Safety Emergency Science

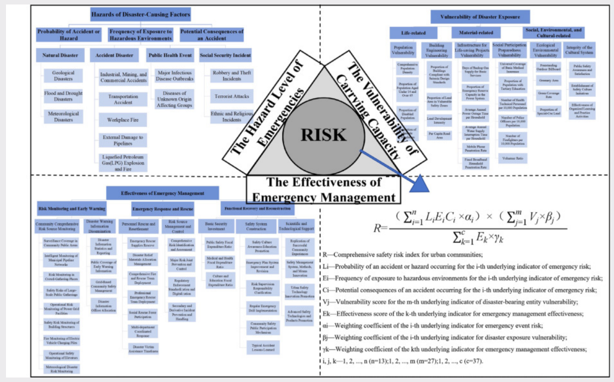
Research Article

Research on the construction of an integrated risk index model for urban communities

Chenzi Teng✉, Bo Bai, Yanfang Wang, Jiwei Ding

Cite this article: Teng CZ, Bai B, Wang YF, et al. *Safety Emergency Science*, 2025, **1**(3): 9590019. https://doi.org/10.26599/SES.2025.9590019

ABSTRACT: Urban communities integrate multiple and complex risk factors. This paper was based on the public safety triangle theory, identified risk factors and hazards associated with communities, and developed a comprehensive risk assessment indicator system. Subsequently, a comprehensive urban community risk index model was established based on the analytic hierarchy process (AHP), which involved assigning weights to each risk indicator. This model integrates several aspects, including the level of hazard posed by emergencies, the vulnerability of disaster exposure, and the effectiveness of emergency management.



KEYWORDS: hazard indicator for emergencies; vulnerability indicator of disaster exposure; emergency management effectiveness indicators; comprehensive risk indicator model

1 Introduction

The research on social risk governance in China started relatively late, with traditional risk governance focusing on the national and urban levels. Practice has shown that urban communities, as the basic units of society, are characterized by multiple and intersecting risk factors. Community safety is important for maintaining the sustainable operation of cities. Research on risk governance at the primary level in China has mainly concentrated on theoretical studies (Gao, 2015; Li, 2015b; Peng, 2015; Song, 2015) such as the causes and countermeasures of social risks (Ge, 2015; Lei, 2019; Yuan, 2016), innovation in risk governance models (Ge et al., 2016; Luo, 2011), optimization of governance pathways (He, 2014; Li, 2015a; Zheng, 2018), and exploration of risk governance resilience (Cui et al., 2019; Fan, 2020; Huang et al., 2020; Liu et al., 2017; Wei et al., 2020).

In recent years, some developed coastal cities have learned from the beneficial experiences of Western countries to explore new models of community governance. Scholars have conducted research in cities such as Beijing (Lü, 2019; Yang, 2019; Zhang, 2019), Guangzhou (Li et al., 2018; Wang, 2014), Wuhan (Zhang et al., 2006), and Chengdu (Zeng, 2019), summarizing innovative models of primary-level governance, promoting social system innovation and modernizing governance structures. Scholars have developed research on urban emergency management mechanisms during unexpected events from an emergency management perspective (Sun et al., 2021; Zhao et al., 2019), improved upon existing emergency management research (Beijing Emergency Committee Office, 2012; Jiang et al., 2013; Yang, 2018; Zhang et al., 2017), and defined the community emergency management framework (Yu et al., 2016) by responding to the primary challenges that exist in dealing with social risk at the community level.

Urban community comprehensive risks involve multiple variables, complex structures, and significant uncertainties, with varying impacts from different factors. In qualitative analysis, research on identifying key multirisk areas in urban settings has primarily focused on the comprehensive assessment of multiple hazards and multidimensional vulnerabilities (Feng et al., 2022; He et al., 2023; Polese et al., 2025). In quantitative analysis, current studies are mainly concentrated on developing indicator systems and models for specific risks, while research on quantitative composite risk indices at the community level is progressing toward multidimensional integration, intelligent methodologies, and refined application scenarios (Gu et al., 2023; Zhu et al., 2023). To quantify the importance of each influencing factor, this paper applies the analytic hierarchy process (AHP) from systems engineering theory. Factors are categorized into related hierarchical levels, and corresponding importance assessments are conducted to construct an urban community comprehensive risk index model. This model enhances risk identification and

Institute of Urban System Engineering, Beijing Academy of Science and Technology, Beijing 100089, China.

✉ Corresponding author. E-mail: tengchenzi@bjast.ac.cn, tengczlucky@163.com

Received: November 17, 2025; Revised: December 18, 2025; Accepted: December 19, 2025

prevention capabilities, thereby optimizing resource allocation and decision-making efficiency.

2 Model construction methods and steps

Guided by the "triangle model" of public safety, as illustrated in Fig. 1, this paper considers factors across three dimensions: the hazard level of emergencies, the vulnerability of carrying capacity, and the effectiveness of emergency management. It constructs a comprehensive risk assessment indicator system, calculates the weights of risk indicators using the analytic hierarchy process (AHP), and explains the weighting of indicators at different levels.

(1) Establish a hierarchical model

The analytic hierarchy process (AHP) first places the decision-making problem within a larger system where multiple interacting factors exist. These factors are then organized hierarchically to form a multilevel analytical structure model. Subsequently, combining mathematical methods with qualitative analysis, the AHP uses a step structure to rank each factor. Finally, it provides decision support by calculating the weight assigned to each alternative.

(2) Determining weights with the hierarchical analysis method

(i) Construct the judgment matrix. Take A to represent the target and u_i and u_j to represent factors (i, j = 1, 2, ..., n). u_{ij} denotes the relative importance value of u_i to u_j, and the u_{ij} elements form the A–U judgment matrix P.

$$P=\begin{bmatrix} u_{11} & \cdots & u_{1n} \\ \vdots & \ddots & \vdots \\ u_{n1} & \cdots & u_{nn} \end{bmatrix} \tag{1}$$

(ii) Calculate the importance ranking. Based on the judgment matrix P, calculate the eigenvalues and eigenvectors that satisfy Eq. (2):

$$PW = \lambda_{\max} \cdot W \tag{2}$$

In the formula, $\lambda_{\max}$ represents the maximum eigenvalue of matrix P, and W is the normalized eigenvector corresponding to $\lambda_{\max}$. The components of W are the weights for the single sorting of the corresponding elements.

(iii) Consistency test. To verify the reasonableness of weight allocation, a consistency test is conducted on the judgment matrix. The test equation is as Eq. (3):

$$CR = \frac{CI}{RI} \tag{3}$$

In the equation, CR is the random consistency ratio of the judgment matrix; CI is the consistency index of the judgment matrix, given by Eq. (4):

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

RI is the average random consistency index for judgment matrices. The RI values for judgment matrices of orders 1 to 9 are shown in Table 1.

When the CR of matrix P is less than 0.1 or $\lambda_{\max} = n$ and $CI = 0$, P is considered to have satisfactory consistency. Otherwise, the elements in P must be adjusted to achieve satisfactory consistency.

(3) Judgment matrix adjustment

To prevent inconsistencies or missing entries in the scoring matrix, the particle swarm optimization (PSO) algorithm is employed to correct the expert scoring matrix due to its distinct advantages in simplicity, ease of implementation, and rapid convergence.

PSO initializes with a population of random particles (initial solutions). It then iteratively searches for the optimal solution. During each iteration, particles update themselves by tracking two "extremes" (pbest, gbest). After locating these two optimal values, the particles update their velocity and position using Eqs. (5) and (6).

$$v_{i+1} = v_i + c_1 \times \mathrm{rand}(0,1) \times (\mathrm{pbest}_i - x_i) + c_2 \times \mathrm{rand}(0,1) \times (\mathrm{gbest}_i - x_i) \tag{5}$$

$$x_{i+1} = x_i + v_i \tag{6}$$

i = 1, 2, ..., M, where M is the total number of particles in the population; V_i is the velocity of a particle; pbest is the best individual value; gbest is the best global value; rand(0, 1) is a random number between 0 and 1; and X_i is the current position of a particle. c_1 and c_2 are learning factors, typically taken as $c_1 = c_2 = 2$. Each particle has a maximum speed limit $V_{\max}$ per dimension. If the speed in any dimension exceeds the set $V_{\max}$, that dimension's speed is constrained to $V_{\max}$.

(4) Hierarchical total ranking test

To obtain the combined weight of elements at a specific level within the hierarchy relative to the overall objective, as well as their mutual influence with elements at higher levels, it is necessary to utilize all single-sort results from that level. This enables the calculation of the combined weight for elements at that level.

Hierarchical overall ranking requires sequential ranking from

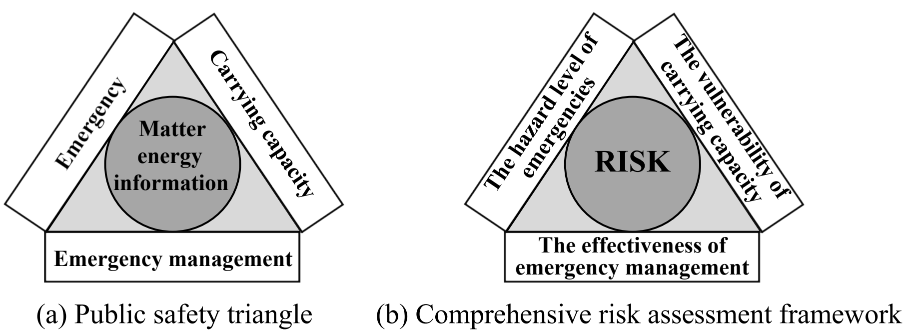


Fig. 1 Integrated risk assessment framework based on the public safety "triangle".

Table 1 Average random coherence index (RI) values

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46

top to bottom, ultimately calculating the relative weights of the bottom-level elements, which determine the priority order of decision options. This hierarchical overall ranking is derived from the single-level ranking within the analytic hierarchy process (AHP), and its procedure is largely consistent with that of single-level ranking.

$$CR = \frac{wi_1 CI_1 + wi_2 CI_2 + \Lambda + wi_m CI_m}{wi_1 RI_1 + wi_2 RI_2 + \Lambda wi_m RI_m} \tag{7}$$

If the overall consistency ratio *CR* is less than 0.1, the model passes the overall consistency test. Otherwise, the model should be reconsidered, or judgment matrices with high consistency ratios *CR* should be reconstructed.

(5) Group decision conclusions

This model uses the direct mean method. Assuming all experts have the same influence factor, the weighted conclusion value for the expert group decision is directly equal to the average of all corresponding weight values from all experts.

3 Risk assessment framework based on the public safety triangle

Based on the public safety triangle, a comprehensive risk assessment framework is established by integrating factors across three dimensions: the hazard level of emergencies, the vulnerability of disaster exposure, and the effectiveness of emergency management. This framework constitutes a whole-process comprehensive risk assessment index, as illustrated in Fig. 2. It primarily includes indicators for evaluating the hazard level of emergencies, the vulnerability of disaster exposure, and the effectiveness of emergency management.

3.1 Emergency risk assessment indicators

With the rapid advancement of urbanization and the deepening of market-oriented reforms in China, the urban system faces increasing and closely interconnected risk factors. The cascading effects of disasters have become obvious, while new risks are becoming increasingly diverse and complicated. This presents significant challenges to urban safety development and comprehensive risk management. Based on an analysis of urban disaster characteristics, China's current urban disasters primarily include four major types of emergencies: natural disasters, accidents and disasters, public health incidents, and social security incidents. Among these, an emergency refers to a random or extreme event occurring in natural or man-made environments that can adversely affect human life, property, or various activities, reaching the level of causing a disaster.

Since urban communities involve multiple risk factors and the severity of emergencies is typically determined by the likelihood of accidents or hazards occurring, the frequency of exposure to hazardous environments, and the potential consequences of incidents, this section focuses on four categories of emergencies to identify hazard sources and establish evaluation indicators for comprehensive urban community risk. This establishes a preliminary emergency risk indicator system consisting of three criteria layers: the likelihood of an accident or hazard occurring, the frequency of exposure to hazardous environments, and the potential consequences of an accident. This framework is illustrated in Fig. 3.

3.2 Disaster exposure vulnerability assessment indicators

Urban communities serve as important living spaces for the populace and represent the frontline positions involved in social security and stability. Community vulnerability, as a critical indicator for evaluating the comprehensive risk prevention capabilities of urban communities, is also a key factor determining the resilience of urban areas. The risk factors for community vulnerability are complicated, including simplistic risks, uncertain risks, and complex risks with unclear causal relationships.

To improve the risk assessment of community-level vulnerability, this section establishes a vulnerability indicator system for disaster exposure. The system includes three criteria levels—life, property, and socioeconomic and cultural categories—and encompasses six aspects of vulnerability: population vulnerability, building and engineering vulnerability, lifeline facility vulnerability, social participation and preparedness vulnerability, ecological and environmental vulnerability, and safety culture system integrity. It includes 27 tertiary indicators, as shown in Fig. 4.

3.3 Emergency management effectiveness evaluation indicators

Based on emergency management principles and the traditional response processes for public safety incidents in China, this

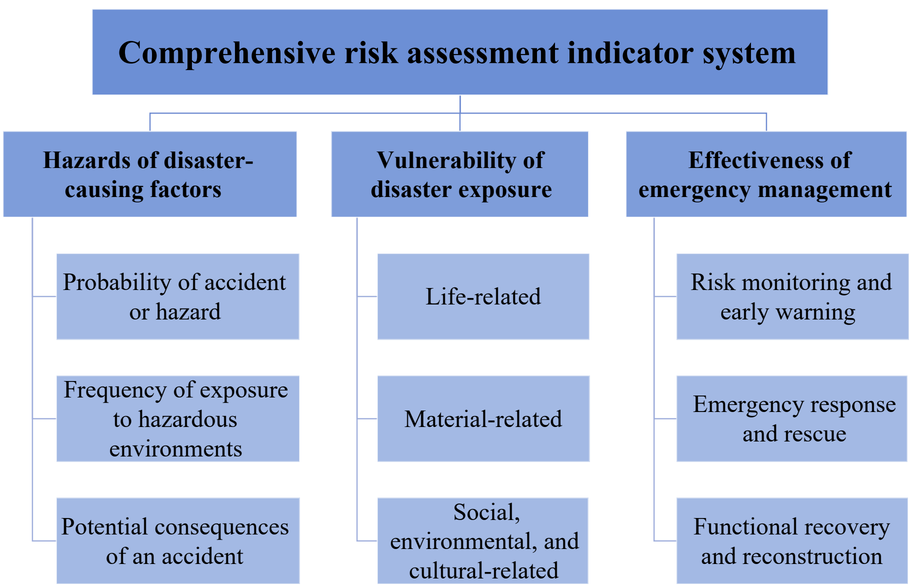


Fig. 2 Overview of the comprehensive risk assessment indicator system.

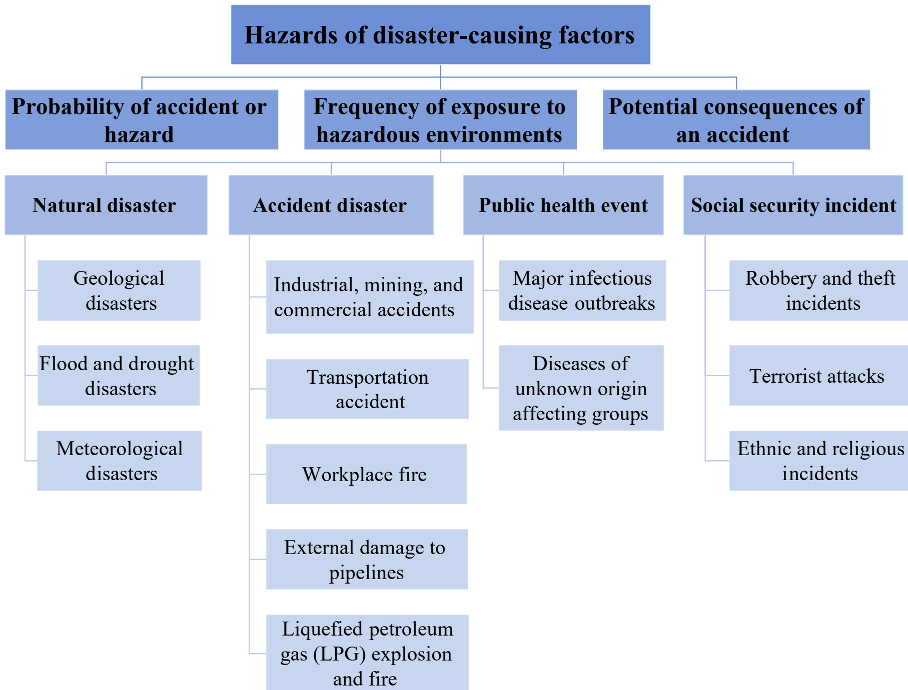


Fig. 3 Hazard indicator system for emergencies.

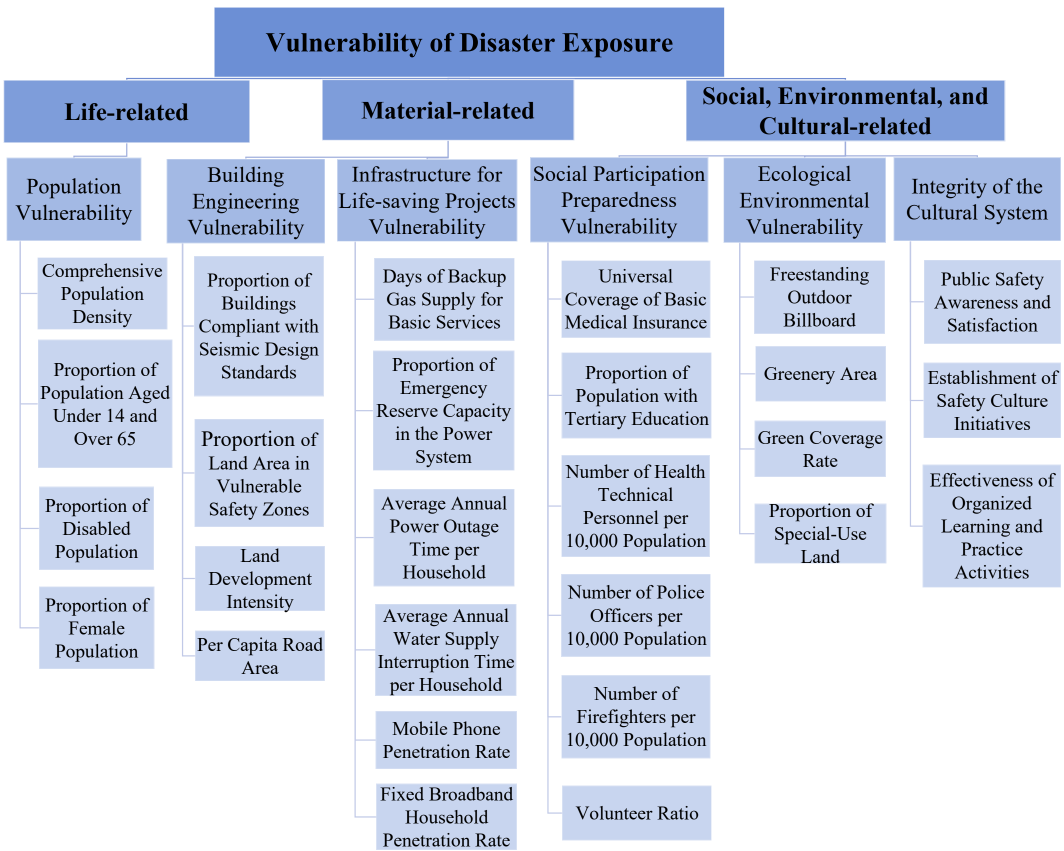


Fig. 4 Vulnerability indicator system for disaster exposure.

framework establishes a risk evaluation index system considering the entire lifecycle of actual risk events—before, during, and after—accounting for variations in natural and human factors within communities. These factors include the geographical structure of buildings, resource distribution, residents' cultural literacy, and safety management systems. Aligned with community characteristics, the system is built around three primary indicators: risk monitoring and early warning, emergency response and rescue, and functional recovery and reconstruction.

Based on the principles of systematicity, scientific, and hierarchical structure, the primary indicators for emergency management effectiveness are divided into seven secondary indicators: community-based comprehensive risk source monitoring, disaster warning information transmission, personnel rescue and resettlement, hazard source management and control, basic support investment, safety system development, and scientific and technological support. These are further subdivided into 37 tertiary indicators, as shown in Fig. 5.

4 Risk assessment indicator weights based on group decision-making

4.1 Evaluation team expert composition

To scientifically assess the weights of risk indicators, an expert panel comprising 20 qualified members was formed, achieving a 100% valid questionnaire response rate. The composition of the expert assessment groups is shown in Table 2. Due to the subjectivity of the scoring process, the differences in individual indicator scores are relatively large. Therefore, the particle swarm optimization (PSO) algorithm was employed to correct the expert scoring matrix.

Combined with the "risk assessment system based on the public safety triangle", a comprehensive risk assessment model questionnaire was developed using the 9-point scoring method. Twenty experts from relevant fields were invited to score the importance of each indicator. The results of their ranking of indicator importance served as the primary criteria for determining the weightings of the evaluation indicators.

4.2 Explanation of the data-solving process by a certain expert

The comprehensive risk assessment model shows that the highest-level judgment matrix, "comprehensive risk assessment model > emergency management effectiveness > risk monitoring and early warning > community comprehensive risk source monitoring", represents a ninth-order hierarchy. Using this as the representative level for calculating single-level importance rankings, the scoring data table from one expert is shown in Fig. 6.

As calculated, $\lambda_{max} = 11.0762$, $CR = 0.1778$, $CI = 0.2595$; the judgment matrix exhibits unsatisfactory consistency. Therefore, the judgment matrix should be modified. Following modification, the calculated weighting matrix A is as Eq. (8):

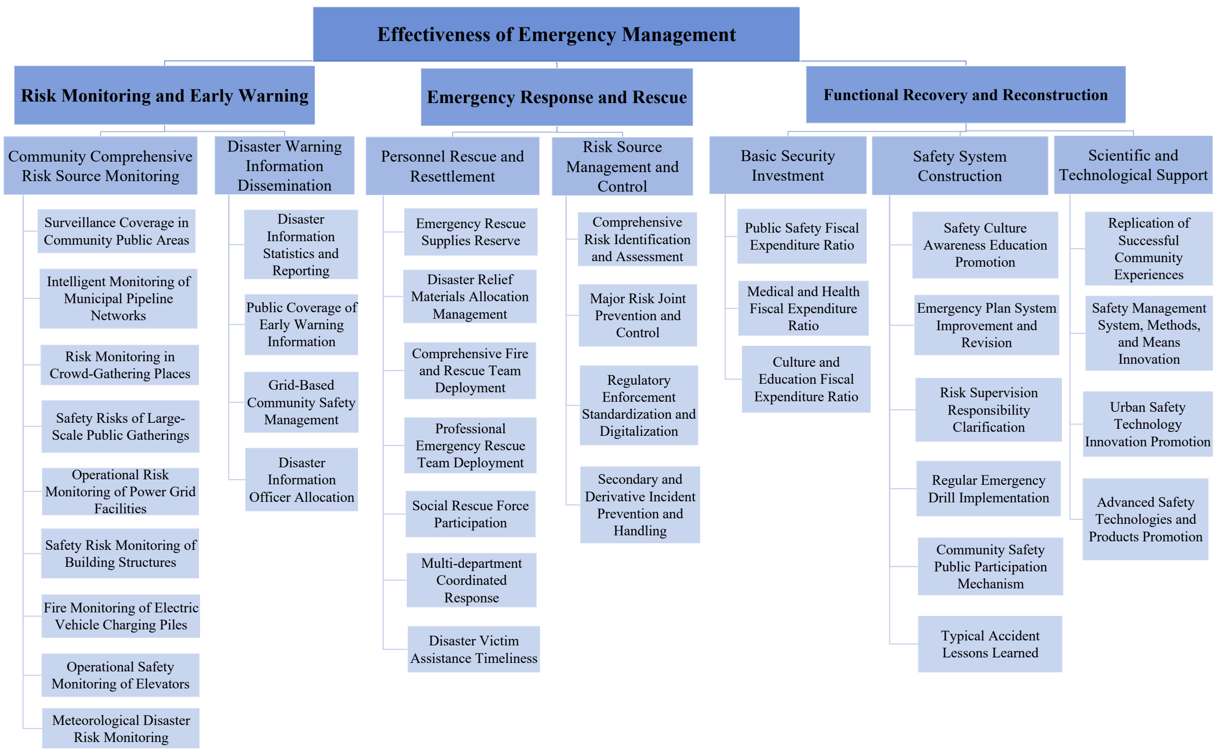


Fig. 5 Emergency management effectiveness indicator system.

Table 2 Composition of the evaluation team experts

Organization	Number of persons	Title/level	Education	Work experience or professional background
Government agencies	3	Division-level	Bachelor degree	Possess 10 or more years of relevant work experience
	1	Section-level	Master degree	Possess 10 or more years of relevant work experience
	1	Cadre	Master degree	Accumulate 5 or more years of research experience in risk governance
Higher education institutions	2	Associate professor	Doctoral degree	Hold a senior professional title in the relevant field
	6	Lecturer/assistant researcher	Doctoral degree	Accumulate 5 or more years of research experience in risk governance
Research institutes	1	Researcher/professor-level senior engineer	Doctoral degree	Hold a senior professional title in the relevant field
	3	Associate researcher/senior engineer	Doctoral degree	Hold a senior professional title in the relevant field
	3	Assistant researcher/engineer	Doctoral degree	Possess extensive practical experience and familiarity with such significant matters

	1	3	5	7	9	1/3	1/5	1/7	1/9
Basic medical insurance coverage: The proportion of the population receiving higher education	☑	☐	☐	☐	☐	☐	☐	☐	☐
Basic medical insurance coverage: The number of medical and health professionals	☐	☐	☐	☐	☐	☑	☐	☐	☐
Basic medical insurance coverage: Number of police officers in the entire population	☐	☐	☐	☐	☐	☑	☐	☐	☐
Basic medical insurance coverage: Number of firefighters in the thousands	☐	☐	☐	☐	☐	☐	☑	☐	☐
Basic medical insurance coverage: Volunteer ratio	☐	☐	☐	☐	☐	☑	☐	☐	☐
The proportion of the population receiving higher education: The number of medical and health professionals	☑	☐	☐	☐	☐	☐	☐	☐	☐
The proportion of the population receiving higher education: Number of police officers in the entire population	☐	☑	☐	☐	☐	☐	☐	☐	☐
The proportion of the population receiving higher education: Number of firefighters in the thousands	☑	☐	☐	☐	☐	☐	☐	☐	☐
The proportion of the population receiving higher education: Volunteer ratio	☐	☑	☐	☐	☐	☐	☐	☐	☐
The number of medical and health professionals: Number of police officers in the entire population	☐	☑	☐	☐	☐	☐	☐	☐	☐
The number of medical and health professionals: Number of firefighters in the thousands	☑	☐	☐	☐	☐	☐	☐	☐	☐
The number of medical and health professionals: Volunteer ratio	☐	☑	☐	☐	☐	☐	☐	☐	☐
Number of police officers in the entire population: Number of firefighters in the thousands:	☑	☐	☐	☐	☐	☐	☐	☐	☐
Number of police officers in the entire population: Volunteer ratio	☐	☐	☑	☐	☐	☐	☐	☐	☐
Number of firefighters in the thousands: Volunteer ratio	☐	☐	☑	☐	☐	☐	☐	☐	☐

Fig. 6 Expert scoring data table (1-equally important, 3-slightly important, 5-relatively important, 7-very important, 9-absolutely important, 1/3-slightly unimportant, 1/5-relatively unimportant, 1/7-very unimportant, 1/9-absolutely unimportant).

$$A=\begin{bmatrix} 1 & 0.2816 & 0.0931 & 0.4769 & 0.174 & 0.34 & 0.4081 & 0.1898 & 0.3244 \\ 3.5517 & 1 & 0.8872 & 0.3827 & 0.7543 & 3.9476 & 2.2251 & 0.5726 & 0.4103 \\ 10.7425 & 1.1271 & 1 & 0.9385 & 1.5879 & 4.2312 & 6.06671 & 1.4406 & 2.9935 \\ 2.0968 & 2.6133 & 1.0655 & 1 & 0.2012 & 0.6026 & 0.5999 & 0.2505 & 0.4344 \\ 5.7479 & 1.3258 & 0.6298 & 4.9696 & 1 & 2.3806 & 2.1893 & 2.0158 & 1.0871 \\ 2.9412 & 0.2533 & 0.2363 & 1.6594 & 0.4201 & 1 & 2.8573 & 0.6846 & 0.483 \\ 2.4505 & 0.4494 & 0.1648 & 1.6671 & 0.4568 & 0.35 & 1 & 0.2948 & 0.3252 \\ 5.2698 & 1.7164 & 0.6941 & 3.9923 & 0.4961 & 1.4606 & 3.3916 & 1 & 0.5156 \\ 3.0828 & 2.4373 & 0.3341 & 2.3019 & 0.9199 & 2.0704 & 3.0749 & 1.9395 & 1 \end{bmatrix} \tag{8}$$

Matrix dimension n: $n = 9$. The matrix A is normalized by columns, and the columns of the normalized matrix A_1 are

$$A_1=\begin{bmatrix} 0.0271 & 0.0251 & 0.0182 & 0.0274 & 0.0289 & 0.0208 & 0.0187 & 0.0226 & 0.0429 \\ 0.0963 & 0.089 & 0.1738 & 0.022 & 0.1255 & 0.241 & 0.102 & 0.0683 & 0.542 \\ 0.2913 & 0.1003 & 0.1959 & 0.054 & 0.2642 & 0.2583 & 0.2781 & 0.1717 & 0.3953 \\ 0.0568 & 0.2326 & 0.2087 & 0.0575 & 0.0335 & 0.0368 & 0.0275 & 0.0299 & 0.0574 \\ 0.1558 & 0.118 & 0.1234 & 0.2858 & 0.1664 & 0.1453 & 0.1004 & 0.2403 & 0.1435 \\ 0.0797 & 0.0225 & 0.0463 & 0.0954 & 0.0699 & 0.061 & 0.131 & 0.0816 & 0.0638 \\ 0.0664 & 0.04 & 0.0323 & 0.0959 & 0.076 & 0.0214 & 0.0458 & 0.0351 & 0.0429 \\ 0.1429 & 0.1555 & 0.136 & 0.2296 & 0.0825 & 0.0892 & 0.1555 & 0.1192 & 0.0681 \\ 0.0836 & 0.217 & 0.654 & 0.1324 & 0.1531 & 0.1264 & 0.141 & 0.2312 & 0.132 \end{bmatrix} \tag{9}$$

Normalized maximum eigenvector (weight) w^{T} (calculated by taking the geometric mean of each row of matrix A_1, then normalizing):

$$w^{\mathrm{T}}=[0.0279, 0.1005, 0.218, 0.0666, 0.1747, 0.0737, 0.0516, 0.1379, 0.1491] \tag{10}$$

Process determinant Aw, $(A{*}w)^{\mathrm{T}}$:

$$Aw=[0.2593, 1.0963, 2.2411, 0.8298, 1.6651, 0.7305, 0.5069, 1.3238, 1.4456] \tag{11}$$

Consistency CR solution:

Table 3 Steps and results for deriving hierarchical total ranking consistency

Indicator level	Consistency verification process	*CR*
Comprehensive Risk Assessment Model	(0.077 816 4*0.042 7+0.435 261*0.014 5+0.486 922*0)/ (0.077 816 4*0.52+0.435 261*0.52+0.486 922*0.52)	0.018 6
Hazardous Factor Risk	(0.668 569*0.038 2+0.157 294*0.051 1+0.174 137*0.062 2)/ (0.668 569*0.89+0.157 294*0.89+0.174 137*0.89)	0.049 9
Probability of Accident or Hazard Occurrence	(0.074 120 6*0+0.564 947*0.079 8+0.191 974*0+0.168 959*0)/ (0.074 120 6*0.52+0.564 947*1.12+0.191 974*0+0.168 959*0.52)	0.059 4
Frequency of Exposure to Hazardous Environments	(0.094 086 7*0+0.371 475*0.091+0.371 475*0+0.162 963*0)/ (0.094 086 7*0.52+0.371 475*1.12+0.371 475*0+0.162 963*0.52)	0.061 5
Potential Consequences of An Accident	(0.238 697*0.014 5+0.413 435*0.059 6+0.276 481*0+0.071 387*0)/ (0.238 697*0.52+0.413 435*1.12+0.276 481*0+0.071 387*0.52)	0.045
Vulnerability of Disaster Exposure	(0.480 64*0+0.113 972*0+0.405 388*0)/(0.480 64*0+0.113 972*0+0.405 388*0.52)	0
Life-related	(1*0.010 9)/(1*0.89)	0.012 3
Material-related	(0.166 667*0.073 8+0.833 333*0.123 8)/(0.166 667*0.89+0.833 333*1.26)	0.096 3
Social, Environmental, and Cultural-related	(0.428 571*0.124 1+0.142 857*0.051 1+0.428 571*0.051 9)/ (0.428 571*1.26+0.142 857*0.89+0.428 571*0.52)	0.093
Effectiveness of Emergency Management	(0.454 545*0+0.454 545*0+0.090 909 1*0.048 3)/(0.454 545*0+0.454 545*0+0.090 909 1*0.52)	0.092 9
Risk Monitoring and Early Warning	(0.5*0.145 8+0.5*0.086)/(0.5*1.46+0.5*0.89)	0.098 7
Emergency Response and Rescue	(0.25*0.071 8+0.75*0.085 3)/(0.25*1.36+0.75*0.89)	0.081 3
Functional Recovery and Reconstruction	(0.223 233*0.051+0.310 861*0.125 5+0.465 906*0.087 4)/ (0.223 233*0.52+0.310 861*1.26+0.465 906*0.89)	0.098 8

Table 4 Weighting system for urban community comprehensive risk level indicators

Objective	Domain layer		Criterion		
	Primary indicator	Weight	Secondary indicator	Same-level weight	Total weight
Comprehensive Risk Level of Urban Communities	Hazards of Disaster-Causing Factors	0.448	Probability of Accident or Hazard	0.329	0.147 4
			Frequency of Exposure to Hazardous Environments	0.217	0.097 2
			Potential Consequences of an Accident	0.454 1	0.203 4
	Vulnerability of Disaster Exposure	0.249 3	Life-related	0.700 3	0.174 6
			Material-related	0.172 3	0.074 9
			Social, Environmental, and Cultural-related	0.127 4	0.031 8
	Effectiveness of Emergency Management	0.302 8	Risk Monitoring and Early Warning	0.579	0.175 3
			Emergency Response and Rescue	0.248 9	0.075 4
			Functional Recovery and Reconstruction	0.172 1	0.052 1

$$\lambda_{\max} = \left(\sum (Aw/w)\right)/n = 10.1668 \tag{12}$$

$$RI = 1.46 \tag{13}$$

$$CI = (\lambda_{\max} - n)/(n-1) = (10.1668 - 9)/(9-1) = 0.1458 \tag{14}$$

$$CR = CI/RI = 0.1458/1.46 = 0.0999 \tag{15}$$

By calculating the importance ranking for each level according to the above method, the weight coefficients for each level's indicators are calculated. According to Eq. (7), a consistency test for the overall hierarchical ranking is then conducted. The derivation steps and results for the overall ranking consistency are shown in Table 3.

The consistency ratios (*CR*) for all levels were less than 0.1, indicating satisfactory consistency. The indicator weights for different levels were obtained, and the weighting results for other experts' scores on different-level indicators were calculated according to this solution method.

4.3 Determination of risk assessment indicator weights

According to the importance scores assigned by 20 experts in relevant fields to each indicator, a hierarchical structure was established sequentially. A judgment matrix was constructed, followed by hierarchical single-ranking and consistency testing, as well as hierarchical overall ranking and consistency testing. Assuming equal influence factors among all experts, the direct mean method was applied to determine the weights of each evaluation indicator based on the expert group decision, as shown in Tables 4 and 5.

5 Comprehensive risk index model for urban communities

5.1 Single-factor risk assessment criteria

Common methods currently used for risk assessment of hazards include SCL (Safety Checklist), FMEA (Failure Mode and Effects Analysis), HAZOP (Hazard and Operability Study), FTA (Fault Tree Analysis), and LEC (Hazard Evaluation of Working Conditions). Among these, the Hazardous Operations Condition Evaluation Method (LEC method), as one of the commonly used risk assessment methods, is used to evaluate the risk of operator injury or fatality by calculating the product of three factor indicators related to system risk.

Table 5 Weighting of sub-indicators for comprehensive risk levels in urban communities

No.	Underlying indicator	Overall weight	No.	Underlying indicator	Overall weight	No.	Underlying indicator	Overall weight
1	Geological Disaster	0.066 1	27	Fixed Broadband Household Penetration Rate	0.001 3	53	Disaster Information Officer Allocation	0.008 5
2	Flood and Drought Disasters	0.043 5	28	Universal Coverage of Basic Medical Insurance	0.005 3	54	Emergency Rescue Supplies Reserve	0.007 4
3	Meteorological Disasters	0.057	29	Proportion of Population with Tertiary Education	0.002 4	55	Disaster Relief Materials Allocation Management	0.006 1
4	Industrial, Mining, and Commercial Accidents	0.039 8	30	Number of Health Technical Personnel per 10,000 Population	0.003 2	56	Comprehensive Fire and Rescue Team Deployment	0.007 2
5	Transportation Accidents	0.030 3	31	Number of Police Officers per 10,000 Population	0.002 8	57	Professional Emergency Rescue Team Deployment	0.007 1
6	Workplace Fires	0.024 6	32	Number of Firefighters per 10,000 Population	0.002 3	58	Social Rescue Force Participation	0.002 4
7	External Damage to Pipelines	0.015 6	33	Volunteer Ratio	0.001	59	Multidepartment Coordinated Response	0.004 7
8	Liquefied Petroleum Gas (LPG) Explosions and Fires	0.028 6	34	Freestanding Outdoor Billboard	0.001 7	60	Disaster Victim Assistance Timeliness	0.007 8
9	Major Infectious Disease Outbreaks	0.054 2	35	Greenery Area	0.002 3	61	Comprehensive Risk Identification and Assessment	0.012 2
10	Diseases of Unknown Origin Affecting Groups	0.025 7	36	Green Coverage Rate	0.002 8	62	Major Risk Joint Prevention and Control	0.010 6
11	Robbery and Theft Incidents	0.018 5	37	Proportion of Special-Use Land	0.001 5	63	Regulatory Enforcement Standardization and Digitalization	0.005
12	Terrorist Attacks	0.027 2	38	Public Safety Awareness and Satisfaction	0.003 4	64	Secondary and Derivative Incident Prevention and Handling	0.004 7
13	Ethnic and Religious Incidents	0.016 8	39	Establishment of Safety Culture Initiatives	0.001 2	65	Public Safety Fiscal Expenditure Ratio	0.012 6
14	Comprehensive Population Density	0.058 4	40	Effectiveness of Organized Learning and Practice Activities	0.001 7	66	Medical and Health Fiscal Expenditure Ratio	0.008 7
15	Proportion of Population Aged Under 14 and Over 65	0.048 2	41	Surveillance Coverage in Community Public Areas	0.016 8	67	Culture and Education Fiscal Expenditure Ratio	0.004 7
16	Proportion of Disabled Population	0.040 3	42	Intelligent Monitoring of Municipal Pipeline Networks	0.016 5	68	Safety Culture Awareness Education Promotion	0.001 3
17	Proportion of Female Population	0.027 6	43	Risk Monitoring in Crowd-Gathering Places	0.015 3	69	Emergency Plan System Improvement and Revision	0.002 1
18	Proportion of Buildings Compliant with Seismic Design Standards	0.008 2	44	Safety Risks of Large-Scale Public Gatherings	0.014 7	70	Risk Supervision Responsibility Clarification	0.002 3
19	Proportion of Land Area in Vulnerable Safety Zones	0.004 8	45	Operational Risk Monitoring of Power Grid Facilities	0.012 7	71	Regular Emergency Drill Implementation	0.002
20	Land Development Intensity	0.002 4	46	Safety Risk Monitoring of Building Structures	0.010 3	72	Community Safety Public Participation Mechanism	0.001 2
21	Per Capita Road Area	0.002	47	Fire Monitoring of Electric Vehicle Charging Piles	0.009 1	73	Typical Accident Lessons Learned	0.001 5
22	Days of Backup Gas Supply for Basic Services	0.005 8	48	Operational Safety Monitoring of Elevators	0.007 9	74	Replication of Successful Community Experiences	0.004 3
23	Proportion of Emergency Reserve Capacity in the Power System	0.006 3	49	Meteorological Disaster Risk Monitoring	0.012 7	75	Safety Management System, Methods, and Means Innovation	0.004 4
24	Average Annual Power Outage Time per Household	0.004 9	50	Disaster Information Statistics and Reporting	0.013 4	76	Urban Safety Technology Innovation Promotion	0.004
25	Average Annual Water Supply Interruption Time per Household	0.005 2	51	Public Coverage of Early Warning Information	0.023 5	77	Advanced Safety Technologies and Products Promotion	0.003
26	Mobile Phone Penetration Rate	0.002	52	Grid-Based Community Safety Management	0.013 8			

To quantitatively assess the risk level of disasters, the LEC method can be applied to assign values to various emergency hazards. This risk assessment approach provides a quantitative description of the hazard levels associated with different indicators. To simplify the evaluation process, a semiquantitative scoring method is adopted. Different scores are assigned to the varying grades of three factors, and the product of these three scores, denoted as D, is used to evaluate the level of hazard in operational conditions: $D = LEC$. Here, D represents the risk value; L denotes the likelihood of an accident or hazard occurring; E indicates the frequency of exposure to hazardous conditions; and C signifies the potential consequences of an accident. The evaluation methodology is illustrated in Table 6.

The emergency hazard assessment index system comprises 13

Table 6 Methods and standards for emergency hazard assessment

L value	Probability of an incident occurring	*E* value	Frequency of exposure to hazardous conditions	*C* value	Consequences of an incident occurring
10	Completely predictable	10	Continuous exposure	100	10 or more fatalities
6	Quite likely	6	Daily exposure during occupied hours	40	3 to 9 fatalities
3	Possible, but not frequent	3	Weekly or occasional exposure	15	1 to 2 fatalities
1	Unlikely, entirely unexpected	2	Monthly exposure	7	Severe
0.5	Highly improbable, conceivable	1	Several exposures per year	3	Major, with injuries or disabilities
0.2	Extremely unlikely	0.5	Very rare exposure	1	Noteworthy
0.1	Practically impossible				
D value	> 320	160–320	70–160	20–70	< 20
Degree of danger (risk level)	Extremely hazardous; Intolerable risk (5)	Highly hazardous; immediate remediation required (4)	Significantly hazardous; remediation required (3)	Moderately hazardous; caution required (2)	Slightly hazardous; acceptable (1)

underlying indicators, with hazard evaluation calculated according to Eq. (16):

$$D=\sum_{i=1}^{n} D_i\times\alpha_i=\sum_{i=1}^{n} L_iE_iC_i\times\alpha_i \tag{16}$$

Here, D represents the total hazard value of the emergency, D_i denotes the hazard value of the i-th underlying indicator for the emergency, L_i indicates the probability of an accident or hazard occurring for the i-th underlying indicator, E_i signifies the frequency of exposure to hazardous environments for the i-th underlying indicator, C_i represents the potential consequences of an accident occurring for the i-th underlying indicator of emergency risk, and α_i denotes the weighting coefficient for the i-th underlying indicator of emergency risk; n equals 13.

For evaluating factors related to disaster exposure vulnerability and emergency management effectiveness, scores are given to each indicator by reference to the GB/T 40947-2021 Guidelines for Safety Resilience City Evaluation and the National Safety Development Demonstration City Scoring Criteria (2019 Edition). The vulnerability of disaster exposure and the effectiveness of emergency management are calculated using Eq. (17) and Eq. (18), respectively:

$$V=\sum_{j=1}^{m} V_j\times\beta_j \tag{17}$$

$$E=\sum_{k=1}^{c} E_k\times\gamma_k \tag{18}$$

where V represents the total vulnerability value of the disaster-bearing entity, E represents the total value of emergency management effectiveness, V_j denotes the vulnerability value of the j-th underlying indicator for the m-th disaster-bearing entity, E_k indicates the effectiveness value of the kth underlying indicator for emergency management effectiveness, β_j is the weight coefficient for the j-th bottom-level vulnerability indicator of the disaster-bearing entity, γ_k is the weight coefficient for the k-th bottom-level indicator of emergency management effectiveness, m ranges from 1 to 26, and c ranges from 1 to 27.

5.2 Comprehensive risk index model

The construction of the urban community comprehensive risk index model is guided by the public safety "triangle". Comprehensive risk considers three-dimensional risk factors: the hazard level of emergencies, the vulnerability of exposure vulnerability, and the effectiveness of emergency management. This index is directly proportional to the hazard level of emergencies and the vulnerability of exposure vulnerability but inversely proportional to the effectiveness of emergency management. To simplify the calculations, the urban community comprehensive risk index considers these three dimensions and utilizes Eq. (19):

$$\text{Urban community comprehensive risk index}=\frac{\text{Hazard level of emergencies}\times\text{the vulnerability of exposure vulnerability}}{\text{Effectiveness of emergency management}} \tag{19}$$

Among these, substituting Eqs. (16), (17), and (18) into Eq. (19) constructs the urban community comprehensive risk index model R:

$$R=\frac{\left(\sum_{i=1}^{n} L_iE_iC_i\times\alpha_i\right)\times\left(\sum_{j=1}^{m} V_j\times\beta_j\right)}{\sum_{k=1}^{c} E_k\times\gamma_k} \tag{20}$$

In the formula:

R—Comprehensive safety risk index for urban communities;

L_i—Probability of an accident or hazard occurring for the i-th underlying indicator of emergency risk;

E_i—Frequency of exposure to hazardous environments for the i-th underlying indicator of emergency risk;

C_i—Potential consequences of an accident occurring for the i-th underlying indicator of emergency risk;

V_j—Vulnerability score for the j-th underlying indicator of disaster-bearing entity vulnerability;

E_k—Effectiveness score of the k-th underlying indicator for emergency management effectiveness;

α_i—Weighting coefficient of the i-th underlying indicator for emergency event risk;

β_j—Weighting coefficient of the j-th underlying indicator for disaster exposure vulnerability;

γ_k—Weighting coefficient of the k-th underlying indicator for emergency management effectiveness;

i, j, k—1, 2, ..., n (n = 13); 1, 2, ..., m (m = 27); 1, 2, ..., c (c = 37).

6 Conclusions

Guided by the public safety "triangular" model, this paper develops a comprehensive risk assessment indicator system that spans three key dimensions: the hazard level of emergencies, the vulnerability of exposed elements, and the effectiveness of emergency management. By applying the analytic hierarchy process (AHP) to determine the weights of risk indicators and clarify their distribution across different levels, a multidimensional risk assessment model is established. The main conclusions are as follows.

(1) The comprehensive risk assessment indicator system primarily includes indicators for evaluating the hazard level of emergencies, indicators for assessing the vulnerability of disaster-bearing entities, and indicators for measuring the effectiveness of emergency management. Specifically, the hazard risk evaluation indicators consist of three criteria layers: the probability of an accident or hazard occurring, the frequency of exposure to hazardous environments, and the potential consequences of an accident. The vulnerability assessment indicators for disaster-bearing entities include three criteria layers: life-related, material-related, and socioeconomic and cultural-related. The emergency management effectiveness evaluation indicators consist of three primary indicators: risk monitoring and early warning, emergency response and rescue, and functional recovery and reconstruction.

(2) A comprehensive risk assessment model questionnaire was developed using a 9-point scoring method. An evaluation team consisting of 20 experts from various institutions across relevant fields was invited to assign scores based on importance. Using the analytic hierarchy process (AHP), a hierarchical structure was established sequentially, constructed a judgment (comparison) matrix and performed hierarchical single-ranking and consistency testing, followed by hierarchical overall ranking and consistency testing. This process yielded the relative weights of factors at each indicator level relative to the criteria factors at the upper level, as well as their peer-level weights and overall weights relative to the overall objective level.

(3) Single-factor risk assessment using quantitative evaluation methods assigns values to various emergency hazard factors by adopting the LEC method, providing quantitative descriptions of risk levels across different indicators. For evaluating factors related to the vulnerability of disaster exposure and the effectiveness of emergency management, scores are assigned to each indicator by referencing the "GB/T 40947-2021 Guidelines for Evaluating Safety-Resilient Cities" and the "National Safety Development Demonstration City Scoring Criteria (2019 Edition)". Based on this, a comprehensive urban community risk index model is constructed, considering three dimensions: the hazard level of emergencies, the vulnerability of disaster exposure, and the effectiveness of emergency management.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (52204200).

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

Beijing Municipal Office of the Emergency Response Committee for Emergencies. 2012. *Beijing Emergency Management: Theory and Practice*. Beijing: Beijing Publishing House.

Cui, M., Wang, X. 2019. Research on the evaluation system of urban community disaster response capabilities from a resilience perspective. *Guangxi Urban Construction*, **12**: 119–122.

Fan, W. 2020. Development trends of resilient cities in safety. *Labor Protection*, **03**: 20–23.

Feng, C., Wu, J., Du, J. 2022. Construction and evaluation of a safe community evaluation index system—A study of urban China. *International Journal of Environmental Research and Public Health*, **19**(17): 10607.

Gao, F. 2015. Governance tensions and their resolution in "tripartite communities". Doctoral Dissertation. Central China Normal University.

Ge, T., Li, Q. 2016. Four models of innovation in urban community governance in China. *Journal of Northwest Normal University* (*Social Sciences Edition*), **53**(06): 5–13.

Ge, T., Xue, L. 2015. Social risks and grassroots community governance: Issues, concepts, and countermeasures. *Social Governance*, **04**: 37–43.

Gu, T., Ma, L., Liu, X., Hao, E. 2023. Study on safety risk assessment of urban old communities based on BT-BN. *Journal of Safety Science and Technology*, **19**(11): 166–172.

He, B., Gilligan, J. M., Camp, J. V. 2023. An index of social fabric for assessing community vulnerability to natural hazards: Model development and analysis of uncertainty and sensitivity. *International Journal of Disaster Risk Reduction*, **96**: 103913.

He, X. 2014. Analysis of pathways for effective participation of community social organizations in grassroots social governance. *Chinese Public Administration*, **12**: 68–70.

Huang, H., Li, R., Yu, F., Ji, X., Zhou, R. 2020. Exploring several issues in building resilient cities. *Journal of Wuhan University of Technology* (*Information and Management Engineering Edition*), **42**(02): 93–97.

Jiang, P., Jia, J., Kong, Q. 2013. *Public Crisis Management and Emergency Response*. Beijing: Hongqi Publishing House.

Lei, L. 2019. Research on the operational mechanisms and enhancement strategies of urban community resilience from a risk governance perspective. Master Thesis. University of Electronic Science and Technology of China.

Li, F. 2015b. Research on urban community emergency management based on governance theory. Master Thesis. Jinan University.

Li, X., Sun, S. 2018. the "three-community collaboration" mechanism for modernizing grassroots social governance in megacities: Practical experience from Guangzhou. *Journal of Foshan University of Science and Technology* (*Social Sciences Edition*), **36**(03): 26–32.

Li, Y. 2015a. Research on optimizing the process of social risk governance in grassroots governments. *Journal of Chongqing University of Technology* (*Social Sciences*), **29**(11): 109–114.

Liu, J., Shen, Y. 2017. Research on community resilience for risk governance. *Urban Development Research*, **24**(12): 83–91.

Lü, H. 2019. "Dual registration": Beijing's experience in urban grassroots governance. *Frontline*, (2): 70–72.

Luo, G. 2011. Research on innovation in urban grassroots social management models. Doctoral Dissertation. Wuhan University.

Peng, Z. 2015. The emergence of a service-oriented government in community reconstruction. Doctoral Dissertation. Nanjing University.

Polese, M., Tocchi, G. 2025. Identification of urban critical context using multi-risk composite-index. *EGU General Assembly*, **24**: 19673.

Song, C. 2015. Research on the grassroots social governance system in Chengdu city. Master Thesis. Southwest Jiaotong University.

Sun, X., Huang, H., Li, R. 2021. Simulation of urban emergency management mechanisms under multi-agent systems during sudden incidents. *Journal of Tsinghua University* (*Natural Science Edition*), **61**(1): 70–76.

Wang, Z. 2014. Research on the "three-sector collaboration" mechanism promoting the development of urban community social work in Guangzhou. Master Thesis. Northwest A&F University.

Wei, Y., Xiu, C. 2020. Exploring the concept and analytical framework of urban network resilience. *Advances in Geographical Science*, **39**(3): 488–502.

Yang, S. 2019. The "Beijing experience" in grassroots governance of megacities. *Urban Management and Technology*, **21**(01): 17–21.

Yang, W. 2018. *Research on Emergency Management for Unconventional Emergencies*. Hangzhou: Zhejiang University Press.

Yu, S., Zhou, L. 2016. Research on the positioning of community emergency management. *Journal of South China University of Technology* (*Social Sciences Edition*), **18**(01): 46–56.

Yuan, K. 2016. Research on community conflicts and governance in China's megacities. Doctoral Dissertation Nankai University.

Zeng, Y. 2019. Community development in community governance innovation: Practical operations and real-world implications—A case study of Chengdu. *Journal of Chengdu Party School of the CPC Chengdu Municipal Committee*, (2): 75–78.

Zhang, D., Chen, W., Kong, N. 2006. Reconstruction and innovation of urban community governance units in China: The case of "courtyard self-governance" and "building self-governance" in Wuhan City. *Urban Problems*, **04**: 59–63.

Zhang, H., Liu, Y., Liu, Y. 2017. *Theory and Methods of Emergency Decision Support for Sudden Incidents*. Beijing: Science Press.

Zhang, M. 2019. Exploring the internal mechanisms, theoretical explanations, and experience summaries of Beijing's "neighborhood-level authorities sound the alarm, government departments respond" system. *Regional Governance*, **41**: 6–9.

Zhao, J., Huang, H., Zhu, H., Su, B., Qiu, F. 2019. Research on emergency response coordination mechanisms for urban clusters in China. *Journal of Disaster Science*, **34**(02): 178–181.

Zheng, A. 2018. Modernization of urban community governance in China: Logical analysis and path selection. Doctoral Dissertation. Jilin University.

Zhu, J., Zou, K., Xiang, S., Gao, K. 2023. Research on the community security risk assessment index system based on FAHP-FTOPSIS from the perspective of the pandemic—A case study of communities in a certain city. *Operations Research and Management Science*, **32**(2): 147–151.

Chenzi Teng received her M.Sc. and Ph.D. degrees from Northeastern University, Shenyang, China, in 2015, and Beijing University of Technology, Beijing, China, in 2020. Her main research interests include risk governance and urban security.