical perspective. Due to the arrangement of experimental sites and the operability of data acquisition, this method is more suitable for small-scale studies such as fault injection zones, while its feasibility for medium-scale studies at the provincial level is poor.

In summary, starting with the three functional systems of natural disasters, selecting appropriate evaluation indicators, and combining quantitative methods such as the entropy method and weighted evaluation method is more suitable for managing the entire process of natural disaster risk prevention. Scholars have already applied these methods in different types of disasters. Du et al. used the Chinese Natural Disaster Database to calculate the risk levels of major natural disasters in China's main cities under the combined effects of disasters such as floods, earthquakes, landslides, mudflows, and dust storms, and compiled a map of urban disaster risk levels in China [24]. Sun et al. considered the disaster-prone environment, vulnerable disaster-bearing bodies, and disaster-causing factors together, constructing a multi-spatial coupling model for disaster risk evaluation in the central urban area of Nanyang [25]. Li et al. calculated the earthquake economic–social wealth loss risk values of 245 countries, and the results showed that the spatial distribution pattern of high-risk areas of economic–social wealth loss is basically consistent with global fault zones, but the impacts of disaster-bearing bodies in local areas is significant [26]. Given these rich case studies, this research chooses to base itself on the theory of natural disaster systems and, considering regional characteristics, selects an appropriate set of evaluation indicators to assess earthquake disaster risks in the Sichuan–Yunnan region.

Seismic disaster risk assessment has always been a focus of scientists in various countries. Chaulagain et al. determined the risk of earthquakes occurring with probabilities of 1%, 2%, 5%, and 10%, and the average economic losses in Nepal in the next 50 years, based on earthquake catalogs and economic data [27]. Dolce et al. evaluated the earthquake risk levels of different cities in Italy based on the earthquake disaster risk assessment process developed by Italian National Risk Assessment Center [28]. Chinese scientists compiled four generations of seismic zoning maps, namely the first-generation seismic zoning map based mainly on qualitative methods [29], the second-generation "Chinese Seismic Intensity Zoning" [30], the-third generation "Chinese Seismic Intensity Zoning (1990)" mainly based on the probabilistic description method [31], and the fourth-generation "China Seismic Parameter Zoning Map (2001)" [32].

Seismic disaster risk assessment is one of the hot topics in disaster research. The core of this research is to identify high-risk areas, accurately judge the trend in seismic disasters, accurately divide regional seismic disaster risk levels, determine key areas for prevention and control, provide a basis for formulating disaster risk prevention measures, and achieve regional sustainable development. Specifically, the study of seismic hazards in the Sichuan–Yunnan region has always been a focal point among researchers. Zhang conducted a comparative analysis of the relationship between seismic activity in the Xianshuihe fault zone in Sichuan based on the concept of the fault activity coordination ratio, emphasizing that anomalies in the coordination ratio might be a precursor to major earthquakes in Sichuan [33]. Chen analyzed changes in apparent stress and the b-value within the rupture zone prior to the Ms6.0 Changning earthquake in Sichuan in 2019, finding a significant increase in tectonic stress before the earthquake [34]. Tian used data from 181 earthquake sequences between 1965 and 2012 in the Yunnan region, applying methods like the b-value intercept, the largest aftershock method, and the mainshock magnitude estimation to find that the strongest aftershocks in Yunnan occurred within three days following the mainshock in as much as 60% of cases [35]. Li used data from the initial P-waves of the mainshock and aftershocks of three major earthquakes in Yunnan in 2014 to validate and study the applicability of the rapid earthquake magnitude estimation model used in Sichuan, showing that the parameters of the maximum outstanding period (τmaxp), characteristic period (τc), and maximum displacement amplitude (Pd) can effectively estimate magnitudes in a short time [36]. These studies help us understand the crustal tectonic movements in the Sichuan–Yunnan region following earthquakes. However, a review of the existing research shows that on the one hand, the research focus is mostly on the activity or hazard assessment of a certain fault zone, and there are relatively few studies at the scale of prefecture-level cities, let alone studies at the scale of geographical units, while on the other hand, the existing empirical research focuses on evaluating the consequences of a certain disaster, while research on the influencing factors of post-disaster effects is relatively scarce.

To address these issues, this study takes the Sichuan–Yunnan region as the research object, develops a seismic disaster risk assessment index system for the Sichuan–Yunnan region based on the natural disaster system theory, uses geographic detectors to calculate the impact of index factors, explores its spatial differentiation pattern and causation mechanism, and aims to provide a theoretical basis and scientific support for formulating reliable disaster reduction policies in the Sichuan–Yunnan region and achieving regional sustainable development.

3. Overview of Study Area and Data Sources

3.1. Overview of Study Area

This study focuses on the Sichuan–Yunnan region, which includes the provinces of Sichuan and Yunnan (Figure 1). In terms of natural environment, the Sichuan–Yunnan region is located in the transitional zone between the first-tier Qinghai–Tibet Plateau and the second-tier Yangtze River middle and lower plain in China's natural geographical division. It features a complex terrain with undulating topography, presenting a general northwest high and southeast low characteristic. The region has a diverse and complex climate, making it sensitive to climate change [37]. It is prone to extreme weather events such as heavy rainfall and drought. Additionally, geological disasters such as landslides and debris flows triggered by earthquakes exacerbate the disaster effects.

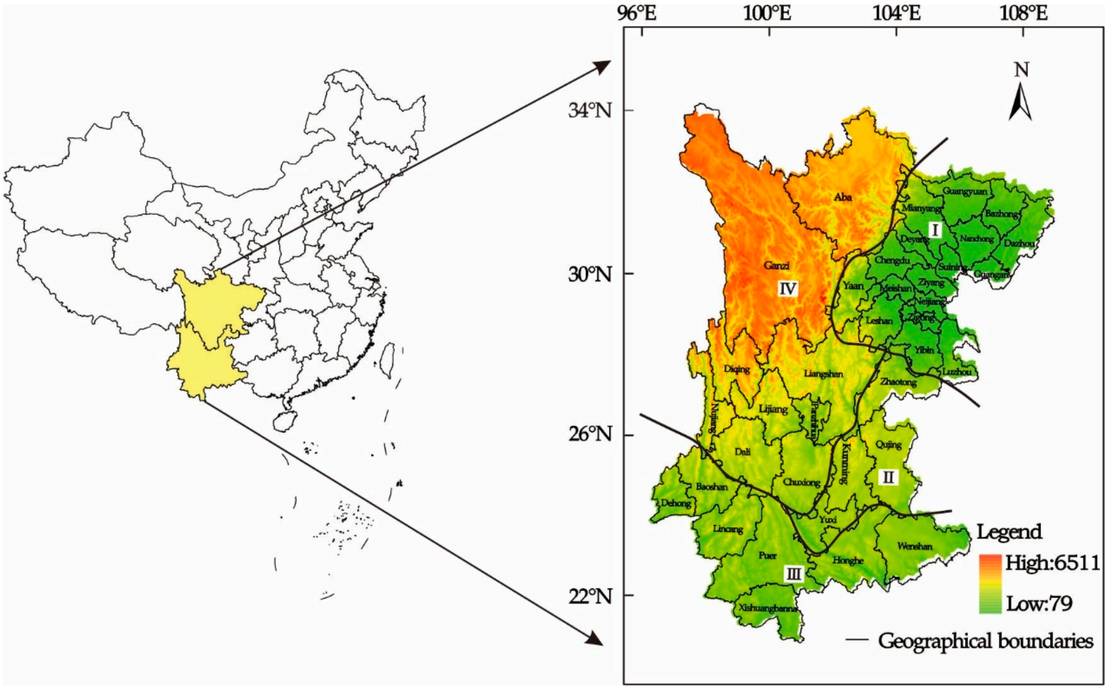

Figure 1. Overview map of study area in the Sichuan–Yunnan region.

In terms of geological structure, the region is significantly affected by the collision and compression between the Eurasian Plate and the Indian Plate. It is also constrained by the uplift of the Qinghai–Tibet Plateau and tectonic movements, resulting in complex geological structures and stress field characteristics. This area is the most frequent and severe region in China for seismic incubation, occurrence, and seismic activity [38]. Major earthquakes such as the Wenchuan 8.0 earthquake in 2008 and the Jiuzhaigou earthquake in 2017 occurred in this region.

In terms of socio-economic factors, the Sichuan–Yunnan region is located in the southwestern border of China with a long border. It covers a total land area of 897,100 square kilometers and consists of 37 prefecture-level administrative divisions, including 26 prefecture-level cities and 11 autonomous prefectures. The proportion of ethnic minorities is relatively high, and the education level of residents varies. The awareness of disaster prevention and mitigation is weak, and the self-rescue capability is relatively poor. There are significant differences in urbanization levels between regions. When struck by earthquakes, extensive casualties and property losses are prone to occur due to building collapses and secondary geological disasters such as landslides and debris flows. Overall, the vulnerability of disaster-bearing bodies is relatively high.

To better assess the seismic disaster risk in Sichuan–Yunnan region, this study divides the region into four geographical areas based on natural geographical environments: Sichuan Basin Area (I), Yunnan Plateau Area (II), North–South Mountain Range Valley Area (III), and Hengduan Mountain Area (IV).

3.2. Development of Index System

The theory of disaster systems was proposed by Shi in 1991. According to the theory, a disaster system is a complex surface variation system of the Earth, which is an important part of the Earth's surface system [39,40]. The purpose of studying a disaster system is to understand the formation process and dynamic mechanism of disaster occurrence and development. The pregnant disaster environment, causative factors, and disaster-bearing bodies constitute the structural system of the regional disaster system [41], and the disaster situation is the result of the interaction of various subsystems in the regional disaster system [39]. Based on the theory of disaster systems, 24 indicators were selected from the three subsystems of causative factors, pregnant disaster environment, and disaster-bearing bodies to evaluate the seismic disaster risk level in the Sichuan–Yunnan region (Figure 2).

Disaster-causing factors are the variables in a disaster-prone environment that can lead to casualties, property damage, and social disorder, and they represent the sources of risk for disasters. This study focuses on earthquake hazards and uses the commensurability trend coefficient and the frequency of earthquakes with a magnitude of Ms $\geq$ 5.0 to assess the danger posed by these disaster-causing factors. The commensurability trend coefficient is a negative indicator determined by commensurability theory, with the specific calculation process detailed in reference [42]. A smaller coefficient value indicates that an earthquake in the fault zone is likely to occur sooner, implying a higher risk from the disaster-causing factor, and vice versa. Earthquake frequency data, derived from the China Seismic Network, have been collected since 1900 for 37 prefecture-level cities in the Sichuan–Yunnan area, with higher frequencies indicating greater danger from disaster-causing factors and lower frequencies indicating lesser danger.

The stability and sensitivity of the disaster-prone environment are significantly influenced by natural geographical factors. Considering the dynamics of earthquake occurrence and the triggers for secondary disasters like landslides and mudflows [43], this study selected the b-value and peak ground acceleration (PGA) as indicators to assess the stability of the disaster-prone environment, and slope, fault zone density, and lithology as indicators to evaluate its sensitivity. The b-value reflects the stress state of the seismic medium and is an important marker of regional seismic activity [44]. The PGA, used to determine regional intensity levels, was chosen based on a Type II site with a 10% probability of exceedance over 50 years [45]. Slope is a primary factor in inducing earthquake-triggered landslides; in the Sichuan–Yunnan area, the highest rate of earthquake-induced landslides occurs when the slope exceeds 25.0° [46,47]. This study used 30 m resolution DEM raster data from the Sichuan–Yunnan region and generated slope data through spatial analysis in ArcGIS (version 10.6), measuring the proportion of land within the dominant slope range for earthquake landslides in each prefecture-level city to assess their sensitivity to secondary disaster-inducing environments. Fault zone density determines the likelihood of earthquakes occurring in a region. By counting the number of fault zones in each prefecture-level city, it is understood that higher fault zone densities make the environment more sensitive and increase the risk of earthquakes. Lithology, an inherent factor fostering earthquake-induced landslides, determines the deformation and failure characteristics of the landslide mass with data obtained from China's 1:2.5 million digital geological map spatial database [48].

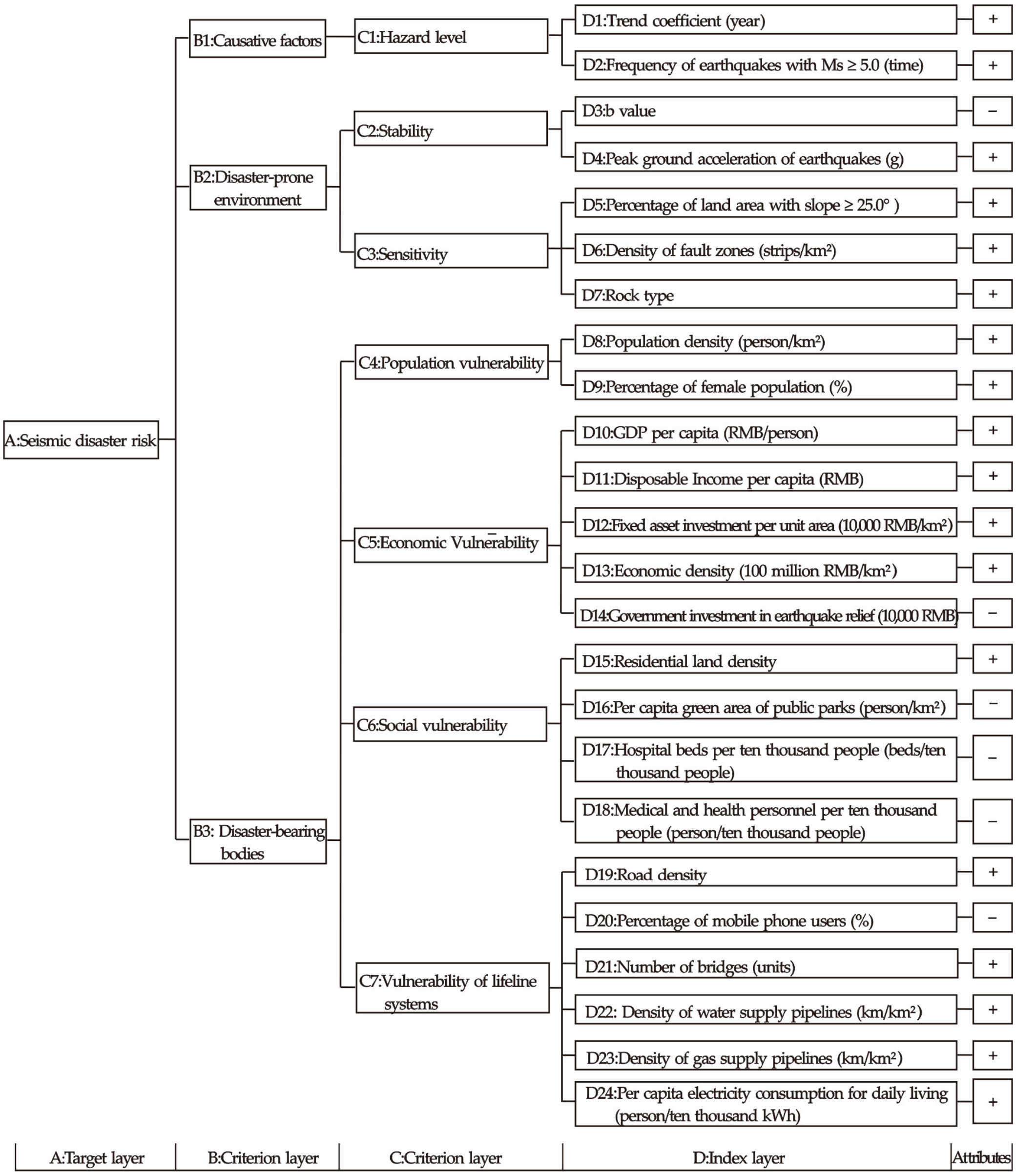

Figure 2. Index system for seismic disaster risk assessment in the Sichuan–Yunnan region.

Disaster-bearing bodies refer to the targets affected by earthquake disasters, including humans themselves, and the conditions that support human productive activities, such as buildings, lifeline systems, and various resources. The vulnerability of disaster-bearing bodies refers to the extent and degree of the loss caused by earthquake disasters within the affected area, under the combined influence of urban physical properties. This study evaluates vulnerability from four aspects: population, economic, social, and lifeline infrastructure. Seventeen indicators were selected for assessment, including population density, percentage of female population, GDP per capita, disposable income per capita, fixed asset investment per unit area, economic density, government investment in earthquake disaster relief, residential land density, per capita park and green space area, hospital beds per 10,000 people, medical staff per 10,000 people, road density, mobile phone user ratio, number of bridges, water pipeline density, gas pipeline density, and per capita domestic electricity use.

3.3. Data Sources

The causative factor and pregnant disaster environment indicators focus on measuring the natural environmental conditions of the Sichuan–Yunnan region, with relatively stable attributes. Therefore, multi-year averages were selected for the study. The disaster-bearing body indicators focus on measuring the level of socioeconomic development, with the data being heavily impacted by national five-year plans. Therefore, the years 2005, 2010 and 2015, which mark the end of the "Tenth Five-Year Plan", "Eleventh Five-Year Plan", and "Twelfth Five-Year Plan", respectively, were chosen as time nodes for evaluating the seismic disaster risk in the Sichuan–Yunnan region.

Earthquake data were obtained from the internal network earthquake catalog of the China Earthquake Administration. Peak ground acceleration data were obtained from the "China Seismic Intensity Zonation Map". The b value was derived from the Gutenberg–Richter seismic recurrence relationship using the maximum likelihood method. In the calculation process, a minimum grid unit of $0.10^\circ \times 0.10^\circ$, a circular radius of 30 km, and a seismicity sliding step of 0.10 km were set. Spatial interpolation was performed on all grid b value data [49]. Slope data were acquired from 30 m resolution Digital Elevation Model (DEM) data of Sichuan and Yunnan obtained from the Geographic Spatial Data Cloud platform, and were extracted using 3D analysis tools in ArcGIS. Rock type data were sourced from the national 1:2,500,000 digital geological map spatial database. Land use type data (e.g., residential land area, park green area) were obtained from Landsat remote sensing images with a 30 m grid resolution provided by the International Scientific Data Service Platform.

Social statistics data were obtained from the "Sichuan Statistical Yearbook" [50–53], "Sichuan Health Statistical Yearbook" [54–56], "Sichuan Electric Power Yearbook" [57–60], "Yunnan Statistical Yearbook" [61–64], and "Yunnan Health Yearbook" [65]. Data for minority ethnic areas were sourced from the "China's Ethnic Yearbook" [66–69], while a certain proportion of missing data were collected from national economic and social development bulletins of various prefectures and cities.

4. Research Method

4.1. Information Entropy

Information entropy was used to determine the weights of each evaluation indicator. This method, proposed by Shannon in 1948, addresses the measurement problem of information quantity and is one of the main methods of objective weighting [70]. It determines the impact level of each indicator's variation on the overall disaster system, calculates the weights of the indicators, and reduces biases caused by subjective factors. The calculation steps are outlined as follows:

Step 1: Normalize the jth evaluation indicators X_{ij} of the ith city in Sichuan–Yunnan region.

Positive indicators:

$$X_{ij} = \frac{(x_{ij} - minx_{ij})}{(maxx_{ij} - minx_{ij})}$$

Negative indicators:

$$X_{ij} = \frac{(maxx_{ij} - x_{ij})}{(maxx_{ij} - minx_{ij})}$$

Step 2: Calculate the proportion Y_{ij} of the jth evaluation indicator values for the ith city in the Sichuan–Yunnan region:

$$Y_{ij} = \frac{X_{ij}}{\sum\limits_{i=1}^{m} X_{ij}} (0 \le y_{ij} \le 1)$$

Step 3: Calculate the entropy value E_j of the jth evaluation indicator for seismic disaster risk in the Sichuan–Yunnan region:

$$E_j = -K \sum_{i=1}^{m} Y_{ij} \ln Y_{ij}$$

$$K = \frac{1}{\ln m}, (K>0, e_j \ge 0, m = 1, 2, \ldots\ldots, 37)$$

Step 4: Calculate the redundancy D_j:

$$D_j = 1 - E_j$$

Step 5: Calculate the weights W_j of each evaluation indicator:

$$W_j = \frac{D_j}{\sum\limits_{i=1}^{n} D_j} \ (n = 1,\ 2,\ 3, \ldots\ldots,\ 24)$$

4.2. Comprehensive Index Method

The comprehensive index method was applied to calculate the comprehensive indices of causative factor hazard (*HI*), disaster-prone environment (*EI*), disaster-bearing body vulnerability (*BI*), and overall earthquake disaster risk (*RI*) for 37 prefecture-level cities in Sichuan–Yunnan region based on dimensionless values and indicator weights. The calculation processes are given as follows:

$$HI = \sum_{i=1}^{n} D_{ij} W_j \cdot 100$$

$$EI = \sum_{i=1}^{m} D_{ij} W_j \cdot 100$$

$$BI = \sum_{i=1}^{k} D_{ij} W_j \cdot 100$$

$$RI = HI + EI + BI$$

where D_{ij} represents the proportion of the jth evaluation indicator for the ith city; W_j represents the weight of the jth evaluation indicator; while n, m, and k represent the total number of indicators for the causative factors, disaster-prone environment, and disaster-bearing bodies, respectively.

4.3. Geographic Detector

A geographic detector is a statistical method used to reveal the driving forces behind geographic phenomena [71]. Its advantage lies in its fewer assumptions, wider applicability, and clearer physical meaning. In this study, geographic detector factor detection was used to analyze the main influencing factors of the spatiotemporal differentiation of the coupling coordination between urbanization and ecological environment systems. The calculation equation is expressed as follows:

$$q_{C,U} = 1 - \frac{1}{N\sigma^2}\sum_{h=1}^{L} N_h {\sigma^2}_h$$

where q represents the measure of indicator differentiation, used to express the explanatory power of the independent variable to the dependent variable; N represents the number of indicators; σ^2 represents the variance of the indicator; $h = 1, \ldots$, L, where L is the number of classifications or partitions. Since $q \in [0, 1]$, a larger value indicates that the indicator has a greater impact on the coupling coordination degree.

5. Results and Analysis

In Table 1, the causative factor hazard index, disaster-prone environment stability index, disaster-bearing bodies vulnerability index, and overall earthquake disaster risk index for 37 prefecture-level cities in the Sichuan–Yunnan region were calculated, and cluster analysis was performed to categorize them into five levels: high, relatively high, moderate, relatively low, and low. The spatial–temporal distribution characteristics were analyzed.

Table 1. Summary of seismic disaster related indices in the Sichuan–Yunnan region.

Geographical Division	City	Causative Factors Hazard Index	Disaster-Prone Environment Stability Index	Disaster-Bearing Bodies Vulnerability Index				Overall Earthquake Disaster Risk Index
				2005	2010	2015	2018	
I	Chengdu	2.06	1.8	23.63	23.26	18.29	22.73	11.9
	Zigong	0.09	0.81	5.72	5.94	9.92	9.86	4.55
	Luzhou	0.77	0.32	2.39	2.5	2.52	2.86	1.5
	Deyang	2.06	1.16	5.92	5.61	4.44	4.61	3.24
	Mianyang	2.06	2.58	2.86	2.81	2.68	3.04	2.63
	Guangyuan	2.06	1.43	1.59	1.67	1.46	1.63	1.63
	Suining	0.01	0.29	4.32	4.94	5.24	5.77	2.59
	Neijiang	0.04	0.29	4.61	4.81	4.52	3.94	2.14
	Leshan	2.22	2.7	2.64	2.53	2.63	2.35	2.46
	Nanchong	0.01	0.04	3.07	3.3	2.96	2.98	1.44
	Meishan	1.75	1.51	3.69	6.79	3.55	2.77	2.67
	Yibin	1.24	0.94	2.5	2.39	2.13	2.86	1.71
	Guangan	0.01	0.21	3.68	3.39	3.45	2.89	1.49
	Dazhou	0.01	1.18	1.95	2.17	2.04	1.93	1.09
	Yaan	5.04	5.23	1.12	1.49	1.23	1.16	3.28
	Bazhong	0.01	0.22	1.41	1.6	1.52	1.38	0.6
	Ziyang	0.01	0.46	2.89	3.18	2.65	2.62	1.34
II	Kunming	1.79	2.97	5.11	3.73	5.03	6.64	4.29
	Qujing	0.34	2.62	1.3	1.3	1.74	2.05	1.51
	Yuxi	5.37	2.56	1.41	1.16	1.19	1.33	2.84
	Zhaotong	1.24	2.51	0.95	1.02	0.74	0.97	1.25
III	Baoshan	6.02	3.5	0.59	0.49	0.7	0.72	2.84
	Puer	5.08	3.39	0.33	0.5	0.33	0.33	2.36
	Lincang	5.08	2.87	0.48	0.6	1.11	0.53	2.39
	Honghe	5.89	2.15	1.65	1.23	2.55	1.66	3.21
	Wenshan	0.21	1.59	1.43	1.05	1.06	0.83	0.81
	Xishuangbanna	3.17	2.78	0.71	0.27	0.61	0.27	1.64
	Dehong	3.34	3.75	1.18	1.09	1.06	0.82	2.3
IV	Panzhihua	0.09	3.81	3.67	2.79	2.9	2.5	2.25
	Aba	3.87	4.49	1.53	1.66	2.76	1.48	3.2
	Ganzi	5.07	8.87	0.54	0.59	1.08	0.63	3.76
	Liangshan	5.88	7.14	0.66	0.74	0.71	0.75	3.65
	Lijiang	4.01	5.09	0.48	0.37	0.28	0.35	2.39
	Chuxiong	5.37	3.15	1.33	0.83	1.12	0.75	2.79
	Dali	8.36	4	1.24	1.17	1.92	0.98	4.12
	Nujiang	5.55	5.71	0.64	0.37	0.95	0.64	3.18
	Diqing	4.83	5.88	0.8	0.66	0.95	0.39	2.95

5.1. Temporal Evolution Characteristics of Seismic Disaster Risk in the Sichuan–Yunnan Region

5.1.1. Causative Factors Hazard Index

When analyzing the causative factor hazard index (Table 1), significant differences between regions were observed. The Hengduan Mountain region, characterized by rugged terrain, active faults, and frequent earthquakes, exhibited the greatest variation in causative factor hazard, with a difference of 8.27. In contrast, the Yunnan Plateau showed relatively stable conditions, with the smallest variation in causative factor hazard index at 5.03. The three cities with the highest causative factor hazard index were Dali (8.36), Baoshan (6.02), and Honghe Prefecture (5.89), while the six lowest-ranking cities were all located in the Sichuan Basin: Suining, Nanchong, Guangan, Dazhou, Bazhong, and Ziyang, with a composite index of only 0.01.

5.1.2. Disaster-Prone Environment Stability Index

When analyzing the disaster-prone environment index (Table 1), significant differences were observed in the Hengduan Mountain region, with a variation of 5.72, while the Yunnan Plateau showed minimal variation, at 0.46. The top three cities with the highest disaster-prone environment index were all autonomous prefectures—Ganzi Prefecture (8.87), Liangshan Prefecture (7.14), and Deqen Prefecture (5.88)—whereas the three lowest-ranking cities were Bazhong (0.22), Guangan (0.21), and Nanchong (0.04).

5.1.3. Disaster-Bearing Bodies Vulnerability Index

When analyzing the disaster-bearing bodies vulnerability index (Table 1), the Sichuan Basin exhibited the largest variation in vulnerability index over the years, with differences of 22.51, 21.77, 17.05, and 21.57 in 2005, 2010, 2015, and 2018, respectively, indicating significant differences in risk levels among regions within the Sichuan Basin. In contrast, the Yunnan Plateau showed the smallest variation in the vulnerability index over the years, with differences of 1.32, 0.96, 2.22, and 1.39 in the same respective years. Chengdu City had the highest vulnerability index over the years (23.63 in 2005, 23.26 in 2010, 18.29 in 2015, and 22.73 in 2018), indicating the greatest loss of life and more economic damage when struck by earthquake disasters. The cities with the lowest vulnerability index over the years were Pu'er (0.33 in 2005), Xishuangbanna (0.27 in 2010 and 2018), and Lijiang (0.28 in 2015), indicating relatively fewer casualties and less social property damage during earthquake disasters.

5.1.4. Overall Earthquake Disaster Risk Index

Analyzing the overall earthquake disaster risk index in the Sichuan–Yunnan region (Table 1), Sichuan Basin exhibited the largest variation in risk index, at 11.3, indicating significant differentiation in earthquake disaster risk among various regions within the basin. In contrast, Hengduan Mountain region showed the smallest variation in risk index, at 1.87. The three cities with the highest earthquake disaster risk index were Chengdu (11.90), Kunming (4.29), and Zigong (4.55), with the first two being provincial capitals of Sichuan and Yunnan provinces, respectively, and representing the highest economic and social development levels in the region. The three lowest-ranking cities were Bazhong (0.60), Wenshan (0.81), and Dazhou (1.09).

5.2. Temporal Evolution Characteristics of Seismic Disaster Risk in the Sichuan–Yunnan Region

5.2.1. Causative Factors Hazard Index

Analyzing the spatial differentiation characteristics of seismic hazard, it was found that high-level areas were mainly distributed in the Hengduan Mountain region and the valleys of the northern and southern mountain ranges, while moderate-level areas were distributed in the northwest edge of the Sichuan Basin, and low-level areas were distributed in the eastern part of the Sichuan Basin and the Yunnan Plateau (Figure 3A).

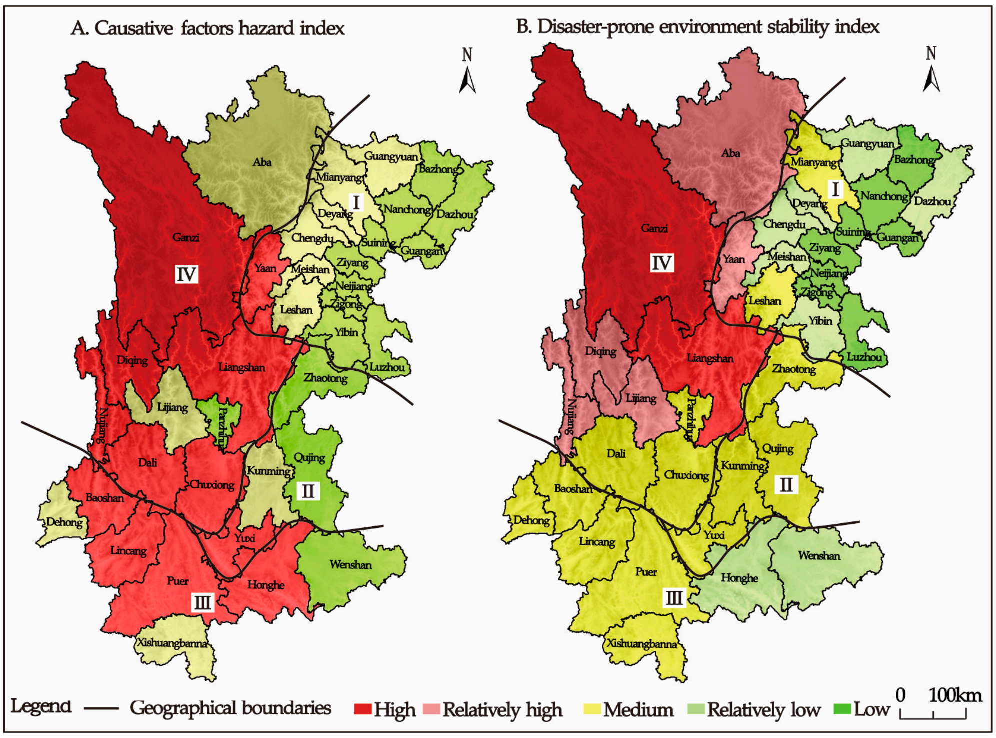

Figure 3. Spatial distribution of seismic disaster. I is Sichuan Basin Area, II is Yunnan Plateau Area, III is North–South Mountain Range Valley Area, and IV is Hengduan Mountain Area.

Specifically, the seismic hazard in the Hengduan Mountain region exhibited a spatial distribution pattern of “high on the periphery, low in the middle”. Apart from Lijiang, Panzhihua, and A’ba Prefecture in the central part, the rest of the region was classified as having high-level seismic hazard. In the valleys of the northern and southern mountain ranges, except for Dehong and Xishuangbanna, the rest of the area was also classified as a high-level hazard zone.

The seismic hazard in the Sichuan Basin and the Yunnan Plateau exhibited a spatial distribution pattern of “overall low, higher in the west than in the east”. Cities including Guangyuan, Mianyang, Deyang, Chengdu, Meishan, and Leshan at the northwest edge of the Sichuan Basin, as well as Kunming in the western part of the Yunnan Plateau, were classified as moderate-level seismic hazard areas. Cities such as Bazhong, Dazhou, Nanchong, Guangan, Suining, Ziyang, Neijiang, Zigong, Luzhou, and Yibin in the eastern part of the Sichuan Basin and cities such as Zhaotong, Qujing, and Wenshan Prefecture in the eastern part of the Yunnan Plateau were classified as low-level seismic hazard areas.

Overall, the risk index of disaster-causing factors is primarily determined by the frequency of seismic activity and the trend in future earthquakes. The Hengduan Mountain region and the North–South Mountain Range Valley Region are densely fractured, home to the Xianshuihe, Xiaojiang, Lijiang–Xiaojin, Lancangjiang, and Red River faults. This region experiences frequent earthquakes, making it a high-risk area for disaster-causing factors. The edge of the Sichuan Basin is a transitional terrain with relatively complex geological structures, also prone to earthquakes, while the Sichuan Basin and the Yunnan Plateau, located within the interior of the landmass, have relatively stable structures and are less likely to experience earthquakes, thus constituting low-risk areas.

5.2.2. Disaster-Prone Environment Stability Index

Analyzing the spatial differentiation characteristics of disaster-prone environment, it was observed that the Hengduan Mountain region had the highest risk level, followed by the Yunnan Plateau. In the western part of the valleys of the northern and southern mountain ranges, the risk level was higher than in the east, while the overall risk level in

Sichuan Basin was relatively low, but contained significant internal differences. Specifically, the Hengduan Mountain region was the concentration area of the high-risk disaster-prone environment in the Sichuan–Yunnan region, with a spatial distribution pattern of "higher in the north, lower in the south". Especially in Ganzi and Liangshan Prefectures, the risk level was the highest, indicating the strongest sensitivity and weakest stability and making it a key area for earthquake and secondary disaster strikes. A'ba, Diqing, Lijiang, and Nujiang Prefectures had relatively high risk levels, with a sensitivity and stability second only to Ganzi and Liangshan Prefectures. Cities such as Dali, Panzhihua, and Chuxiong in the south were classified as moderate-risk areas, indicating relatively weaker impacts from earthquakes and secondary disasters.

The Yunnan Plateau and the western part of the valleys of the northern and southern mountain ranges were classified as moderate-risk areas (Figure 3B). It is worth mentioning that due to the low stability and sensitivity of the disaster-prone environment in Yuxi, the risk level was moderate due to the combined effect of multiple factors, whereas Pu'er, although having higher stability in disaster-prone environments, had higher sensitivity, which could amplify the disaster; thus, it belongs to the moderate-risk areas in terms of disaster-prone environment.

The Sichuan Basin was the region with the lowest risk level for disaster-prone environments in the Sichuan–Yunnan region, with significant spatial differentiation characteristics, showing a gradual decrease from west to east (Figure 3B). Cities like Ya'an, located in the transition zone between the Sichuan Basin and the Hengduan Mountain region, had a relatively high risk level of disaster-prone environment; compared to Ya'an, the sensitivity of disasters in Leshan and Mianyang was relatively low, presenting a moderate risk level. The rest of the Sichuan Basin was at a relatively low risk level of disaster-prone environment, especially in the central part, where cities including Bazhong, Nanchong, Suining, Guangan, Suining, Ziyang, Neijiang, Zigong, Luzhou, and Yibin had strong stability and weak sensitivity regarding disaster-prone environments, and were thus classified as low-risk areas.

Overall, the stability index of the disaster-prone environment is primarily determined by natural background factors such as the regional geomorphic type, mountain slope, lithology, and peak ground acceleration of seismic activity. The Hengduan Mountain region feature a complex and varied landscape, including the Daxue Mountains, Yunling, Nu Mountains, and the Red River Gorge, predominantly composed of silty sandstone and shale, which are prone to landslides and other secondary disasters. The western part of the north–south mountainous river valleys on the Yunnan Plateau features plateaus and karst landscapes with gentle slopes and predominantly basalt and conglomerate rock types, where the disaster-prone environment has weaker stability and is susceptible to mudslides and other secondary disasters. The Sichuan Basin has a relatively flat terrain, primarily composed of siliceous rocks and mudstone, resulting in an overall lower risk level for the disaster-prone environment.

5.2.3. Disaster-Bearing Bodies' Vulnerability Index

Analyzing the spatial differentiation characteristics of disaster-bearing bodies vulnerability index, it was observed that the developed areas in the Sichuan Basin and the Yunnan Plateau were medium- to high-risk areas, while the valleys of the northern and southern mountain ranges and the Hengduan Mountain region were overall low-risk areas (Figure 4).

The disaster-bearing bodies' vulnerability in Yunnan Plateau, except for Kunming, is mainly low to moderate risk. Kunming's vulnerability as a disaster-bearing body is the highest in the Sichuan–Yunnan region, consistently maintaining a relatively high risk level, except in 2010. In the event of an earthquake disaster, the magnitude of losses to the population, economy, society, and lifeline systems will be the highest in the Yunnan Plateau. Yuxi and Qujing consistently maintained a low risk of vulnerability as disaster-bearing bodies, while in 2010, Zhaotong's vulnerability as a disaster-bearing body was influenced by population fluctuations, fluctuating from low-risk to moderate-risk, then declining after 2015 to return to a low risk level.

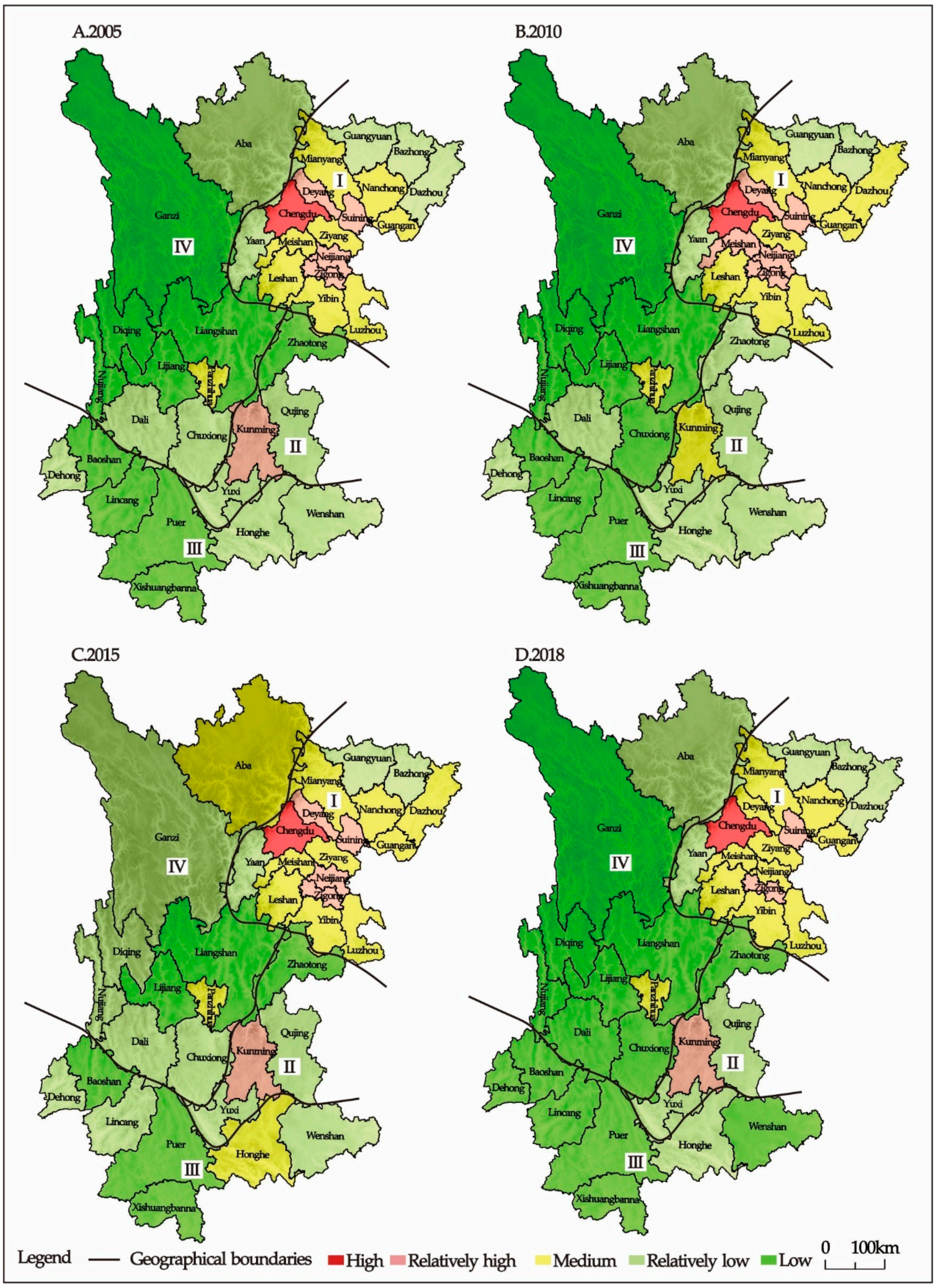

Figure 4. Spatial distribution of disaster-bearing bodies' vulnerability index in the Sichuan–Yunnan region. (**A**) Disaster-bearing bodies' vulnerability index in 2005; (**B**) disaster-bearing bodies' vulnerability index in 2010; (**C**) disaster-bearing bodies' vulnerability index in 2015; (**D**) disaster-bearing bodies' vulnerability index in 2018. I is Sichuan Basin Area, II is Yunnan Plateau Area, III is North–South Mountain Range Valley Area, and IV is Hengduan Mountain Area.

The disaster-bearing bodies' vulnerability in the Sichuan Basin exhibited a spatial distribution pattern of being high in the central part and low on the periphery. Chengdu was classified as a high-risk area, while cities including Zigong, Suining, Mianyang, Neijiang, Meishan, and Leshan formed a high- to moderate-risk area in the central part of the Sichuan Basin, and then spread to the north and south, forming a moderate-risk area in cities like

Ziyang, Leshan, Yibin, Luzhou, Mianyang, Nanchong, Guangan, and Zigong. Cities such as Guangyuan, Bazhong, Dazhou, and Ya'an at the northern edge of the basin and the transition zone between the Sichuan Basin and the Hengduan Mountain region maintained a relatively low vulnerability and risk level.

The disaster-bearing bodies' vulnerability in the valleys of the northern and southern mountain ranges is mainly low to moderate risk, making it the area with the lowest risk of earthquake disaster losses in the Sichuan–Yunnan region. Specifically, there has been no significant change in the overall vulnerability risk of this area, especially in regions like Baoshan, Pu'er, and Xishuangbanna, where the vulnerability risk consistently remained low from 2005 to 2018. In 2015, the vulnerability risk levels of Lincang and Honghe fluctuated from low to moderate risk, and then returned to their original risk levels by 2018. The vulnerability risk levels of Dehong and Wenshan slightly decreased, shifting from moderate- to low-risk areas.

There is a noticeable polarization in the vulnerability risk levels of disaster-bearing bodies in the Hengduan Mountain region, with Panzhihua consistently having a higher risk level compared to other areas. As an industrial city, Panzhihua's level of urbanization and economic development is higher than in other parts of the Hengduan Mountain region, making it the area with the highest risk level for disaster-bearing bodies, consistently maintaining a moderate risk level. The vulnerability of disaster-bearing bodies in Liangshan and Lijiang remained unchanged, maintaining a low risk level. In 2015, the vulnerability risk levels of A'ba, Deqin, and Nujiang fluctuated upwards, especially in A'ba, which rose from moderate to high risk levels before returning to its original risk level by 2018. The vulnerability risk levels of Chuxiong and Dali decreased, shifting from moderate to low risk levels.

Overall, the vulnerability index of disaster-bearing bodies is primarily determined by social factors such as the population density, level of economic development, and social development in the region. The Sichuan Basin and the Yunnan Plateau, with their relatively flat terrain, are well-suited to urban development and are centers of population, economic activity, and social production. In these areas, urban buildings are taller, economic activities are concentrated, and the density of infrastructure networks for water, natural gas, and transportation is high. Consequently, when an earthquake occurs, the potential for a high level of casualties and economic losses per unit area is significant, classifying these areas as medium- to high-risk zones regarding the vulnerability of disaster-bearing bodies. In contrast, the geomorphology of the north–south mountainous river valleys and the Hengduan Mountains is predominantly mountainous, with a relatively dispersed population and less developed economic activities. Although these regions experience frequent seismic activity and have a higher risk of disaster-inducing factors, the scattered human activities mean that the overall vulnerability risk level of the disaster-bearing bodies is generally low.

5.2.4. Comprehensive Earthquake Disaster Risk Index

Analyzing the spatial pattern of earthquake disaster risk in the Sichuan–Yunnan region reveals significant differences in risk levels within the Sichuan Basin. This can be further subdivided into high-risk areas in the transition zone, medium-risk areas in the central part, and low-risk areas at the periphery (Figure 5). The high-risk areas in the transition zone primarily include regions with high and moderate risk levels, mainly distributed in Chengdu, Deyang, Ya'an, and Zigong, located at the transition zone between the Sichuan Basin and the Hengduan Mountain region. Medium-risk areas in the central part extend north and south from the high-risk zone, mainly covering cities including Mianyang, Suining, Meishan, Neijiang, and Leshan. Low-risk areas are mainly found along the northern and southern edges of the Sichuan Basin, including cities like Guangyuan, Bazhong, Dazhou, Nanchong, Guangan, Luzhou, and Yibin.

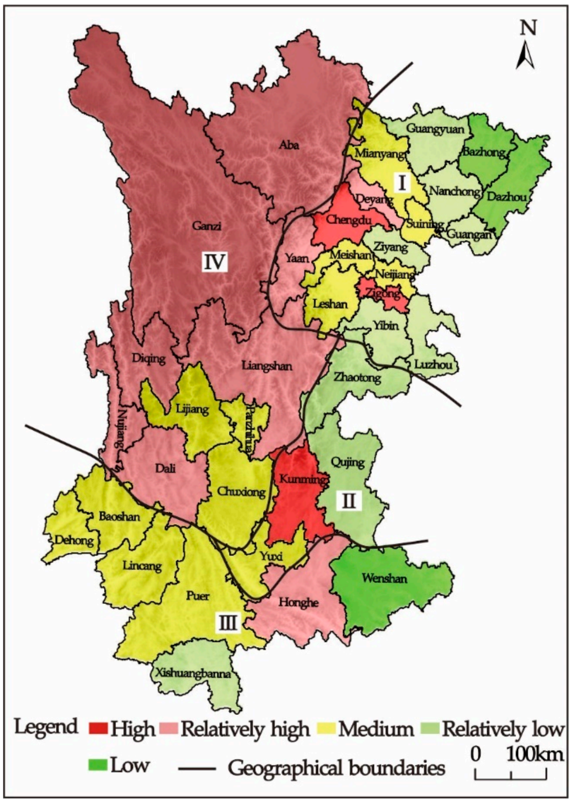

Figure 5. Spatial distribution of risk index for seismic disasters in the Sichuan–Yunnan region. I is Sichuan Basin Area, II is Yunnan Plateau Area, III is North–South Mountain Range Valley Area, and IV is Hengduan Mountain Area.

The earthquake disaster risk levels in the Yunnan Plateau exhibit a west-to-east decrease pattern. Kunming has the highest earthquake risk in the Yunnan Plateau, classified as high-level risk, followed by Yuxi, classified as a moderate-risk area; Qujing and Zhaotong in the eastern part have a lower risk level.

The earthquake disaster risk levels in the valleys of the northern and southern mountain ranges are predominantly at a medium level. Honghe Prefecture has the highest risk level in these valleys, at a moderate level, while Dehong, Baoshan, Lincang, and Pu'er in the west show a moderate risk level. Wenshan and Xishuangbanna have low to moderate risk levels.

In the Hengduan Mountain region, earthquake disaster risk is predominantly at a high level. High-risk areas, including Liangshan, A'ba, Ganzi, Deqen, Nujiang, and Dali, are contiguous in space, surrounded internally by medium-risk areas centered around Lijiang, Chuxiong, and Panzhihua.

5.3. Analysis of Factors Affecting Earthquake Disaster Risk Levels in the Sichuan–Yunnan Region

5.3.1. Univariate Analysis

The earthquake disaster risk level in the Sichuan–Yunnan region is impacted by various factors, such as topography, geological structure, and socio-economic development level. Seven indicator factors from the causative factors hazard risk (C1), disaster-prone environmental stability (C2), disaster-prone environmental sensitivity (C3), population vulnerability (C4), economic vulnerability (C5), social vulnerability (C6), and lifeline system vulnerability (C7) at the criterion layer were selected. Utilizing geographic detectors, the impact (q) of each indicator factor was quantified to explore the underlying causes affecting the earthquake disaster risk level in the Sichuan–Yunnan region.

The factor detection revealed the impact of seven indicator factors on the earthquake disaster risk level in the region. There were differences in the range of q values for each indicator

(Figure 6). The results indicate that the explanatory power of each indicator factor on the earthquake disaster risk level, from highest to lowest, is C5 > C7 > C4 > C6 > C1 = C2 > C3, with values of 0.78, 0.77, 0.73, 0.15, 0.12, 0.12, 0.06, respectively.

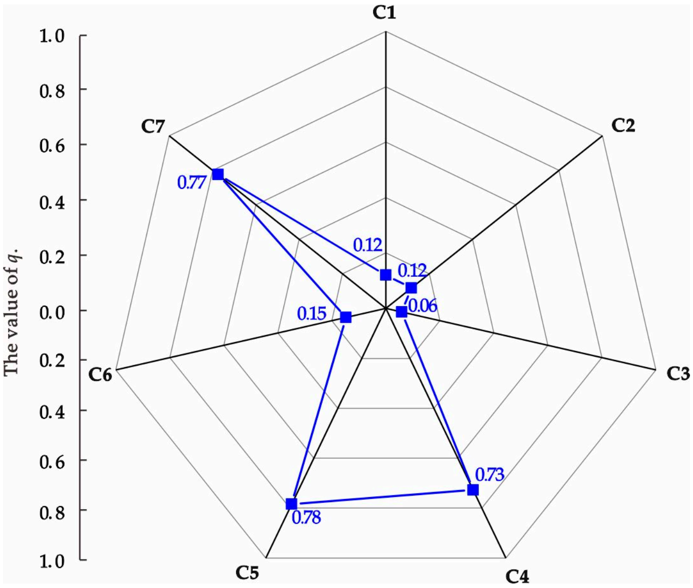

Figure 6. Influence detection index of seismic risk in the Sichuan–Yunnan region.

Population vulnerability (C5), economic vulnerability (C7), and lifeline system vulnerability (C4) were identified as the primary controlling factors with q values greater than 0.70. This suggests that the extent of casualties and property damage caused by earthquakes primarily depends on the post-disaster rescue speed and the vulnerability of lifeline system engineering per unit area.

Factors such as causative factors' hazard risk (C1), disaster-prone environmental stability (C2), and disaster-prone environmental sensitivity (C3), which are relatively stable natural factors, exhibited a relatively low explanatory power, with q values all below 0.15. Due to the prolonged formation process of the geological background of earthquakes and the relatively stable global tectonic pattern, earthquake-prone areas are mainly concentrated near fault zones. Cities located in earthquake-prone areas have already made provisions during the planning process and appropriately increased the seismic intensity grade of buildings. Adequate preparation during the disaster preparedness stage results in relatively few casualties and property losses in areas with relatively dangerous environmental conditions when earthquakes of the same magnitude occur.

5.3.2. Interaction Effects' Detection

Interaction effects' detection identifies whether there is a cooperative effect when different indicators interact (i.e., whether there is an enhancing or weakening effect on the earthquake disaster risk level).

The results in Table 2 indicate that any two indicators in the Sichuan–Yunnan region exhibit enhanced effects after interaction. This means that the interaction between two factors manifests as either mutual enhancement or nonlinear enhancement, indicating that the interaction effect of any two indicators on the earthquake disaster risk in the region is greater than the individual effect of a single indicator. Additionally, the q values after the interaction of two indicators all showed varying degrees of improvement, indicating that the spatial distribution difference in the earthquake disaster risk level in the Sichuan–Yunnan region is determined by the joint action of multiple indicators.

Table 2. q-values of interaction detection for seismic disaster risk levels in the Sichuan–Yunnan region.

q (Cx∩Cy)	q-Statistic Value	Type of Interaction	q (Cx∩Cy)	q-Statistic Value	Type of Interaction
q (C1∩C2)	0.212	Bifactor enhance	q (C3∩C4)	0.887	Nonlinear enhance
q (C1∩C3)	0.347	Nonlinear enhance	q (C3∩C5)	0.888	Nonlinear enhance
q (C1∩C4)	0.861	Bifactor enhance	q (C3∩C6)	0.420	Nonlinear enhance
q (C1∩C5)	0.887	Bifactor enhance	q (C3∩C7)	0.887	Nonlinear enhance
q (C1∩C6)	0.281	Bifactor enhance	q (C4∩C5)	0.793	Bifactor enhance
q (C1∩C7)	0.886	Bifactor enhance	q (C4∩C6)	0.858	Bifactor enhance
q (C2∩C3)	0.215	Bifactor enhance	q (C4∩C7)	0.816	Bifactor enhance
q (C2∩C4)	0.930	Nonlinear enhance	q (C5∩C6)	0.855	Bifactor enhance
q (C2∩C5)	0.912	Bifactor enhance	q (C5∩C7)	0.841	Bifactor enhance
q (C2∩C6)	0.337	Nonlinear enhance	q (C6∩C7)	0.833	Bifactor enhance
q (C2∩C7)	0.898	Bifactor enhance			

Due to the impact of earthquake disaster mechanisms, the synergistic effect of causative factors' hazard risk (C1), disaster-prone environmental stability (C2), and disaster-prone environmental sensitivity (C3) is the most significant. When these three indicator factors are superimposed with the corresponding indicator factors of the carrying system, except for social vulnerability (C7), the explanatory power of each factor exceeds 0.85.

Upon closer examination, the causative process of earthquakes primarily involves the collapse of buildings, resulting in casualties, and the triggering of secondary disasters such as landslides and debris flows. Earthquakes occurring in uninhabited areas do not lead to loss of life or property and are insufficient to cause disasters. Conversely, earthquakes in densely populated areas, even if of moderate magnitude, can result in significant loss of life and property, leading to severe disaster consequences. Therefore, the epicenter location is a crucial factor in determining whether an earthquake will lead to a disaster and the severity of its impact.

6. Discussion

Due to global climate change and an increase in disaster activity, urban areas are facing escalating disaster risks and impacts. To reduce the impact of earthquake disasters on cities, this study evaluates the earthquake disaster risk for 37 prefecture-level cities in the Sichuan–Yunnan region. Moving beyond traditional single-factor assessments of earthquake hazard, this study emphasizes a comprehensive approach. On one hand, it thoroughly considers the roles of disaster-causing factors' hazard levels, the stability and sensitivity of the disaster-prone environment, and the vulnerability of the disaster-bearing bodies during the earthquake-induced disaster process. On the other hand, it introduces a commensurability trend coefficient into the evaluation system to dynamically assess the future earthquake trends of different cities. Compared to previous studies, the results of this research are derived from a comprehensive consideration of the regularity of historical earthquakes in the Sichuan–Yunnan area, the specificity of the geological structures, the vulnerability of the disaster-bearing bodies, and the probability of future earthquakes, providing a scientific basis for accurately identifying high-risk earthquake disaster areas.

In the process of obtaining specific evaluation indicators, this study selects the commensurability trend coefficient as one of the indicators for assessing the hazard of disaster-causing factors. The commensurability trend coefficient is calculated using commensurability theory, a method belonging to the information forecasting category. This involves the extraction of effective signals from earthquake disaster events and making judgments about earthquake trends based on the seismic information contained in these signals. This method was proposed by the Chinese academician Wen Wengbo and was developed through theoretical and practical research into a disaster prediction method [72,73]. Subsequently, Yan Junping enhanced this method by constructing bowtie diagrams and spatial structure systems to express the spatiotemporal symmetry of disaster events, thus refining the commensurability theory methodology. In 2008, Long Xiaoxia and others successfully predicted the Wenchuan earthquake using commensurability theory [74], which has gradually gained attention in the academic community. The use of commensurability theory to assess the spatiotemporal variations and trend predictions of earthquake disasters has been successful in some cases [75–79]. Since earthquake trend prediction is not the main focus of this study, this study only uses specific results, and the detailed calculation process can be found in the references [42].

In the practical application of the findings of this study, the process of an earthquake-induced disaster can be divided into four phases: the incubation period, the outbreak period, the impact period, and the recovery period. The goal of conducting earthquake disaster risk assessments is to accurately identify high-risk areas, providing a basis for decision-making in precise earthquake disaster risk management. Compared to other studies, the evaluation system developed in this research emphasizes comprehensiveness. At the criterion level, it considers the hazard of disaster-causing factors, the sensitivity and stability of the disaster-prone environment, and the vulnerability of the affected entities throughout the entire earthquake disaster process. Other regions or countries can adopt this evaluation system framework directly to conduct earthquake disaster risk assessments in their specific areas. They can also use geographic detectors to analyze the main controlling factors of earthquake disasters in various cities and develop region-specific emergency management measures accordingly. It is important to note that the specific indicators in the evaluation system can be adjusted based on local natural factors and the level of social development within the scope of the criteria layer due to influences such as the scope, type, and local factors of government statistics in different regions. Overall, the approach of this study is valuable for other regions aiming to develop precise earthquake risk prevention measures, comprehensively enhance urban safety levels, and coordinate regional sustainable development.

7. Conclusions

Based on the natural disaster system theory, this study developed an earthquake disaster risk assessment index system for the Sichuan–Yunnan region. Methods such as the entropy method, comprehensive index method, and geographic detector are used to explore the temporal distribution characteristics and influencing factors of 37 prefecture-level cities' causative factors index, disaster-prone environment stability index, disaster-bearing bodies vulnerability index, and comprehensive earthquake disaster risk index in the Sichuan–Yunnan region. The main conclusions are summarized as follows.

High-risk areas of causative factors are mainly distributed in the Hengduan Mountain region and the valleys of the northern and southern mountain ranges, which are areas where earthquakes with $Ms \geq 5.0$ are frequent. Medium-risk areas are mainly distributed at the northwest edge of the Sichuan Basin, i.e., the transitional zone of landform types, with frequent geological activities. Low-risk areas are mainly distributed in the eastern part of the Sichuan Basin and the Yunnan Plateau.

High-risk areas of the comprehensive disaster-prone environment index are mainly distributed in the Hengduan Mountain region, medium-risk areas are distributed in the Yunnan Plateau and the western part of the valleys of the northern and southern mountain ranges, and low-risk areas are distributed in the Sichuan Basin.

High-value areas of disaster-bearing bodies' vulnerability are mainly distributed in the central part of the Sichuan Basin and Kunming in the Yunnan Plateau, which is the most densely populated and economically developed area in the Sichuan–Yunnan region, where the casualties and economic losses per unit area caused by earthquakes are the highest. Medium-value areas are mainly distributed in the eastern and western parts of the Sichuan Basin. Low-value areas are mainly distributed in the marginal areas of the Sichuan Basin, underdeveloped areas of the Yunnan Plateau, valleys of the northern and southern mountain ranges, and the Hengduan Mountain region, where ethnic minorities are concentrated. Although earthquakes occur frequently, casualties and economic losses per unit area are relatively small.

The high-risk areas of earthquake disasters are mainly concentrated in the developed areas of the Sichuan Basin and the Yunnan Plateau, the relatively high-risk areas are concentrated in the Hengduan Mountain region, the medium-risk areas are concentrated in the western part of the valleys of the northern and southern mountain ranges, and the relatively low-risk areas are concentrated in the eastern part of the Sichuan Basin and the eastern part of the Yunnan Plateau, with low-risk areas scattered in the eastern part of the Sichuan–Yunnan region.

Impacted by the mechanism of earthquake disaster, single-factor analysis indicates that population vulnerability, economic vulnerability, and vulnerability of the lifeline system are the main controlling factors affecting the earthquake disaster risk level in the Sichuan–Yunnan region, with q values exceeding 0.70. Hazard risk, environmental stability, and environmental sensitivity, as relatively stable natural factors, have a relatively low explanatory power. The synergistic effect of hazard risk, environmental stability, and environmental sensitivity is the most significant, with the explanatory power of each factor after interaction exceeding 0.85.

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