World Journal of Management Science
Print ISSN: 2959-9628
Online ISSN: 2959-9636
DOI: https://doi.org/10.61784/wms3122

SUITABILITY EVALUATION OF EMERGENCY SHELTER SITE SELECTION BASED ON GIS: A CASE STUDY OF PENGZHOU CITY

Ning Li[1,2], GuoChao Ma[1*], LiJuan Wang[1], Song Ma[1], Yong Xu[3], ZhiHao He[1,2], Wei Chen[4], Shuai Zhou[1*]
[1]*Sichuan Academy of Safety Science and Technology, Chengdu 610045, Sichuan, China.*
[2]*Xihua University, Chengdu 610059, Sichuan, China.*
[3]*Transportation Bureau of Ngari Prefecture, Ngari 859000, Xizang, China.*
[4]*Shaanxi Xingtong Supervision Consulting Co., Ltd., Xi'an 710000, Shanxi, China.*
[*]*GuoChao Ma and Shuai Zhou contribute the same to the article and are the corresponding authors.*
[*]*Corresponding Author: GuoChao Ma, Shuai Zhou*

Abstract: As vital urban disaster prevention infrastructures, emergency shelters underpin urban disaster reduction and post-disaster resettlement capacity. Taking Pengzhou City as an example, a typical mountain-plain transitional and hazard-prone area, this study establishes a GIS-based shelter suitability evaluation system with nine core indicators screened via two-round Delphi consultation from safety, accessibility and effectiveness dimensions. The study area is classified into four suitability grades using the weighted sum method and Natural Breaks. Spatial mismatch is prominent across the region: the southeastern plain presents high suitability with redundant shelters, while the geological-risk-prone northwestern mountains have low suitability, insufficient facilities and widespread service blind spots. Corresponding zoning optimization strategies and a citywide dynamic guarantee system are proposed for refined shelter layout. This study can provide scientific references for shelter planning in similar piedmont hazard-affected regions.
Keywords: Emergency shelter; GIS spatial analysis; Suitability evaluation; Pengzhou city

1 INTRODUCTION

In recent years, the frequency of global extreme rainfall, severe convective weather, and other hazardous weather events has kept rising, and multi-hazard disaster chains have become a severe threat to urban and rural safety at the county level. Against this backdrop, grassroots emergency response and population relocation capacity gain greater importance. As a core component of such work, emergency shelters serve as vital facilities for rapidly and properly resettling affected residents, calming public sentiment, and maintaining social stability [1]. The period since 2012 has seen a sustained commitment to a people-centered approach in national governance, with disaster risk reduction placed high on the agenda. This strategy has demanded the synchronization of development and security, leading to a marked strengthening of natural disaster resilience. It has also explicitly required high attention to emergency shelter development, featuring scientific rational planning and high-standard construction [2].
Following the institutional reform in 2018, driven by the newly established Ministry of Emergency Management, the construction of emergency shelters nationwide has entered a new phase. Emergency shelters have delivered remarkable performance in the emergency response of various disasters in recent years. For instance, nearly 2.998 million people were relocated and resettled amid the catastrophic rainstorm and flood in the Yangtze-Huaihe River Basin in 2020, and 1.43 million people were evacuated during Typhoon In-fa in 2021. Despite tangible progress in emergency shelter construction in China, deficiencies remain in scientific planning, hierarchical classification, and operation-maintenance mechanisms. Evolving urban risks driven by social development continuously raise new requirements for shelter planning. Moreover, notable disparities exist between China and foreign countries in theories and practices of emergency shelter construction, and relevant domestic research is still in the initial stage [3].
Research on emergency shelters started relatively early in developed countries, including Europe, America, and Japan, where sound legal frameworks, quantitative assessment systems, and operation management mechanisms have been established. Existing studies mainly focus on four themes: shelter layout planning, multi-dimensional evaluation, cross-regional collaborative support, and quantitative simulation based on GIS technology. Scholars widely integrate GIS, remote sensing, and spatial modeling to calculate shelter capacity and accessibility. Nevertheless, most mature analytical frameworks are designed for plain cities. They have limited adaptability to mountainous counties characterized by rugged terrain and linked multi-hazards, and seldom consider dynamic supply-demand fluctuations caused by seasonal tourist population variations [4-5]. Domestic research on emergency shelters gradually emerged in the early 21st century. Alongside continuous improvement of the national disaster prevention and mitigation system, research hotspots concentrate on suitability evaluation, dual-purpose planning for ordinary and emergency scenarios, and optimization of shelter facilities in mountain villages, forming localized research systems matching China's urban-rural development features. However, most existing studies focus on single plain cities or single-hazard scenarios

[6]. Integrated evaluation frameworks targeting multi-hazard coupling in county-level mountain-fault transition zones remain insufficient [7-8].

Overall, domestic and international studies have achieved substantial advances in theoretical systems, assessment methodologies, and technical applications for emergency shelters, yet obvious gaps persist. Mature foreign frameworks mostly apply to plain cities or single-hazard contexts and poorly adapt to mountain-fault transition zones and chain multi-hazard risks. Although domestic research emphasizes dual-use facilities and practices in geological disaster-prone regions, most existing evaluation systems rely on static suitability assessment, lacking coupled evaluation frameworks for shelter suitability in complex mountainous terrain [3, 9]. Accordingly, this study takes Pengzhou City, a typical county located in the mountain-plain transition zone, as the research object. Integrating geological risks, population heterogeneity, and seasonal tourist fluctuation characteristics, it constructs a comprehensive evaluation framework adopting ArcGIS spatial overlay analysis. This paper systematically identifies structural deficiencies of current shelters and proposes zoned planning strategies, aiming to provide scientific support for the transformation of county-level emergency shelter systems from quantity coverage to precision and efficiency.

2 OVERVIEW OF THE STUDY AREA AND DATA PREPROCESSING

2.1 Basic Profile of Pengzhou City

Pengzhou City lies in the transition zone between the Chengdu Plain and the Longmen Mountains. It borders Wenchuan County and Maoxian County of Aba Prefecture along the Longmen Mountain ridge in the north, faces Pidu District and Xindu District across the Qingbai River in the south, adjoins Deyang City, Shifang City, and Guanghan City in the east, and connects Dujiangyan City in the west. The territory features diverse landforms, consisting of mountains (50%), hills (11%), and plains (39%). Taizicheng in the northern mountainous area is the highest point with an altitude of 4814 m, while Wuyayan in the southern plain represents the lowest point at an altitude of 489 m, creating a vertical elevation difference of 4325 m and resulting in complex and varied terrain. Hydrologically, Pengzhou belongs to two major river systems, namely the Tuojiang River and Minjiang River, with more than 90 rivers densely distributed across the region. The geographical location of the study area is shown in Figure 1.

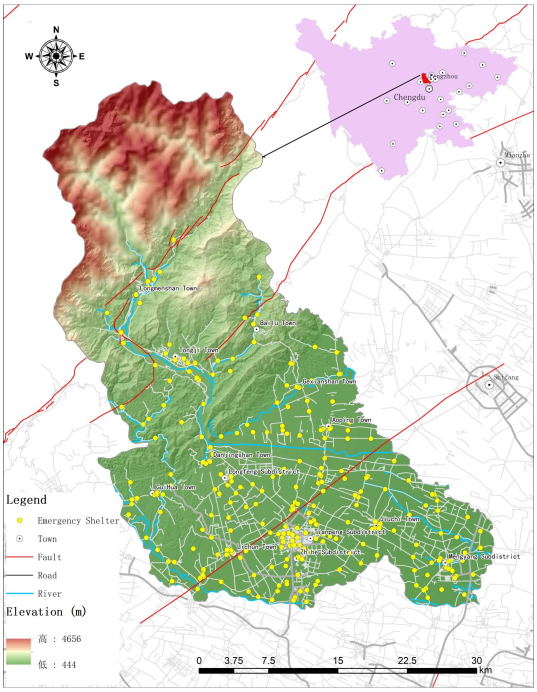

Figure 1 Geographic Location of Pengzhou City
Source: http://bzdt.ch.mnr.gov.cn

Pengzhou City administers 9 towns, 4 subdistricts, and 202 villages (communities), including 119 village committees and 83 community committees. The permanent population reached approximately 780,100 in 2024 and remains generally stable. Its urban population is 383,400, corresponding to an urbanization rate of 56.77%.

The terrain gradient of Pengzhou declines evidently from northwest to southeast, which directly shapes its population distribution. The spatial pattern is characterized by dense population in the southeast and sparse population in the northwest, as well as concentrated settlement in towns and scattered residence in rural areas. Densely populated regions such as Tianpeng Subdistrict and Mengyang Subdistrict have urgent demands for emergency shelters. From the perspective of demographic structure, people aged over 60 account for 25.27% of the total population, indicating a high level of population aging. The phenomena of population aging and rural hollowing are more prominent in mountainous areas. Nevertheless, the emergency shelters in mountainous regions suffer incomplete service radius coverage, low operational efficiency, and unreasonable allocation standards, accompanied by potential safety risks. Therefore, it is necessary to increase the number of emergency shelters in mountainous zones to guarantee emergency service demands of vulnerable groups.

Pengzhou lies in the core zone of the Longmen Shan fold fault belt with extremely unstable geological conditions. Two major faults, namely the Yingxiu Fault and Guanxian Fault, run through the territory, each stretching roughly 22 km. They constitute critical segments of the Longmen Shan Central Fault and the Piedmont Fault. The study area features fractured rock masses, densely distributed folds and faults, containing metamorphic basement of the Pengguan Complex and klippe structures, resulting in inherently weak geological stability. As of 2024, numerous registered geological hazards, including landslides, rockfalls, and debris flows, are concentrated in mountainous towns such as Longmenshan, Xiaoyudong, Bailu, and Danjingshan. Most geological hazards occur during summer flood seasons, featuring sudden onset and short early-warning duration, which imposes stringent requirements on population evacuation and resettlement. Accordingly, suitability evaluation is of great significance for the assessment and planning of emergency shelters.

2.2 Data Sources and Preprocessing

2.2.1 Inventory of multi-source spatial data

Topographic data: Digital Elevation Model (DEM) with a resolution of 12.5 m, used to extract slope, elevation, and landform types. Geological data: Vector layers of active faults and regional geological hazard hidden danger points generated through vectorization based on the 1:200,000 regional geological map. River and road network data: OpenStreetMap open-source vector dataset. Public facility data: POI coordinates of medical institutions across the study area. Emergency shelter data: Coordinates of township-level and higher emergency shelters provided by the Pengzhou Emergency Management Bureau. A total of 125 shelters are distributed in the whole region, among which 82 valid samples are selected for this evaluation. Population data: WorldPop 100 m gridded population density dataset. Land use and soil moisture data: Raster products retrieved from remote sensing images. Socioeconomic data: 2025 Pengzhou Statistical Yearbook and geological hazard archives.

2.2.2 Unified preprocessing procedures

All raster and vector layers are projected to the CGCS2000 planar coordinate system, and rasters are resampled to a uniform resolution of 12.5 m. Topological inspection and small polygon merging are carried out for vector features. The Natural Breaks (Jenks) method is adopted to realize a five-level quantitative assignment for each single-factor layer to eliminate dimensional differences, which lays a standardized data foundation for weighted overlay analysis.

Table 1 Indicator System and Quantitative Grading Standards for Suitability Evaluation of Emergency Shelters in Pengzhou City

Negative Criterion Layer	Indicator Layer	Indicator Characteristic	Grading Standard	Data Source
B1 Safety	C1 Distance to geological hazard points	Negative	≥1000m(5 pts),800-1000m(4 pts),500-800m(3 pts),200-500m(2 pts),<200m(1 pt)	Distribution data of geological hazards
	C2 Distance to active fault	Negative	≥2000m(5 pts),1500-2000m(4 pts),1000-1500m(3 pts),500-1000m(2 pts),<500m(1 pt)	Vectorization of 1:200,000 geological map
	C3 Terrain slope	Negative	0-5°(5 pts),5-10°(4 pts),10-15°(3 pts),15-25°(2 pts),>25°(1 pt)	DEM （5.0m）
	C4 Soil moisture index	Negative	<0.3（5 pts),0.30-0.45（4 pts）,0.45-0.60（3 pts）,0.60-0.75（2 pts), >0.75（1 pt）	Remote sensing inversion data
	C5 Landform type	Qualitative	Plain (5 pts), Hill (3 pts), Mountain (1 pt)	DEM （5.0m）
	C6 Distance to river	Negative	≥1000m(5 pts),800-1000m(4 pts),500-800m(3 pts),200-500m(2 pts),<200m(1 pt)	OSM river network data
B2 Accessibility	C7 Distance to road	Positive	<200m(5 pts),200-400m(4 pts), 400-600m(3 pts),600-800m(2 pts) ,>800m(1 pt)	OSM road network data
	C8 Distance to hospital	Positive	<500m(5pts),500-1000m(4pts), 1000-1500m(3 pts),1500-2000m(2 pts),>2000m(1 pt)	POI data
B3 Effectiveness	C9 Distance to existing emergency shelters	Positive	<500m(5 pts),500-1000m(4 pts),1000-1500m(3 pts), 1500-2500m(2 pts),>2500m(1 pt)	Engzhou Emergency Management Bureau
	C9 Population density	Positive	>2000（5 pts）,1000-2000（4 pts）, 450-1000（3 pts）,150-450（2 pts）, <150（1 pt）	WorldPop dataset

Negative Criterion Layer	Indicator Layer	Indicator Characteristic	Grading Standard	Data Source
	C11 Land use type	Qualitative	Vacant construction land (5 pts), public facility land (4 pts), cultivated land/grassland (3 pts), forest land (2 pts), water body/wetland (1 pt)	Remote sensing interpretation data

The establishment of an indicator system for suitability evaluation of emergency shelters forms the core basis for spatial assessment of shelters in Pengzhou City. Following the principles of scientificity, regional adaptability, and data availability, evaluation factors are selected from three dimensions: safety, accessibility, and effectiveness. A three-level evaluation indicator system is constructed, covering 6 safety indicators, 2 accessibility indicators, and 3 effectiveness indicators, with a total of 11 evaluation factors. Detailed descriptions of evaluation attributes are shown in Table 1 and Table 2.

Table 2 Description of Evaluation Indicator Attributes

Criterion Layer	Number of Indicators	Positive Indicators	Negative Indicators	Qualitative Indicators
B1 Safety	6	0	5（C1、C2、C3、C4、C6）	1（C5）
B2 Accessibility	3	3（C7、C8、C9）	0	0
B3 Effectiveness	2	1（C10）	0	1（C11）
Total	11	4	5	2

2.3 Selection and Quantification of Safety Evaluation Factors

Following the logical principle of safety priority, accessibility support, and effectiveness guarantee, and referring to domestic and international research methodologies, 11 evaluation factors were initially selected from three dimensions: safety, accessibility, and effectiveness [6, 10-12]. Through two rounds of Delphi expert consultation, two redundant indicators—distance to active fault zones and soil moisture index—were eliminated due to spatial collinearity, poor temporal dynamics, and limited practicability for county-level planning. As shown in Table 3 and Figure 2, 9 core evaluation factors were retained ultimately.

Table 3 Two-Round Weight Scoring for Expert Suitability Evaluation

First-round Expert Weight Scoring				Second-round Expert Weight Scoring			
Indicator	Mean	Standard Deviation	Coefficient of Variation (CV)	Indicator	Mean	Standard Deviation	Coefficient of Variation (CV)
C1	1.67	0.516	0.310	C1	3.67	0.516	0.141
C2	2.83	1.169	0.413	C2	3.50	0.548	0.157
C3	2.50	1.049	0.420	C3	3.17	0.408	0.129
C4	3.17	1.472	0.465	C4	2.83	0.753	0.266
C5	2.67	1.211	0.454	C5	2.83	0.753	0.266
C6	3.50	1.517	0.433	C6	3.50	0.548	0.157
C7	2.83	0.753	0.266	C7	3.50	0.548	0.157
C8	3.33	1.033	0.310	C8	3.33	0.516	0.155
C9	3.33	1.506	0.452	C9	3.17	0.408	0.129
C10	2.33	0.816	0.350	C10	4.50	0.548	0.122
C11	2.00	1.095	0.548	C11	3.67	0.516	0.141

2.4 Quantitative Analysis of Core Factors in Three Dimensions

2.4.1 Safety dimension

Safety constitutes the rigid constraint for emergency shelter site selection. Focusing on three types of primary disaster risks, including geological hazards, topographic risks, and flood risks, this dimension includes distance to geological hazard hidden danger points (C1), terrain slope (C2), and distance to water systems (C3).

Distance to geological hazard hidden danger points (C1): Longer distances from hazard points correspond to lower threats of landslides and debris flows. High-risk zones are concentrated at the junction of Guihua, Tongji, and Danjingshan Towns, as well as along river valleys in Longmenshan Town. The southeast plain covering Tianpeng, Zhihe, and Mengyang Subdistricts is far away from hazard points and possesses optimal site safety conditions.

Terrain slope (C2): Steeper slopes bring poorer conditions for site construction and crowd evacuation and assembly. The southeast alluvial plain with slopes of 0–8° represents the most preferred area for site selection. Steep slopes above 18° are mainly distributed in the northern Longmen Mountain area, imposing severe restrictions on the construction of large-scale emergency shelters.

Landform type (C3): Plains are most suitable for constructing emergency shelters, followed by hilly areas, while mountainous regions are the least suitable.

Distance to water systems (C4): Areas adjacent to river channels face prominent risks of flash floods and dam breaks during flood seasons. The 500 m buffer zone along river valleys of the Jianjiang River and Baishui River constitutes a high flood-risk belt. The southeast plain is distant from major water systems with extremely low inundation risks.

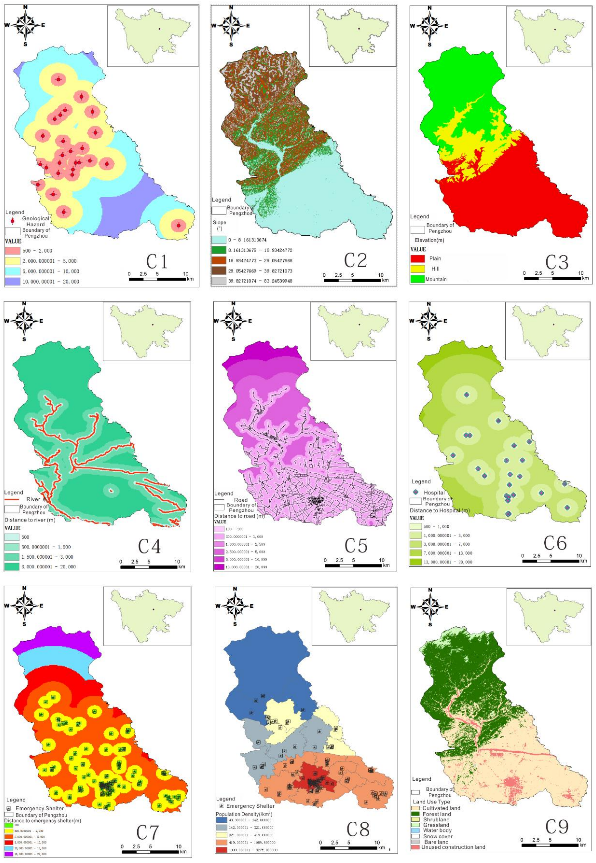

Figure 2 Vector Maps of Core Evaluation Factors

Source: http://bzdt.ch.mnr.gov.cn

2.4.2 Accessibility dimension (3 core factors)

Accessibility determines evacuation efficiency during disasters and measures the convenience for residents and tourists to reach emergency shelters. It contains distance to roads (C5), distance to medical institutions (C6), and distance to existing emergency shelters (C7).

Distance to roads (C5): Shorter distances to road networks ensure stronger evacuation connectivity. The southeast plain features dense expressways and provincial highways with optimal accessibility. Only single valley roads exist in the northern mountainous areas, and road network coverage is insufficient in remote mountain zones.

Distance to medical institutions (C6): Proximity to medical facilities can shorten the transfer and treatment time of the injured. Municipal general hospitals are concentrated in Tianpeng Subdistrict, while township health centers are scarce in northern mountainous towns. Large service blind spots of medical services exist in high-altitude forested areas.

Distance to existing emergency shelters (C7): This indicator is adopted to identify service blind zones of current facilities. Emergency shelters are densely distributed in the southeast plain, leading to overlapping service coverage. Mountainous areas of Longmenshan, Bailu, and Danjingshan have sparse shelter sites, with widespread uncovered blank zones exceeding 2 km.

2.4.3 Effectiveness dimension

Population density (C8) characterizes the spatial intensity of shelter demand. Higher population density means greater demands for shelter capacity and expansion. Population density in the southeast urban area exceeds 1,000 persons/km², bringing heavy resettlement pressure. The northern mountainous areas have sparse permanent residents, yet instantaneous population peaks during peak tourist seasons significantly raise regional shelter demand.

Land use type (C9) represents various land categories, covering eight types: vacant construction land, public facility land, grassland, cultivated land, forest land, snow cover land, wasteland, and water bodies. The suitability of these land types for constructing emergency shelters decreases sequentially.

3 EVALUATION RESULTS AND ANALYSIS

3.1 Suitability Evaluation Based on the Weighted Sum Tool in ArcGIS

Seven standardized single-factor raster layers were imported into ArcGIS. Combined with weights obtained via the Delphi method, the weighted sum operation was implemented to generate continuous suitability scores across the whole study area. The Natural Breaks (Jenks) method was adopted to classify the results into four grades: highly suitable area, suitable area, basically suitable area, and unsuitable area.

Highly suitable area (score: 7.50–9.30): Covering an area of 58.56 km², accounting for 4.12% of the total area of Pengzhou. This zone is mainly distributed in built-up areas of the southeast plains, including Tianpeng, Zhihe, and Mengyang, partially extending to the boundary between Aoping and Gexianshan. The terrain here is flat, far away from geological hazards and river channels, with dense road networks, medical institutions, and emergency shelters. Benefiting from high population agglomeration and few construction restrictions, this region is prioritized for the layout of permanent and high-standard emergency shelters.

Suitable area (score: 5.70–7.50): Covering an area of 331.69 km², accounting for 23.34% of Pengzhou. Encircling the periphery of highly suitable areas, this zone includes the outskirts of plain towns and gentle hilly platforms in southern Guihua and Tongji Towns. Only mild topographic and flood restrictions exist. After simple engineering renovations, the land can satisfy construction requirements for emergency shelters, making it the core potential area for expanding shelters on plains and constructing new facilities in piedmont zones.

Basically suitable area (score: 3.90–5.70): Covering an area of 411.59 km², accounting for 28.97% of Pengzhou. It presents a zonal distribution along piedmont hills from Bailu and Tongji to south-central Longmenshan Town, covering the peripheral areas of Guihua and Lichun Towns. Characterized by rugged terrain and poor road connectivity together with moderate geological risks, this zone is only suitable for constructing small village-level emergency evacuation sites with relatively high development and construction costs.

Unsuitable area (score: 2.10–3.90): Covering an area of 619.15 km², accounting for 43.57% of Pengzhou. Concentrated in high-altitude mountainous areas in northwest Longmenshan Town, this region features steep slopes and contiguous geological hazard points, superimposed with flash flood risks along river valleys. Conditions are inadequate for large-scale fixed emergency shelters; only temporary emergency evacuation yards can be arranged here.

3.2 Statistical Analysis of Spatial Matching with Current Situations

On the basis of a qualitative description of spatial patterns, quantitative statistics are further adopted to reveal prominent problems in the layout of emergency shelters in Pengzhou. Using the Zonal Tabulate tool in ArcGIS, spatial overlay statistics were conducted between the 125 actual shelter points and the four-level suitability zoning (Figure 3).

The results indicate that merely 68 shelters (approximately 54.4%) are located within highly suitable areas; 35 shelters (around 28%) lie in suitable areas. In contrast, up to 19 shelters (15.20%) are distributed in basically suitable areas. More alarmingly, 3 existing shelters are situated within unsuitable areas. Furthermore, multiple shelters in northern mountainous areas are adjacent to gullies with geological hazards, creating a hidden danger of “evacuating to risky zones”.

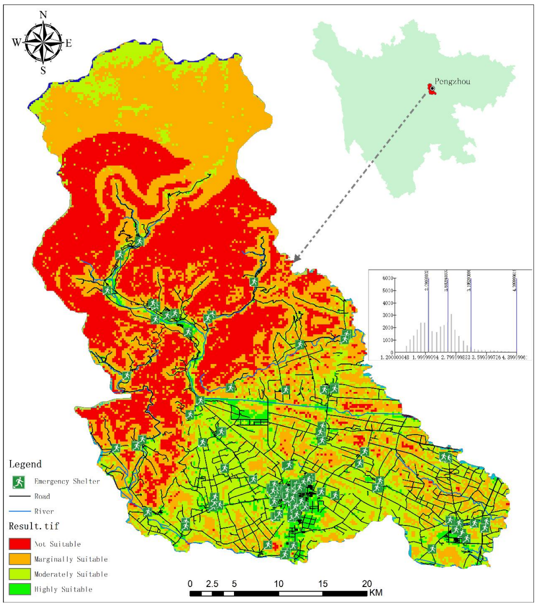

Figure 3 Site Suitability Evaluation Results of Emergency Shelters in Pengzhou City
Source: http://bzdt.ch.mnr.gov.cn

Pengzhou shows obvious spatial imbalance in shelter distribution. In the southeast plain, shelters in highly suitable areas are densely arranged with overlapping service coverage, leading to surplus resource supply. The basically suitable and unsuitable areas in northern mountainous regions occupy half of the whole territory. Although these areas suffer the highest disaster risks, existing shelters are insufficient. Large service blind spots exist in tourist scenic spots and scattered villages, and seasonal population peaks further intensify the contradiction between shelter supply and demand.

In addition, the spatial distribution of emergency shelters in Pengzhou presents a prominent imbalance. Facilities are highly concentrated in the southeast plain, including Tianpeng and Zhihe, and dense sites lead to extensive overlapping of service coverage. A zonal distribution of shelter nodes is formed along the Jianjiang Valley from Guihua to Tongji. Mountainous areas with high geological risks such as Longmenshan and Bailu are severely short of shelter facilities. Many sites are adjacent to landslide and debris flow hazard zones with insufficient site safety, resulting in a spatial mismatch pattern where shelters in high-risk disaster areas feature low suitability. The sharp surge of floating population during the mountain tourist peak season further widens the shelter capacity gap. The regional shelter system suffers not only from insufficient quantity of facilities, but also unbalanced spatial layout and defective site selection, which defines priority optimization directions for the site selection of newly-built shelters.

3.3 Zoned Optimization Planning Strategies for Emergency Shelters

Combined with the spatial differentiation of suitability and evaluation results of existing shelters, differentiated optimization schemes for three major zones are proposed following the ideas of improving stock shelters in plain areas, supplementing new shelters in mountainous regions, and realizing coordinated linkage in buffer zones.

3.3.1 Southern Plain Zone: stock optimization for quality and efficiency improvement

The Southern Plain Zone covers subdistricts including Tianpeng and Zhihe, as well as multiple plain towns. It enjoys generally high shelter suitability with an adequate total number of emergency shelters, yet problems such as redundant layout and uneven functional distribution remain. The core planning strategy for this zone focuses on stock optimization. On the one hand, small evacuation sites with overlapping coverage and duplicated functions will be integrated, and public spaces such as schools and stadiums will be upgraded into standardized medium- and long-term emergency shelters with complete supporting facilities for medical treatment, material storage, sewage disposal, and water purification. On the other hand, a peacetime-emergency conversion system will be established. Urban parks and squares will be reserved as emergency resettlement spaces, and flood control and geological disaster supplies will be stored regularly to satisfy resettlement demands of permanent and floating residents. Meanwhile, traffic bottlenecks on urban branch roads will be dredged to form multi-route evacuation road networks and avoid road congestion during disasters. No new large-scale emergency shelters will be constructed in this zone. Instead, efforts will concentrate on renovating aging shelters by adding barrier-free facilities and special resettlement areas for the elderly to adapt to the local highly aging population structure and realize precise and efficient utilization of shelter resources (Figure 4).

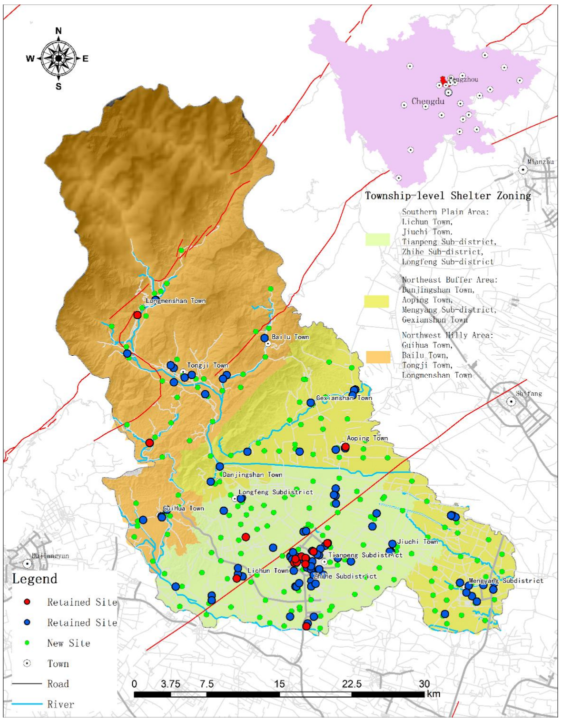

Figure 4 Planning Layout of Emergency Shelters in Pengzhou City
Source: http://bzdt.ch.mnr.gov.cn

3.3.2 Northeastern Buffer Zone: balancing internal and external demands with regional coordination

The Northeastern Buffer Zone features transitional terrain of hills and plains. It serves as the core receiving area for affected residents evacuated from northern Pengzhou. Adjacent to high-disaster-risk areas including Shifang and Mianzhu, it undertakes cross-regional emergency resettlement functions. Following the principle of balancing internal and external demands and promoting regional coordination, the zone will improve the three-level shelter system covering county, town, and village levels to guarantee basic local shelter demands. Relying on abundant township school resources, four county-level long-term emergency shelters will be arranged to primarily accommodate affected populations evacuated from northern mountainous areas and other regions. In addition, supporting facilities and comprehensive support capacity of key shelters will be strengthened to fully improve the zone's buffering capacity and emergency resettlement capacity, consolidating the regional buffer line for disaster evacuation.

3.3.3 Northwestern Mountain and Hilly Zone: supplementing new facilities with hierarchical layout

The Northwestern Mountain and Hilly Zone is a high-risk area for geological hazards with low shelter suitability. Existing shelters are sparsely distributed, leaving extensive service blind zones. The zone adopts the planning mode of supplementing new facilities with hierarchical layout, establishing a three-level system consisting of micro emergency evacuation points, township short-term shelters, and seasonal scenic shelter sites to meet the respective demands of on-site evacuation for villages, centralized resettlement in towns, and accommodation of tidal tourist flows in scenic spots. For hidden risks of existing shelters, geological safety reviews will be carried out. High-risk sites will be relocated or equipped with protective projects to eliminate safety hazards. Mountain traffic lifelines will be upgraded simultaneously: main roads will be widened, and emergency branch roads and passing bays will be added to tackle emergency transportation difficulties. In light of mountain conditions, modular mobile storage facilities will be adopted to cut construction costs, with exclusive evacuation spaces for vulnerable groups matching the mountain population structure.

3.3.4 Citywide supporting guarantee measures

To promote the implementation of zoned planning, Pengzhou City shall establish an all-round citywide guarantee system. A dynamic population early-warning mechanism will be set up to monitor tourist flows in scenic spots in real time and dynamically allocate emergency materials and resettlement sites. Hierarchical management responsibilities shall be implemented at township and community levels; regular facility maintenance and material renewal shall be carried out to form a long-term operation and maintenance mechanism. A digital management platform based on GIS technology will be constructed to update real-time data including site suitability, bearing capacity, and material reserves, so as to realize dynamic management and precise planning of emergency shelters. Furthermore, the standardized GIS evaluation model and zoned planning strategies summarized in this research can be extended and applied to similar piedmont counties along the Longmen Mountains, offering references for the construction of regional emergency shelter systems.

4 CONCLUSIONS AND DISCUSSION

The site suitability of emergency shelters in Pengzhou exhibits obvious stepped spatial differentiation, presenting an overall pattern of high suitability in the southeast and low suitability in the northwest. Towns and urban areas on the southeastern plain form concentrated highly suitable zones, while the northern mountainous and hilly areas are mostly basically suitable and unsuitable zones with intensive geological hazards. This leads to spatial mismatch: regions facing severe disaster risks lack sufficient shelter supply.

Through two rounds of the Delphi method for indicator screening, seven core evaluation factors are finally determined: terrain slope, distance to geological hazard hidden danger points, distance to water systems, distance to roads, distance to medical institutions, distance to existing emergency shelters, and population density. This approach effectively avoids problems such as indicator collinearity and insufficient timeliness, establishing a lightweight suitability evaluation system adaptable to the transitional mountain-plain landform.

In terms of the existing layout, all 125 emergency shelters across Pengzhou meet basic construction standards with no unqualified sites. Nevertheless, a prominent imbalance exists in spatial distribution. The southeastern plain suffers from redundant shelter resources, while large service blind zones appear in northern mountainous areas. In addition, some mountain shelters are threatened by geological hazards and floods with inadequate emergency support capacity.

Targeting the above spatial differentiation and existing problems, differentiated zoned planning strategies are proposed. The plain zone focuses on integrating existing resources to improve service quality and efficiency, whereas mountainous areas prioritize supplementing new facilities, hierarchically arranging evacuation sites, and renovating risky existing shelters, so as to build a composite emergency shelter system catering to permanent residents and seasonal floating tourist populations.

Meanwhile, this study has certain limitations. The evaluation adopts static single-phase remote sensing and population data without multi-scenario dynamic population simulation. Restricted by data timeliness, indicators such as soil moisture and dynamic land use are not incorporated into the evaluation model. Future research can carry out dynamic suitability simulation using multi-temporal remote sensing data and big data of scenic passenger flows. Coupled with multi-hazard prediction models of flash floods and landslides, a simulation system integrating disaster risk forecasting, dynamic shelter capacity assessment, and real-time evacuation route optimization can be developed. It will provide more comprehensive technical support for refined and dynamic planning and governance of emergency shelters at the county level.

FUNDING

This research was financially supported by the Sichuan Provincial Science and Technology Program Project entitled"Research on the Early Warning 'Calling and Response' Mechanism for Construction Camps Under Construction in Complex Mountainous Areas of Sichuan Province" (Grant No. SCJJ25RKX168) and the No.57 Project (JH2024015). The authors sincerely appreciate the financial support that made this study possible. We also thank all relevant institutions and personnel who provided field data, technical guidance and valuable suggestions during the research and investigation process.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

[1] Zhao L J, Wang K, Wang J. Theory and Methods of Urban Emergency Shelter Planning and Construction. Beijing: Science Press, 2014.
[2] Zhao L. Two departments of Sichuan issued special planning for emergency shelters. Resources and Habitant Environment, 2026(1).
[3] Hu Y J. Current situation and prospect of emergency shelter management in China. China Disaster Reduction, 2026(7): 14-17.
[4] Sun Z. Research on optimization path of disaster prevention shelter layout in central urban area based on synergy theory. Tianjin: Tianjin University, 2021.
[5] Ji W J, Qu J S, Xu L. Disaster reduction capacity evaluation of emergency shelters in Lanzhou based on AHP and GIS. Remote Sensing Technology and Application, 2021, 36(4): 948-958.
[6] Wang P M. Problems and countermeasures of urban emergency shelter layout. City and Disaster Reduction, 2019(2): 23-28.
[7] Zhang X, et al. Spatial distribution characteristics of emergency shelters in Deyang, Sichuan Province. Sichuan Earthquake, 2024, (4): 14-19.
[8] Gao Y K, Qin T X, Zhang X K, et al. Overview on construction and management development of emergency shelters in China. 2022: 17-19.
[9] Zhang H P. Enlightenments of foreign emergency shelters to the construction of shelters in China. City and Disaster Reduction, 2020(3): 29-33.
[10] Wu C, Wang Q D, Li S. Spatial layout of emergency shelters based on accessibility analysis: A case study of Guangzhou. City Planning Review, 2018, 42(4): 107-112, 124.
[11] Kang L, Zhu J, Li W L. Site selection of emergency shelters for barrier lakes in mountainous areas based on dam-break flood model. Journal of Natural Disasters, 2018, 27(5): 39-45.
[12] Fan C J. Research on optimization method of shelter site selection for comprehensive multi-hazard response. Nanjing: Nanjing University, 2016.