Research Paper

Regional Comprehensive Disaster Prevention System Planning from the Perspective of Resilient Cities: A Case Study of Mentougou District, Beijing Municipality

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Abstract

Urban ecosystems are increasingly vulnerable to extreme weather events, making resilient city planning vital for disaster prevention and mitigation. This study focuses on Beijing's Mentougou district, identifying high-risk areas for various disasters and quantitatively assessing three major natural hazards and their key influencing factors. It evaluates resilience within regional ecosystems and infrastructure systems to map the district's safety landscape comprehensively. Integrating multi-hazard risk assessments with urban resilience evaluations, the research proposes disaster prevention zones, identifies critical urban life corridors, and incorporates disaster relief nodes, enhancing the spatial organization of disaster management. The findings highlight the distinct roles of urban ecosystem quality and infrastructure in disaster prevention and relief, leading to the development of a comprehensive system tailored to Mentougou's temporal disaster characteristics. This system aims to improve urban resilience, safeguard land use, and support high-quality urban development.

Keywords

Resilient City; Coupling Analysis; Risk Assessment; Disaster Prevention and Mitigation; Mentougou District

1. Introduction

Climate is the fundamental condition for the survival and maintenance of human and natural ecosystems. Since the late 1970s and early 1980s, global warming has become increasingly pronounced, leading to a heightened risk of climate-related disasters, which pose a severe threat to human production and livelihoods. Currently, research in the relevant field primarily addresses two aspects: first, it focuses on the spatiotemporal characteristics(Huang et al., 2020) and patterns(Shen et al., 2022; Li et al., 2014) of climate change, particularly studying the risks of individual extreme events such as flooding and heatwaves(Han et al., 2019; Zhao et al., 2022); second, it conducts comprehensive analyses and evaluations of the resilience development level in study areas, considering factors such as spatiotemporal evolution, spatial differentiation, influencing factors, and optimization paths(Zhang et al., 2022; Li et al., 2022; Liu et al., 2023). The scale of research is mainly concentrated on urban and watershed levels (Luo et al., 2022; Wang et al., 2023). Although existing research has yielded significant results, it still faces considerable theoretical and practical limitations. From a theoretical perspective, analyses based solely on single-hazard risks or resilience perspectives lack a systematic and scientific coupled assessment framework, as well as a theoretical analysis of the interactive evolution between the two (Wu et al., 2024). From an applied perspective, specialized mitigation measures for individual hazards overlook the trade-offs and synergies among multiple hazard factors, making the actual effectiveness difficult to measure. Therefore, conducting a comprehensive multi-hazard risk assessment from the perspective of resilient cities, identifying the baseline of urban disaster risks, and optimizing the spatial structure of urban disaster prevention is critical to achieving resilient urban development.

In summary, this study selects Beijing's Mentougou District as a case study area. Utilizing Remote Sensing (RS) and Geographic Information Systems (GIS) within the appropriate model framework, we quantitatively assess the geological, flood, and fire disaster risks of the district and systematically evaluate the resilience development levels of regional ecosystems and infrastructure systems. Building upon a comprehensive integration of existing territorial spatial planning outcomes, the research clarifies the city's emergency support nodes, identifies key life corridors, and delineates disaster prevention and control zones from the three dimensions of "point, line, and plane." The findings reveal the spatial misalignment between comprehensive multi-hazard risks and urban resilience patterns in Mentougou District, offering data support and a theoretical basis for disaster risk prevention and resilient urban development in the region.

2. Materials and methods

2.1. Study area

Mentougou district (Figure 1) is located in the mountainous western region of Beijing, covering an area of 1,455 km², with mountains accounting for 98.5% of the total area. As the only fully mountainous district in Beijing, it has uneven vegetation coverage, severe soil erosion, and frequent landslides and debris flows. Additionally, due to the instability of mid-latitude atmospheric circulation and the influence of monsoons, the Mentougou district experiences significant interannual variations in precipitation, with uneven distribution throughout the year. Approximately 85% of the annual rainfall occurs during the flood season, making the area highly prone to major floods and flood-related disasters.

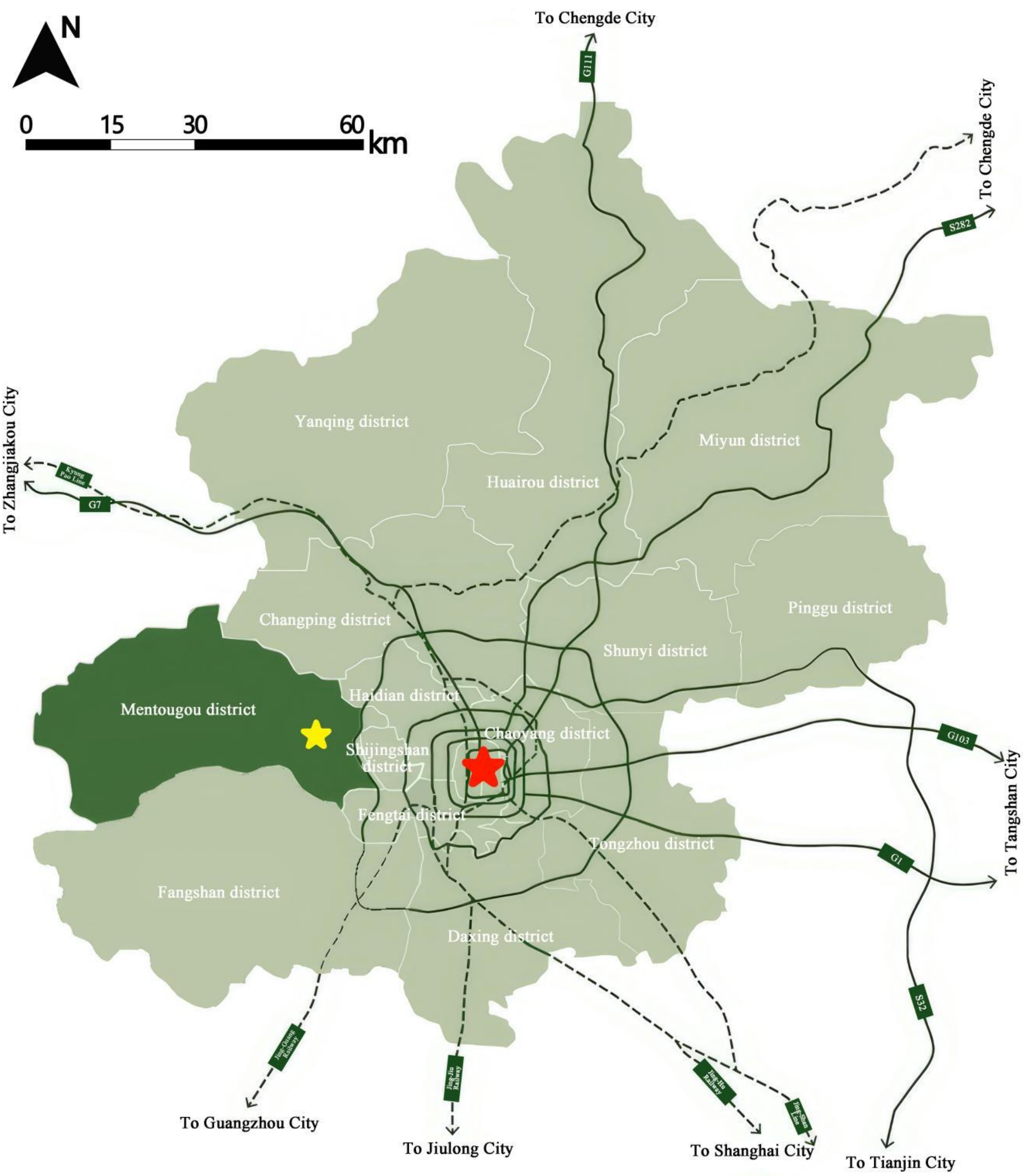

Figure 1. Location analysis of the study area.

2.2. Data

The data used in this study primarily consists of four types: land use data, disaster distribution data, natural environment data, and socioeconomic data (Table 1). To ensure the scientific rigor and consistency of the study, the administrative boundaries of the Mentougou district were used as spatial constraints. All data were projected using the WGS_1984_UTM_Zone_50N coordinate system, with a uniform resolution of 30 meters, and the rows and columns of raster data were aligned accordingly.

Table 1. Data profile and sources.

Data types	Specific data	Data format	Sources of the data (Providers)
Land Use/Cover	China National Land Use/Cover Change Dataset (CNLUCC）	Raster	Resource and Environmental Science and Data Center (https://www.resdc.cn/)
Disaster distribution data	Hazard distribution coordinate data	CSV	Mentougou District Government (http://www.bjmtg.gov.cn/)
Natural environment data	Digital Elevation Data	Raster	Geospatial Data Cloud (https://www.gscloud.cn/)
	Annual NDVI Spatial Distribution Dataset in China	Raster	Resource and Environmental Science and Data Center (https://www.resdc.cn/)
	Annual spatial interpolation data of meteorological elements in China	Raster	Resource and Environmental Science and Data Center (https://www.resdc.cn/)
	Natural element boundary data	Shapefile	National Catalogue Service for Geographic Information (https://www.webmap.cn/)
	Seismically active fault data	Shapefile	Institute. of Geology, China Earthquake Administration (https://www.eq-igl.ac.cn/)
Socio-economic data	Transportation network classification data	Shapefile	OpenStreetMap (https://extract.bbbike.org/）
	Infrastructure distribution data	Shapefile	OpenStreetMap (https://extract.bbbike.org/）
	Administrative boundary data	Shapefile	Resource and Environmental Science and Data Center (https://www.resdc.cn/)
	GDP spatial distribution kilometer grid data in China	Raster	Resource and Environmental Science and Data Center (https://www.resdc.cn/)
	Population Spatial Distribution Kilometer Grid Data in China	Raster	Resource and Environmental Science and Data Center (https://www.resdc.cn/)

2.3. Multi-hazard Comprehensive Risk Assessment

This paper reveals the comprehensive disaster risk level of the study area by coupling the individual risk assessment results of geological hazards, flood hazards, and fires. As shown in Equation (1), the risk of a single hazard consists of two components: hazard risk and susceptibility (Lu et al., 2024). Hazard risk refers to the intensity of hazardous factors and the likelihood of their occurrence. For each type of disaster, this study selected five independent factors with significant influence as evaluation indicators and determined the weight of each factor using expert scoring and public participation methods (Table 2) (Shan et al., 2024; Bai et al., 2024; Li et al., 2024). Susceptibility refers to the spatial density and temporal frequency of disaster occurrences. This study collected historical data on various disasters by reviewing statistical records consulting relevant organizations, and performing spatial visualization based on the GIS platform. Additionally, to eliminate the impact of dimensional differences, all individual factor indicators were standardized (Equation 2).

$$R_f = H_f \times eV_f \qquad (1)$$

In the equation, R_f represents the risk level of a single hazard, H_f denotes hazard risk, V_f refers to susceptibility, and e is the proportional coefficient.

$$X' = \frac{(X_i - X_{min})}{(X_{max} - X_{min})} \qquad (2)$$

In the equation, X' epresents the standardized result, with values ranging between 0 and 1; X_i is the value of the i-th raster; X_{max} and X_{min} are the maximum and minimum values of the raster, respectively.

Table 2. Indicators and weights for single-hazard evaluation.

Type of disaster	Indicator name	Relevance	Weight
Geological disaster	DEM	Positive correlation	0.2
	Rate of change of slope	Positive correlation	0.25
	Slope	Positive correlation	0.25
	NDVI	Negative correlation	0.2
	Distance from the fault	Negative correlation	0.1
Flood disaster	Precipitation	Positive correlation	0.2
	Rate of change of slope	Positive correlation	0.15
	Slope	Positive correlation	0.15
	NDVI	Negative correlation	0.2
	Distance from the water body	Negative correlation	0.3
Fire disaster	Temperature	Positive correlation	0.2
	NDVI	Positive correlation	0.3
	Distance to timber-framed buildings	Negative correlation	0.15
	Distance from the deflagration risk area	Negative correlation	0.15
	Soil water content	Negative correlation	0.2

2.4. Assessment of the development level of urban resilience

This study uses the completeness of urban roads, power supply facilities, water supply facilities, communication facilities, and fire-fighting facilities as the basic indicators for evaluating the resilience of the urban infrastructure system. The weight of each factor was determined through expert scoring and public participation methods (Table 3).

Table 3. Indicators and weights for single-hazard evaluation.

Code	Indicator name	Relevance	Weight
1	Distance from the road	Positive correlation	0.4
2	Distance from the fire-fighting facilities	Positive correlation	0.15
3	Distance from the power supply facilities	Positive correlation	0.15
4	Distance from the water supply facilities	Positive correlation	0.15
5	Distance from the communications facilities	Positive correlation	0.15

Drawing on previous research, this paper constructs an urban ecological resilience assessment model from three aspects: resistance, adaptation, and restoration (Equation 3) (Xia et al., 2022). Resistance (P) refers to the ability of an urban ecosystem to withstand external disturbances, which in this study is evaluated by calculating the ecosystem service value index of the study area (Equation 4) (Huang et al., 2018; Ren et al., 2000a; Xie et al., 2015). Restoration (R) refers to the ability and potential of an ecosystem to return to its original state after being harmed and is calculated using the ecological resilience model proposed by Peng et al. (Equation 5) (Peng et al., 2015). Adaptation (A) refers to the stability of the landscape structure in the study area, which is assessed using landscape indices from two aspects: landscape heterogeneity and landscape connectivity (Ren et al., 2000b). The specific secondary indicators and weight distribution are shown in Table 4 (Peterson, 2002; Turner, 1989; Peng et al., 2015).

$$Resilience = \sqrt[3]{A \times P \times R} \quad (3)$$

$$P = ESV = \sum A_k \times VC_{fk} \quad (4)$$

$$R = \sum A_k \times RC_i \quad (5)$$

Table 4. Analysis of landscape pattern factor.

Evaluation indicators	Landscape pattern factor	Weight
Landscape heterogeneity	Shannon Diversity Index	0.25
	Area-Weighted Mean Patch Fractal Dimension	0.25
Landscape connectedness	Landscape Fragmentation	0.5

3. Results

3.1. Mentougou district multi-hazard comprehensive risk

3.1.1. Geological Disaster Risk

Geological disasters in the Mentougou district are primarily sudden-onset, characterized by diversity, clustering, concealment, and concentration. The mountainous areas of Mentougou account for 98.5% of its total area, making the impact of terrain on urban development more pronounced than in other regions. As shown in Figure 2-a, areas with high seismic hazard levels are mainly located in the northwestern mountains and along the Yongding River in the Yanchi, Wangping, and Miaofengshan villages. Additionally, the new city area, Tanzhesi Town, and Junzhuang Town, with a long history of coal mining and large subsidence areas, are also high-risk zones for mine-induced earthquakes. Susceptibility results (Figure 2-b) indicate that Mentougou district contains five high-vulnerability zones, four medium-vulnerability zones, and several low-vulnerability zones, most of the low and medium-vulnerability zones are located in patches. Zhaitang, Qingshui, and Yanchi towns each have over 350 geological disaster points, while Datai subdistrict, Tanzhesi town, and Wangping town have over 150 points. The Longquan area is the location of major geological hazards in the New City.

Overall, the most severe geological hazards in Mentougou district are concentrated in Dong and Xi Wangping villages in Wangping town, Sanjiadian village in Longquan town, and the northwestern mountainous area, with typical cases in Lingshan mountains, Bijingsi village, and Huangtugui village. Medium-scale hazards are concentrated in the northern part of Caodianshui village in Tanzhesi town, the central parts of Shangdamo village, the Xidamoand village, and the eastern parts of Huangta villages in Qingshui town, and the northern part of Huiyu village in Junzhuang town (Figure 2-c).

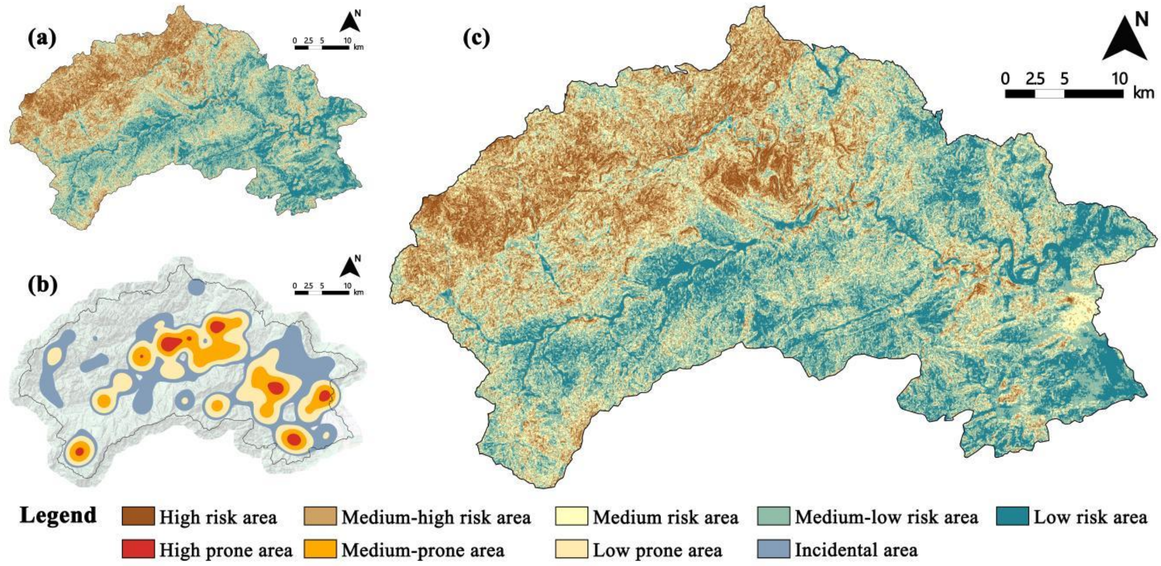

Figure 2. Mentougou district multi-hazard comprehensive risk (Geological disaster). (a)Results of disaster risk assessment. (b)Results of risk susceptibility assessment. (c)Results of multi-hazard comprehensive risk.

3.1.2. Flood disaster risk

Flood disasters in Mentougou district are primarily caused by torrential rain, leading to collapses and waterlogging. As shown in Figure 3-a, areas with high flood risk are concentrated in the mainstream of the Yongding River and its tributaries, including the Qingshui River, Weidiangou, and Jiangou regions. Additionally, due to the low elevation of Mentougou new city area, surrounded by mountains on the north, west, and south sides, the city's main drainage channels are insufficient during heavy rainfall in the flood season, posing certain disaster risks. Susceptibility results (Figure 3-b) show that high-vulnerability flood zones are concentrated along the Qingshui River, from Zhaitang town to Yanchi town along the Yongding River. This region has numerous sharp river bends, causing significant increases in runoff. Three high-vulnerability areas are located in Donghulin village, Taizimu village, and Chengzi subdistrict of Mentougou new city area, with five medium-vulnerability areas and several low-vulnerability zones.

Overall, the most severe flood risks in Mentougou district are concentrated in the northern Yongding River basin section of the new city area, the confluence of water systems in Miaofengshan town and Wangping town, and the area between Zhuwo-Weizishui reservoir area. Medium-scale risks are concentrated in the Zhaitang reservoir and the Tanzhesi section of the Daqing River. Additionally, the southern of the new city area, Junzhuang town, Miaofengshan town, Yanchi town, Zhaitang town, and the central areas of Qingshui town are under significant waterlogging threats (Figure 3-c).

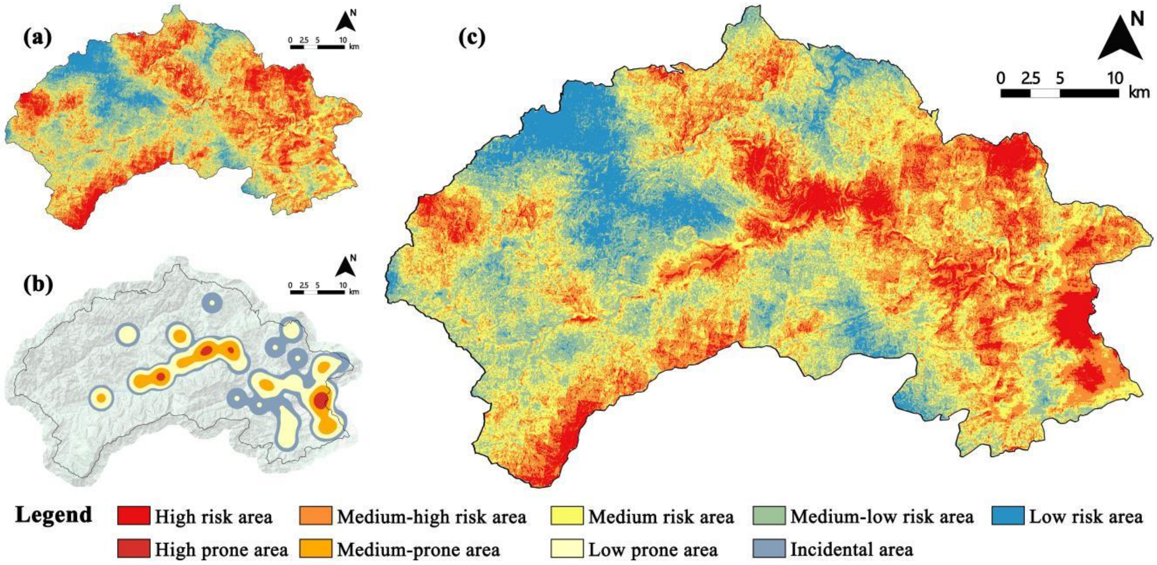

Figure 3. Mentougou district multi-hazard comprehensive risk (Flood disaster). (a)Results of disaster risk assessment. (b)Results of risk susceptibility assessment. (c)Results of multi-hazard comprehensive risk.

3.1.3. Fire disaster risk

Fire hazards in Mentougou district are mainly concentrated in units handling flammable and explosive materials, high-density old urban areas, protected historic buildings, and forest fires. As shown in Figure 4-a, fire risks are highest in the Qingshui River basin and the new city area, with a gradient decreasing from east to west and from the rivers to the forests. Susceptibility results (Figure 4-b) indicate that Mentougou district has three high-vulnerability zones, four medium-vulnerability zones, and several low-vulnerability zones, mostly scattered.

Overall, major fire hazard zones in Mentougou district are concentrated in Junzhuang town, Zhaitang town, and Yanchi town, while medium-risk areas are concentrated in the new city area, Tanzhesi town, Junzhuang town, and Zhaitang town. Fire risks are scattered across various regions in a point pattern (Figure 4-c).

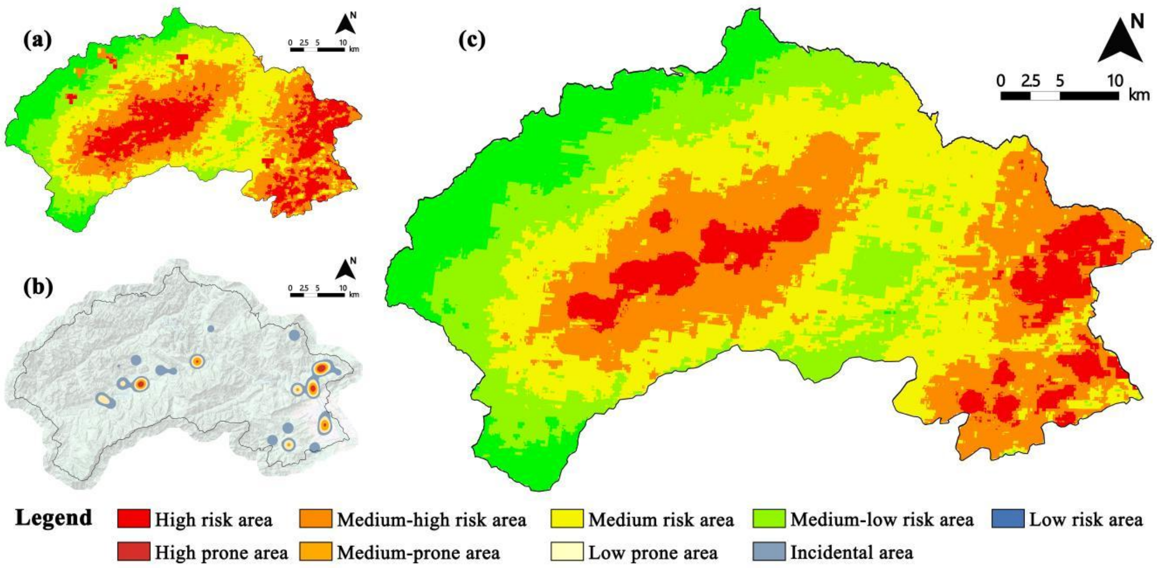

Figure 4. Mentougou district multi-hazard comprehensive risk (Fire disaster). (a)Results of disaster risk assessment. (b)Results of risk susceptibility assessment. (c)Results of multi-hazard comprehensive risk.

3.1.4. Mentougou district multi-hazard comprehensive risk

As shown in Figure 5, areas with high comprehensive disaster risk in Mentougou district are primarily located in the northern section of Chengzi village in the new city area, the southern part of Sanjiadian village, the Seshufen area in Wangping town, the northeastern part of Datai subdistrict, and the Fajiatai and Zhuwuo village areas in Yanchi town. Medium-risk areas are distributed in Chengzi village, Shigang village, and Mentoukou village in the new city area; Dongxin village in Tanzhesi town; the Huiyu village in Junzhuang town; Longjiazhang village in Miaofengshan town; Dong and Xi Wangping villages in Wangping town; and the southern part of Datai subdistrict. Low-risk areas are concentrated in villages with ongoing construction activities.

From a spatial distribution perspective, the comprehensive disaster risk closely mirrors the spatial pattern of flood risk, highlighting that flood disasters are a critical factor affecting the stability of the natural environment and socio-economic development. This also corroborates the complex interplay between various disasters in the Mentougou district, where floods caused by heavy rains can trigger subsidence, landslides, and debris flows. Additionally, most high-risk disaster zones are located along the Yongding River, underscoring the importance of maintaining the ecological security of the Yongding River basin for disaster prevention and relief in the Mentougou district.

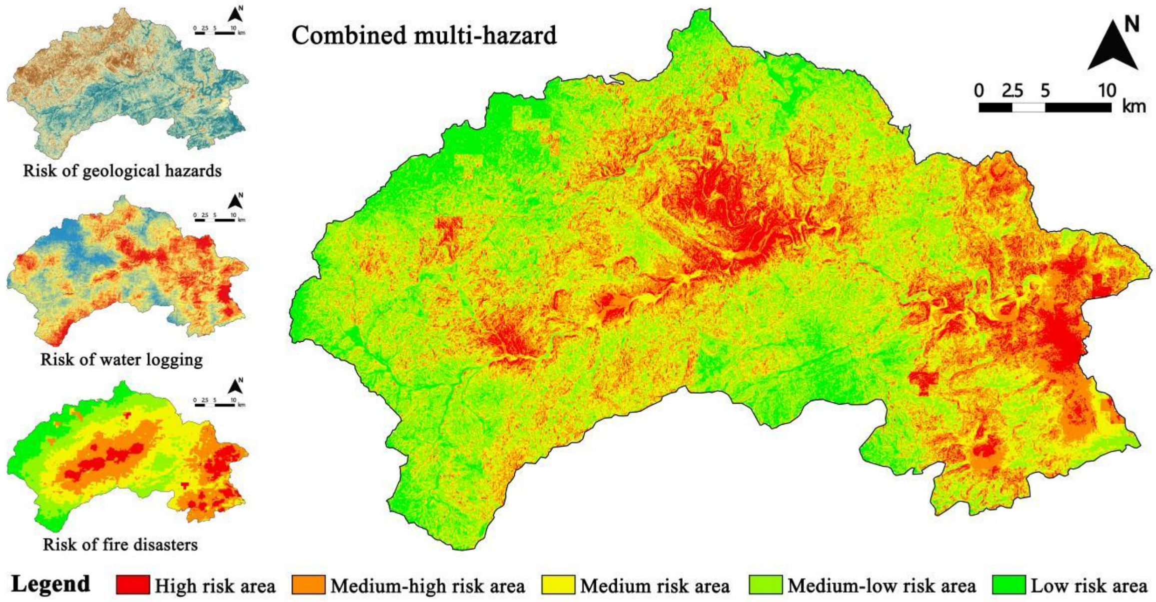

Figure 5. Mentougou district multi-hazard comprehensive risk.

3.2. Development level of urban resilience in Mentougou district

3.2.1. Resilience level of the infrastructure system in the Mentougou district

As shown in Figure 6, the resilience level of the infrastructure system in Mentougou district is centered around Mentougou new city area, Fujiatai village in Yanchi town, and Junxiang village, with a gradient decline from the center toward the periphery. Notably, high-resilience infrastructure areas in the

Mentougou district are fragmented and scattered around town centers, and have yet to form an interconnected and cohesive coverage system..

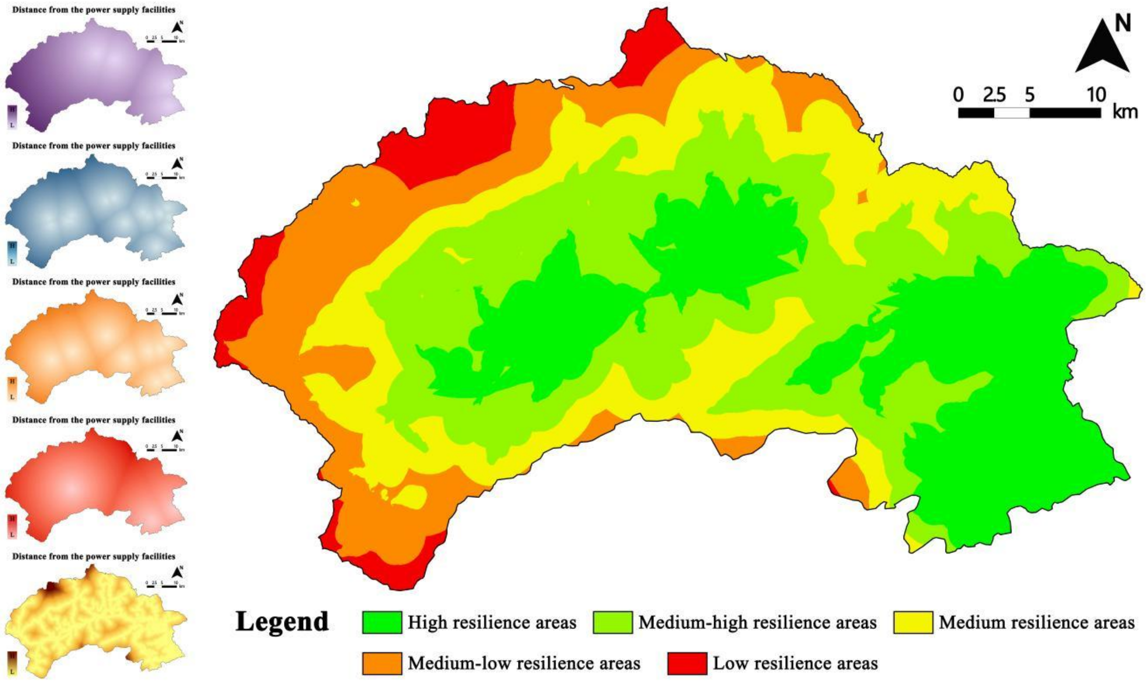

Figure 6. Evaluation results of the resilience level of the infrastructure system.

3.2.2. Resilience level of the urban ecosystem in the Mentougou district

The ecosystem resistance (P) in the Mentougou district is relatively weak, with an average value of only 0.37. The high-resistance areas are mainly distributed along the Yongding River, including the Longkou reservoir, Sanjiadian reservoir, Luopoling reservoir, Zhuwo reservoir, Fujiatai village, and Taizimu village, while low-resistance areas are concentrated in the new city area and Junzhuang town (Figure 7-a). The ecosystem restoration (R) in Mentougou district is relatively high, with an average value of 0.86. Mountainous forest areas and the Yongding River and its tributaries have high resilience, while low-resilience areas are located in the new city area, Junzhuang town, and Tanzhesi town (Figure 7-b). The ecosystem adaptation (A) in Mentougou district is extremely low, with an average value of only 0.09. The land use structure in the district is predominantly single-type forest land, with high adaptability areas concentrated in the old and new urban areas and the construction-intensive towns in mountainous areas (Figure 7-c).

Overall, the ecosystem resilience level in the Mentougou district is relatively low, with an average value of only 0.17, although the ecological resilience of the Yongding River and its tributaries is generally higher (Figure 7-d). Spatial autocorrelation analysis of resilience levels (Figure 7-e) indicates a significant clustering of high values (Z=25.4101), with the hotspots primarily located at the boundary between Miaofengshan town and Wangping town, Dingdu peak, Zhuwuo reservoir, and Zhaitang reservoir. The coldspots are mainly distributed in the Lingshan Scenic Area, Cuandixia village, and Shenquanxia Scenic Area.

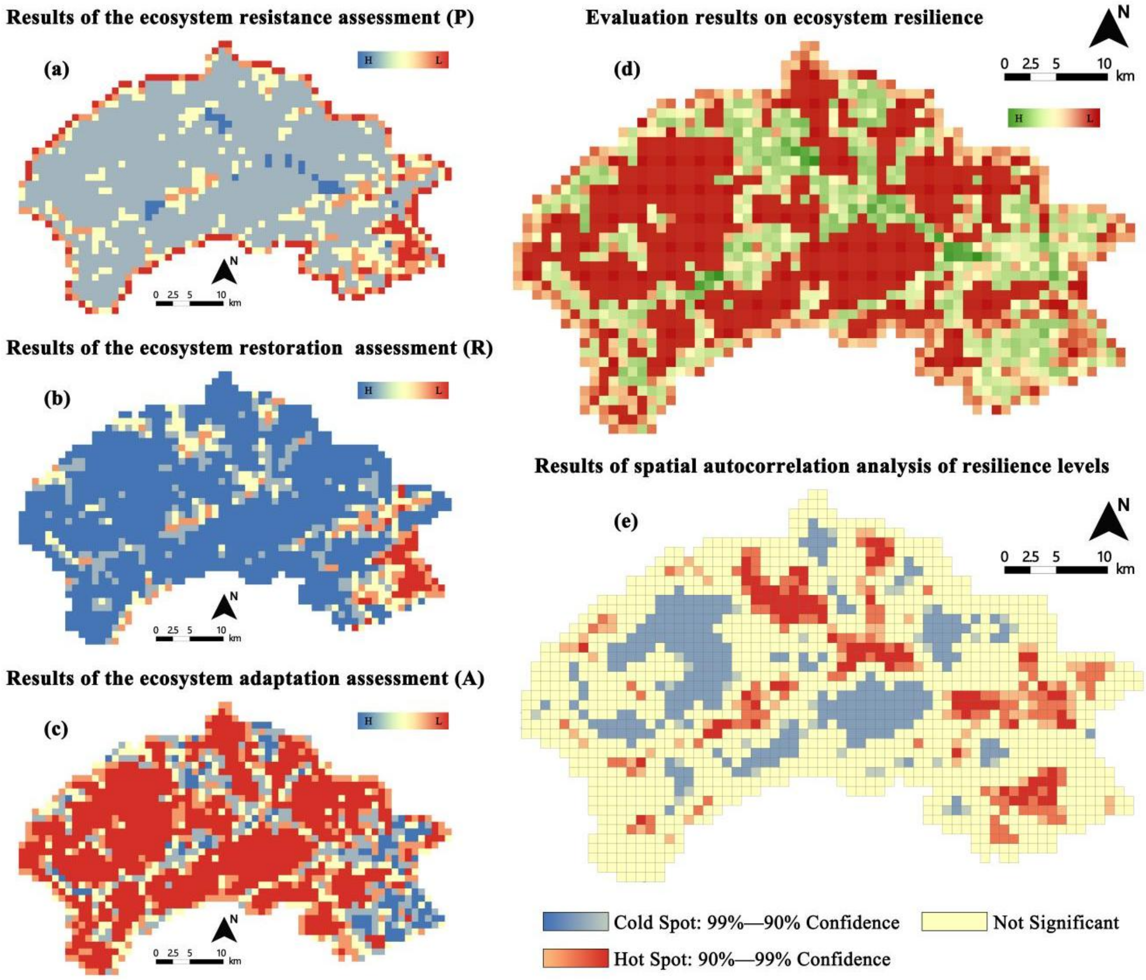

Figure 7. Evaluation results of the resilience level of the urban ecosystem.

4. Discussion

4.1. Mentougou district disaster prevention spatial layout

Mentougou district currently has 10 emergency shelters with a total evacuation area of 257,000 m2, providing approximately 0.86 square meters per capita. However, since most villages in Mentougou district are scattered across 98.5% mountainous terrain, and with rugged roads, the difficulty of emergency rescue is increased. Therefore, this study proposes a disaster prevention spatial layout tailored to local conditions. For developed towns and central urban areas, a unit-based management approach for prevention and control is recommended, with evacuation planned based on population density to ensure that the per capita effective area in fixed shelters exceeds 2 m². For mountainous towns, 19 additional emergency rescue points with a service radius of 3 km are proposed, including 6 in Qingshui town, 5 in Zhaitang town, 5 in Yanchi town, and 3 in Miaofengshan town (Figure 8). Each emergency rescue point will be built within village infrastructure, ensuring that the walking time from each village to the nearest rescue center is no more than 1 hour.

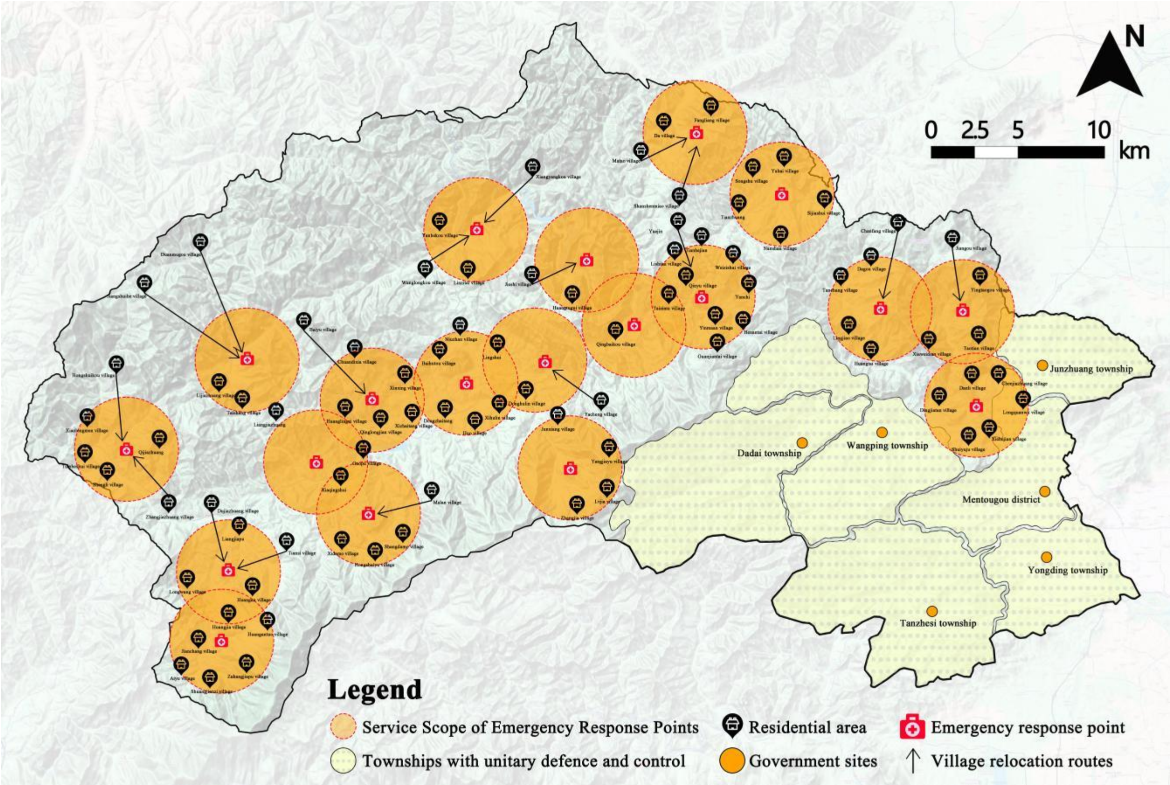

Figure 8. Mentougou district disaster prevention spatial layout planning.

4.2. Mentougou District life corridor construction

Based on the standards for urban life passageway construction and the disaster prevention spatial layout of Mentougou District, this study proposes a regional life corridor construction concept of "reliable, passable, and accessible." The study suggests dividing the corridors into three levels based on emergency support levels, which together form a "two rings and two belts" life corridor system (Figure 9). The first-level life corridor is structured as "two horizontal and one vertical," primarily responsible for ensuring basic urban traffic under major or catastrophic disasters, and for facilitating internal and external rescue transport. The second-level life corridor is structured as "two horizontal and two vertical," focusing on maintaining internal circulation for disaster relief and facilitating the transport of relief materials and personnel within the city. The third-level life corridors are dispersed and mainly connect the first and second-level corridors, extending the coverage of disaster relief and ensuring quick evacuation in the event of small to moderate disasters or pre-disaster evacuation.

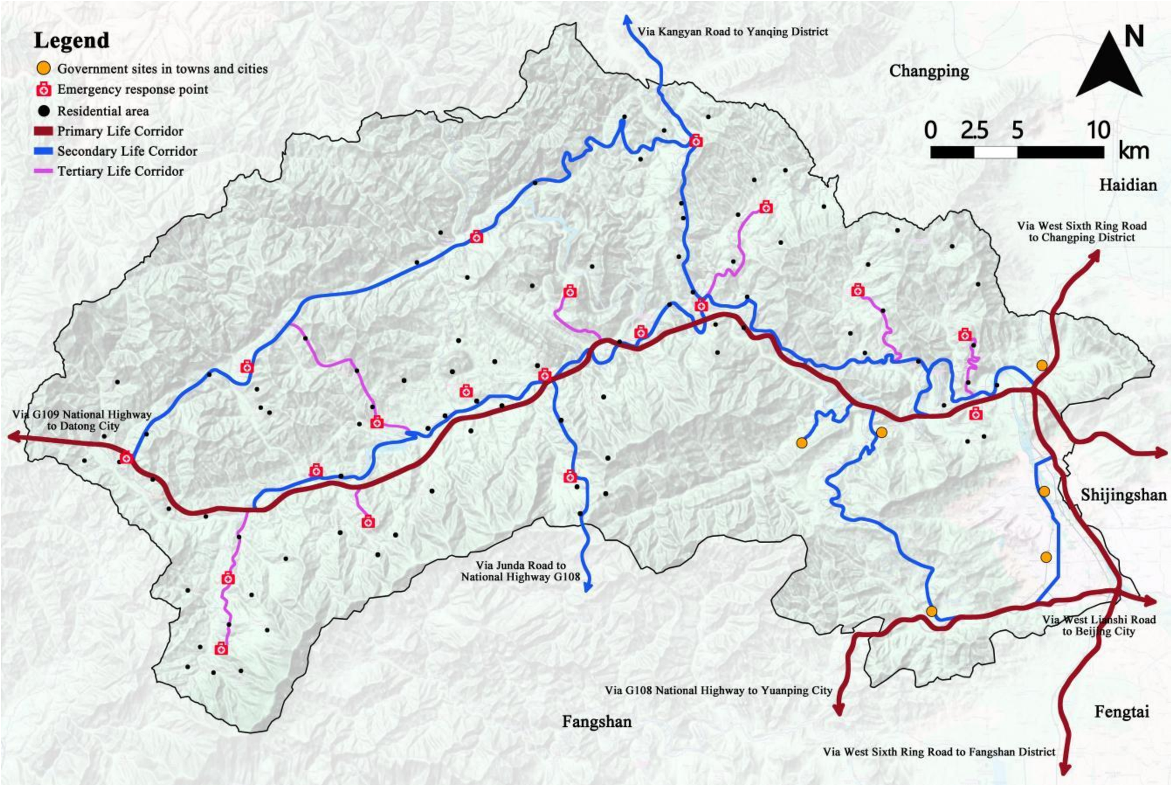

Figure 9. Mentougou district life corridor planning.

4.3. Mentougou district emergency security points identification

To meet the emergency needs of the Mentougou district during disasters, the study optimizes infrastructure coverage in four key areas: power supply, water supply, communication, and firefighting facilities. It also classifies support levels based on disaster frequency and severity, establishing a coordinated district-wide emergency support system. For power supply, the study proposes designating the Gaojing and Jingxi power plants as key support plants, with the addition of two first-level support substations and four second-level support substations (Figure 10-a). In terms of water supply, the study plans to designate the Sanjiadian reservoir, Luopoling reservoir, and Zhaitang reservoir as emergency water sources. Additionally, the study categorizes existing and planned waterwork by support level and adds one first-level waterwork (Figure 10-b). For firefighting, the study proposes to set up 9 additional fire stations to enhance the region’s disaster emergency response capacity. Existing and planned fire stations are categorized by support level (Figure 10-c). For communication, the existing communication facilities are sufficient to meet regional needs, so the study categorizes them by support level and optimizes high-support equipment to ensure stable district-wide communication network coverage (Figure 10-d).

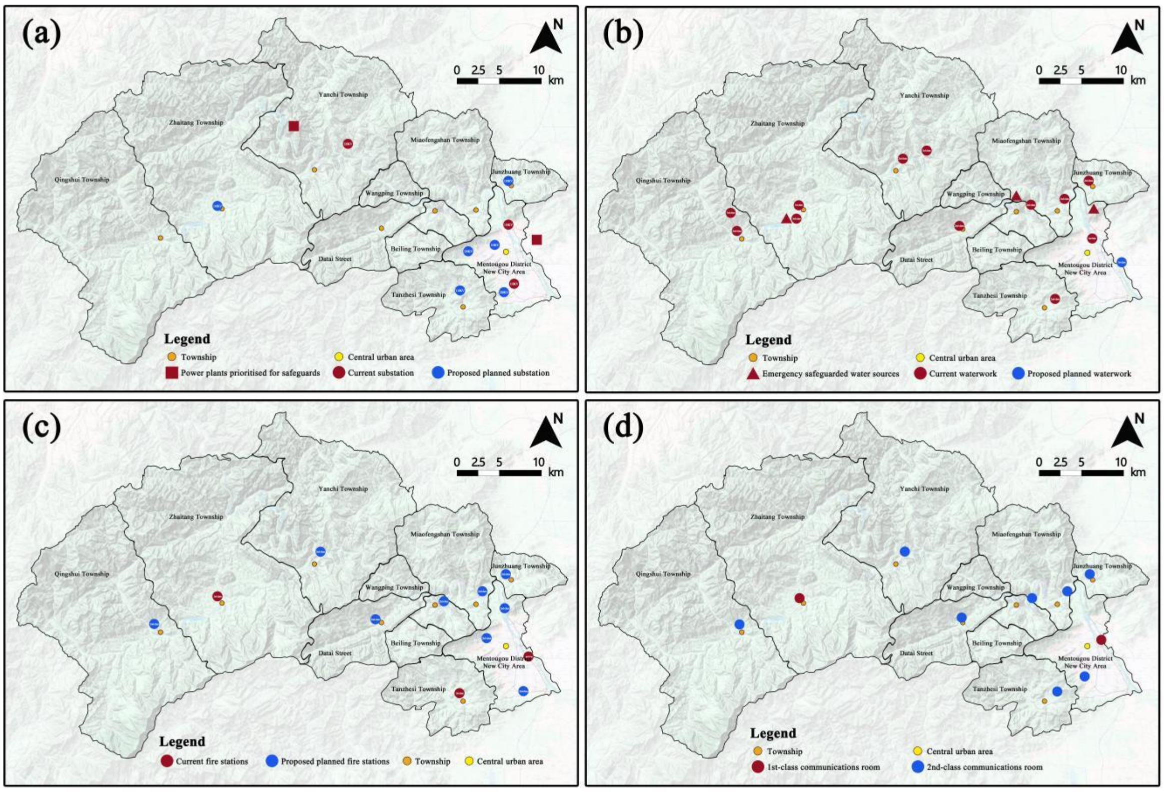

Figure 10. Mentougou district emergency security points planning.

5. Conclusion

As an important ecological barrier for Beijing, the ecological security of the Mentougou district holds significant importance for regional socio-economic development. This study, using Rs and ArcGIS platforms, assesses the comprehensive risk of multiple hazards in the Mentougou district by evaluating both hazard risk and susceptibility. By constructing a multi-factor evaluation system, the study also examines the resilience of the city ecosystems and infrastructure systems. The study proposes a disaster evaluation method from the perspective of resilient cities and establishes an integrated point-line-plane framework for urban disaster prevention and mitigation planning. Finally, the study provides strategic recommendations for disaster prevention and mitigation in the Mentougou district. The main conclusions of the research are as follows:

(1) Flooding is the type of disaster that has the highest combined risk level (Domain-wide average is 0.47) and the widest threat area (36.25% of the whole area) in Mentougou district. They primarily endanger the safety of production and construction activities in towns along the mainstream and parts of the tributaries of the Yongding River. Additionally, floods can trigger a variety of geological disasters such as subsidence and landslides, making them the key disaster type that affects the stability of the natural environment and socioeconomic development in the region.

(2) The resilience level of the infrastructure system in the Mentougou district is relatively high, with an average value of 0.71 across the region. Its spatial pattern is centered around the new city area, Fujiatai village in Yanchi town, and Junxiang village, showing a gradient decline from the center to the periphery. In contrast, the resilience level of the ecosystem in Mentougou district is generally low, with an average

value of 0.17. The spatial pattern of ecosystem resilience shows significant clustering of high values, primarily concentrated in the border area between Miaofengshan town and Wangping town, the Dingdu peak area, and the region between Zhuwo reservoir and Zhaitang reservoir.

(3) Based on the spatial patterns and temporal characteristics of various disasters in the Mentougou district, the study develops an integrated point-line-plane urban disaster prevention and mitigation system across three areas: urban planning, emergency support, and recovery enhancement. In terms of area planning, the study proposes adding 19 emergency rescue points with a service radius of 3 km, covering 83.5% of existing villages, while ensuring that the remaining villages are within 5 km of a rescue center village. For corridor planning, the study classifies corridors into three levels based on emergency support, forming a "two rings and two belts" life corridor system. After planning, the life corridors will directly connect 70.7% of villages, significantly improving the city's emergency transport capacity and ensuring the orderly execution of emergency rescue and lifesaving activities. In terms of node planning, the study optimizes infrastructure coverage in four areas—power supply, water supply, communication, and firefighting facilities—by categorizing them according to disaster frequency and severity. After optimization, the coverage of power supply, water supply, and communication facilities will increase by 126.19%, 5.59%, and 328.01%, respectively.

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