

The Concept, Quantitative Measurement, and Spatial Differentiation of Urban Spatial Vulnerability: A Case Study of Prefecture-level Cities in the Chengdu-Chongqing Economic Circle

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Abstract: Urban vulnerability encompasses diverse elements including economic, social, cultural, environmental, and management aspects, posing significant challenges for conceptual recognition and quantitative measurement. As the physical vehicle of a city, urban space directly determines overall urban vulnerability. Recognizing this, this study reconceptualizes the notion of urban spatial vulnerability and constructs a comprehensive evaluation framework based on the 'Exposure-Sensitivity-Adaptability' paradigm from a physical space perspective. Taking the urban space of 16 prefecture-level cities in the Chengdu-Chongqing Economic Circle as the research object, we examine the spatial differentiation characteristics and contributing factors of vulnerability and propose targeted optimization strategies. The results demonstrate that the overall urban spatial vulnerability within the Chengdu-Chongqing Economic Circle is in a moderate state, exhibiting a spatial pattern characterized by 'high at the northern and southern poles, low in the middle.' Ya'an and Dazhou exhibit exceptionally high vulnerability. Highly complex urban spatial morphology, high building density, geological hazard risks, and a deficit of open spaces emerge as the primary drivers of vulnerability. Based on these findings, we propose corresponding planning and policy recommendations from a spatial dimension to offer scientific guidance for resilient city construction.

Keywords: urban spatial vulnerability; comprehensive measurement; spatial differentiation; Chengdu-Chongqing economic circle

1 Introduction

Urban space serves as a highly concentrated geographic area for contemporary populations and industries. As a complex integrated system, it not only accommodates physical infrastructure but also functions as the critical arena for social, economic, and cultural activities. Consequently, the spatial attributes of an urban area profoundly influence its level of disaster risk. Propelled by rapid industrialization, urbanization, and extreme climate events, the structural configurations and environmental states of urban spaces are undergoing substantial transformations. This shift has progressively compromised their disaster mitigation capabilities and destabilized system equilibria, triggering pervasive underlying vulnerabilities. It is thus imperative to execute systematic 'health checks' on urban environments to diagnose their current structural integrity, a task for which quantitative vulnerability measurement provides an effective diagnostic tool.

Extensive research has been conducted globally on urban vulnerability, spanning multiple sub-domains including eco-environmental vulnerability, natural disaster vulnerability, and social vulnerability. However, existing research largely remains confined to descriptive qualitative accounts of spatial

vulnerability phenomena, with relatively fewer quantitative explorations undertaken strictly from a physical-spatial perspective. The objective of urban spatial vulnerability research is to identify and evaluate the extent to which spatial systems are susceptible to potential threats. This shifts the paradigm from a reactive stance—addressing damage after it occurs—to proactive spatial governance that mitigates external disruptions via pre-emptive spatial control measures. Measuring spatial vulnerability involves diagnosing fragile elements within the spatial network, enabling planners and policymakers to enhance these components, reinforce urban disaster-defense mechanisms, and formulate sound spatial layout optimizations. To bridge this gap, this paper selects 16 prefecture-level cities within the Chengdu-Chongqing Economic Circle as empirical cases to build a comprehensive measurement index system, analyze spatial differentiation and key drivers, and delineate spatial refinement strategies to support resilient regional development.

1.1 Conceptualizing Urban Spatial Vulnerability

Existing literature conceptualizes vulnerability into two predominant categories: structural vulnerability and stress-induced vulnerability. The former is primarily dictated by intrinsic system characteristics, such as internal structural instability and susceptibility to disturbance; the latter stems from external pressures or perturbations, including anthropogenic actions and environmental shifts. Synthesizing these perspectives, other scholars view vulnerability as an emergent property combining both sensitivity and a deficiency in adaptive capacity under internal and external stressors. Recently, urban spatial vulnerability has gained traction. Drawing on typhoon risk contexts, some researchers argue that urban spatial vulnerability represents not merely an intrinsic property but also the probability of physical structures being exposed to external shocks, alongside their sensitivity and capacity to recover. Evident in these views, the understanding of spatial vulnerability has evolved toward an interactive mechanism between internal spatial structures and external disturbances. Accordingly, this study defines urban spatial vulnerability as an inherent systemic attribute reflecting the exposure, sensitivity, and adaptive capacity of the urban physical space layout when subjected to external disturbances, which ultimately induces changes in its core structures and operational functions.

From the perspective of stress sources, external disruptions incorporate both natural hazards (such as earthquakes, floods, and debris flows) and socioeconomic activities. External disturbances serve as the external catalysts driving vulnerability manifestation, while the internal structure of the spatial system constitutes the direct internal cause. When external shocks act upon an urban spatial system and exert pressures exceeding the threshold required to maintain baseline structural integrity and functional stability, vulnerability manifests openly. Urban spatial vulnerability is intrinsically latent; external shocks act as the critical lens through which it becomes pronounced. Under varying levels of external pressure, the system displays distinct degrees of vulnerability; when external disruptive forces approach infinity, the system's latent vulnerability unfolds entirely, leading to systemic collapse. In terms of internal composition, urban spatial vulnerability is structured across three primary dimensions: exposure, sensitivity, and adaptability.

1.2 Research Progress and Existing Gaps

Scholars worldwide have conducted multi-tiered explorations into urban spatial vulnerability, yielding robust theoretical and methodological foundations. For instance, Pinto defined spatial vulnerability at the urban scale by identifying and integrating socio-spatial parameters, thereby offering a highly granular methodology for urban disaster risk reduction. Tang applied machine learning to construct a spatio-temporal evaluation framework for urban spatial vulnerability under flood scenarios. Garcia-Ayllon leveraged Geographic Information Systems (GIS) combined with spatial autocorrelation analysis to measure spatial vulnerability dynamics. Domestically, Zhang analyzed urban 'human-land' coupled systems to formulate a comprehensive measurement model blending non-spatial and spatial variables. Chen devised an evaluative index based on exposure, sensitivity, and resilience to investigate urban spatial vulnerability under typhoon hazards. Concurrently, broader vulnerability frameworks have begun integrating isolated spatial factors; Cheng incorporated urban scale, density, and morphology as key sensitivity indicators within a large-city vulnerability index, while Li constructed an 'Exposure-Sensitivity-Adaptation' model leveraging spatial and statistical datasets via principal component analysis and cluster analysis to assess intra-urban spatial vulnerability.

Despite these valuable contributions, systematic investigations dedicated exclusively to a spatial viewpoint remain scarce. It is critically necessary to deepen systematic research from a physical-spatial lens to enhance our comprehensive understanding and adaptive capacity toward urban spatial vulnerability.

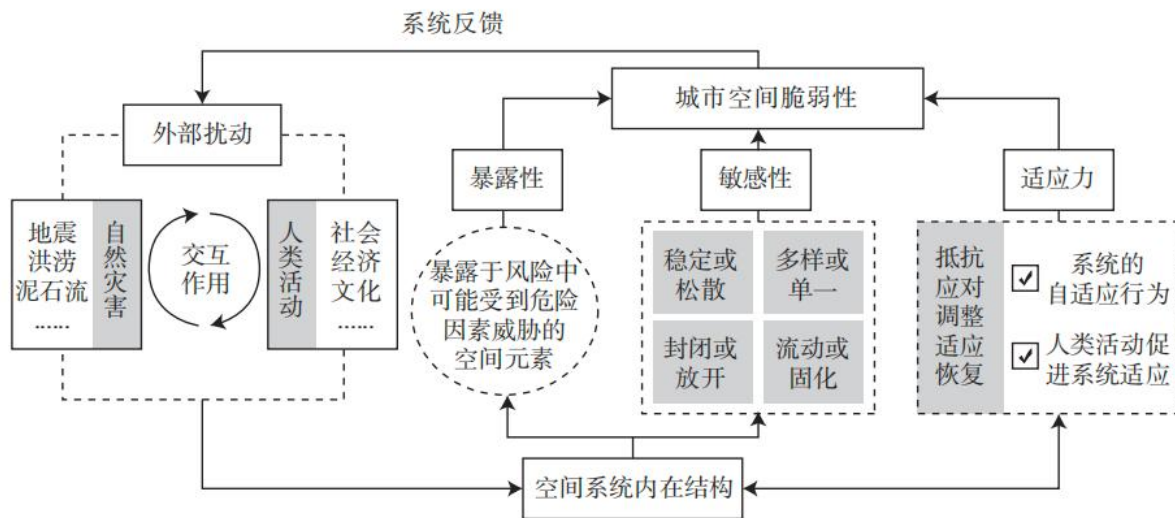


Fig.1 The concept of urban space vulnerability

2 Methodology and Data Sources

2.1 Data Sources

To satisfy the construction of the spatial vulnerability measurement model, various datasets were integrated for the year 2020–2023. These encompass spatial population distributions (7th National Population Census and WorldPop), building footprints (Google Bigemap and National Tibetan Plateau

Data Center), topographic data (Geospatial Data Cloud), land cover grids (GlobeLand30), geological hazard records (Chinese Academy of Sciences Resource and Environmental Science Data Center), transportation infrastructure networks (OpenStreetMap), Point of Interest (POI) data and Area of Interest (AOI) boundaries (Gaode API), water bodies (OpenStreetMap), and night-time light intensity records (National Earth System Science Data Center).

2.2 Measurement Framework and Workflow

This study evaluates 16 prefecture-level cities across the Chengdu-Chongqing Economic Circle. The analytical workflow incorporates the Analytic Hierarchy Process (AHP) and the Entropy Weight Method to construct a hybrid weighting model. Upon defining the principal regional hazards and the spatial boundaries of the evaluation, an indicator framework was established based on theoretical mechanisms and expert validation. Raw spatial datasets were preprocessed and calculated using ArcGIS and Python. Finally, the calculated indices were mapped to delineate the overarching spatial vulnerability patterns and differentiation across the study area.

2.3 Indicator System Construction

Adhering to principles of spatial relevance, systemicity, and operational feasibility, a tiered indicator system was constructed using a mixed-method approach. First, a preliminary framework was designed through literature reviews, causal mechanism modeling, and expert consultations. Second, high-frequency spatial indicators were filtered and tailored based on empirical data availability and the spatial characteristics of the study area. Finally, expert feedback was integrated to refine the metrics, establishing the formal evaluation framework. Higher values in the exposure and sensitivity dimensions indicate an elevated degree of spatial vulnerability, whereas larger values within the adaptability dimension denote superior self-adjustment and recovery capabilities, implying reduced vulnerability.

Table 1: Comprehensive evaluation index system of urban spatial vulnerability

Target Layer	Criterion Layer	Indicator Layer	Property
Urban Spatial Vulnerability	Exposure (EI)	Population Density	+
		Building Density	+
	Sensitivity (SI)	Topographic Relief	+
		Normalized Difference	+
		Water Index (NDWI)	+
		Fractal Dimension	+
		Urban Spatial	+
		Expansion Intensity	
		Index	
	Adaptability (AI)	Ratio of Geological Hazard-Prone Area	+
		Diversity of Public	-
		Service Facilities	
		Internal Urban Traffic	-
		Accessibility	
		Number of External	-

Backbone	
Transportation	
Corridors	
Open Space Index	-
Nighttime Light Index	-

2.4 Data Standardization and Weighting

To eliminate dimensional discrepancies across heterogeneous data types, indicators were categorized into positive and negative attributes and normalized using the min-max standardizing method. To enhance statistical objectivity and capture professional domain insights, the integrated weight of each metric was computed by combining subjective weights from the Analytic Hierarchy Process (AHP) and objective weights from the Entropy Weight Method, minimizing unilateral bias.

2.5 Comprehensive Measurement Model

The Urban Spatial Vulnerability Index (SVI) models a system's propensity for damage or its functional limitations under external stresses. It covaries positively with Exposure (EI) and Sensitivity (SI), and negatively with Adaptability (AI). A linear weighted-sum model calculates the composite index as follows:

$$SVI = f(EI, SI, AI) = EI + SI - AI$$

Where SVI represents the overall urban spatial vulnerability index, EI denotes the spatial exposure index, SI denotes the spatial sensitivity index, and AI corresponds to the spatial adaptability index. Sub-indices are calculated through the linear sum of their respective standardized indicator scores multiplied by their comprehensive weights.

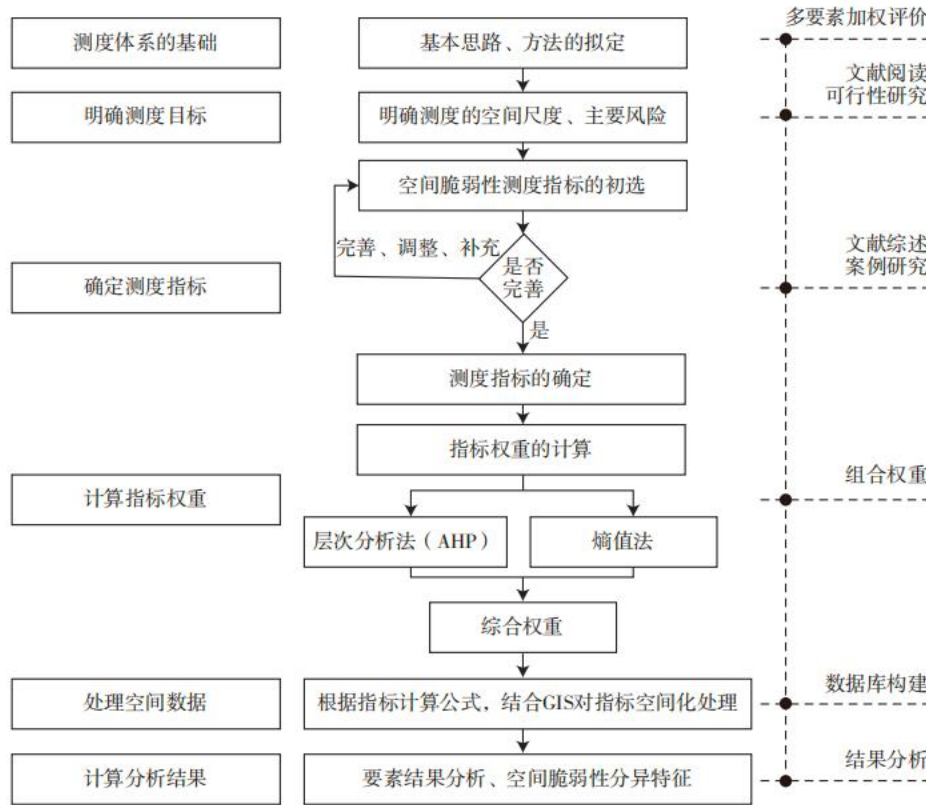


Fig.2 Urban space measurement flow chart

3 Results and Analysis

3.1 Subsystem Measurement

Using the natural breaks (Jenks) classification method, the computed indexes for exposure, sensitivity, and adaptability were categorized into five discrete levels (Low, Relatively Low, Moderate, Relatively High, and High) to reveal their spatial distribution patterns.

3.1.1 Spatial Exposure: Areas with elevated exposure are highly clustered in the established historic urban cores of each municipality, presenting a radial, outward-decreasing spatial configuration. Overall, the majority of urban land falls within the low to relatively low exposure categories, indicating that the baseline physical footprint of development remains manageable for most cities. Notably, Chongqing demonstrates a remarkably low spatial exposure score due to its multi-nucleated cluster form, whereas Suining and Ya'an display a higher share of highly exposed urban land.

3.1.2 Spatial Sensitivity: The distribution of sensitivity values displays stark regional polarization. Ya'an, Dazhou, and Guang'an exhibit significantly higher spatial sensitivity than their peers. For most municipalities, the predominant sensitivity grades fall squarely into the relatively low, moderate, and relatively high bands, mirroring a balanced regional average. Ya'an registers the largest proportion of

high-sensitivity zones, closely followed by Dazhou. Conversely, Deyang and Zigong represent cities with exceptionally low baseline sensitivity profiles.

3.1.3 Spatial Adaptability: High-adaptability core areas correspond strongly to central business districts and mature urban centers where public facilities are dense. This capacity tapers off toward peripheral urban fringes. Crucially, specific cities demonstrate severe bottlenecks in their adaptive capacities—most notably Mianyang and Dazhou. The regional share of spatial adaptability is generally skewed toward the lower tiers. Neijiang leads the region with the highest proportion of high-adaptability space, while the remaining cities fail to cross a 10% threshold for high adaptive capability. High proportions of low-adaptability zones are concentrated in Dazhou, Mianyang, and Ya'an.

3.2 Spatial Differentiation Characteristics

3.2.1 Overall Vulnerability Pattern: The baseline calculation across the region yields an average SVI of 0.5134, classifying the Chengdu-Chongqing Economic Circle as moderately vulnerable overall. Geographically, spatial vulnerability is distributed unevenly, outlining a prominent 'bipolar-high, central-low' pattern. The primary development axis connecting Chengdu and Chongqing benefits from intensive infrastructure investments and collaborative governance, rendering its alignment highly resilient. Conversely, cities sitting on the periphery—such as Ya'an, Leshan, Zigong, Luzhou, Dazhou, and Mianyang—receive weaker spillover benefits from the twin-core engines and suffer from constrained physical geographies, causing their structural vulnerability to peak.

3.2.2 Subsystem Vulnerability Variations: High-exposure, high-sensitivity, and low-adaptability profiles are heavily concentrated among peripheral municipalities. Exposure categories appear highly fragmented and interspersed across the landscape, whereas sensitivity values display clear regional clustering. Specifically, high-sensitivity zones are prominent in the southwest sector (anchored by Ya'an) and the northeast sector (anchored by Dazhou). In terms of adaptability, a clear outward-radiating decline is observable, where adaptive capacities degrade progressively moving from the geographical core of the economic circle toward its external boundaries.

3.3 Diagnostic Analysis of Contributing Drivers

To uncover the specific mechanisms driving spatial fragility, an obstacle degree model was deployed to quantify the negative impacts of individual parameters. The diagnostic results demonstrate that across the Chengdu-Chongqing Economic Circle, urban vulnerability is predominantly driven by highly convoluted urban spatial forms (fractal dimension), excessive building densities in localized zones, high exposure to geological hazards, and a critical deficit of open green spaces. Population density, building density, topographic relief, and natural disaster susceptibility are confirmed as the definitive bottleneck variables. Future sustainable planning must explicitly target these elements to suppress regional vulnerability.

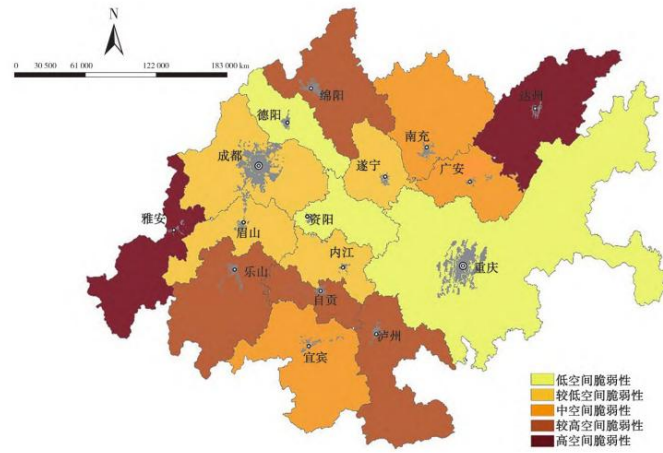


Fig.3 Spatial vulnerability distribution of cities in Chengdu-Chongqing economic circle

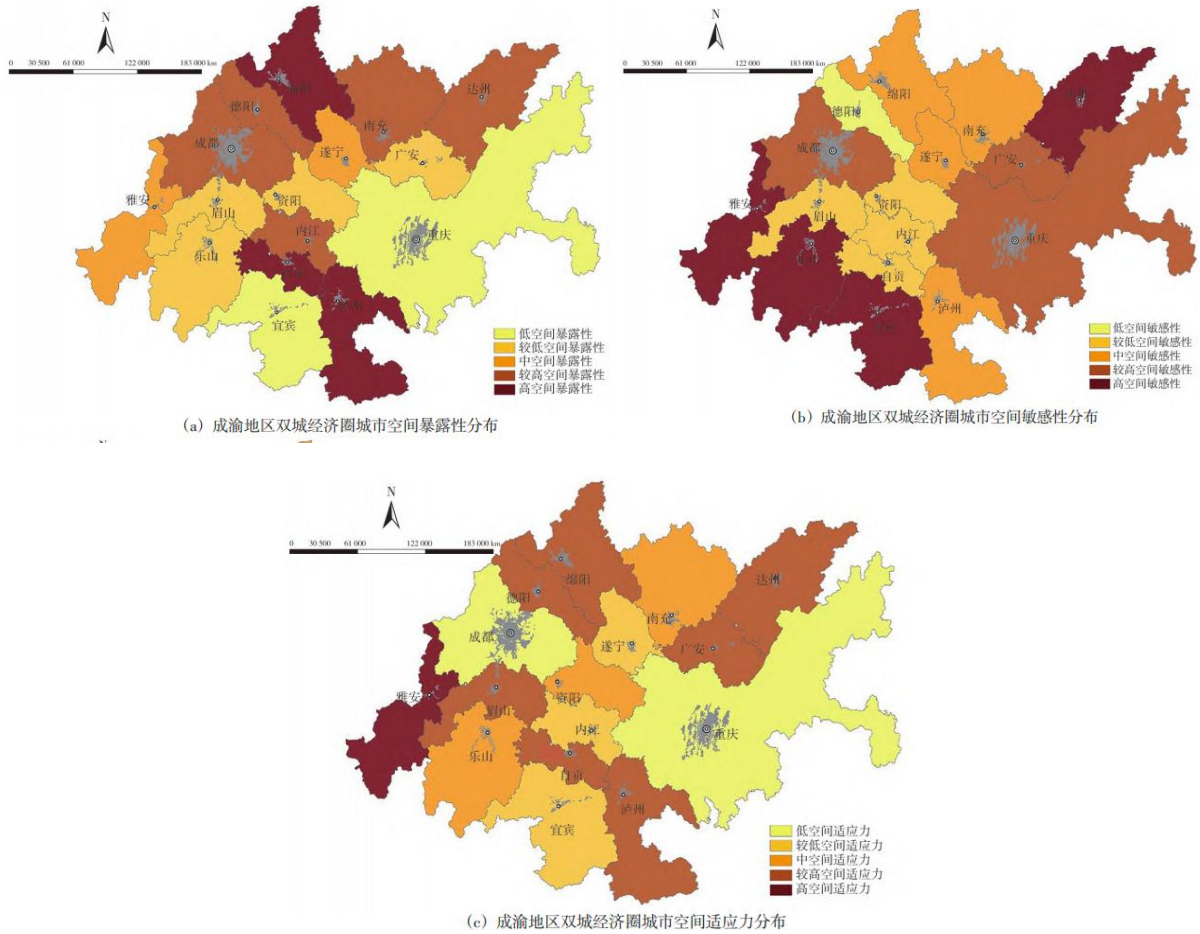


Fig.4 Spatial vulnerability distribution of urban subsystems in Chengdu-Chongqing economic circle

4 Discussion and Policy Implications

4.1 Theoretical and Methodological Discussion

Urban spaces act as both receptors of disaster energy and potential generators of secondary cascading risks. Under prolonged exposure to compound risks, spatial vulnerability intensifies, making systematic measurement an indispensable tool for steering resilient development. This study validates that the regional vulnerability centers on a moderate baseline, punctuated by high-fragility nodes within historic urban centers, aligning with broad empirical consensus. Methodologically, the integration of AHP and the Entropy Weight Method over multi-source big data (e.g., POI, AOI, OSM, and night-light grids) enhances measurement precision compared to conventional analyses reliant solely on static annual statistical yearbooks. While previous literature often treats space as an isolated sub-component of broader socioeconomic vulnerability, or focuses heavily on singular hazard contexts (like exclusive flood or typhoon modeling), this paper institutes an independent, comprehensive spatial-centric index comprising 12 metrics. This framework offers transferable diagnostic values for other expanding urban agglomerations. Nonetheless, this study primarily focuses on macro- and meso-scale interactions, leaving micro-urban structural elements open for future multi-scale verification.

4.2 Planning and Optimization Strategies

- (1) Cultivating Urban Spatial Forms with High Ecological Connectivity: Optimizing the spatial arrangement of ecological spaces by constructing continuous ecological corridors and greenways is vital to link isolated ecological patches. This intervention addresses habitat fragmentation and enhances regional ecological resilience, effectively lowering baseline vulnerability.
- (2) Restructuring Hierarchical Road Infrastructure Networks: Evidence shows that merely increasing road density cannot guarantee improved spatial resilience; grid morphology and structural hierarchy are paramount. Municipalities must optimize their networks by refining the hierarchy of primary, secondary, and local roads. At the macro scale, robust trunk lines guarantee structural network robustness; at the micro-meso scale, heightened grid density and cross-tier connectivity facilitate the efficient deployment of emergency relief and civilian evacuation.
- (3) Engineering Modular and Collaborative Public Service Systems: Urban frameworks must guarantee an equitable distribution of public services to ensure comprehensive coverage. Different functional modules should maintain clear administrative boundaries yet interface fluidly to foster resource sharing. Leveraging cloud computing and big data enables predictive, intelligent resource allocation. Furthermore, fostering community participation builds shared responsibility, while green building and energy-efficient technologies should be embedded to promote long-term ecological quality.

4.3 Conclusions

This study constructed a comprehensive measurement framework under the 'Exposure-Sensitivity-Adaptability' paradigm, using 16 prefecture-level cities in the Chengdu-Chongqing Economic Circle as an empirical base. The key conclusions are as follows:

First, spatial vulnerability is heterogeneously distributed across the region, maintaining a moderate average that is tied closely to local socioeconomic variances, topographic structures, and historical policy leanings.

Second, spatial vulnerability increases progressively as one moves outward from the dual core nodes of Chengdu and Chongqing. This core-periphery degradation is driven by higher building densities, convoluted spatial structures, and elevated hazard exposure in peripheral zones, combined with inadequate open spaces.

Third, population density, localized building density, topographic relief, and geological hazard susceptibility constitute the primary regional obstacle factors demanding strict control in future resilience initiatives.

Fourth, spatial refinement must be tailored to local contexts through fractal-based morphological controls, active-passive spatial decentralization, targeted public service upgrades, and proactive natural disaster prevention.

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