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Original Paper

Evaluation of Social–Ecological System Stability and Analysis of Its Influencing Factors in Karst Desertification Control Areas

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Abstract

A stable social-ecological system can more effectively respond to natural disasters, climate change, and human-induced disturbances. Karst desertification control areas are subject to the dual constraints of ecological restoration and economic development; however, research on the stability of social-ecological systems in such regions remains limited. Therefore, this study developed a social-ecological system stability evaluation framework to assess the stability of three desertification control areas with varying degradation levels, and subsequently applied a factor contribution model and an obstacle degree diagnostic model to analyze the key determinants influencing system stability. The study found that: (1) The stability of the Qingzhen study area (0.3920) was higher than that of the Salaxi study area (0.3162), which in turn exceeded that of the Huajiang study area (0.2154). (2) Indicators across the study areas exhibited clear asymmetry between contribution and obstacle degrees, with no one-to-one correspondence, such as high contribution-low obstacle or low contribution-high obstacle. (3) The stability formation mechanisms in different study areas shared common characteristics of "multi-factor co-driving and universal constraints from public services." Specifically, the obstacle degrees of public service criteria were 62.44%, 57.63%, and 60.00% in the Salaxi, Qingzhen, and Huajiang study areas, respectively.

Keywords

Stability, Sustainable development, Social-ecological system, Karst desertification control

1. Introduction

Karst desertification refers to a process in fragile karst ecosystems whereby unsustainable human socio-economic activities lead to vegetation degradation, soil erosion, progressive rock exposure, and loss of land productivity, resulting in landscapes that visually resemble desertification (Xiong et al., 2002; Chong et al., 2021; D'Ettorre et al., 2024). It is one of the most severe ecological problems in karst regions. Extensive karst desertification, acting as a negative feedback in karst regions, severely restricts local economic development, making these areas both a priority and a challenge for the "Beautiful China" initiative (Bai et al., 2024). This situation highlights the necessity and urgency of promoting coordinated ecological restoration and socio-economic development. Over the past two decades, the importance and urgency of karst desertification management have been widely recognized internationally, and previous governance efforts have achieved measurable success (Wang et al., 2019; Xiong et al., 2016). Against the backdrop of Chinese government initiatives, including the "National Major Project for the Protection and Restoration of Key Ecosystems (2021-2035)" and the 2024 No.1 Central Document on applying the "Thousand-Village Demonstration and Ten-Thousand-Village Restoration" experience to promote comprehensive rural revitalization, there is an urgent need to study these areas from an integrated perspective. Accordingly, some scholars have approached karst desertification areas as large-scale human-environment systems for research (Yue et al., 2024). The social-ecological system is a coupled system used to study the complex interactions between human societies and the natural environment (Ostrom, 2009). This system emphasizes the interdependence and co-evolution of humans and the natural environment, treating human society and nature as a unified whole to understand dynamic changes, governance mechanisms, and sustainability challenges. This perspective aligns closely with current objectives in karst rocky desertification management (Ren et al., 2025). Moreover, the stability of social-ecological systems in desertification control areas is a critical foundation for the sustained provision of regional ecosystem services. Under increasing pressures from climate change and human activities, maintaining such stability has become a core challenge for sustainable development (Huang et al., 2026). Therefore, it is essential to evaluate the system stability of desertification areas from a social-ecological system perspective. Such evaluation is crucial for understanding the current status, guiding future desertification management, and promoting local socio-economic development.

Over the past decades, numerous scholars have emphasized the integration of socio-economic and natural ecological systems. Concepts such as the socio-economic-natural complex ecosystem (Ma and Wang, 1984), the human-land regional system (Lu & Guo, 1998; Ye, 2001), and the social-ecological system framework all highlight the significance of integrating social and ecological systems in research (Ostrom, 2009). Among these, social-ecological system research aims to explore the dynamics of social-ecological systems and promote transitions toward sustainability (Folke, 2006). Furthermore, in response to the complexity of environmental issues, interdisciplinary research has gradually developed, and the social-ecological system framework is considered a highly promising analytical approach and a frontier in the field (Glaser et al., 2008; Leslie et al., 2015). However, current research on karst rocky desertification from a social-ecological system perspective remains limited, particularly studies focusing on social-ecological system stability, which are even scarcer.

The karst regions of southern China represent a typical ecologically fragile area (Xiong and Chi, 2015). Guizhou, located at the center of southern China's karst region, is the most developed karst province in the country. Karst desertification is the primary environmental issue in this area, severely restricting socio-economic development and threatening the living space and sustainable development of certain regions (Su et al., 2002). This region is characterized by ecological sensitivity, fragility, and infertile land, where ecosystems are highly prone to degradation under human disturbances. At the same time, it faces significant social challenges, including population pressure and weak economic foundations, which make the coupling between ecological and social systems more complex and tense (Tan et al., 2025; Tang et al., 2026). In this context, traditional assessments that focus solely on ecological, social, or economic conditions are insufficient to comprehensively reflect the overall regional situation or to anticipate future development trends (Li et al., 2025). Therefore, conducting stability assessments from an integrated social–ecological systems perspective enables a more comprehensive evaluation of regional conditions. Moreover, the assessment results can help examine the long-term effectiveness of ecological restoration and engineering measures implemented in the region, identify vulnerable components, inform the formulation of stability enhancement goals and strategies, and provide a scientific basis for further improving governance outcomes in the future.

In summary, conducting social-ecological system stability assessments in karst desertification control areas is critically important and practically necessary. This study selected three representative demonstration areas in Guizhou with varying degrees of karst desertification to conduct social-ecological system stability assessments and analyze influencing factors. The aim is to provide scientific guidance for consolidating desertification management outcomes, promoting coordinated ecological restoration and regional economic development, and informing future desertification governance.

2. Materials and Methods

2.1 Study Area

The South China Karst region spans eight provincial-level areas—Guangdong, Guangxi, Hunan, Hubei, Chongqing, Sichuan, Guizhou, and Yunnan—and is one of the largest and most representative continuous karst landscapes in the world. It is also recognized as a typical ecologically fragile region (Luo et al., 2024; Wang et al., 2023). In recent years, the continuous implementation of comprehensive karst desertification control projects has led to significant ecological restoration achievements in the region (Xiong et al., 2025). The resulting governance model was recognized as a Global Best Practice under the United Nations Decade on Ecosystem Restoration. This study selected three representative karst desertification control areas in the South China Karst region—Salaxi in Bijie, Hongfeng Lake in

Qingzhen, and Huajiang in Guanling–Zhenfeng—as case study sites (Figure 1). These sites represent potential–mild, mild–moderate, and moderate–severe karst desertification types, respectively (Chen, 2025). Specifically, the Salaxi site is located in the Liuchong River Basin, Qixingguan District, Bijie City, northwestern Guizhou Province (105°00′11″–105°08′38″E, 27°11′09″–27°17′28″N), covering an area of 86.27 km² (Yao et al., 2021). The Qingzhen site is located in the Maiweng River Basin of Hongfeng Lake, central Guizhou (26°21′00″–26°59′09″N, 106°07′06″–106°33′00″E), and covers an area of 60.44 km² (Chen et al., 2014). The Huajiang site is situated in the Huajiang section of the Beipan River Canyon, Anshun City, southwestern Guizhou (25°38′19″–25°41′32″N, 105°38′31″–106°40′51″E), covering 51.62 km² (Gao et al., 2020).

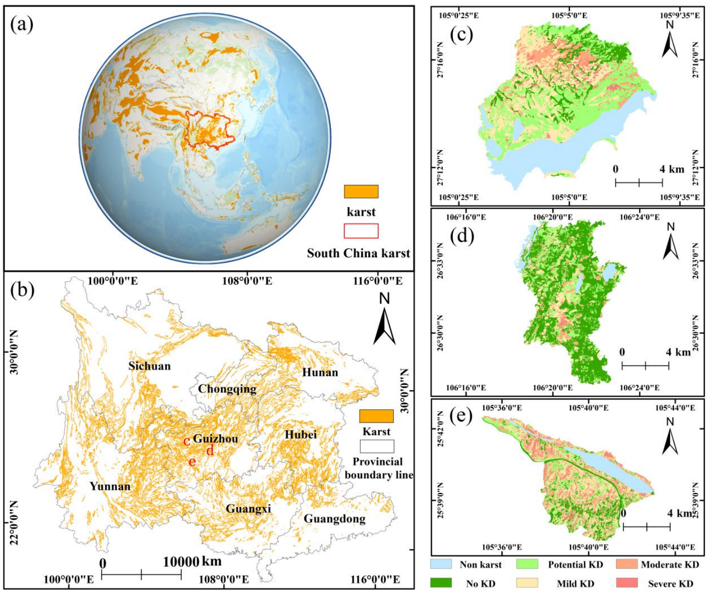

Figure 1. Overview of the study area (a. Global distribution of Karst; b. South China Karst; c. Bijie Salaxi study area; d. Qingzhen Hongfeng lake study area; e. Guanling-Zhenfeng Huajiang study area; KD: karst desertification)

2.2 Data Sources

Socio-economic and public service data were collected through two primary channels: village-level surveys and household surveys. Village-level data were obtained through face-to-face interviews and structured questionnaires administered to members of the village committees. The survey covered population size and structure, per capita income, civil disputes,, medical insurance coverage rate, streetlight coverage, number of retail shops, infrastructure conditions, and implementation of ecological protection policies. At the household level, ordinary rural households were selected and surveyed through in-home interviews. The survey focused on household income structure, labor composition, agricultural inputs, and environmental awareness to validate and supplement village-level macro data, thereby enhancing data accuracy and reliability. Land-use data were derived from 30 m spatial resolution Landsat imagery. A supervised classification method combined with manual visual interpretation was applied to preliminarily extract land-use types. The initial classification results were further validated and refined by comparing them with historical datasets from the research team, high-resolution Google Earth imagery, and field verification results. Vegetation coverage was estimated using NDVI calculated from Landsat imagery and retrieved through the pixel dichotomy model. Soil conservation was estimated using the RUSLE model. Water yield was simulated using the water yield module of the InVEST model.

2.3 Research Methods

2.3.1 Weight Calculation

The indicators in the system involve different measurement units, making direct comparison and integration in a comprehensive evaluation impossible. Therefore, data needs to be standardized to enhance the objectivity and robustness of the evaluation results. The specific steps for data processing are as follows:

Standardization: To eliminate differences in measurement units among indicators, the min-max method is used to map indicators of different attributes to a standard range from 0 to 1.

Standardization of positive indicators:

$$X_{ij}^{'}=\frac{(X_{ij}-X_j^{min})}{(X_j^{max}-X_j^{min})} \tag{1}$$

Standardization of negative indicators:

$$X_{ij}^{'}=\frac{(X_j^{max}-X_{ij})}{(X_j^{max}-X_j^{min})} \tag{2}$$

Standardization of moderate indicators:

$$X_{ij}^{'}=1-\frac{|X_i-d_i|}{max|X_i-d_i|} \tag{3}$$

In the equation, $X_{ij}^{'}$ ranges from 0 to 1, representing the standardized value of the j indicator for the i item. is the actual value of the j indicator for the i item, while and denote the maximum and minimum values, respectively. di is the predefined standard value. A higher indicates a higher level of social-ecological system stability in the region, implying greater coordination between natural and social systems, a more rational system structure, and improved regional resilience.

(2) Weight calculation: This study employs the entropy method to determine indicator weights. The main reason is that it can assess the contribution of each indicator to the comprehensive evaluation based on the inherent variability of the data. The greater the variability of an indicator, the lower its information entropy, the more information it provides, and consequently, the higher its assigned weight.

Step 1: Proportion calculation

$$Y_{ij}^{'}=\frac{X_{ij}^{'}}{\sum_{i=1}^{n} X_{ij}^{n}} \tag{4}$$

Step 2: Information entropy

$$E_j=-\frac{1}{\ln n}\sum_{i=1}^{n} Y_{ij} \ln Y_{ij} \tag{5}$$

Step 2: Information entropy

$$G_j=1-E_j \tag{6}$$

Step 4: Weight assignment

$$W_j=\frac{G_j}{\sum_{i=1}^{p} G_j} \tag{7}$$

Based on the established evaluation indicator system for the stability of social-ecological systems in karst desertification control, the indicator data were collected and processed according to the steps described above. The weights of each indicator were then calculated using the entropy method (Table 1).

Table 1. Social-ecological System Stability Evaluation index System for Karst Desertification Control

Target layer	Criteria layer	Structure layer	Index layer	Attribute	Weight
Social-ecosystem stability	Social economy	Population structure	Population density (X1)	-	0.0067
			Dependency ratio (X2)	+	0.0150
		Employment structure	Proportion of agricultural Workers (X3)	+/-	0.0223
			Proportion of migrant workers (X4)	+/-	0.0258
		Community govern	Proportion of village leaders with college education or above (X5)	+	0.0223
			Civil dispute rate (X6)	-	0.0118
		Economic condition	Per capita income (X7)	+	0.0356
			Proportion of households Owning private cars (X8)	+	0.0132
		Social Security	Proportion of people receiving minimum living security (X9)	-	0.0161
			Medical insurance coverage rate (X10)	+	0.0225
	Public service		Road network density (X11)	+	0.0224
			Street light coverage rate (X12)	+	0.0350
			Tap water access rate (X13)	+	0.0057
			Number of garbage bins (X14)	+	0.0282
			Number of convenience stores	+	0.0529

		(X15)		
	Infrastructure level	Number of express delivery stations/Agents(X16)	+	0.0595
		Broadband usage rate (X17)	+	0.0095
		Sanitary toilet coverage rate (X18)	+	0.0355
	Healthcare infrastructure	Number of clinics (X19)	+	0.1872
		Number of doctors(X20)	+	0.1179
Natural condition	Land use	Proportion of cultivated land (X21)	+/-	0.0246
		Proportion of forest land (X22)	+	0.0179
		Proportion of grassland (X23)	+	0.0701
		Proportion of orchard Land (X24)	+	0.0483
		Proportion of Built-up area (X25)	+/-	0.0074
	Vegetation Condition	Vegetation Coverage (X26)	+	0.0204
	Ecological Function	Soil conservation (X27)	+	0.0383
		Water yield X28	+	0.0279

Note. "+" indicates a positive indicator, "-" indicates a negative indicator, and "±" indicates a moderate indicator.

2.3.2 Composite Index Method

The stability of social-ecological systems in karst desertification control is influenced by multiple factors across different dimensions, which vary considerably. The composite index method effectively integrates indicators from these dimensions into a single index reflecting the overall system state. Moreover, this method preserves the information contained in each indicator, avoiding bias that may result from using a single indicator, and makes the stability characteristics more intuitive, comparable, and interpretable. Therefore, this study employs the composite index method to calculate the stability of the social-ecological system, providing a scientifically quantified assessment of the overall system state. In this method, indicators from each dimension are combined according to their respective weights to derive a stability index ranging from 0 to 1, where higher values indicate greater system stability, and lower values indicate reduced stability. The specific calculation formula is as follows:

$$S_i=\sum_{j=1}^{p} W_j X'_{ij} \tag{8}$$

In the equation, S_i represents the stability index of the social-ecological system;W_j is the weight of the j indicator, and denotes the standardized value of the j indicator for the i item.

2.3.3 Factor Contribution Model

To identify the key contributing factors to the stability of social-ecological systems in karst desertification control, the factor contribution model is introduced to quantify the contribution of each indicator to system stability. The calculation formula is as follows:

$$G_i=\frac{W_j\times x_j^{'}}{\sum_{j=1}^{m} W_j\times x_j^{'}}\times 100\% \tag{9}$$

$$G_r=\sum_{j=1}^{n} G_i \tag{10}$$

In the equation, G_i represents the contribution of the indicator to system stability, W_j denotes the weight of the indicator, is the standardized value of the indicator, and G_r represents the contribution of the criterion-level factor to system stability.

2.3.4 Obstacle Degree Model

To identify the key factors that hinder improvements in the stability of social-ecological systems in karst desertification management, the obstacle degree model is introduced. This model quantifies the obstructive effect of each indicator on system stability by measuring its deviation from the optimal state and combining it with the indicator's weight. The calculation formula is as follows:

$$P_i=1-x_j^{'} \tag{11}$$

$$Z_i=\frac{W_j\times P_i}{\sum_{j=1}^{m} W_j\times P_i}\times 100\% \tag{12}$$

$$Z_r=\sum_{j=1}^{n} Z_i \tag{13}$$

In the equation, P_i represents the deviation of the indicator, is the standardized value of the indicator, W_j denotes the indicator's weight, Z_i is the obstacle degree of the indicator layer with respect to system stability, and Z_r represents the obstacle degree at the criterion level.

2.4 Classification of Stability Levels

Currently, studies on the stability of social-ecological systems in karst desertification management are relatively limited, and a standardized set of criteria for classifying stability levels has yet to be established. As a typical social-ecological system, karst desertification management areas exhibit marked ecological fragility and social sensitivity, resulting in gradual differences in stability changes. Therefore, this study draws on Li Xiaoxiu’s approach to classifying the stability of mountainous ecosystems (Li, 2000) and Lin Li’s method for grading village ecosystem stability (Lin, 2024), adopting a five-level arithmetic division to classify the stability of social-ecological systems in karst desertification areas. This approach maintains consistency with previous classification logic, ensures continuity between levels, and enhances the comparability and scientific rigor of the evaluation results. The specific classification is presented as follows (Table 2):

Table 2. Classification Standards for Social-ecological System Stability of Karst Desertification Control

Stability Level	I	II	III	IV	V
Range	$0 \leq S_i < 0.2$	$0.2 \leq S_i < 0.4$	$0.4 \leq S_i < 0.6$	$0.6 \leq S_i < 0.8$	$0.8 \leq S_i \leq 1$
Status	Unstable	Relatively low stability	Moderate stability	Relatively high stability	High stability

3. Result

3.1 Evaluation Results of Social-ecological System Stability in Karst Desertification Control

3.1.1 Status of Social-ecological System Stability in the Salaxi Study Area

The stability level of the social-ecological system in the Salaxi study area (0.2154) exhibits the characteristics of “generally low with a few outstanding cases.” Among the nine villages in the area, eight have stability indices below 0.4, accounting for 88.89% of all villages (Figure 2). Among them, Shuiying Village (0.5661) is classified as moderately stable. Salaxi Village (0.3622), Yongfeng Village (0.3595), Longfeng Village (0.3303), and Shale Village (0.3287) are classified as having low stability. However, Chaoying Village (0.1867) is classified as unstable. Field surveys indicate that the overall ecological conditions in the area are relatively good. Karst desertification is mainly at potential to mild levels, with moderate to severe desertification being rare and occurring only in scattered patches across various mountain hollows. At the social level, Chaoying Village exhibits considerable gaps compared to other villages in terms of dependency ratio, education level of management personnel, per capita income, private car ownership, road hardening, street lighting, broadband usage, and sanitary toilet coverage. These issues are interrelated and constitute systemic shortcomings, representing the main factors underlying the low stability of the regional social-ecological system.

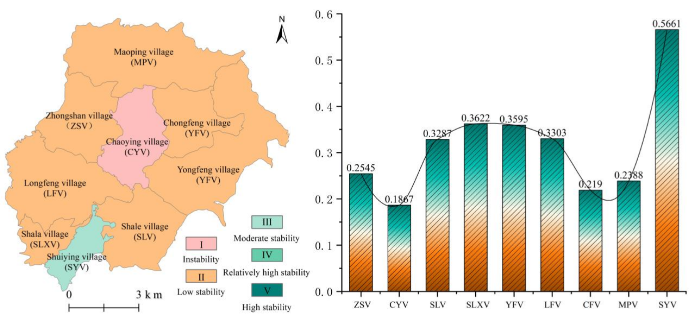

Figure 2. Social-ecological System Stability Status of Karst Desertification Control in the Salaxi Study Area

3.1.2 Status of Social-ecological System Stability in the Qingzhen Study Srea

The stability level of the social-ecological system in the Qingzhen study area (0.3920) is close to moderate stability, exhibiting some internal variability, with a few villages classified as moderately stable or relatively high stability (Figure 3). Among them, Minle Village (0.6562) is classified as relatively high stability, while Gaole Village (0.4845) is classified as moderately stable. Maojiazai Village (0.3234), Youqi Village (0.3460), Gaoshanbao Village (0.2524), Luojiaqiao Village (0.3379), and Ludishao Village (0.3433) are classified as having low stability, although all stability indices exceed 0.3. This is mainly because the Qingzhen study area performs well in terms of ecosystem quality, industrial foundation, and infrastructure, demonstrating greater resistance and resilience to external disturbances, although systemic vulnerability has not been completely eliminated. Comparative analysis of social and ecological conditions across villages and field surveys indicate that the Qingzhen area exhibits similar conditions to Salaxi. The internal ecological environment has achieved significant improvements through comprehensive karst desertification management, with desertification effectively controlled. The previously contiguous light-to-moderate desertified areas have been continuously reduced and are now scattered. Therefore, ecological constraints, particularly the ecological pressure from desertification, are no longer the primary limiting factors for system stability in the area, and their influence has clearly diminished.

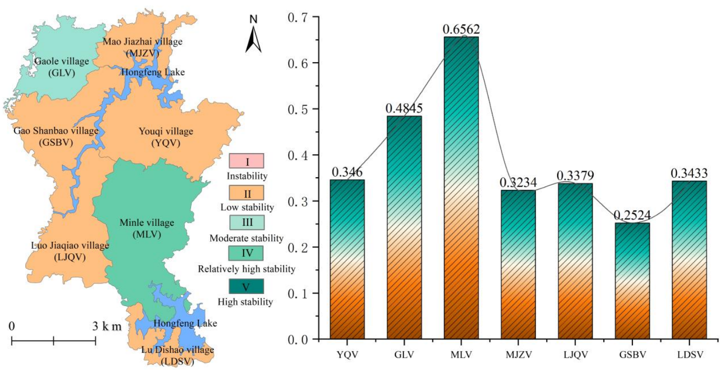

Figure 3. Social-ecological System Stability Evaluation Results of Karst Desertification Control in the Huajiang Study Area

3.1.3 Status of Social-ecological System Stability in the Qingzhen Study Area

The stability level of the social-ecological system in the Huajiang study area (0.2154) is classified as low, with stability indices ranging from 0.16 to 0.26. All villages fall into either low stability or unstable categories, showing strong overall consistency (Figure 4). Among them, Wuli Village (0.1698), Chaeryan Village (0.1873), and Mugong Village (0.1979) are classified as unstable, while Xiagu Village has the highest stability level at only 0.2529. This is mainly due to the generally fragile social and ecological system structure in the Huajiang area, which is prone to functional and structural degradation under natural or anthropogenic disturbances and exhibits severely insufficient resistance to internal and external stressors. At the ecological level, the area represents a typical moderate-to-severe karst desertification region, where long-term desertification management projects have led to significant vegetation recovery. However, the extremely fragile ecological base and extensive exposed bedrock make the overall ecosystem highly sensitive, rendering it highly susceptible to ecological degradation and desertification expansion under anthropogenic disturbances. At the socio-economic level, under the comprehensive desertification management framework, the area initially developed endogenous industries based on Sichuan pepper and, leveraging the unique dry-hot river valley climate, introduced specialty agroforestry products such as dragon fruit, honey plum, Wokan orange, and loquat, which promoted local economic growth in the short term. However, with the development of similar industries in external regions, the impact of homogeneous or superior agroforestry products has gradually eroded the initially established advantages and brand effects. In summary, the combination of a fragile ecological base and industrial challenges has resulted in a low stability level of the social-ecological system in the region.

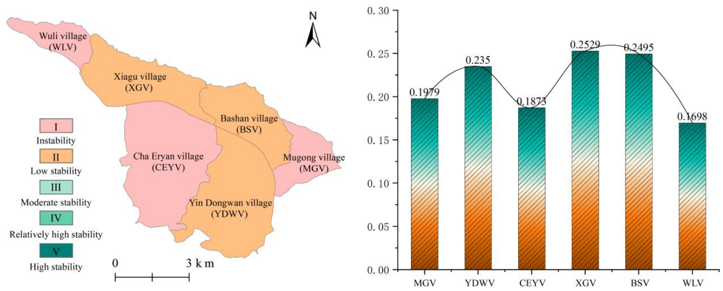

Figure 4. Social-ecological System Stability Evaluation Results of Karst Desertification Control in the Huajiang Study Area

3.2 Factors Influencing the Stability of Social-ecological Systems in Karst Desertification Control

3.2.1 Factors Affecting the Stability of the Social-ecological System in the Salaxi Study Area

A comparison of the contribution and obstacle degrees of the social-ecological system stability in the Salaxi study area reveals a clear asymmetry between these two measures (Figure 5). There is no one-to-one correspondence between high contribution-low obstacle or low contribution-high obstacle for individual indicators. For example, indicators X20 (9.1%), X28 (7.98%), X5 (6.9%), X3 (5.55%), and X26 (5.12%) exhibit significantly high contributions, acting as the main contributors to system stability. In contrast, the indicators with the lowest obstacle degrees are X13 (0.13%), X5 (0.2%), X1/X6/X25 (0.33%), X17 (0.54%), and X2 (0.71%), which do not correspond to the highest contributors. Moreover, indicators X19 (23.46%), X20 (11.52%), X23 (8.00%), X16 (7.03%), and X15 (6.82%) show notably high obstacle degrees, representing the main bottlenecks restricting system stability. Meanwhile, the indicators with the lowest contributions—X24 (1.33%), X14 (1.45%), X13 (1.64%), X1 (1.80%), and X25 (1.85%)—do not correspond to the major obstacles. Furthermore, comparison indicates that indicators X7, X12, X14, X15, X16, X18, X19, X20, X23, X24, and X27 have contribution effects smaller than their obstacle effects. This indicates that the constraining effects of these indicators on social-ecological system stability exceed their positive contributions. Their current levels, structural configuration, or functional performance lag behind system stability requirements, making them key bottlenecks limiting stability improvement. These factors tend to amplify external shocks and internal vulnerabilities within the region, thereby weakening system resilience and recovery capacity. Therefore, these factors should be prioritized in strategies aimed at enhancing system stability.

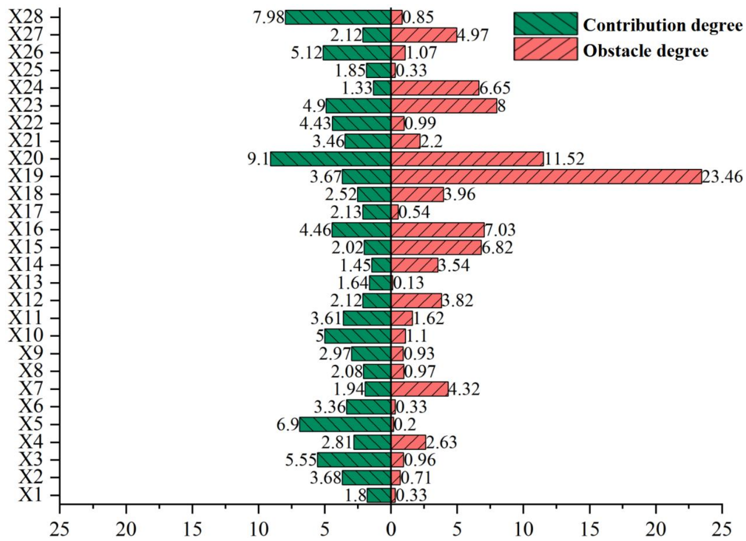

Figure 5. Comparison of Contribution and Obstacle Degree to Social-ecological System Stability in the Salaxi Study Area (Mean)

3.2.2 Factors Affecting the Stability of the Social-ecological System in the Qingzhen Study Area

A comparison of contribution and obstacle degrees in the Qingzhen study area similarly reveals an asymmetrical relationship between these measures, with few indicators exhibiting a one-to-one correspondence of high contribution-low obstacle or low contribution-high obstacle (Figure 6). For example, indicators X19 (9.59%), X18 (9.45%), X7 (6.20%), X23 (6.08%), and X12 (5.59%) show the highest contributions, acting as the primary contributors to system stability. In contrast, the indicators with the lowest obstacle degrees—X13/X17 (0.00%), X9 (0.13%), X1 (0.20%), X25 (0.27%), and X18 (0.33%)—do not correspond to the highest contributors. Moreover, indicators X19 (19.73%), X20 (17.87%), X23 (7.48%), X16 (7.05%), and X15 (6.18%) exhibit the highest obstacle degrees, representing the main bottlenecks limiting system stability. The indicators with the lowest contributions—X28 (0.85%), X27 (1.46%), X22 (1.50%), X1 (1.55%), and X25 (1.58%)—do not correspond to these major obstacles. Furthermore, comparison indicates that indicators X15, X16, X19, X20, X22, X23, X24, X27, and X28 have contribution effects smaller than their obstacle effects. This indicates that the negative effects of these indicators on regional system stability outweigh their positive contributions. Therefore, these indicators should be prioritized as key targets for intervention in future efforts to enhance regional system stability.

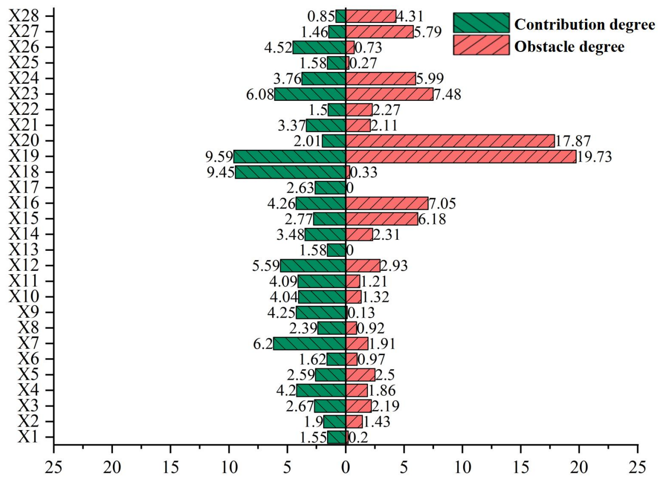

Figure 6. Comparison of Contribution and Obstacle Levels to Social-ecological System Stability in the Qingzhen Study Area (Mean)

3.2.3 Factors Affecting the Stability of the Social-ecological System in the Huajiang Study Area

A comparison of contribution and obstacle degrees in the Huajiang study area similarly reveals an asymmetrical relationship between these measures, with few indicators showing a one-to-one correspondence of high contribution-low obstacle or low contribution-high obstacle(Figure 7) . For example, indicators X24 (11.38%), X27 (10.03%), X5 (6.54%), X28 (5.28%), and X12 (4.88%) exhibit the highest contributions, acting as the primary contributors to system stability. In contrast, indicators with the lowest obstacle degrees—X13/X17 (0.00%), X1 (0.17%), X25 (0.34%), X5 (0.73%), and X9 (0.95%)—do not correspond to the highest contributors. Moreover, indicators X19 (21.88%), X20 (13.26%), X23 (7.90%), X16 (6.47%), and X15 (6.27%) show the highest obstacle degrees, representing the main bottlenecks restricting system stability. The indicators with the lowest contributions—X19 (0.00%), X4 (1.07%), X26 (1.47%), X10 (1.87%), and X15 (2.06%)—do not correspond to the major obstacles, except for X19. Comparison indicates that indicators X3, X4, X7, X10, X14, X15, X16, X20, X23, and X26 have contribution effects smaller than their obstacle effects. This indicates that the negative effects of these indicators on regional system stability exceed their positive contributions. Therefore, these indicators should be prioritized as key targets for intervention in future efforts to enhance regional system stability.

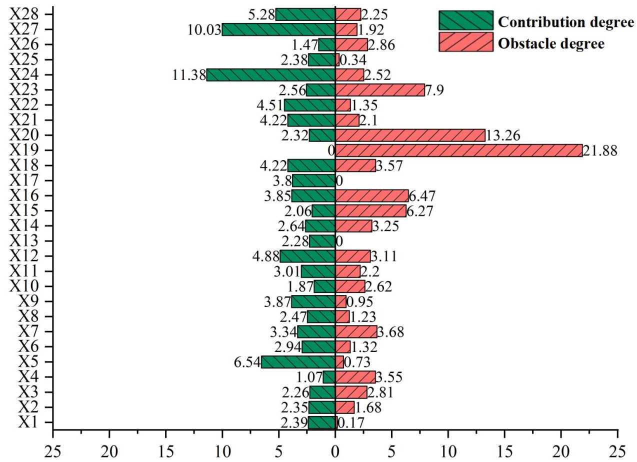

Figure 7. Social-ecological System Stability Contribution-obstacle Coupling Discrimination Index in Huajiang Study Area

4. Discussion

4.1 Comparison of Social-ecological System Stability Across Study Areas

The stability levels of social-ecological systems differ significantly across study areas, with Qingzhen (0.3920) exhibiting the highest stability, followed by Salaxi (0.3162) and Huajiang (0.2154). Field investigations indicate that the lower stability observed in Salaxi and Huajiang, compared with Qingzhen, is primarily due to the relatively simple regional economic structure, limited land-use resources, and low productivity, which have driven substantial labor outmigration. Meanwhile, limited economic benefits constrain the provision of public services and infrastructure, resulting in relatively weak risk resistance and adaptive capacity within the social subsystem (Chen., 2025). Under the combined effects of natural vulnerability and insufficient development support, the coupling and coordination among social-ecological system components remain low, resulting in overall reduced stability. Compared with Salaxi, Huajiang exhibits even lower stability, with parts of the area falling into an unstable state. This is primarily due to a more fragile ecological base and overlapping difficulties in industrial development, which have pushed the region into a livelihood crisis (Ren et al., 2020). Specifically, in Huajiang, the widespread distribution of moderate to severe karst desertification, limited land resources, and the influence of a hot-dry river valley climate contribute to highly fragile and sensitive ecological conditions, exacerbating human-land conflicts (Jia et al., 2024).

4.2 Analysis of Factors Influencing Social-ecological System Stability across Study Areas

Based on the contribution and obstacle analyses at the criterion level across the three types of karst desertification management study areas (Figure 8), the impacts of social-ecological system criteria on stability show significant inter-area differences. In terms of contributions, all three management types exhibit multidimensional synergistic effects, with social economy, public services, and natural conditions all significantly influencing stability. However, the dominant dimension varies with desertification severity: in the potential–mild Salaxi area, contributions are relatively balanced, each exceeding 30%—social economy 36.09%, public services 32.72%, and natural conditions 31.19%. In the mild-moderate Qingzhen area, contributions are 31.42% for social economy, 45.47% for public services, and 23.11% for natural conditions, with public services as the primary contributor. In the moderate-severe Huajiang area, contributions are 29.11%, 26.74%, and 44.15% for social economy, public services, and natural conditions, respectively, indicating that natural conditions play the dominant role in overall regional stability. Regarding obstacles, all three study areas share the characteristic that public services constitute the primary limiting factor, with overall obstacle degrees significantly higher than those of social economy and natural conditions. In Salaxi, Qingzhen, and Huajiang, public service obstacle degrees are 62.44%, 57.63%, and 60.00%, respectively, indicating that underdeveloped public service systems represent a key bottleneck constraining improvements in regional social-ecological system stability. Overall, the three study areas exhibit a common pattern in stability formation mechanisms characterized by "multi-factor joint driving and widespread public service constraints." Stability enhancement depends on the coordinated optimization of social economy, public services, and natural conditions, while insufficient public service capacity represents a universal core limitation. Furthermore, in the ecologically extremely fragile Huajiang area, ecological risks and development challenges remain strongly coupled, representing a key challenge for sustained improvements in system stability.

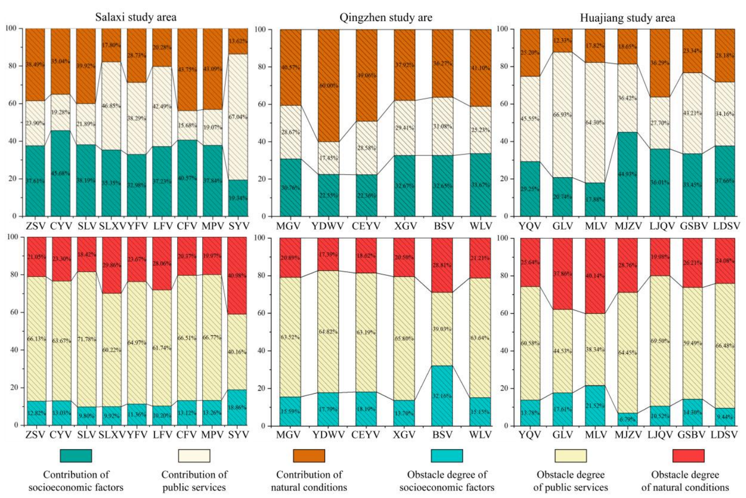

Figure 8. Contribution and Obstacle Degree of the Criterion Layer of Social–ecological System Stability in Different Study Areas

4.3 Limitations and Prospects

4.3.1 Lack of Long-term Time Series Evaluation of System Stability

Given the difficulty of obtaining long-term continuous regional data, this study focuses on assessing social-ecological system stability across management areas with different degrees of desertification over a short-term timescale. However, karst desertification management and its outcomes are inherently long-term and exhibit delayed effects (He et al., 2019). That is, the restoration of vegetation and the enhancement of soil and water conservation functions only become apparent under the sustained implementation of various management measures, while the associated socio-economic benefits require even longer periods to gradually materialize (Yang et al., 2008). This characteristic implies that the evolution of social-ecological systems in desertification management areas is a dynamic process. Therefore, relying solely on short-term data collection for analyzing system structure and evaluating stability provides insights primarily into the system's stage-specific state, failing to capture its long-term evolution. This may lead to underestimation or overestimation of the true influence of certain factors. Future studies could establish multi-source, multi-scale long-term monitoring systems—including ecological monitoring data, remote sensing imagery, socio-economic statistics, and policy implementation information—to construct continuous and stable long-term time series datasets. Subsequently, building on existing analytical and evaluation methods, time series analysis techniques—such as autoregressive integrated moving average (ARIMA) models and seasonal-trend decomposition using Loess (STL)—can be applied to reveal temporal patterns of social-ecological system structure and stability across different desertification management areas, and to forecast future changes in system structure and stability over time.

4.3.2 The Evaluation Indicator System for Social-ecological System Stability Still Has Certain Limitations

The current indicator system mainly selects general social, economic, and ecological indicators, which can reflect the overall functioning of the system. However, it remains insufficient for characterizing social-ecological system stability in the specific context of desertification management areas. Future studies should select comprehensive indicators within the social-ecological system theoretical framework, constructing the system across three levels: ecological, socio-economic, and their coupling. At the ecological level, indicators should reflect ecological conditions and quality, such as vegetation cover, rock exposure, effective soil layer thickness, soil organic matter content, soil retention, water conservation capacity, and habitat connectivity. They should also capture disturbance resistance and ecological resilience, including vegetation recovery stability indices, ecosystem recovery rates, and functional fluctuations under extreme climatic events or human disturbances. At the socio-economic level, indicators should focus on regional development and governance support capacity. In addition to population structure, livelihood composition, public services, and infrastructure accessibility, policy support capacity should also be included. At the coupling level, indicators may include ecological industry development, coordination between ecological compensation and land-use structure, and changes in social pressures on the ecosystem.

5. Conclusion

This study developed a social-ecological system stability evaluation framework to assess three study areas with varying degrees of karst desertification and to identify the key factors influencing stability. The main conclusions are as follows: (1) Stability levels rank as follows: Qingzhen (0.3920) > Salaxi

(0.3162) > Huajiang (0.2154). Within Salaxi, Chaoying Village (0.1867), and within Huajiang, Wuli Village (0.1698), Chaeryan Village (0.1873), and Mugong Village (0.1979) are classified as unstable. Targeted human interventions are therefore required to enhance social resilience and improve ecological conditions in order to reverse the unstable state. (2) All indicators exhibit clear asymmetry between their contribution and obstacle effects. Specifically, X15, X16, X20, and X23 show lower contribution effects than obstacle effects across all three study areas, and should therefore be prioritized as key intervention targets for improving system stability. (3) In all three study areas, social-ecological system stability is jointly driven by ecological, socio-economic, and public service dimensions. However, the obstacle effect of public services is particularly pronounced, with criterion-level obstacle degrees reaching 62.44% in Salaxi, 57.63% in Qingzhen, and 60.00% in Huajiang.

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