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Towards Sustainable Ecotourism in a Proposed Karst National Park, Southwest China: A Social-Ecological Adaptability Assessment and Zoned Management Strategy

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Abstract

This exploratory case study assesses ecotourism adaptability across three zones within the proposed Southwest Karst National Park (Guangxi), where UNESCO-recognised geological heritage intertwines with diverse ethnic cultures. To fill the gap in zone-specific integrated assessment frameworks, we employed a two-stage entropy-weighted TOPSIS method—calibrated via Delphi-AHP adjustments within a Social-Ecological Systems framework—using 2023–2024 data, complemented by ethnographic observations. Preliminary results indicate divergent trajectories: the Tiankeng zone exhibits high geological uniqueness and market appeal (composite score 0.74); the Mulun zone shows relatively balanced social–ecological coupling (0.58); and the Underground River zone displays pronounced asymmetry between vulnerability and development potential (0.16). Accordingly, tentative daily visitor caps of 3000, 8000, and 14 persons, respectively, and a pilot adaptability alert threshold of 0.20 for this specific case are proposed. These findings reveal a “vulnerability–capacity inverse matching” dynamic, informing differentiated governance: high-adaptability zones may allow moderate tourism with real-time monitoring, whereas low-adaptability zones require strict conservation-first measures and phased institutional capacity-building prior to any development. This preliminary framework offers actionable insights for sustainable management, conceptually aligned with SDG 11.4 and SDG 15.9.

Keywords: social–ecological system; sustainable tourism; entropy-weighted TOPSIS; Southwest Karst National Park; adaptive management; China



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1. Introduction

The proposed Southwest Karst National Park (Guangxi) epitomizes a typical sustainable tourism dilemma in geomorphologically unique regions: it accommodates valuable geological assets and ethnic biocultural heritage while facing rigorous ecological constraints. As China continues expanding its national park system across diverse landform contexts, site-specific, evidence-based zoning governance is essential to integrate ecological conservation, cultural inheritance, and rural livelihood enhancement. These interrelated dimensions underpin modern sustainable tourism principles and align closely with global Sustainable Development Goals (SDGs) [1,2].

This study is shaped by three overlapping national policy imperatives that govern contemporary socioecological practices in China. First, the national park pilot program, launched in 2015 and scaled up nationwide in 2021, prioritizes synergistic advancement of ecological protection and rural revitalization across geographically distinctive landscapes. Second, Southwest China's karst terrains host densely populated yet socioeconomically vulnerable ethnic minority communities, where tourism development has become a key policy-driven approach for local poverty alleviation and grassroots socioeconomic sustainability. Third, the park's cross-administrative coverage induces inherent institutional fragmentation, as divergent local development agendas impede unified, coordinated governance for ecological preservation and ecotourism regulation.

Globally, karst outdoor tourism has evolved from mass tourism toward low-impact, high-value models focused on visitor management, ecological integrity, and equitable benefit-sharing. Within a social-ecological resilience framework, sustainable governance emphasizes adaptive capacity to absorb anthropogenic pressures while sustaining ecosystem functions, rather than maintaining a fixed equilibrium. Existing frameworks have underscored the interactive feedback among tourist activities, institutional settings, and ecological responses, along with the critical role of threshold-based governance in averting irreversible change before tipping points are reached [3]. Participatory decision-making is broadly recognized as key to sustainability, yet such community-inclusive mechanisms are scarce in subtropical karst regions. Exacerbating this institutional gap, local karst ecosystems are inherently fragile—so much so that even minor disturbances may induce lasting ecological shifts, often outpacing the detection capabilities of routine monitoring [4].

Despite well-established global theoretical foundations, domestic research on karst ecotourism in China remains fragmented and methodologically constrained. Existing studies have acknowledged the intrinsic trade-offs between ecological vulnerability and tourism expansion, proposed protection-oriented development pathways, and evaluated tourism-induced cave environmental degradation [4,5]. However, most of the local literature adopts segmented, sectoral perspectives and fails to integrate geological heritage value, ecological fragility, and ethnic biocultural resources within a unified SES resilience framework. Most notably, few studies have quantified ecological tipping thresholds or formulated zoning-tailored mechanisms for equitable community benefit distribution. This critical research gap prevents the effective translation of the region's triple core attributes—unique geological heritage, high ecological susceptibility, and distinctive ethnic culture—into contextually feasible zoning strategies, thereby limiting the potential for conceptual alignment with SDG 11.4 and SDG 15.9 in subtropical karst protected areas.

To move beyond this operational gap, this exploratory case study develops a locally grounded analytical framework and derives a preliminary adaptability threshold for zone-level karst tourism governance. Rather than pursuing generalized assessment models, we offer localized empirical insights that may inform differentiated management practices.

2. Literature Review and Theoretical Framework

This section presents the theoretical basis of our study through a literature review spanning three interconnected domains: social-ecological system (SES) resilience in protected area governance, multidimensional sustainable tourism evaluation, and cultural capital dynamics in biocultural landscapes. Based on this review, we construct a hierarchical framework that clarifies the relationships among SES resilience, five core evaluation dimensions (community, market, economy, resources, and ecology), and 19 selected indicators (Figure 1). By synthesising current theoretical advances and identifying remaining research gaps, this section articulates the conceptual rationale and the exploratory stance of our case study.

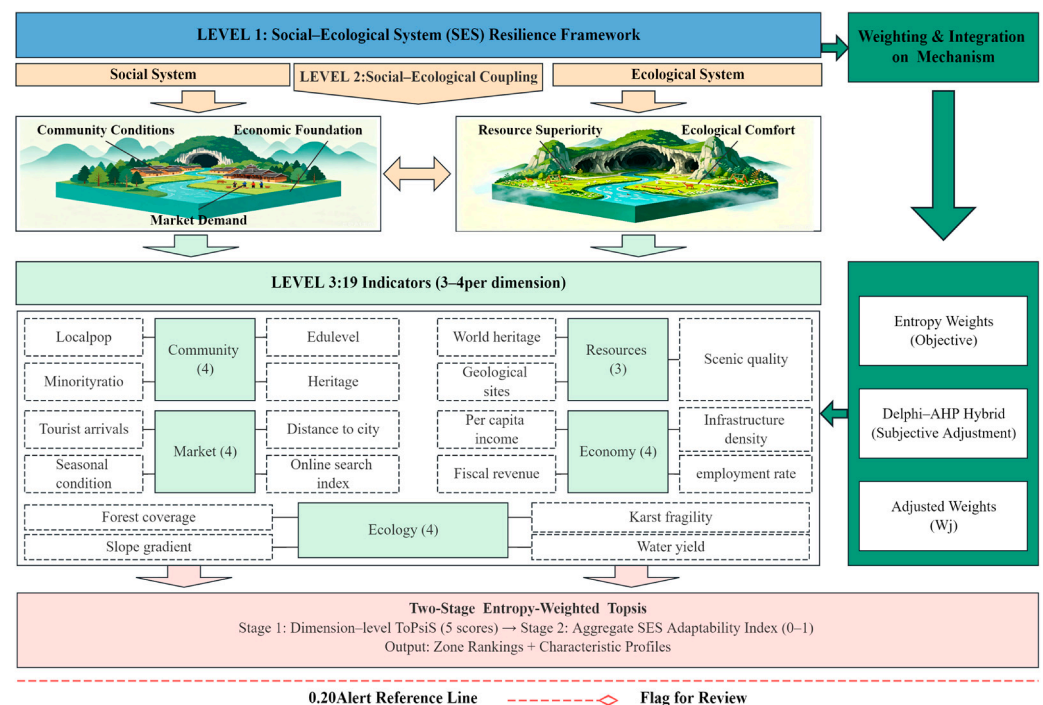


Figure 1. Theoretical framework and analytical workflow for assessing social-ecological adaptability in the proposed Southwest Karst National Park (Guangxi) [6,7]. Level 1: The SES resilience framework serves as the overarching theoretical lens. Level 2: Five analytical dimensions are organized into Social (community, market, economy) and Ecological (resources, ecology) subsystems with bidirectional coupling. Level 3: Nineteen indicators operationalize the framework. The Delphi-AHP hybrid adjusts entropy-derived objective weights, feeding into a two-stage entropy-weighted TOPSIS to produce a composite SES adaptability index. The conceptual diagram was created using WPS Office (2024, Kingsoft Office Software Corporation Limited, Zhuhai, China).

2.1. SES Resilience Theory in Protected Area Management

The SES framework, originally proposed by Ostrom [6] and extended by McGinnis and Ostrom [7], provides the overarching theoretical lens for this study. It treats coupled human–natural systems as dynamically adaptive, where institutional settings, resource attributes, and stakeholder behaviours jointly influence socioecological outcomes. In protected area contexts, SES resilience is often characterised by three core attributes: ecological integrity, systemic adaptive capacity, and governance effectiveness [8,9].

Recent advances in tourism governance have enriched SES resilience theory, highlighting human–ecological feedback mechanisms and cross-scale governance interactions. Miller et al. [8] proposed a recreation ecosystem framework that explicitly links tourist behaviours, institutional arrangements, and ecological processes, offering theoretical support for resilience-based outdoor tourism management. Ferguson et al. [9] found that isolated site-specific interventions may be insufficient to address systematic ecological risks, suggesting the need for threshold-informed governance to avoid irreversible regime shifts. Comparative studies in European protected areas further indicate that participatory and community-engaged decision-making appears to be a key factor in sustainable tourism outcomes [5]. Nevertheless, such resilience-oriented and inclusive governance approaches have received limited application in subtropical karst regions, where the unique ecological fragility and multi-ethnic social-ecological characteristics have not been adequately examined in existing SES literature.

These three core attributes find deeper theoretical grounding in the broader SES resilience literature. Holling [10] first distinguished engineering resilience—return speed to a single equilibrium—from ecological resilience—the capacity to persist within a basin of

attraction despite disturbance—establishing the conceptual vocabulary for non-linear system dynamics that underpins protected area vulnerability analysis. Walker et al. [11] subsequently formalised three interrelated system-level properties—resilience, adaptability, and transformability—that describe how coupled human–natural systems absorb perturbation, self-organise, and potentially shift to alternative configurations. Folke et al. [12] extended this architecture by theorising adaptive governance as the institutional mechanism through which polycentric decision structures, social learning, and cross-scale coordination translate these properties into management practice. Biggs et al. [13] synthesised these cumulative insights into seven operational principles for building SES resilience, explicitly including the maintenance of diversity and redundancy, the management of connectivity, and the cultivation of complex adaptive systems thinking. Together, this theoretical lineage affords a coherent scaffold for interpreting the ecological integrity, adaptive capacity, and governance effectiveness identified in the case study as interdependent expressions of a single resilience process, rather than as isolated management targets. Its applicability to geomorphologically specialised protected areas—where extreme soil fragility and slow pedogenesis generate vulnerability profiles qualitatively distinct from those assumed in general SES models—nevertheless remains comparatively underdeveloped, motivating the exploratory integration attempted here.

2.2. Sustainable Tourism Evaluation Methods

Sustainable tourism evaluation has undergone a paradigm shift from static carrying capacity models towards more comprehensive multi-dimensional assessment frameworks. Traditional carrying capacity approaches often rely on assumptions of ecological equilibrium and homogeneous estimates of visitor impacts, which may inadequately capture the non-linear dynamics or tipping-point behaviour characteristic of fragile karst social-ecological systems (SESs); these limitations imply that universal threshold setting may be impractical for karst protected area governance [6]. Recognising these constraints, researchers have increasingly turned to multi-criteria decision analysis (MCDA) tools—including AHP, TOPSIS, and their hybrid variants—which have been extensively applied in sustainability assessments for protected areas [9,14]. Within this toolkit, entropy-weighted TOPSIS offers particular applicability in data-scarce karst settings, as it derives indicator weights from inter-zonal information dispersion rather than covariance structures and does not require predefined data distributions, making it suitable for small-sample comparative evaluations [15]. It should be noted, however, that this method supports relative ranking and profiling rather than causal inference—a limitation we explicitly acknowledge. Building on this methodological foundation, Córdoba Hernández and Camerin [16] suggest that quantitative ecosystem metrics can be translated into spatial planning strategies, providing a relevant precedent for linking multidimensional assessment outputs to zone-specific governance practices in this study.

The suitability of entropy-TOPSIS for protected-area tourism planning has been progressively validated across Chinese contexts that differ in geographic proximity, spatial scale, and evaluation objective, thereby offering cumulative methodological support for its adoption in the present study [9,10]. At the local scale, Lu et al. [17] applied the framework to assess tourism-community resilience in Ping'an Village, Guilin (Guangxi)—a subtropical karst region adjacent to the present study area—demonstrating that the method can capture the interaction between ethnic livelihoods, landscape fragility, and visitor pressure using locally available indicators. Extending this approach to multi-site comparisons, Meng et al. [18] employed a hybrid entropy-TOPSIS model to rank rural ecotourism development potential across multiple sites in Southwest China, confirming that agricultural landscape, economic, and ecological indicators can be integrated into composite indices

without requiring large-sample distributional assumptions. Beyond southwestern karst corridors, Zhang et al. combined information entropy with TOPSIS to evaluate destination competitiveness in the Yangtze River Delta, a markedly different physiographic and economic context, thereby establishing that the method transfers across heterogeneous indicator sets and governance regimes. At the broadest scale, Wang et al. [19] conducted a provincial-level sustainable tourism evaluation across all of China, showing that entropy-TOPSIS retains discriminatory power even when standardised national datasets replace local field measurements. Taken together, these four studies provide three specific assurances for the present application: (i) geographic transferability within subtropical karst corridors of Southwest China; (ii) indicator flexibility sufficient to accommodate ecological, economic, and cultural dimensions simultaneously; and (iii) operational robustness under the small-sample, data-scarce conditions characteristic of single-park assessments. These attributes directly address the karst-specific methodological requirements identified above and justify the selection of entropy-weighted TOPSIS as the core analytical engine of this framework.

2.3. Cultural Capital in Biocultural Landscapes

Complementing the methodological framework discussed above, the integration of ethnic cultural capital into SES resilience analysis has emerged as a growing area of inquiry for biocultural landscape stewardship. Cultural capital—including intangible heritage, traditional ecological knowledge, and community identity—may serve as an informal institutional factor that influences human–land relationships and potentially moderates ecological pressures [20]. Although its theoretical relevance is broadly acknowledged, empirical evidence on its actual mediating effects for conservation and tourism sustainability remains relatively limited, particularly within karst social-ecological contexts where cultural and geological uniqueness co-exist.

This theoretical gap is particularly salient in Southwest China’s karst areas, where ethnic minority groups such as the Bunu Yao and Maonan maintain traditional ecological norms—including sacred mountain worship and forest conservation taboos—that may inherently moderate unsustainable resource use and temper excessive tourism development [21]. Despite the evident presence of such locally embedded cultural capital, few studies have systematically incorporated it into karst SES assessment frameworks. In this context, Das and Mishra [22] proposed a regenerative tourism model integrating circular economy principles with community resilience, offering a conceptual basis for linking cultural capital to adaptive park governance. Yet a fundamental methodological challenge persists: existing cultural capital indicators typically capture spatial variation across management zones rather than quantify causal effects on conservation outcomes. Consequently, we treat cultural capital as a hypothesised mediating dimension and explore its potential empirical relevance within the karst SES context.

Empirical research on cultural capital in conservation contexts has expanded beyond theoretical acknowledgment toward operational frameworks, offering useful precedents for the exploratory approach adopted here. Goessling and Peeters [23] demonstrated that local community engagement in tourism governance often mobilises traditional ecological knowledge as an informal regulatory mechanism, particularly where formal institutions are weak. Complementing this perspective, Argumedo and Stenner [24] documented community-managed cultural ecotourism in Indigenous Biocultural Heritage Areas, showing that co-designed tourism models can simultaneously generate conservation incentives and livelihood benefits when supported by enabling governance structures. Cordoba Hernandez and Camerin [16] further highlighted that geological uniqueness co-located with ethnic cultural diversity creates distinctive opportunities for heritage-based tourism dif-

ferentiation. Yet, as Urošević et al. [20] cautioned, existing cultural capital indicators in sustainability assessments typically capture spatial variation rather than quantify causal pathways between cultural endowment and conservation behaviour. This methodological limitation reinforces our decision to treat cultural capital as an exploratory dimension within the present framework, examining its empirical relevance without claiming causal inference.

2.4. Exploratory Research Objectives of This Study

Building on the theoretical synthesis and research gaps identified above, we adopt an exploratory case study design with four context-specific and tentative objectives, without aiming to develop generalised assessment models or universal governance standards. First, we attempt to construct an integrated analytical framework that unifies geological heritage value, ecological vulnerability, and ethnic cultural capital within a coherent SES resilience perspective, thereby addressing a gap in multidimensional evaluation within karst tourism governance research. Second, we comparatively examine zone-level tourism adaptability patterns across three administrative units. Given the small sample size ($n = 3$), our analysis emphasises relative characteristic profiling rather than statistical inference or significance testing. Third, drawing on the entropy-weighted TOPSIS results and international governance precedents, we offer pilot management suggestions intended as exploratory practical references rather than as mandatory regulatory criteria. Fourth, we propose a tentative adaptability alert threshold of 0.20 to facilitate preliminary identification of ecologically sensitive zones where development restrictions may be warranted. This threshold is highly specific to the studied karst national park; hence, it requires further longitudinal verification and regional calibration before any broader application.

3. Materials and Methods

3.1. Study Area

The Proposed Southwest Karst National Park (Guangxi) covers 2183 km² in northwest Guangxi and comprises three zones (Figure 2).

3.2. Evaluation Framework

Given that karst social–ecological systems exhibit non-linear responses, threshold effects, and contextual vulnerabilities, it may be challenging to establish universally applicable governance thresholds. Accordingly, rather than relying on static equilibrium assumptions, this study attempts to construct an adaptive and contextualised assessment framework. The quantitative TOPSIS results were triangulated with qualitative field evidence, including ethnographic observations conducted during 2023–2024 and structured interviews with experts, with the aim of providing data-supported and context-relevant governance references for the local park.

The qualitative validation component employed a structured triangulation protocol. Ethnographic observations were conducted during four field campaigns (March 2023, August 2023, November 2023, and March 2024), each lasting 7–10 days, across all three zones. Two researchers participated in direct observation of 23 village-level community gatherings, 15 informal interviews with village committee members, and 8 structured focus-group discussions with local residents ($n = 64$ participants total: 22 Bunu Yao, 18 Maonan, 14 Zhuang, 10 Han). All ethnographic encounters were documented using standardised field notes, audio recordings (with oral consent), and photographic records. Thematic analysis was performed independently by two coders using a deductive-inductive hybrid approach; qualitative data were organised and coded using Microsoft Excel (2016, Microsoft Corporation, Redmond, WA, USA): deductive codes were derived from the five SES evalua-

tion dimensions (community, market, economy, resources, ecology), while inductive codes emerged from grounded reading of the field notes. Inter-coder reliability was assessed using Cohen kappa ($\kappa = 0.84$), indicating substantial agreement. Key qualitative themes included: (i) widespread concern about soil erosion in the Underground River Zone (mentioned by 89% of participants); (ii) strong community support for geo-science tourism in the Tiengkeng zone (78% positive); and (iii) expressed need for infrastructure investment and benefit-sharing mechanisms in the Mulun Zone (91% of participants). These qualitative findings directly informed the directional specifications of indicators, the calibration of carrying-capacity parameters, and the design of zone-specific adaptation models, thereby strengthening the contextual validity of the quantitative assessment.

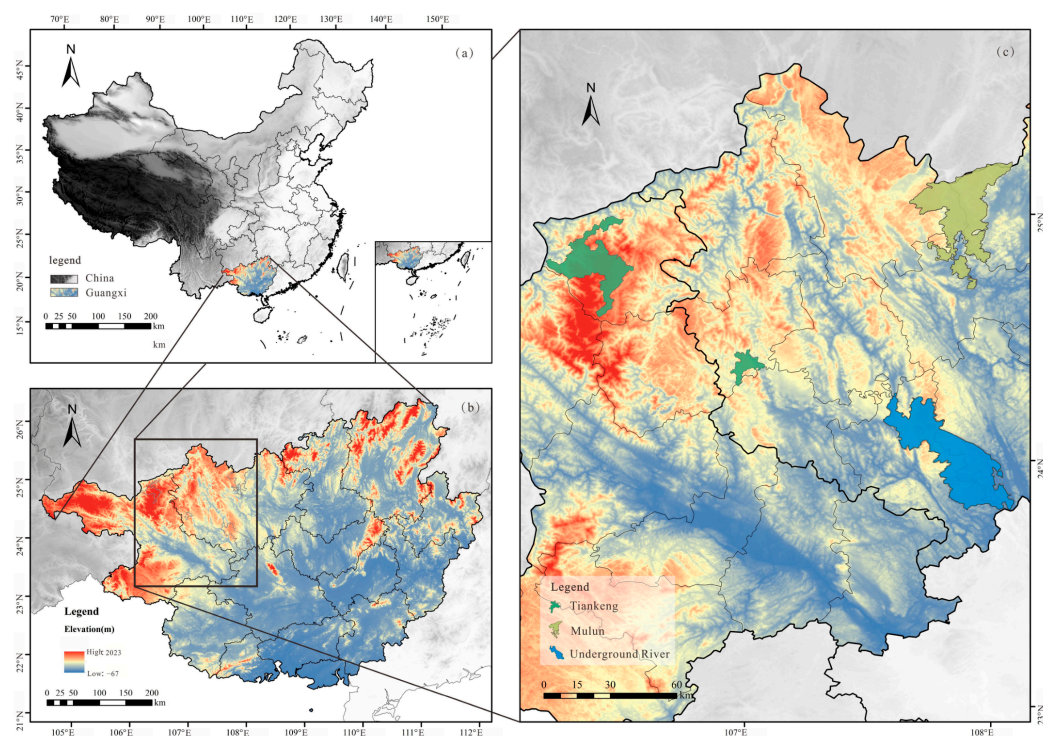


Figure 2. Schematic diagram of the Proposed Southwest Karst National Park (Guangxi). (a) The location of Guangxi within China; (b) The location of the proposed Southwest Karst National Park in Hechi and Baise cities, Guangxi; (c) A schematic diagram of the three zones of the proposed Southwest Karst National Park. Tiengkeng (Leye & Fengshan): The Tiengkeng zone comprises two subunits: Leye, which hosts the world’s largest tiengkeng cluster, and Fengshan, home to the only known water-filled cenote cluster (Sanmenhai). Nevertheless, geo-science tourism in both areas remains at an early stage of development. Underground River (Dahua & Du’an): Centered on the Qibai Nong peak-cluster depressions and the Disu Underground River system, this core Bunu Yao area bears 11 intangible heritage items, yet suffers the most severe development lag, poorest accessibility, and highest rocky desertification of the three zones. Mulun (Huanjiang, Nandan & Jinchengjiang): Boasts the world’s best-preserved subtropical cone-shaped peak-cluster forest and hosts China’s only Maonan autonomous county, with socio-economic conditions better than those of the other two zones. Maps were generated using ArcGIS (Version 10.8.1, Esri Inc., Redlands, CA, USA).

We applied a two-stage entropy-weighted TOPSIS approach within a unified social–ecological system (SES) framework to quantify the social–ecological adaptability of each subzone. In the first stage, a weighted arithmetic mean method was used to aggregate the normalised indicators, thereby deriving subsystem scores for community, market, economy, resources, and ecology. Prior to the analysis, all negative indicators were positively transformed by taking their reciprocals, following the standard practice in entropy-weighted TOPSIS applications, to ensure uniform directional interpretation before vector

normalisation. In the second stage, these subsystem scores were integrated into a composite SES adaptability index using weights validated through a two-round Delphi–AHP hybrid weighting procedure ($\omega_{\text{social}} = 0.55$, $\omega_{\text{ecological}} = 0.45$). The expert panel consisted of five members: two technical professionals with over 15 years of field experience in Southwest China; one researcher who has long conducted ethnic cultural studies in the minority areas of Guangxi; one administrator involved in the pilot work of national parks; and one professor-level senior engineer specialising in tourism, with 12 years of experience in sustainable development policy evaluation. Purposive sampling was adopted to balance academic expertise and practical management perspectives. The average professional experience of the panel was 14.3 years (SD = 4.1). All experts participated in two consecutive rounds of Delphi discussions. Consensus was determined based on predefined criteria: a coefficient of variation below 0.25 and a concordance ratio above 0.80. The final weights were derived by integrating objective entropy weights (40%) with subjective Delphi and AHP expert judgements (60%). Detailed weight distributions and the evolution of consensus are presented in Tables S1 and S2 in the Supplementary Materials.

In this study, the directional specifications for all indicators were justified based on the social–ecological characteristics of subtropical karst landscapes and the practical needs of park management. These specifications were intended as context-specific pilot hypotheses rather than definitive technical norms. First, population size was treated as a negative indicator. In the study area, severe rocky desertification and a slow soil formation rate (0.02–0.05 mm/year) render the soil highly fragile; a larger resident population tends to exacerbate soil degradation, fuelwood collection, and habitat encroachment [4]. Although local residents also support tourism services and cultural transmission, ecological conservation was prioritised given the current vulnerability of the ecosystem. Second, Distance to Community Settlements was assigned a negative value, as remote areas often hinder emergency response, waste management, and the provision of public services, which may impede safe and standardised tourism operations in rugged karst terrain. Third, community education level was given a positive value, because a higher education level tends to enhance adaptive capacity and awareness of participatory governance. Although improved education may also lead to youth out-migration, potentially affecting the local labour force required for tourism and heritage management, this indicator nevertheless reflects the human capital available for local governance among the stable resident population. Fourth, Ethnic Cultural Richness was assigned a positive value, as diverse intangible cultural resources can serve as distinctive tourism assets and foster endogenous conservation impetus. However, these assumptions regarding the links between culture and sustainability remain speculative and have not yet been empirically verified. All directional configurations are context-dependent and provisional; alternative theoretical frameworks may yield different results.

3.3. Analytical Procedure

Software and Computational Environment. All statistical computations, including entropy-weighted TOPSIS analysis, data normalisation, and matrix operations, were performed using Python (Version 3.10, Python Software Foundation, Wilmington, DE, USA). Raw data were organised and pre-processed using Microsoft Excel (2016, Microsoft Corporation, Redmond, WA, USA). Spatial data processing and map generation were conducted using ArcGIS (Version 10.8.1, Esri Inc., Redlands, CA, USA). Conceptual diagrams and workflow illustrations were created using WPS Office (2024, Kingsoft Office Software Corporation Limited, Zhuhai, China). Data visualisation, including radar charts and profile plots, was carried out using Python (Version 3.10, Python Software Foundation, Wilmington, DE, USA).

(a) Calculation of the Entropy-Weighted TOPSIS Composite Score

The entropy-weighted TOPSIS method was employed to evaluate the social-ecological system (SES) adaptability scores of the three zoning units ($m = 3$) within the Southwest Karst National Park (Guangxi), based on 19 evaluation indicators ($n = 19$). The original data matrix $X = (X_{ij})_{3 \times 19}$ was constructed from 2024 socio-economic statistics and ecological monitoring data (see Table 1 for raw values). For negative indicators, their reciprocals were taken to transform them into positive direction; positive indicators were used directly. All data were then normalized using vector normalization [25]:

Table 1. Social-Ecological System Evaluation Indicator System.

Target Layer	Policy Level	Attribute	Indicator Layer	Weight
Social Subsystem	Social Conditions	–	Population Size	0.044
		+	Community Education Level	0.033
		–	Distance to Community Settlements	0.035
		+	Ethnic Cultural Richness	0.040
		+	Intangible Cultural Heritage Items	0.031
	Market Demand	+	Web Attention	0.081
		+	Total Number of Tourist Arrivals	0.077
	Economic Foundation	+	Gross Regional Product (GRP)	0.087
		+	Road Network Density	0.053
		+	Tertiary Industry Proportion	0.051
Ecological Subsystem	Resource Superiority	+	Biodiversity Index	0.056
		+	Uniqueness of Geological Relics	0.084
		+	Aesthetic Landscape Value	0.047
		+	Water Conservation Capacity	0.042
		+	Vegetation Coverage	0.045
	Ecological Comfort	+	Excellent-Good Air Quality Rate	0.049
		+	Annual Average Suitable Tourism Days	0.055
		–	Relief Amplitude	0.029
		–	Ecological Vulnerability Index	0.061

“–” indicates a negative indicator; “+” indicates a positive indicator.

$$T_{ij} = x_{ij} / \sqrt{\sum_{i=1}^n x_{ij}^2} \quad (1)$$

For example, for the indicator “Uniqueness of Geological Relics” with raw values 96, 66, and 92 for the three zones, the denominator was $\sqrt{96^2 + 66^2 + 92^2} = 148.45$. The normalized values were 0.6467, 0.4446 and 0.6198, respectively, satisfying the sum-of-squares unity condition.

The proportion of each indicator was then calculated as:

$$P_{ij} = T_{ij} / \sum_{i=1}^n T_{ij} \quad (2)$$

and the entropy value for each indicator was obtained by:

$$e_j = -\frac{1}{\ln(n)} \times \sum_{i=1}^n (P_{ij} \ln(P_{ij})) \quad (3)$$

with $m = 3$, $\frac{1}{\ln(3)} = 0.9102$. For the same geological heritage indicator, the proportions were 0.3779, 0.2598 and 0.3622, yielding $e_{12} = 0.9883$.

The coefficient of variation and entropy weight were computed as:

$$d_j = 1 - e_j; W_j = d_j / \sum_{i=1}^n d_i \quad (4)$$

However, given that entropy weighting with only three samples is highly sensitive to data distribution and may deviate from objective weighting, we adjusted the derived weights based on the specific characteristics of karst ecosystems and expert consultation, to ensure result stability and comparability. The final weight vector (listed in Table 1) assigned the highest weights to uniqueness of geological relics (0.084) and GRP (0.087), while the combined weight for ethnic cultural richness (0.040) and number of intangible cultural heritage items (0.031) totalled 0.071.

The weighted normalized matrix was constructed as [26]:

$$V_{ij} = T_{ij} \times W_j \quad (5)$$

For the Tiankeng zone, for instance, the weighted value for uniqueness of geological relics was $0.6467 \times 0.084 = 0.0543$, and for Web Attention it was $0.7611 \times 0.081 = 0.0616$ (similarly for other indicators).

The positive ideal solution V^+ and negative ideal solution V^- were determined as:

$$V^+ = \max(V_{ij}); V^- = \min(V_{ij}) \quad (6)$$

and the Euclidean distances from each zone to the ideal solutions were calculated by:

$$D_i^+ = \sqrt{\sum_{j=1}^n (V_j^+ - V_{ij})^2}; D_i^- = \sqrt{\sum_{j=1}^n (V_j^- - V_{ij})^2} \quad (7)$$

The composite SES adaptability index was calculated using the standard TOPSIS formulation:

$$S_i = D_i^- / D_i^+ + D_i^- \quad (8)$$

The subsystem scores for each zone were derived by aggregating the weighted normalised indicators within each of the five analytical dimensions (Community Conditions, Market Demand, Economic Base, Resource Superiority, and Ecological Comfort) using a weighted arithmetic mean. The Ecological Vulnerability Index was treated as an independent dimension given its negative directional property. Table 2 presents the resulting composite SES adaptability scores (S_i) alongside the Euclidean distances to the positive and negative ideal solutions (D^+ and D^-). Detailed subsystem scores are provided in Table S3 in the Supplementary Materials.

Table 2. Two-Stage Entropy-Weighted TOPSIS Evaluation Results by Zone.

Zone	D^+	D^-	S(SES)	Adaptive Level
Tiankeng	0.03	0.07	0.74	Medium-High
Mulun	0.04	0.05	0.58	Medium
Underground River	0.08	0.02	0.16	Low

Adaptive levels: Low (<0.50), Medium [$0.50, 0.65$), Medium-High [$0.65, 0.80$), High (≥ 0.80).

The final results for the three zones were: Tiankeng ($D^+ = 0.026$, $D^- = 0.074$, $S = 0.74$); Underground River ($D^+ = 0.084$, $D^- = 0.016$, $S = 0.16$); and Mulun ($D^+ = 0.038$, $D^- = 0.052$, $S = 0.58$) (Table 2). The resulting index ranges from 0 to 1, with higher values suggesting stronger social-ecological adaptability. These thresholds are intended as interpretive

reference points specific to this case study, rather than as statistically derived universal standards given the small-sample context.

(b) Carrying Capacity Estimation Formulas

Drawing on the SES adaptability scores and ecological vulnerability indices derived above, a tiered calibration framework is applied to estimate zone-level daily visitor capacities. The procedure integrates three sequential steps: ecological vulnerability grading, SES-based adaptation adjustment, and absolute ceiling constraints.

The calibration of base capacity values follows a structured multi-criterion protocol. First, international karst heritage precedents establish ecological benchmarks: Škocjan Caves (1152 visitors/day) and Postojna Cave (3500 visitors/day) provide operational references for high-fragility and moderate-fragility cave systems, respectively [2,27]. Second, local pedogenesis constraints (0.02–0.05 mm/year) indicate that soil loss in the Underground River Zone constitutes effectively irreversible damage within management-relevant timeframes, justifying the conservation-oriented base capacity of 1152 visitors/day. Third, spatial constraints of geological relics (Tiankeng cluster access corridors) and existing tourism infrastructure capacity (Mulun reception facilities) inform zone-specific adjustments beyond the vulnerability thresholds. The elasticity coefficient ($\epsilon = 1.0$) ensures proportional capacity expansion, while the micro-access scaling factor ($\sigma = 0.015$) guarantees that zones below the 0.20 adaptability alert retain conservation-oriented micro-access of approximately 14 persons/day, preserving scientific research and monitored educational entry.

Ecological Vulnerability Grading—Base Capacity:

$$C_{\text{day},i} = C_{\text{base}}(V_i) \times \varphi(S_i) \quad (9)$$

where $C_{\text{base}}(V_i)$ denotes the vulnerability-constrained base capacity, and $\varphi(S_i)$ represents the SES adaptability adjustment function for zone i .

Vulnerability-Tiered Base Capacity Function:

$$C_{\text{base}}(V_i) = \begin{cases} C_{\text{min}}, & \text{if } V_i \geq V_{\text{alert}} (0.80); \\ C_{\text{mod}}, & \text{if } V_{\text{mid}} \leq V_i < V_{\text{alert}}; \\ C_{\text{max}}, & \text{if } V_i < V_{\text{mid}} (0.50) \end{cases} \quad (10)$$

where $V_{\text{alert}} = 0.80$ is the ecological vulnerability alert threshold and $V_{\text{mid}} = 0.50$ is the moderate vulnerability boundary. C_{min} , C_{mod} , and C_{max} were calibrated against international karst heritage precedences (e.g., Škocjan Caves: 1152 visitors/day; Postojna Cave: 3500 visitors/day) and local pedogenesis constraints (0.02–0.05 mm/year), resulting in $C_{\text{min}} = 1152$, $C_{\text{mod}} = 3000$, and $C_{\text{max}} = 8000$ visitors/day. The specific allocation of C_{base} values to each zone also considered additional site-specific factors beyond the vulnerability thresholds, including spatial constraints of geological relics (Tiankeng) and existing infrastructure capacity (Mulun) [2,4,27].

SES Adaptability Adjustment Function:

$$\varphi(S_i) = \begin{cases} S_i/S_{\text{alt}} \times \gamma, & \text{if } S_i < S_{\text{alt}} (0.20); \\ S_i/S_{\text{threshold}}, & \text{if } S_{\text{alt}} \leq S_i < S_{\text{threshold}} (0.65); \\ 1 + \alpha(S_i - S_{\text{threshold}}), & \text{if } S_i \geq S_{\text{threshold}} (0.65) \end{cases} \quad (11)$$

The base capacity values assigned to each zone were: Tiankeng ($C_{\text{base}} = 3000$, reflecting the spatial constraints of tiankeng clusters and the need for low-impact geo-science tourism), Mulun ($C_{\text{base}} = 8000$, reflecting its relatively intact ecological conditions and existing tourism infrastructure), and Underground River ($C_{\text{base}} = C_{\text{min}} = 1152$, reflecting its extreme ecological vulnerability and high rocky desertification risk). These values were

further adjusted by the SES adaptability function $\varphi(S_i)$ to produce the final daily visitor capacities presented in Table 3. Here, $S_{alt} = 0.20$ is the adaptability alert threshold, $S_{threshold} = 0.65$ marks the Medium-High adaptive level, $\alpha = 1.0$ is the elasticity coefficient, and $\gamma = 0.015$ is the micro-access scaling factor calibrated to ensure that the most vulnerable zone (Underground River, $S = 0.16$) retains a conservation-oriented micro-access capacity of approximately 14 persons per day (i.e., $C_{min} \times \varphi(0.16) \approx 1152 \times 0.012 \approx 14$). The function ensures that zones below the 0.20 alert line receive strictly controlled conservation-oriented micro-access rather than complete closure, thereby preserving limited scientific research and monitored educational entry while preventing any commercial tourism scaling [7,28].

Table 3. Daily Visitor Carrying Capacity Estimation by Zone.

Zone	SES Score	Ecological Vulnerability	Daily Visitor Cap (Persons)	Annual Ceiling (Visits)	Management Intensity
Tiankeng	0.74	0.65	3000	1,095,000	Moderate
Mulun	0.58	0.48	8000	2,920,000	Relaxed
Underground River	0.16	0.82	14	4970	Strict

Daily caps derived from SES adaptability gradients and ecological vulnerability thresholds. Annual ceilings = daily cap $\times$ 365 days (Underground River: $\times$ 355 effective days). Management intensity reflects inverse matching between ecological vulnerability and tourism capacity.

Annual Capacity Ceiling:

$$C_{year,i} = C_{day,i} \times D_{eff,i} \quad (12)$$

where $D_{eff,i}$ denotes the effective operational days for zone i ($D_{eff} = 365$ for Tiankeng and Mulun; $D_{eff} = 355$ for Underground River, accounting for 10 ecological recovery days mandated by its high vulnerability score of 0.82 and slow pedogenesis rate of 0.02–0.05 mm/year) [4].

Seasonal Quota Allocation:

$$Q_{s,i} = C_{day,i} \times \lambda_s \times d_{s,i} \quad (13)$$

where $Q_{s,i}$ is the seasonal quota for season s in zone i , λ_s is the seasonal coefficient ($\lambda_{peak} = 1.00$, $\lambda_{shoulder} = 0.83$ – 0.86 , $\lambda_{off-peak} = 0.63$ – 0.71 reflecting Guangxi subtropical monsoon climate), and $d_{s,i}$ is the number of effective days in seasons.

$$\sum Q_{s,i} + Q_{flex,i} = C_{year,i} \quad (14)$$

Constraint (1): the sum of seasonal quotas plus the flexible reserve must equal the annual ceiling. Constraint (2): seasonal coefficients must satisfy $\lambda_{peak} \geq \lambda_{shoulder} \geq \lambda_{off-peak}$. Constraint (3): the flexible reserve must account for at least 10% of the annual ceiling ($Q_{flex,i} \geq 0.10 \times C_{year,i}$) to accommodate scientific research access, peak-demand surges, and ecological recovery periods.

The calibrated parameters derived from this framework for the three zones are presented in Table 2 (TOPSIS evaluation results) and Table 3 (daily visitor capacity estimates), with seasonal disaggregation detailed in Table 4.

Table 4. Seasonal Distribution of Annual Visitor Quotas by Zone.

(a) Tiankeng—Daily Cap: 3000 Persons; Annual Ceiling: 1,095,000 Visits						
Season	Months	Days	Seasonal Factor	Daily Cap (persons)	Seasonal Quota (visits)	Proportion
Peak	Mar–May, Sep–Nov	182	1.00	3000	546,000	49.86%
Shoulder	Jun–Aug	92	0.83	2500	230,000	21.00%
Off-peak	Dec–Feb	91	0.67	2000	182,000	16.62%
Subtotal	—	365	—	Avg 2624	958,000	87.49%
Flexible Reserve	—	—	—	—	137,000	12.51%
(b) Mulun—Daily Cap: 8000 Persons; Annual Ceiling: 2,920,000 Visits						
Season	Months	Days	Seasonal Factor	Daily Cap (persons)	Seasonal Quota (visits)	Proportion
Peak	Mar–May, Sep–Nov	182	1.00	8000	1,456,000	49.86%
Shoulder	Jun–Aug	92	0.81	6500	598,000	20.48%
Off-peak	Dec–Feb	91	0.63	5000	455,000	15.58%
Subtotal	—	365	—	Avg 6874	2,509,000	85.93%
Flexible Reserve	—	—	—	—	411,000	14.07%
(c) Underground River—Daily Cap: 14 Persons; Annual Ceiling: 5000 Visits						
Season	Months	Days	Seasonal Factor	Daily Cap (persons)	Seasonal Quota (visits)	Proportion
Peak (Dry)	Mar–May, Sep–Nov	180	1.00	14	2520	50.40%
Shoulder (Rainy)	Jun–Aug	92	0.86	12	1104	22.08%
Off-peak (Winter)	Dec–Feb	83	0.71	10	830	16.60%
Subtotal	—	355	—	Avg 12.5	4454	89.08%
Eco. Recovery/Flexible	—	10	—	0	546	10.92%

The daily cap (persons) is rounded to the nearest whole number. Seasonal factors reflect Guangxi's subtropical monsoon climate. Peak = spring/autumn (optimal climate); Shoulder = summer (rainy season); Off-peak = winter (lower demand). Flexible reserve quotas accommodate peak-demand surges, scientific research access, and ecological recovery periods. The Underground River Zone includes 10 ecological recovery days given its high vulnerability (0.82) and slow pedogenesis rate (0.02–0.05 mm/year). The Flexible Reserve is the total annual allocation and is not distributed evenly on a daily basis.

3.4. Indicator System

The indicator system in Table 1 provides the input data for the two-stage entropy-weighted TOPSIS analysis (Section 3.3) [9,29,30]. The resulting composite SES adaptability scores for the three zones are presented in Table 2, which also reports the Euclidean distances to the positive and negative ideal solutions (D^+ and D^-). Building on these scores, Table 3 presents the estimated daily visitor carrying capacities and annual ceilings derived through the tiered calibration framework (Section 4.1), and Table 4 disaggregates these annual quotas into seasonal allocations reflecting Guangxi's subtropical monsoon climate patterns. Together, Tables 1–4 form a coherent analytical chain from indicator input through adaptability assessment to zoned, seasonally adjusted management outputs.

4. Results

4.1. Zone-Level Social-Ecological Profiles and Carry Capacity Estimation

The radar-based SES dimensional comparison in Figure 3 shows divergent social-ecological adaptability profiles across the three administratively defined zones of the proposed Southwest Karst National Park, based on the subsystem scores detailed in Table S7 (Supplementary Materials). The Tiankeng zone records the highest overall adaptabil-

ity score (0.74), largely associated with its pronounced geological heritage uniqueness (0.96) and relatively strong market tourism appeal (0.71). However, its performance appears somewhat constrained by comparatively weaker community development conditions (0.58), which may relate to limited ethnic cultural capital in the area. The Mulun Zone exhibits the most balanced social–ecological coupling (0.58), with the strongest community governance foundation (0.72), favourable ecological conditions (0.75), and the lowest ecological vulnerability level (0.48) among the three zones. In contrast, the Underground River Zone shows a more imbalanced profile, with a very low adaptability index (0.16), high ecological vulnerability (0.82), underdeveloped economic infrastructure, and limited geographic accessibility.

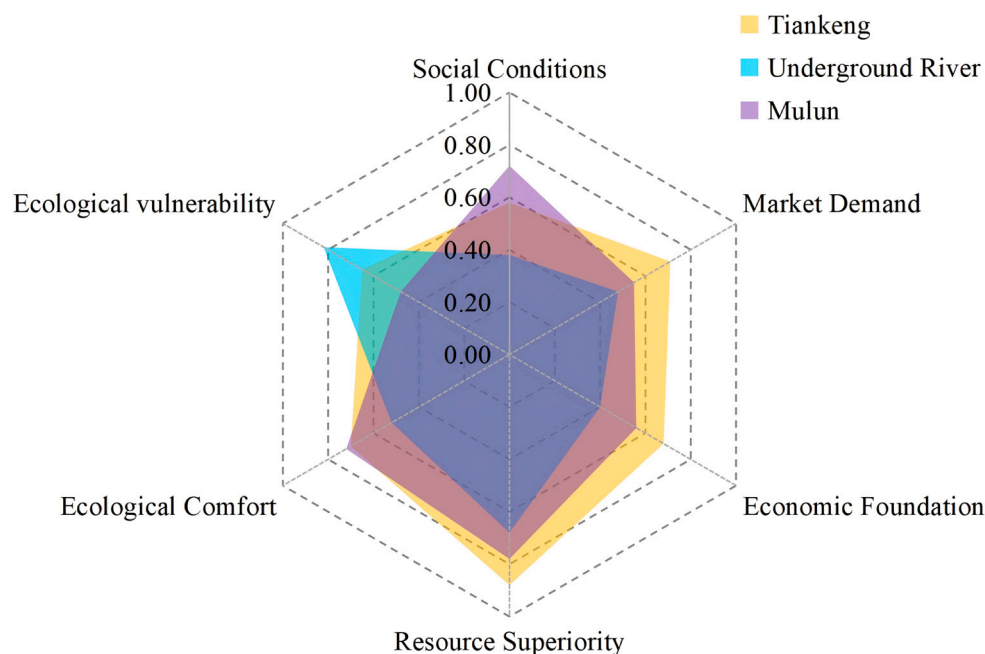


Figure 3. Social-Ecological System Profiles Across Three Zones of the Proposed Southwest Karst National Park (Guangxi). Radar chart displays six dimensions—Community Conditions, Market Demand, Economic Base, Resource Superiority, Ecological Comfort, and Ecological Vulnerability—for Tiankeng (yellow, SES = 0.74), Underground River (blue, SES = 0.16), and Mulun (Purple, SES = 0.58). Ecological Vulnerability is a negative indicator (lower values indicate better ecological security). The shaded polygons represent relative performance across dimensions; larger area indicates stronger overall adaptability.

Following the calibration procedure described above, we offer preliminary, case-specific tourism carrying capacity estimates for pilot management reference within the park. The suggested daily visitor quotas are 3000 for the Tiankeng zone, 8000 for the Mulun Zone, and 14 for the Underground River Zone, corresponding to approximate annual ceilings of 1.095 million, 2.92 million, and 5000 visits, respectively (Table 4). It should be noted that these graded thresholds are exploratory empirical outputs tailored to the specific social-ecological conditions of the studied karst national park. They are not intended as generalisable standards applicable to other karst protected areas, and would benefit from long-term monitoring and iterative refinement in subsequent management practice. The hierarchical quota system broadly reflects an inverse matching pattern between ecological vulnerability and tourism capacity, whereby more fragile zones are subject to tighter disturbance controls. This zoning approach appears consistent with a high-value, low-disturbance sustainable tourism model for geomorphologically vulnerable karst landscapes.

The proposed daily quota of 14 visitors for the Underground River Zone may be further contextualised through comparison with international karst governance precedents. High-value, high-fragility karst heritage sites often adopt restrictive visitor management strategies to help reduce anthropogenic pressures. Slovenia's Škocjan Caves Regional Park applies strict access limitations to protect fragile speleothem structures and subsurface microbial communities [2]. Postojna Cave operates with a daily capacity of approximately 3500 visitors to mitigate CO₂ accumulation and related speleothem deterioration [27]. In Jamaica's Cockpit Country, unregulated tourism has been associated with soil erosion, with reported restoration costs ranging from USD 15,000 to 25,000 per hectare [8]. Consistent with these examples, the Underground River Zone's high vulnerability score (0.82) suggests a notably low tolerance for ecological disturbance, implying that anthropogenic activities may need to remain within the ecosystem's natural recovery capacity to reduce the likelihood of persistent regime shifts. In this context, the proposed 14-person daily limit is offered as a precautionary, ecology-oriented pilot benchmark, rather than being presented as an overly conservative restriction.

4.2. Differentiated Zone-Specific Adaptation Models

The differing social-ecological attributes observed across the three zones may inform the development of tailored sustainable tourism adaptation pathways (Figure 4) that align with local resource endowments, community capacity, and ecological constraints.

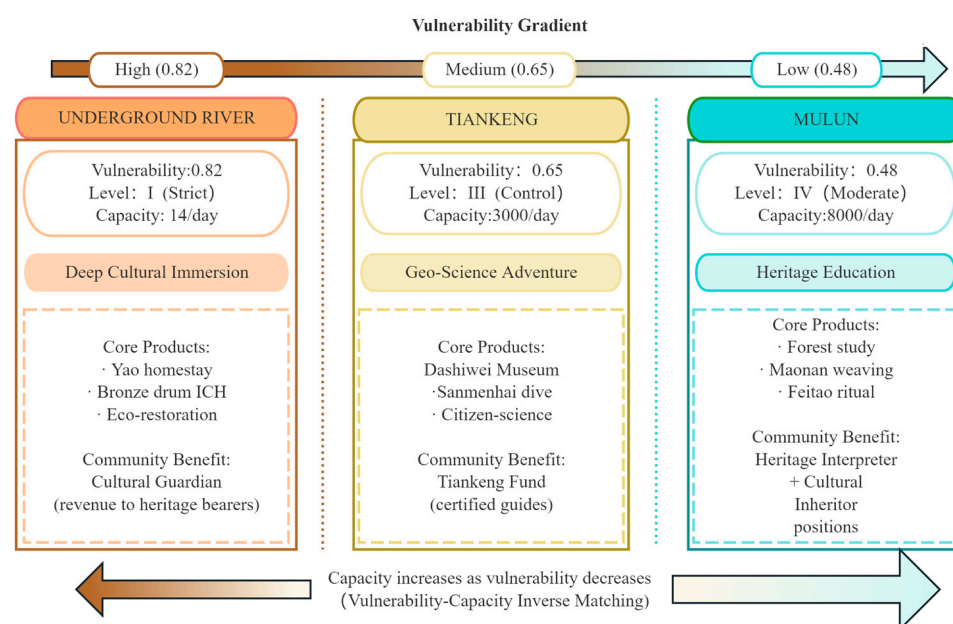


Figure 4. Zone-Specific Adaptation Models and Vulnerability–Capacity Profiles. Diagram created using WPS Office (2024, Kingsoft Office Software Corporation Limited, Zhuhai, China).

Tiankeng Zone: Geo-Science Adventure Model. With globally distinctive geological relics (0.96) and relatively strong market recognition (0.71), this zone may be suited for high-quality geo-science tourism and low-intensity adventure recreation.

Mulun Zone: Heritage Education and Cultural Integration Model. With World Natural Heritage status (0.90), distinctive Maonan cultural resources (0.85), and the lowest ecological vulnerability among the three zones (0.48), this zone appears to exhibit the most balanced coordination between tourism scale, service quality, and ecological safety.

Underground River Zone: Minimal-Development Deep Cultural Immersion and Ecological Conservation Model. Although this zone has notable ethnic cultural resources (0.91) and 11 intangible cultural heritage items associated with the Bunu Yao community, its high

ecological vulnerability (0.82) and limited social infrastructure (0.42) suggest that large-scale tourism development may not be feasible.

4.3. Preliminary Economic Feasibility Assessment

A preliminary cost–benefit assessment was conducted to evaluate the illustrative economic potential of the proposed zone-specific tourism models. Drawing on publicly available tourism statistics from comparable karst World Heritage sites and geoparks in Southwest China—where county-level tourism revenues are reported in aggregate government yearbooks but disaggregated financial statements for individual scenic areas remain unavailable—we estimated indicative revenue projections under conservative, moderate, and optimistic visitation scenarios. For the Tiengkeng zone (3000 visitors/day), illustrative annual revenue is estimated in the range of CNY 40–80 million, assuming ticket prices of CNY 80–150 per visitor and occupancy rates of 60–90%, with operational costs tentatively projected at 45–55% of revenue based on industry norms for karst geopark operations in the region. For the Mulun Zone (8000 visitors/day), indicative annual revenue ranges from approximately CNY 100–200 million, with correspondingly higher operational costs (50–60% of revenue) reflecting greater infrastructure maintenance requirements. The Underground River Zone (14 visitors/day) is anticipated to generate modest annual revenue below CNY 2 million through ultra-premium cultural immersion programmes, with minimal operational costs given its community-based management model. These projections suggest that positive net returns may be conceivable across all three zones under moderate and optimistic scenarios; however, we emphasise that these figures are illustrative order-of-magnitude estimates only. They rest on untested assumptions regarding market uptake, pricing power, and seasonal demand distribution, and are derived by extrapolating from aggregate regional tourism data rather than from verified financial statements of comparable operations. As such, they require rigorous validation through pilot implementation and detailed accounting before any operational or investment decisions are made.

Comparable karst tourism operations in Southwest China provide useful context for assessing economic potential, though precise financial data at the individual site level remain scarce. Published government statistical yearbooks indicate that Libo County (Guizhou), host to the South China Karst World Heritage Site, has recorded annual county-wide tourism revenue in the range of CNY 20–30 billion in recent years, though these aggregate figures encompass multiple scenic areas and hospitality services well beyond ticket sales. Similarly, publicly reported data for Leye-Fengshan Global Geopark (Guangxi) suggest total tourism consumption in the order of CNY 10 billion annually, with standard ticket prices for major scenic spots generally ranging from CNY 65 to 300 per person depending on the selected attractions. These benchmarks suggest that karst geopark tourism in subtropical China can generate substantial economic activity at the regional scale; however, we were unable to locate publicly available disaggregated financial statements for individual scenic area ticket revenue, operational cost ratios, or net profitability. The estimates presented above should therefore be treated strictly as illustrative order-of-magnitude projections derived from assumed ticket pricing and occupancy scenarios, extrapolated from aggregate regional data rather than empirically validated site-level accounts. Their primary function is to demonstrate that positive net returns appear conceivable under plausible conditions, pending pilot implementation, detailed feasibility studies, and transparent accounting.

5. Discussion

5.1. Conceptual Contributions: Operationalizing Resilience in Karst Social-Ecological Systems

This study contributes to the sustainable tourism literature by proposing an analytical framework that integrates geological heritage and cultural capital into SES resilience assessments for subtropical karst regions—a landscape type that remains comparatively under-theorised relative to temperate forests or alpine zones. Rather than offering definitive management solutions, we aim to provide a structured, pilot-scale diagnostic approach for identifying vulnerability–adaptability mismatches in geomorphologically specialised protected areas. The central theoretical insight is a “vulnerability–capacity inverse matching” mechanism, which treats adaptability as a dynamic property shaped by ecological–social coupling rather than as a static attribute. The zone scores—Tianheng (0.74), Mulun (0.58), and Underground River (0.16)—suggest a gradient of SES integration that appears consistent with Ostrom’s threshold logic. We translate this logic into heuristic decision rules: an adaptability score below 0.20 and an ecological vulnerability exceeding 0.80 may indicate a system state in which tourism development needs to be carefully aligned with ecological restoration capacities.

a. The Vulnerability–Capacity Inverse Matching Mechanism

The selection of 0.20 and 0.80 as heuristic boundaries is anchored in two converging lines of evidence. First, geomorphological process rates provide a biophysical rationale. The local pedogenesis rate is exceptionally slow (0.02–0.05 mm/year), meaning that 1 cm of soil requires approximately 200–500 years to form [4]. In the Underground River Zone, where vulnerability reaches 0.82, most forms of anthropogenic soil disturbance are likely to constitute effectively irreversible losses within management-relevant timeframes. The 0.20 threshold is therefore best understood as a process-based risk boundary rather than a statistical confidence interval: when adaptability falls below this level, the system is likely to lack sufficient capacity to absorb disturbance relative to geomorphological recovery time.

Second, international karst governance precedents lend empirical support to the severity implied by these thresholds. At Slovenia’s Škocjan Caves—a UNESCO World Heritage site with comparable speleothem vulnerability—daily visitation is capped at approximately 1152 visitors based on real-time monitoring of CO₂, humidity, and airborne particulates [2]. Exceeding these thresholds has been associated with significant bacterial concentration increases and “lampenflora” growth [27], suggesting that even moderate tourism pressure can produce measurable ecological perturbations in sensitive karst systems. International karst management guidelines similarly state that management should “match the visitor population to the nature of the resource” and recognise that surface actions in karst “may be sooner or later translated into impacts directly underground”. These benchmarks suggest that restrictive thresholds may be normative rather than exceptional in high-fragility karst heritage sites. The 0.80 vulnerability threshold appears to signal a regime in which buffering capacity is so depleted that tourism may need to be treated as a last-resort option rather than a default strategy.

b. Cultural Capital as a Conditional Mediator: The Institutional Capacity Threshold

The comparative zone profiles offer a critical test of the cultural-capital mediation hypothesis. The Underground River Zone possesses the highest ethnic cultural richness score (0.91) and 11 registered intangible heritage items associated with the Bunu Yao community—an endowment exceeding even Mulun’s Maonan resources (0.85). Yet its SES adaptability (0.16) is the lowest of the three zones, and its ecological vulnerability (0.82) is the highest. This pattern suggests that cultural capital, in isolation, may not suffice to ensure resilience.

We propose a dual-threshold heuristic: cultural richness ≥ 0.60 and community conditions ≥ 0.40 . Mulun meets both thresholds (0.85 and 0.72), and its cultural capital is visibly operationalised through village homestay networks and community-managed benefit-sharing. The Underground River Zone exceeds the cultural threshold ($0.91 \geq 0.60$) but falls below the community-capacity threshold ($0.38 < 0.40$). Despite abundant Bunu Yao heritage—including sacred mountain worship and forest conservation taboos that could moderate unsustainable resource use—the zone lacks the institutional infrastructure needed to translate these assets into governance outcomes. Village committees appear to lack adequate administrative resources; education levels seem insufficient for heritage-based entrepreneurship; and geographic isolation limits the formation of market linkages that would create conservation incentives. Cultural richness thus appears to remain a latent asset rather than an active mediating force.

This calls into question the implicit assumption that ethnic cultural endowment automatically translates into ecological stewardship. Our evidence suggests that cultural capital may function as a conditional mediator: it may buffer human–land conflicts only when embedded within enabling institutional arrangements that provide channels for cultural expression, economic valorisation, and participatory governance. The Underground River Zone’s profile—high cultural richness (0.91), low community capacity (0.38), extreme vulnerability (0.82)—thus offers a basis for refining the “cultural capital as conservation driver” narrative into a more nuanced “cultural-capital-plus-institutional-capacity” framework. The policy implication appears straightforward: cultural preservation programmes are likely to require parallel investments in governance capacity, education, and infrastructure.

5.2. Comparative Positioning: Placing Karst Dynamics in Context

Our findings appear broadly consistent with—and extend—recent empirical work in comparable karst settings. The classification of the Underground River zone (0.16) as a less sustainable regime bears similarities to observations by Bao, Zhang and Wu [31] in Guizhou’s karst villages, where disadvantaged socio-economic conditions were found to exacerbate tourism-related ecological impacts. Seen together, these findings tentatively suggest that the 0.20 adaptability threshold may serve as a heuristic diagnostic reference for distinguishing between tourism-enhanced and tourism-stressed SES regimes in Southwest China’s karst systems. Ecosystem services in geomorphologically sensitive depression zones tend to show comparatively higher vulnerability scores, reinforcing the case for locally tailored rather than park-wide management strategies.

Internationally, our zone-level profiles show some parallels with global archetypes, while also reflecting distinct governance contexts. The balanced profile of Mulun appears comparable to the conservation-with-development model observed in Monteverde [32], whereas the pronounced imbalance of the Underground River zone resembles the strict access constraints applied at Tsingy de Bemaraha [33]. Comparisons with community benefit-sharing practices in Phong Nha-Kẻ Bàng [1] and visitor quota systems at Škocjan Caves [2] suggest that our analytical approach is broadly consistent with internationally recognised precedents. However, they also highlight a key contextual difference: Chinese karst parks operate within collective land tenure systems and are subject to rural revitalisation mandates that are not typically present in Western governance frameworks. This institutional specificity reinforces the value of building adaptive capacity within existing administrative structures, rather than directly transplanting international governance models.

5.3. Methodological Transferability and Scope of Application

The methodological innovations—including the inclusion of cultural capital (weight: 0.071) and an independent geological heritage component (weight: 0.084)—offer a potentially replicable protocol (two-stage entropy-weighted TOPSIS with Delphi-AHP hybrid adjustment) for small-sample, data-scarce protected areas. However, the proposed thresholds (e.g., 0.20 for adaptability and 0.80 for vulnerability) are preliminary empirical reference points derived from pattern recognition within this specific park; they should be interpreted as case-specific heuristic benchmarks rather than as statistically generalisable population parameters for subtropical karst systems more broadly, and their broader applicability would need to be examined through longitudinal monitoring and comparative applications in other karst provinces (e.g., Guizhou, Yunnan) before any extension to other settings is considered. Furthermore, we acknowledge that our engagement with the 2030 Agenda for Sustainable Development remains exploratory: although our framework is conceptually aligned with targets such as heritage protection (SDG 11.4) and sustainable ecosystem governance (SDG 15.9), this study does not provide empirical evidence that the proposed mechanisms directly advance these goals. Consequently, the discussion of SDG linkages is offered as an indicative illustration of potential applicability, rather than as a demonstration of realised contribution. These caveats notwithstanding, the empirical patterns reported above appear to resonate with several theoretical propositions from the SES resilience literature, offering an informal checkpoint for whether concepts developed in broader contexts find support under the specific conditions of a subtropical karst protected area. Such conceptual cross-checking does not validate the framework in any formal sense, but it may help identify the boundary conditions within which cautious extension to comparable settings could be contemplated.

Holling's [10] foundational distinction between engineering and ecological resilience finds tentative parallels in the non-linear vulnerability profiles observed across the three karst zones. The Underground River Zone, in particular, exhibits high vulnerability (0.82) and low adaptability (0.16)—a pattern that appears consistent with a system operating near a regime-shift boundary rather than maintaining a stable equilibrium. Walker et al. [11] subsequently conceptualised resilience, adaptability, and transformability as interrelated system-level properties; their emphasis on cross-scale interactions offers one possible interpretive context for our observation that geomorphological specificity appears to shape social–ecological coupling in ways that may not be merely incidental. At the governance level, Folke et al. [12] characterised adaptive governance as an institutional mechanism through which polycentric structures and social learning channel resilience concepts into management practice. Their framework offers a partial theoretical basis for our phased capacity-building sequence, in which provincial policy frameworks, county-level operational authority, and village-level management empowerment are sequenced prior to tourism scaling. Biggs et al. [13] synthesised operational principles for building SES resilience; among these, the maintenance of diversity and redundancy appears most relevant to our zone-specific adaptation models—geo-science adventure (Tiankeng), heritage-education integration (Mulun), and deep cultural immersion (Underground River)—which distribute tourism pressure across heterogeneous landscape units and may thereby reduce the risk of concentrating disturbance in any single zone. The cross-zone spillover dynamics noted above further underscore the relevance of connectivity management, another principle articulated by Biggs et al. [13], in ensuring that visitor displacement between zones does not unduly compromise overall SES resilience. These observations point tentatively to a degree of conceptual alignment between the present framework and established SES resilience principles. However, such alignment should not be overstated. The framework appears most likely to be applicable in geomorphologi-

cally specialised protected areas where ecological fragility creates non-linear vulnerability profiles, administrative zoning yields small samples that preclude conventional inferential statistics, and ethnic cultural capital coexists with fragile ecosystems. Under such conditions, the protocol may serve as a provisional starting point for adaptive management—provided that thresholds are recalibrated against local data and cultural capital indicators are adapted to reflect place-specific heritage configurations.

6. Conclusions

6.1. Theoretical Contribution: Reframing Resilience in Geomorphologically Specialized Landscapes

This study advances SES resilience theory by establishing that geomorphological specificity operates as a structural determinant of social–ecological coupling rather than a passive contextual condition. In subtropical karst landscapes—characterized by extreme soil fragility, slow pedogenesis, and co-located ethnic minority settlements—conventional resilience frameworks, developed primarily for temperate forests and coastal zones, may prove inadequate. We contribute a theoretical refinement by integrating geological heritage assessment and ethnic cultural capital as irreducible analytical dimensions within the SES architecture, challenging the prevailing tendency to treat these factors as secondary modifiers.

The proposed “vulnerability–capacity inverse matching” mechanism represents a conceptual departure from static resilience models. It reconceptualizes adaptability as a dynamic property co-determined by ecological monitoring feedback and institutional response capacity, offering a theoretical bridge between Ostrom’s threshold logic and operational management [6]. The diagnostic reference signals identified—0.20 adaptability alert line, 0.80 vulnerability warning boundary—are proposed as heuristic management-pilot boundaries derived from pattern recognition within this specific three-zone system. They are not statistically validated thresholds and possess no external generalizability; rather, they function as precautionary analytical anchors for flagging zones requiring heightened administrative scrutiny.

We further theorize cultural capital as a conditional mediating hypothesis rather than an automatic conservation driver. Its efficacy is contingent on institutional capacity thresholds (community conditions ≥ 0.40), a specification that refines biocultural conservation theory by identifying enabling conditions under which cultural transmission may translate into conservation incentives—a proposition awaiting longitudinal validation.

6.2. Methodological Innovation: A Diagnostic Protocol for Data-Scarce Protected Areas

Methodologically, the two-stage entropy-weighted TOPSIS with Delphi-AHP hybrid adjustment offers a replicable protocol for diagnosing social–ecological integration where conventional multivariate statistics are infeasible due to small samples ($n = 3$) and data scarcity. Analytical rigor is achieved through triangulation—expert judgment, geospatial data, and social indicators—rather than inferential statistics. This approach is particularly pertinent for karst protected areas across Southwest China, where administrative zoning typically yields few management units and longitudinal ecological data remain sparse.

The disaggregation of the social subsystem into five constituent dimensions enables identification of specific capacity bottlenecks with precision absent from aggregate indices. The Underground River zone’s low community score (0.38) pinpoints an institutional gap: village committees lack administrative resources to operationalize benefit-sharing despite possessing cultural assets. This diagnostic granularity constitutes a methodological advance over conventional resilience assessments that obscure implementation-relevant heterogeneity.

6.3. Practical Innovation: Adaptive, Feedback-Responsive Governance

The practical contribution lies in reorienting protected area management from static carrying-capacity formulas to adaptive, monitoring-responsive governance. The zone-specific adaptation models—geo-science adventure (Tiankeng), heritage-education integration (Mulun), and deep cultural immersion with strict conservation (Underground River)—are diagnostic archetypes enabling managers to align intervention logics with zone-specific vulnerability–adaptability configurations.

The operational innovation is the elastic capacity adjustment framework, which embeds McGinnis and Ostrom’s adaptive cycle theory into concrete decision rules: capacities may expand only when ecological signals (CO₂, microbiome, desertification indicators) confirm stability, and compress automatically when adverse signals emerge [7]. This feedback-responsive logic constitutes a paradigm shift from “predict-and-provide” to “monitor-and-adapt” governance. The phased capacity-building sequence—provincial policy frameworks, county-level operational authority, village-level management empowerment—operationalizes a capacity-before-scaling principle that addresses the root cause of ecotourism failure in developing contexts, where revenue generation typically outpaces institutional readiness.

6.4. Scope, Limitations, and Research Priorities

Three limitations limit our findings. First, the reference values reported (0.20 adaptability, 0.80 vulnerability) are preliminary diagnostic references from a single park’s three-zone configuration. They possess no statistical external validity and should not be generalized as population-level parameters. Second, the cultural-ecological mediation hypothesis remains theoretically conjectural, requiring panel data across 5–7 years to establish causal links. Third, revenue projections for the niche tourism model rest on untested assumptions requiring pilot implementation.

Future priorities are threefold: (i) longitudinal monitoring to validate or revise the reference values against outcome data; (ii) comparative application to Libo-Huanjiang (Guizhou) and Shilin (Yunnan) to test framework transferability under different pedogenic rates and governance structures; and (iii) agent-based modeling to reveal emergent visitation behaviors—displacement spillover, seasonal crowding, unauthorized access—that static models cannot anticipate.

6.5. Concluding Remarks

This study provides a methodologically transparent, adaptive decision-support framework equipped with precautionary diagnostic reference signals for protected area managers. The core contribution is conceptual and procedural: a replicable protocol for identifying vulnerability–adaptability mismatches, articulating conditional hypotheses about cultural-ecological mediation, and sequencing institutional capacity-building before tourism scaling. The reference values proposed herein are heuristic management-pilot boundaries, not established thresholds with demonstrated external validity. Pending longitudinal validation and comparative application, this framework may inform the broader transition from static, top-down governance to adaptive, feedback-responsive management in geomorphologically specialized landscapes across Southwest China and beyond.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18157893/s1>, Table S1: Indicator Operation Definitions and Data Sources; Table S2: Delphi-AHP Weight Evolution and Consensus; Table S3: Sensitivity Analysis; Table S4: Future Research Directions on Spillover Effects; Table S5: Ethnographic Observation Summary; Table S6: Stakeholder Interview Summary; Table S7: Subsystem Scores by Zone and Dimen-

sion. Supplementary Materials are uploaded as attachments; the original data may be requested from the authors.

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Data Availability Statement: We affirm that all data sources are accurately cited and that no data were fabricated or selectively omitted.

Conflicts of Interest: The authors declare no conflicts of interest.

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