

Article

A Study on the Characteristics and System Construction of Urban Disaster Resilience in Shanghai: A Metropolis Perspective

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Abstract: As climate change intensifies, cities face growing risks. Natural disasters underscore the vulnerabilities inherent in urban systems. Resilience provides a dynamic and developmental approach to urban disaster management. This study focuses on Shanghai to examine its urban disaster resilience by analyzing compounded disaster scenarios, the impacts on vulnerable entities, and spatial differentiation within the city. Specifically, it explores the internal mechanisms of resilience across three dimensions, functional, procedural, and systemic, forming the foundation for the model. A three-dimensional urban disaster resilience model is then constructed. The first-level indicators afford the overall framework, the second-level indicators emphasize resilience based on resources and geographical endowments, and the third-level indicators are tailored to the current political, economic, cultural, and social characteristics of the region. Using actual collected data, along with the Analytic Hierarchy Process (AHP) and expert judgment methodologies, the resilience indicator system for Shanghai can scientifically reflect the city's capacity to withstand disasters and offers a foundation for developing targeted solutions. The results highlight the framework's potential generalizability to other metropolises and its contributions to global resilience research.

Keywords: disaster risk; urban resilience; resilience characteristics; system construction



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1. Introduction

China frequently experiences natural disasters, and the complex and variable nature of these events has caused significant losses to lives, property, and the economy [1]. Over the past decade, resilience has emerged as a guiding principle for urban development and disaster risk management, aimed at enhancing cities' capabilities in disaster prevention and mitigation [2]. A resilient city is one that can effectively prevent and withstand various major shocks, quickly recover its functions after an impact, maintain core urban functions, and enhance overall urban safety through learning and innovation during and after such events [3].

At the end of 2023, President Xi Jinping emphasized during his visit to Shanghai the importance of “advancing the construction of resilient and safe cities and striving to pioneer a uniquely Chinese path for the modernization of metropolis governance”. This directive underscored the need for Shanghai to integrate resilience into its metropolis governance approach. As one of the world's largest cities, Shanghai is characterized by high population density, substantial economic scale, livability, and relatively low disaster risk. Residents enjoy high standards of living and working conditions, but with the intensifying effects of global climate change, there is an urgent need to proactively implement a robust disaster

risk reduction mechanism to protect these cities and their residents. This requires not only addressing immediate risks but also anticipating future threats [4].

International and domestic experiences show that building a resilient city requires a comprehensive and coordinated policy and action system, including planning guidance, system development, social governance, economic regulation, resource redundancy, intelligent applications, and cultural education [5]. These elements provide valuable insights for Shanghai as it advances its initiative for a resilient and safe city [6].

This study, supported by funding from the project “Construction of Shanghai’s Urban Disaster Resilience Indicator System and Evaluation Methods” based on the findings from China’s first national disaster survey, explores the characteristics of Shanghai’s comprehensive, all-encompassing urban resilience construction [7]. Despite the availability of global best practices in urban resilience, a significant research gap exists regarding tailored frameworks for metropolises like Shanghai, which require adaptive and scalable approaches that reflect their unique characteristics. This study aims to address this gap by constructing a comprehensive urban disaster resilience indicator system that is specifically designed for megacities with similar features [8]. The developed indicator system accurately reflects the city’s capacity to withstand disasters, laying the groundwork for future resilience assessments and urban development [9].

Research questions explored in this study include the following:

How can an effective urban resilience framework be designed to address the unique challenges faced by metropolises?

What are the appropriate methodologies for evaluating urban resilience indicators in a scientifically valid manner?

2. Disaster Risk and the Concept of Resilience

2.1. Disaster Risk and Vulnerability

Disaster risk refers to the probability of life loss and property damage, determined by hazard, exposure, vulnerability, and capacity [10]. According to the “Three Elements of Disaster” theory, disaster risk can be viewed as a function of the hazard posed by disaster-causing factors, the vulnerability of the environment that harbors the disaster, and the susceptibility of the affected entities [11]. The disaster-causing factors and the environment illustrate the natural aspects of a disaster, while the affected entities reflect its social aspects [12]. Different affected entities lead to varying disaster outcomes, as disaster-causing factors trigger the event, the entities influence the consequences, and the environment impacts the interaction between the factors and the entities [13].

Vulnerability is a core concept in disaster prevention and response. It represents the susceptibility of systems, populations, or infrastructure to adverse effects of disasters, determined by their sensitivity to hazards and their capacity to cope, adapt, or recover [14]. For example, according to Shi Peijun (2016) [15], vulnerability reflects the sensitivity of affected entities to disaster-causing factors and their ability to respond.

Studying vulnerability helps to understand the mechanisms of disaster events and provides theoretical support for crisis management [16]. Research on vulnerability focuses on the impact of internal system structures during disaster events, offering new perspectives for disaster prevention and mitigation efforts [17].

2.2. Disaster Risk Management and Resilience

The United Nations Office for Disaster Risk Reduction defines disaster risk management as the application of policies and strategies to prevent new risks, reduce existing risks, and manage residual risks, all of which contribute to strengthening resilience and reducing disaster losses [18].

Resilience is the “capacity of individuals, communities, societies, and cultures to survive and develop in a constantly changing environment [19]”. It encompasses the ability to withstand shocks, minimize damage, restore functionality, and adapt to future conditions. The multidimensional nature of resilience is particularly appealing to researchers working on natural disaster management. In practice, analysts often operationalize resilience as a capability, either by using a set of multidimensional indicators to capture various aspects of resilience or by applying data reduction techniques like a factor analysis to consolidate these indicators into a single measure [20]. The “Guidelines for Evaluating Safe and Resilient Cities” define a “safe and resilient city” as one that can withstand, adapt to, and recover from a disaster environment [21]. This definition emphasizes the protection and restoration of urban functions, offering new perspectives for addressing urban risks.

Effective risk management measures can enhance resilience [22]. Preventive and preparedness efforts within disaster risk management reduce potential risks before disasters occur, thereby strengthening system resilience [23]. Post-disaster response efforts help systems recover swiftly and adapt to new environments [24]. Therefore, integrating disaster risk management with resilience strategies provides a comprehensive approach to addressing disaster challenges, protecting lives and property, and promoting the sustainable development of communities [25].

3. Characteristics of Urban Disaster Resilience in Shanghai

The “Shanghai Urban Master Plan (2017–2035)” proposes the development of [26] a “more sustainable and resilient ecological city”. As part of its series of special planning initiatives, the “Shanghai Comprehensive Disaster Prevention and Mitigation Plan (2022–2035)” sets the goal of establishing a resilient and safe city by 2035. The plan outlines the construction of an integrated urban disaster prevention and safety resilience system, composed of functional resilience, procedural resilience, and systemic resilience, as well as a spatial resilience governance structure. It sets a quantitative target for disaster resilience indicators, aiming for a 90% resilience rate by 2035. Analyzing the disaster resilience characteristics of Shanghai and constructing a system based on these characteristics will enhance the city’s disaster prevention and mitigation capacity [27], providing a reference for other cities in natural disaster management.

3.1. Compounded Disaster Scenarios in Shanghai

According to the “Technical Report on the Risk Assessment and Zoning Results of Natural Disasters in Shanghai”, the city faces six major types of natural disasters: seismic disasters, marine disasters, meteorological disasters, hydrological disasters (floods and droughts), forest disasters, and geological disasters [28]. Urban development is affected by multiple natural disasters, which interact in a multidimensional manner. In cases involving multiple disasters, the environment, disaster-causing factors, and affected entities—three critical components—can combine in various ways across space, time, and intensity. The connections between different disasters are described as cascading effects or domino effects, indicating a relationship where one disaster triggers another [29].

This study statistically analyzes the correlation of compounded occurrences of various natural disasters, as shown in Table 1.

Table 1. Compounded Disaster Scenarios in Shanghai.

Original Disaster Type	Compounded Disaster Types
Seismic Disaster	The impact of earthquakes on Shanghai is minimal; the probability of earthquakes above magnitude 5 is extremely low. Therefore, compounded scenarios involving earthquakes are not analyzed in this study.
Meteorological Disaster	Flood and drought disasters (floods), forest disasters, marine disasters, geological disasters
Hydrological Disaster	Meteorological disasters, forest disasters, geological disasters
Forest Disaster	Meteorological disasters
Marine Disaster	Meteorological disasters
Geological Disaster	Meteorological disasters

It is important to note that seismic disasters, despite being listed among the six major disaster types, were excluded from the compounded disaster scenario analysis. This exclusion is based on the findings of the Technical Report on the Risk Assessment and Zoning Results of Natural Disasters in Shanghai [30], which indicates that the probability of earthquakes above magnitude 5 in Shanghai is extremely low. Given this low probability and limited historical impact, seismic disasters were deemed less relevant for compounded disaster scenarios in Shanghai. As a result, the focus of this study is directed toward more prevalent and impactful disaster types, ensuring that the analysis remains both practical and aligned with Shanghai’s specific risk profile.

3.2. Impact Characteristics of Disasters on Affected Entities in Shanghai

Affected entities comprise the human, social, and various resource components within a city [31]. They are the recipients of the impact from disaster-causing factors and serve as the carriers of disaster losses. The type of affected entities determines the potential disaster outcomes, as their characteristics influence the severity and nature of disaster risks [32]. The same disaster-causing factor can lead to different disaster outcomes based on the type of affected entity involved, and the inherent differences among these entities contribute to their vulnerability [33]. Similarly, the same affected entity can experience varying consequences depending on the specific disaster-causing factor.

According to the “Shanghai Comprehensive Disaster Prevention and Safety Resilience Zoning and Classification Guidelines”, the city is divided into four spatial resilience governance strategies based on the spatial characteristics of disaster risks and regional resource attributes: disaster evacuation-oriented, resource integration-oriented, regional coordination-oriented, and compounded disaster-oriented zones. Each type of zoning and spatial distribution corresponds to different disaster environments and types.

3.2.1. Spatial Differentiation of Disasters in Shanghai

Based on the results of the first national survey on natural disaster risk, a comprehensive assessment of disaster risks in various areas was conducted. This assessment considered factors such as disaster frequency, the vulnerability of affected entities within the region, and the potential severity of outcomes [34]. The findings in Table 2 are derived from the Shanghai Comprehensive Disaster Prevention and Mitigation Plan (2022–2035) [35]. This table integrates data and analyses on disaster risk zoning, combining spatial attributes and resilience governance strategies. By synthesizing and adapting the information in the plan, we categorized Shanghai’s territorial space into differentiated zones. The categorization involved both systematic document reviews and expert consultations, ensuring practical relevance and scientific validity.

The spatial distribution of Shanghai was categorized according to zoning types, resulting in a resilience governance plan and disaster differentiation overview, as shown in Table 2 [36]. The results of this assessment help determine risk levels and resilience strategies for different regions, providing a scientific basis for the implementation of disaster prevention and mitigation efforts in the city. The table below presents the specific findings, including the risks of various disaster types and their manifestations across different regions.

3.2.2. Impact of Disasters on Various Affected Entities in Shanghai

Affected entities are crucial components of a city's disaster resilience, and their impact varies depending on the type of disaster. By analyzing the performance of these entities under different disasters, we can better identify their vulnerable aspects and provide guidance for developing more effective urban disaster mitigation strategies [37]. Table 3 is based on the integration, analysis, and adaptation of the Technical Report on the Risk Assessment and Zoning Results of Natural Disasters in Shanghai [30], compiled by the Shanghai Municipal Office for the First National Natural Disaster Risk Census. The data in the table were derived through systematic reviews of disaster risk assessments and zoning studies, highlighting the specific impacts on various affected entities across different disaster scenarios. This approach ensures the relevance of the findings to Shanghai's unique urban characteristics.

Table 2. Shanghai National Territorial Space Resilience Governance Zoning and Disaster Differentiation.

Zoning Type and Spatial Distribution		Disaster Types					
Zoning Type	Spatial Distribution	Seismic Disaster	Marine Disaster	Meteorological Disaster	Hydrological Disaster	Forest Disaster	Geological Disaster
Disaster Evacuation-Oriented	Pudong New Area: Outside the Outer Ring Road	Low seismic risk across all of Shanghai	Storm Surge	Heavy Rain, Typhoon, High Temperatures			
	Chongming District: Entire Area		Storm Surge	Heavy Rain, Low Temperatures			
	Baoshan District: Outside the Outer Ring Road		Storm Surge	High Temperatures			
	Fengxian District: Haiwan Town, Zhelin Town		Storm Surge	Low Temperatures			
	Jinshan District: Shanyang Town, Jinshanwei Town, Zhangyan Town, Caojing Town		Storm Surge	Low Temperatures			Land Subsidence
	Qingpu District: Zhujiajiao Town, Jinze Town, Liantang Town		Storm Surge	High Temperatures, Snowstorm		Forest Fire	
Resource Utilization and Integration	Huangpu, Jing'an, Xuhui, Changning, Hongkou, Yangpu Districts (Entire Area)		Storm Surge	Typhoon, Heavy Rain, Thunderstorm	Flood		
	Putuo District: Inside the Outer Ring Road			Typhoon, Heavy Rain, Thunderstorm			
	Pudong New Area: Inside the Outer Ring Road		Storm Surge	Heavy Rain, Typhoon, High Temperatures			
	Minhang District: Main Urban Area			Heavy Rain, High Temperatures, Thunderstorm			Land Subsidence
	Baoshan District: Central Urban Area		Storm Surge				

Table 2. Cont.

Zoning Type and Spatial Distribution		Disaster Types					
Zoning Type	Spatial Distribution	Seismic Disaster	Marine Disaster	Meteorological Disaster	Hydrological Disaster	Forest Disaster	Geological Disaster
Regional Coordination and Enhancement	Jiading District: Excluding Central Urban Area	Low seismic risk across all of Shanghai		High and Low Temp			
	Baoshan District: Dachang Town (Outside Outer Ring), Taopu Town (Outside Outer Ring)		Storm Surge	High Temperatures			
	Qingpu District: Excluding Hongqiao Business District		Storm Surge	High Temperatures, Snowstorm		Forest Fire	
	Songjiang District (Entire Area)			Low Temperatures		Forest Fire	Land Subsidence
	Jinshan District: Tinglin Town, Lvxiang Town, Langxia Town, Zhujing Town, Fengjing Town		Storm Surge	Low Temperatures			Land Subsidence
	Fengxian District: North of Ring Expressway		Storm Surge	Low Temperatures			
	Minhang District: Pujiang Town, Pujin Subdistrict		Storm Surge	Heavy Rain, High Temperatures			
	Pudong New Area: South of Dazhi River, East of Ring Expressway		Storm Surge	Typhoon, Heavy Rain, High Temperatures			
Compounded Disaster-Oriented	Shanghai Chemical Industry Park (Entire Area)			Thunderstorm			
	Lingang New Area		Marine	Typhoon			Land Subsidence
	Hongqiao Airport, Pudong Airport			Typhoon, Heavy Rain, Snow and Ice			
	Yangtze River Delta Integration Demonstration Zone				Flood		

Table 3. Impact of Disasters on Various Affected Entities in Shanghai.

Disaster Factors Affected Entities			1 *	2 *	3 *	4 *	5 *	6 *	7 *	8 *	9 *	10 *	11 *	12 *	13 *	14 *	15 *	16 *	17 *
Disaster Scope			Determined by the Risk Levels of Each Disaster Prevention Zone																
Urban Disaster Prevention Facilities	Coastal Protection Facilities	Seawall	★	★	★	✓	✓	★				✓	✓		★★	★★	★★★★	★★★★	★★
		Reservoirs	★	★★	★	✓	✓				✓	★★	✓		★				★★
	Urban Flood Control and Drainage Facilities	Sluice Projects	★	★★	★	✓	✓					★★	✓		★★			★★★★	✓
		Dike Projects	★	★★	★	✓	✓					★★	✓		★★			★★★★	✓
		Flood Detention Area	★	★★	★	✓	✓					★★	✓		★★			★★★★	
		Drainage Devices	★	★★	★	✓	✓					★★	✓		★★			★★★★	✓
	Firefighting	Fire Stations	★	★	★	✓	✓					✓	✓		✓				✓
		Communication	★	★	★	✓	✓	✓	✓	✓	★	✓	✓	✓	✓	✓			✓
	Urban Lifeline Disaster Defense	Water Supply	★	★	★	★	★					✓	✓		✓				✓
		Drainage	★	★	★	✓	✓					✓	✓		✓				✓
		Power Supply	★	★	★	★	✓	✓	✓	✓	★	✓	✓	✓	✓	✓			✓
		Gas Supply	★	★	★	★	✓					✓	✓		✓				✓
Public Facility Maintenance Capability	Bridges	Aging Bridges	★	★	★	✓	✓	★		✓		★	✓		✓				✓
	Key Units	Thunderstorm Defense Key Units	★								★★	✓	✓						
		Earthquake Defense Key Units	★									✓	✓						
	Urban Transport Facilities	Roads	★	★	★★	✓		★		✓		★	✓			✓			★
		Metro	★	★	✓	✓						★★	✓						★
		Ports	★	✓	★★	✓		★★		✓	★	★★	✓		★★	★★	★★	★★	✓
		Inland Waterways	★	★★	★	✓	✓	★			✓	★★	✓		★★		★	★	
		Navigable Structures	★	✓	★	✓	✓	★				★★	✓		★★	★★	★★	★	★
		Shipping Hubs	★	✓	★★	✓	✓	★				★★	✓		★★	★★	★★	★	
		Coastal Tourist Areas	★	✓	★★	✓	✓	★				✓	✓		★★	★	★★	✓	
	Lifeline Projects	Integrated Utility Tunnels	★	✓	✓	✓	✓					✓	✓						★
		Aging Gas Pipelines	★	✓	✓	✓	✓					✓	✓						★
		Aging Water Supply Network	★	✓	✓	✓	✓					✓	✓						★

Notes: ① * In the table, numbers 1 through 17 represent different disaster factors to simplify the presentation and save space. These numbers correspond to the following disaster factors: 1. Earthquake, 2. Heavy Rain, 3. Typhoon, 4. High Temperature, 5. Low Temperature, 6. Strong Wind, 7. Hail, 8. Snow, 9. Thunderstorm, 10. Flood, 11. Drought, 12. Forest Fire, 13. Storm Surge, 14. Sea Wave, 15. Tsunami, 16. Sea Level Rise, 17. Geological Disaster. ② A “✓” indicates an impact; the number of “★” symbols represents the severity of the impact: “★★★★” indicates a high impact on the affected entity by the disaster factor. “★★★” indicates a moderate impact on the affected entity by the disaster factor. “★” indicates a low impact on the affected entity by the disaster factor. ③ Key urban risk units refer specifically to high-risk industrial enterprises, old buildings, construction sites, schools, hospitals, and other densely populated locations. These units are categorized into two main types: fire safety critical units and high-density population units. Fire safety critical units include high-rise residential buildings, large public industrial buildings, old communities, large commercial complexes, small businesses, rural self-built rental houses, and urban self-built houses. High-density-population units include medical and health facilities, elderly care institutions, schools, religious activity venues, tourist attractions, public entertainment venues, public cultural venues, hotels and guesthouses, sports facilities, shopping malls, farmers’ markets, large amusement facilities, and national exhibition centers.

This section summarizes the impact of various disaster types on different affected entities in Shanghai, as shown in Table 3. This summary provides a foundation for enhancing disaster mitigation capabilities in the future [38].

4. Construction of Shanghai's Urban Disaster Resilience System

The “Shanghai Urban Master Plan (2017–2035)” proposes the development of a “more sustainable and resilient ecological city”. As part of its series of special planning initiatives, the “Shanghai Comprehensive Disaster Prevention and Mitigation Plan (2022–2035)” sets the goal of establishing a resilient and safe city by 2035. The plan [39] outlines the construction of an integrated urban disaster prevention and safety resilience system, composed of functional resilience, procedural resilience, and systemic resilience, as well as a spatial resilience governance structure. It sets a quantitative target for disaster resilience indicators, aiming for a 90% resilience rate by 2035. Analyzing the disaster resilience characteristics of Shanghai [40] and constructing a system based on these characteristics will enhance the city's disaster prevention and mitigation capacity, providing a reference for other cities in natural disaster management.

4.1. Urban Disaster Resilience Capability System Framework

This study integrates the “Three-Dimensional Space” theory [41] with Hall's three-dimensional model [42]. Under the content of the “Three-Dimensional Space” theory, we consider various conditions, skills, and expertise that constitute the urban disaster resilience capability system. The disaster resilience model includes the following:

Knowledge Dimension: Covers the professional knowledge needed to address disaster management, including the concept of resilience, risk, and management elements.

Logical Dimension: Outlines the logical steps to address issues, including a disaster analysis, risk assessment, and risk control [43].

Temporal Dimension: Represents the procedural steps to address disasters, divided into three stages: the stable state before a disaster occurs, the maintenance state during the disaster (disaster phase), and the recovery and reconstruction process after the disaster [44].

The specific structure of the capability system framework is illustrated in Figure 1, which is based on Hall's three-dimensional model [42] and refined according to the context of urban disaster resilience construction. The framework highlights the interplay between knowledge, logic, and time in disaster resilience capabilities.

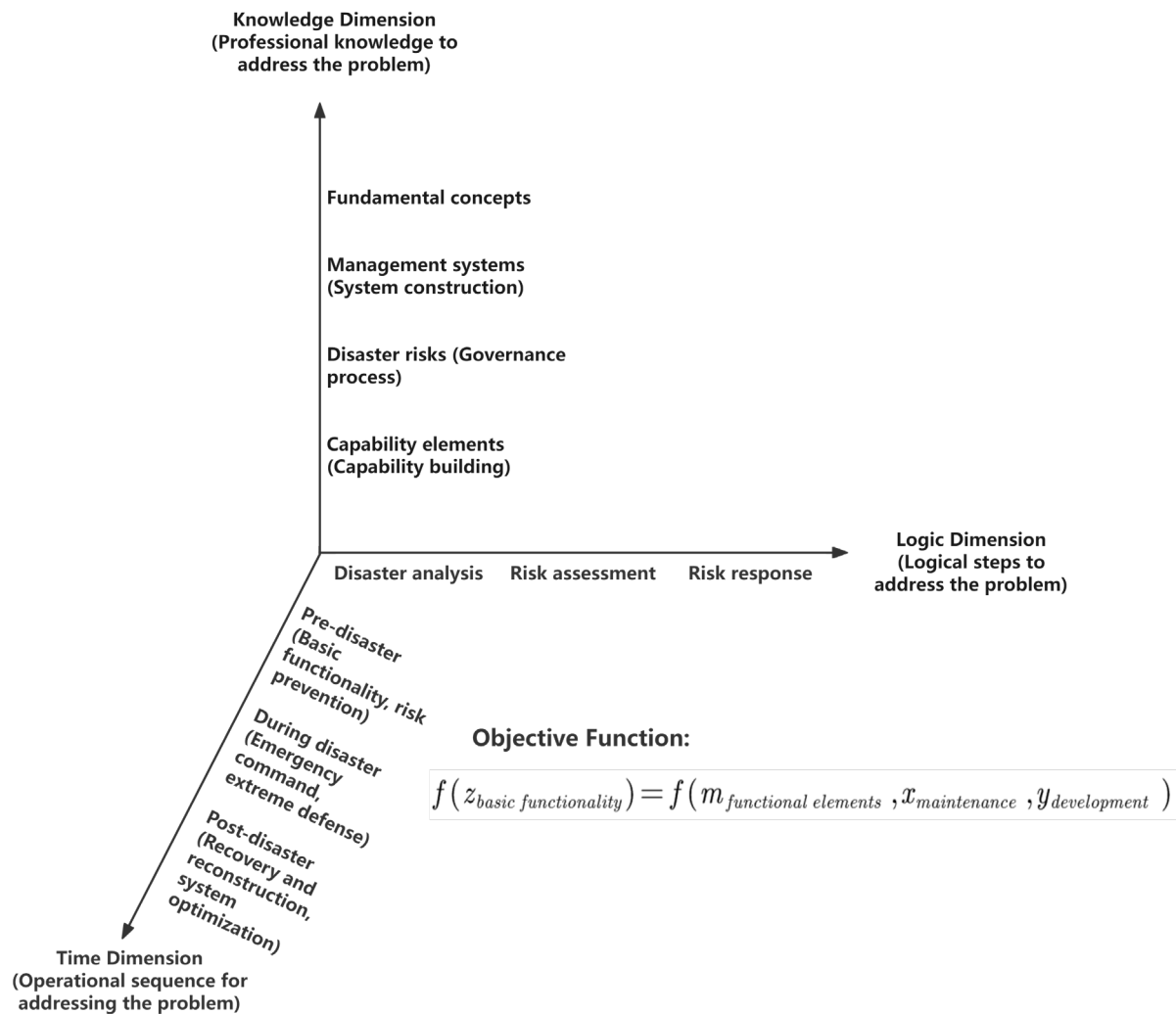


Figure 1. Three-dimensional framework of urban disaster resilience capability system (adapted from Hall's three-dimensional model [42]).

4.2. Structural Elements of Urban Disaster Resilience Capability

Shanghai's comprehensive disaster prevention and safety resilience index plan was developed by the Shanghai Municipal Office for the First National Natural Disaster Risk Census as part of a broader initiative to assess and enhance disaster resilience across the city. This plan is based on the findings of the Technical Report on the Risk Assessment and Zoning Results of Natural Disasters in Shanghai [30] and integrates detailed evaluations of disaster vulnerabilities, hazard probabilities, and urban resilience capabilities. It reflects a systematic effort to adapt global best practices to the unique characteristics of Shanghai, leveraging the city's socioeconomic and spatial attributes.

Shanghai's comprehensive disaster prevention and safety resilience index plan is based on three categories: functional resilience, procedural resilience, and systemic resilience. It develops a resilience framework across three dimensions: functional points, process chains (lines), and system surfaces [45]. This framework encompasses the various capabilities required for the city to respond to disasters, ultimately summarizing nine primary indicators [46]. These indicators are grouped into three main domains: functional resilience, procedural resilience, and systemic resilience.

The study focuses on building foundational resilience capabilities by setting four indicators for functional resilience: governance foundation, spatial layout, community renewal, and integrated governance [47]. For procedural resilience, the study establishes three

indicators: risk prevention and control, emergency command, and extreme defense [48]. These indicators were defined by this study based on structured analyses of Shanghai's socioeconomic conditions and disaster management requirements. The process involved expert consultations and reviews of relevant policies and reports to ensure their applicability and alignment with practical needs [49]. For systemic resilience, it includes two indicators [50]: Monitoring and Early Warning, and Digital Empowerment (see Figure 2).

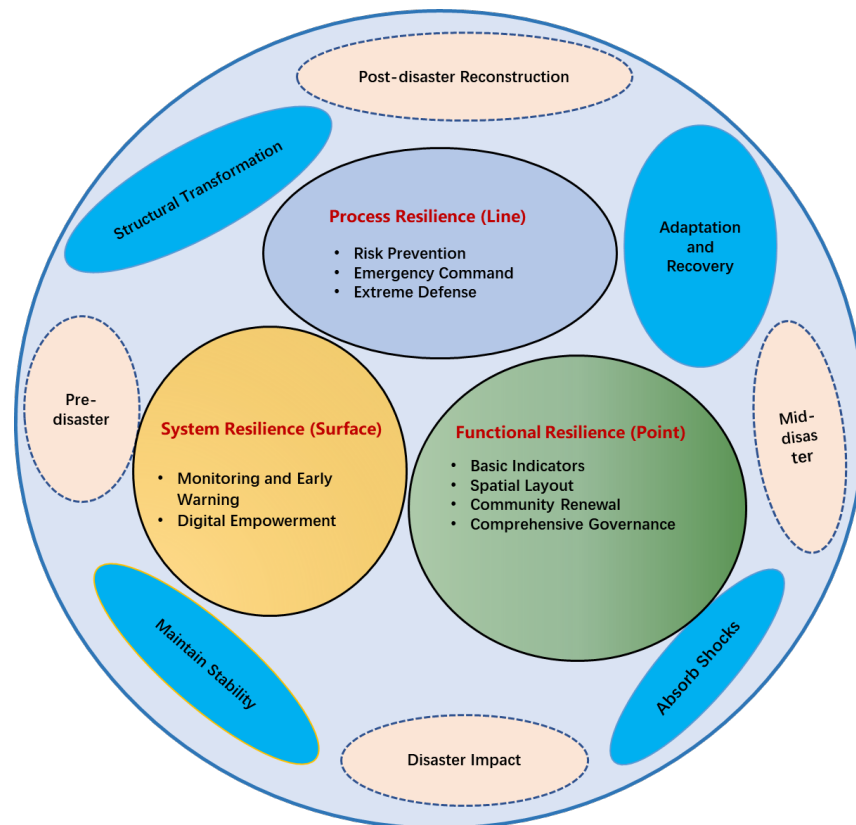


Figure 2. Structure of urban resilience elements' framework.

4.2.1. Functional Resilience Elements

Functional resilience reflects the basic capacity of social systems, under national government leadership, to respond to and withstand disasters. It encompasses four aspects: governance foundation, spatial layout, community renewal, and integrated governance.

Governance foundation includes the organizational management, protection of vulnerable groups, and basic safety indicators [51]. These three elements ensure that the city has adequate response capabilities in the face of disasters. Organizational management involves the development and enhancement of urban safety production and natural disaster prevention systems, along with the implementation of responsibilities—an essential guarantee for disaster response. The protection of vulnerable groups addresses the specific needs of demographic groups, such as the elderly and people with disabilities, ensuring that diverse populations receive appropriate protection during disasters. Basic safety indicators measure the overall safety level of the city using metrics like the fatality rate from industrial accidents and fires.

Spatial layout focuses on the rational allocation of national land planning and emergency facilities [52]. Land use planning must ensure scientifically sound disaster prevention layouts, with urban disaster prevention zones and community grid coverage to meet rapid response and evacuation requirements. Emergency facilities include shelters, fire stations,

material storage depots, and emergency medical stations. The distribution and scale of these facilities directly affect the city's response efficiency during disasters.

Community renewal emphasizes safe community construction and residential environment renovation [53]. In conjunction with the national “15-min living circle” plan, disaster prevention infrastructure is integrated into daily community life, ensuring strong response capabilities during both daily activities and disaster events. Residential environment improvements focus on issues such as the safety of water and power lines and the structural safety of building exteriors. Timely updates and renovations enhance the community's overall disaster resistance.

Integrated governance covers the development of emergency forces, safety education, technological innovation, and disaster insurance. The development of emergency forces includes increasing and improving the number and quality of professional firefighters, emergency rescue teams, and registered volunteers, which play a critical role in disaster response. Safety education, through awareness days, disaster prevention museums, and school-based disaster prevention programs, raises public awareness and skills for disaster preparedness. Technological innovation focuses on the development of technologies related to disaster prevention and reduction and the support of expert teams to improve the technological capabilities of disaster response. Disaster insurance involves enhancing mechanisms like catastrophe insurance and liability insurance for safety production [54], helping disaster-affected citizens receive economic compensation and reduce disaster-related economic losses.

Comprehensive development of these functional resilience elements allows the city to enhance its response capabilities before disasters, maintain stability during disasters, and recover rapidly afterward. “Functional Points” focus on the static state and basic construction, reflecting the city's foundational capacity to resist disasters before they occur, embodying the characteristics of stability of physical elements.

Functional resilience supports urban resilience through both hardware and software components: hardware mainly refers to various types of urban infrastructure, while software involves governance technologies. According to functional types, it is classified into layout functions, management functions, social functions, and defense functions. The indicators are shown in Table 4.

Table 4. Urban Safety Functional Resilience Indicators.

	Primary Indicator	Secondary Indicator
Functional Resilience Indicators	Governance Foundation A1	Risk Management Essentials B1 Key Protected Population B2 Basic Safety Indicators B3
	Spatial Layout A3	Territorial Spatial Planning B7 Emergency Response Facilities B8
	Community Renewal A4	Safe Community Construction B9 Residential Safety Renovation B10
	Comprehensive Governance A5	Development of Emergency Forces B11 Safety Education and Promotion B12 Foundation for Emergency Technology and Innovation B13 Disaster Insurance Mechanism B14

4.2.2. Process Resilience Elements

The core of urban resilience construction lies in implementing full-cycle governance, which includes pre-disaster, during-disaster, and post-disaster resistance and recovery [55]. Once a disaster strikes, the city enters the phases of resistance and adaptation. Urban

resilience enables the city to eliminate disaster impacts in the shortest time possible; restore normal functions of infrastructure, economy, and society swiftly; and minimize losses to people's lives and property. Based on this, the city learns from experiences, optimizes its risk prevention system, and prepares more thoroughly for future disasters, thus continuously enhancing its security capabilities through each cycle of disaster management.

Incorporating risk management expert Robert Heath's "4R Theory" [56] of crisis management, risk management permeates the entire process of urban resilience construction, including risk identification, assessment, and response. In the risk management process [57], organizations need to strengthen communication and consultation to enhance risk awareness and understanding, gain decision support, and improve monitoring and review to ensure the quality and effectiveness of risk management implementation and outcomes.

Process resilience primarily consists of three "process chain" elements, risk prevention and control, emergency command, and extreme defense, which together form the city's dynamic response mechanism before, during, and after disasters, ensuring flexibility in emergency response and quick recovery post-disaster.

Risk prevention and control are pre-disaster measures [58] taken by the city to ensure the safe operation of critical facilities and infrastructure, preventing the weakening of functional resilience over time. This element is designed across three aspects:

Safety of Critical Facilities includes protective capacities for seawalls, urban flood control and drainage systems, and backup capacities for gas and power systems, forming the essential defense line against natural disasters [59].

Operational Safety of Urban Infrastructure ensures the stability of essential infrastructure needed for daily life before and after a disaster.

Key Risk Management focuses on the strict management and monitoring of high-risk enterprises and densely populated areas to prevent major accidents. Routine maintenance and management help maintain a well-functioning social system before disasters occur.

Emergency command is crucial during disasters, directly influencing the efficiency and effectiveness of emergency response [60]. This element comprises three aspects:

Effectiveness of Emergency Plans ensures that emergency plans and drills are systematic, structured, and coordinated, with regular exercises to enhance emergency preparedness [61].

Command and Dispatch Coordination is where the robustness of the command network and communication systems determines the timeliness and accuracy of command operations.

Emergency Rescue Operations include the quick response capabilities of firefighting and medical rescue teams, which are vital during critical moments of disaster. These elements ensure the efficiency of emergency command during disasters, preventing system collapse due to improper responses and maintaining resilience throughout the disaster.

Extreme defense aims to manage extreme events and large-scale disasters, ensuring the city's capacity to respond to extraordinary disasters. It includes three aspects:

Preparation for Extreme Scenarios involves simulations and drills for extreme disasters, and pre-stocking the necessary supplies to ensure sufficiency and diversity during disaster events [62].

Extreme Emergency Support includes backup energy supplies, communication networks under extreme conditions, and data backup, ensuring uninterrupted information and energy supply and data security even in the harshest conditions.

Recovery and Reconstruction Mechanisms ensure the swift initiation of recovery work, particularly data restoration and backup, to minimize disaster-induced losses. These measures help maintain city operations during extreme disasters and facilitate the quick restoration of normalcy post-disaster.

Process resilience reflects the city's proactive measures before disasters and its adaptive responses during and after disasters, characterized by dynamics of organization activities and flow of information and resources. Through systematic dynamic adjustments and controls, the city can effectively respond to disasters, avoid failures during disaster events, and quickly restore functionality, showcasing the overall risk management and emergency capabilities of the social system.

According to the needs of full-cycle governance, three dimensions are proposed: sustainability, recoverability, and developability. Sustainability ensures that the system remains balanced under minor disturbances; recoverability helps the system return to its original equilibrium state within a short period under major disturbances; and developability represents the system's ability to progress, correcting vulnerabilities and achieving a new state of balance. The indicators are shown in Table 5.

Table 5. Urban Safety Process Resilience Indicators.

	Primary Indicator	Secondary Indicator
Process Resilience Indicators	Risk Prevention A2	Safety of Critical Facilities B4 Operational Safety B5 Key Risk Management B6
	Emergency Command A6	Effectiveness of Emergency Plans B15 Emergency Command and Dispatch B16 Emergency Rescue Operations B17
	Extreme Defense A7	Extreme Scenario Preparedness B18 Extreme Emergency Support B19 Recovery and Reconstruction Mechanism B20

4.2.3. System Resilience Elements

System resilience is primarily summarized into two core elements [63], Monitoring and Early Warning and Digital Empowerment, emphasizing the use of digital technology and intelligent systems to enhance the city's overall disaster resistance and management efficiency.

Monitoring and Early Warning is a crucial component [64] that ensures that the city can obtain dynamic information and respond promptly when facing risks. It consists of three aspects:

A Dynamic Risk Survey involves maintaining comprehensive monitoring of potential risks through continuously updated survey mechanisms [65], enabling regular risk assessments and dynamic management.

Specialized Early Warning Capabilities focus on establishing specialized monitoring and warning systems for common natural disasters in Shanghai, such as meteorological events and floods, to ensure that relevant departments and the public receive disaster information in advance and take preventive measures.

Integrated Early Warning Capabilities enhance the accuracy and timeliness of warnings through the comprehensive analysis and evaluation of multiple disasters, thereby improving the ability to respond to various risks. These measures ensure that the city receives timely information before disasters occur, enabling scientific decision making and avoiding unpreparedness.

Digital Empowerment uses modern technology to provide robust support for urban emergency management [66], comprising three main aspects:

Information Dissemination ensures that disaster information is rapidly disseminated across multiple channels to reach a broad audience, enhancing the timeliness and efficiency of emergency response.

An Emergency Management System develops an integrated platform to facilitate seamless coordination among departments, ensuring unified and efficient information sharing, resource allocation, and command operations during disaster responses.

Safety Service Infrastructure provides foundational infrastructure support [67] for emergency management through emergency capability development modules, enhancing the professional level of emergency management. These systematic empowerment measures offer efficient management tools for the city when facing complex disasters, ensuring the smooth operation of information, logistics, and human flows before and after disasters.

System resilience focuses on “Digital Governance”, empowering urban disaster resilience construction through digital means. Leveraging advanced technology, the city can achieve intensive and precise pre-disaster prevention, maximize efficiency during disaster response and post-disaster recovery, and ultimately minimize the impact of disasters on society. This approach forms an integrated “monitoring, forecasting, prevention, response, and rescue” operational system, as shown in Table 6.

Table 6. Urban Safety System Resilience Indicators.

	Primary Indicator	Secondary Indicator
System Resilience Indicators	Monitoring and Early Warning A8	Dynamic Risk Survey B21 Professional Early Warning Capability B22 Comprehensive Early Warning Capability B23
	Digital Empowerment A9	Information Consolidation and Dissemination B24 Emergency Management System B25 Safety Service Infrastructure B26

4.2.4. Tertiary Indicator Construction for Urban Disaster Resilience Capabilities

The design of the tertiary indicators is based on the current status of Shanghai’s urban environment, guided by the government’s phased objectives to form implementable and manageable indicators that are easy to standardize. This study focuses on building the core capabilities of disaster resilience [68], aligning with the targets and capability development requirements specified in Shanghai’s “14th Five-Year Plan for Emergency Management” and the “Long-term Comprehensive Disaster Prevention and Mitigation Plan”. The tertiary indicators present the current state and specific requirements for each primary and secondary indicator. Over the implementation period in the coming years, these indicators can be dynamically adjusted or parameters iterated based on actual circumstances [69].

Table 7 is divided into three key sections, each focusing on different aspects of urban disaster resilience:

Table 7. Tertiary Indicator Framework for Urban Disaster Resilience Capabilities.

Tertiary Indicator Framework for Functional Resilience of Urban Disaster Capabilities	
Secondary Indicator	Tertiary Indicator
Risk Management Essentials B1	Urban Safety Production and Natural Disaster Prevention System Construction C1
	Urban Safety Production and Natural Disaster Prevention Responsibility C2
Key Protected Population B2	Population Age Structure Index C3 Proportion of Disabled Population C4
Basic Safety Indicators B3	Production Safety Accident Mortality Rate per Unit of GDP C5 Fire Mortality Rate per Million People C6

Table 7. Cont.

Tertiary Indicator Framework for Functional Resilience of Urban Disaster Capabilities	
Territorial Spatial Planning B7	General Requirements for Disaster Prevention Spatial Planning C22 Urban Disaster Prevention Zoning C23 Community Grid Coverage Rate C24
Emergency Response Facilities B8	Requirements for Emergency Shelters C25 Per Capita Emergency Shelter Area C26 Fire Station Coverage Rate C27 Scale and Coverage of Material Reserves' Warehouses C28 Emergency Relief Storage Building Area per 10,000 People C29 Layout and Capability of Emergency Medical Points C30 120(999) Emergency Medical 15-Minute Coverage Rate C31 Integrity Rate of Municipal Fire Hydrants C32
Safe Community Construction B9	Disaster Prevention Construction in the "15-Minute Living Circle" C33 Investment Intensity in "Dual-Use" Public Facilities C34
Residential Safety Renovation B10	Proportion of Residences with Pipeline Damage Issues C35 Proportion of Residences with Exterior Wall Material and Suspension Hazards C36
Development of Emergency Forces B11	Number of Professional Firefighters per 10,000 People C37 Number of Professional Emergency Rescue Teams C38 Proportion of Registered Volunteers C39
Safety Education and Promotion B12	Coverage of Thematic Day Safety Education C40 Construction of Safety Culture Experience (Science Education) Centers or Bases C41 Annual Coverage Rate of Disaster Science Education for Primary and Secondary Students C42 Resilient City Cooperative Research and Exchange C43
Foundation for Emergency Technology and Innovation B13	Development of Safety (Disaster Prevention) Industries and Technological Innovation C44 Construction of Expert Teams C45
Disaster Insurance Mechanism B14	Catastrophe Insurance Density C46 Proportion of Production Safety Liability Insurance C47
Tertiary Indicator Framework for Process Resilience of Urban Disaster Capabilities	
Secondary Indicator	Tertiary Indicator
Safety of Critical Facilities B4	Seawall Hazard Density Index C7 Compliance Rate of Urban Flood Control and Drainage Standards C8 Seismic Requirements for High-Risk Units C9 Emergency Natural Gas Reserve Capacity C10 Backup Rate of Power Systems C11
Operational Safety B5	Number of Repairs for Infrastructure Interruptions or Damage per 10,000 People C12 Renovation Rate of Aging Water Supply Networks C13 Completion Rate of Gas Hazard Pipeline Rectification C14 Disaster Defense Response of Urban Transport Facilities (Roads, Bridges) C15 Quadruple Coordination Mechanism at Metro Stations C16
Key Risk Management B6	Compliance Rate of Safety Standards for Enterprises in Hazardous Chemical and Trade Industries C17 Risk Control of Key Urban Risk Units (High-Risk Production Enterprises) C18 Risk Control of Key Urban Risk Units (Densely Populated Locations) C19 Risk Control of Key Urban Risk Units (Fire Safety in Old Buildings) C20 Risk Control of Key Urban Risk Units (Seismic Requirements for Buildings) C21
Effectiveness of Emergency Plans B15	Emergency Plan System C48 Implementation of Emergency Drills C49 Coordination and Structural Integration of Departmental Emergency Plans C50
Emergency Command and Dispatch B16	Construction of Command Centers and Emergency Command Network C51 Emergency Command Dispatch and Communication C52

Table 7. *Cont.*

Emergency Rescue Operations B17	Compliance Rate of Emergency Response Time for Firefighting C53 Average Response Time of Pre-Hospital Emergency Medical Services C54
Extreme Scenario Preparedness B18	Simulation and Drill of Emergency Plans for Extreme Scenarios C55 Scale and Variety of Emergency Material Reserves C56
Extreme Emergency Support B19	Emergency Energy Supply Capacity and Layout C57 Communication Support in Extreme Conditions C58 Data Backup and Emergency Communication Backup Lines C59
Recovery and Reconstruction Mechanism B20	Construction of Post-Disaster Recovery and Reconstruction Mechanism C60
Tertiary Indicator Framework for System Resilience of Urban Disaster Capabilities	
Secondary Indicator	Tertiary Indicator
Dynamic Risk Survey B21	Disaster Survey Continuous Data Support System C61 Dynamic Data Collection System for Hazard Inspection C62
Professional Early Warning Capability B22	Meteorological and Flood Disaster Monitoring C63 Earthquake and Geological Disaster Monitoring C64 Remote Monitoring of Forest Fires C65
Comprehensive Early Warning Capability B23	Comprehensive Risk Monitoring and Early Warning System for Natural Disasters C66 Urban Safety Risk Monitoring and Early Warning System C67
Information Consolidation and Dissemination B24	Information Aggregation, Sharing, and Dissemination System C68 Meteorological Disaster Risk Early Warning Release System C69
Emergency Management System B25	“Integrated Management” Platform Emergency Function Construction C70 Urban Emergency Management Comprehensive Information Platform C71
Safety Service Infrastructure B26	Emergency Escape Map System Construction C72 Intelligent Equipment Development for Emergency Teams C73 Digital System for Recovery and Rescue Construction C74

Tertiary Indicator Framework for Functional Resilience of Urban Disaster Capabilities: Addresses the core capabilities necessary for maintaining urban functions in the face of disasters.

Tertiary Indicator Framework for Process Resilience of Urban Disaster Capabilities: Focuses on the operational aspects of disaster response and management.

Tertiary Indicator Framework for System Resilience of Urban Disaster Capabilities: Deals with the resilience of infrastructure, monitoring systems, and early warning mechanisms.

The final system of indicators is structured as follows [70]:

4.3. Weight Calculation for Urban Disaster Resilience Indicators

To accurately assess a city’s response and recovery capabilities in the face of disasters, this study applies the Analytic Hierarchy Process (AHP) [71] to calculate the weights of urban disaster resilience indicators. AHP requires expert opinions to establish a weight evaluation matrix, ensuring objectivity and reliability. It involves constructing a judgment matrix, calculating the weights of indicators at each level, and conducting a consistency test to ensure the scientific validity and rationality of the evaluation system [72] (Figure 3 provides a detailed illustration of the stepwise process).

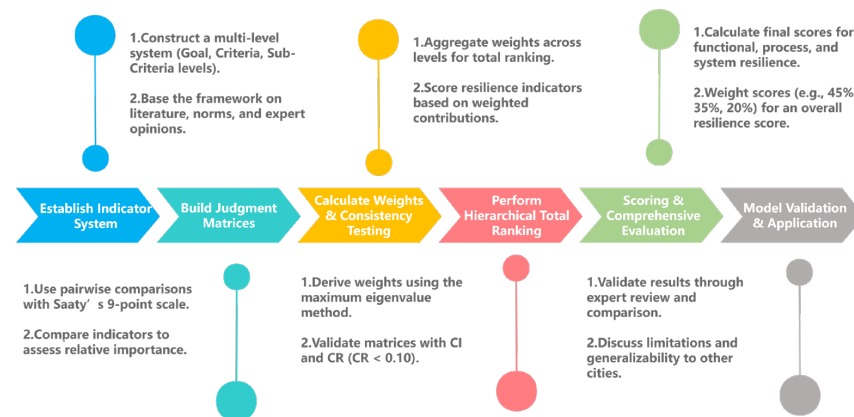


Figure 3. Stepwise framework for assessing urban disaster resilience using AHP.

The indicators were developed based on the results of structured expert interviews with disaster management specialists from Shanghai's 16 districts. In three rounds of expert panel discussions, more than 30 urban risk management specialists clarified the definitions, evaluation methods, and weight assignments for the tertiary indicators. The judgment matrix used in AHP for this study was derived from expert consultations and is region-specific to Shanghai, providing localized relevance [73].

4.3.1. Construction of Process Resilience Indicator System

In the urban disaster response and assessment process, to accurately reflect the city's emergency capabilities, its recovery capabilities, and the resilience level of its infrastructure, this study constructs a multi-level process resilience evaluation system. This system logically ensures the correlation between indicators, allowing it to comprehensively reflect the city's overall characteristics, infrastructure features, and emergency response capabilities. To ensure the scientific and operational validity of the evaluation system, the construction process maintained the comprehensiveness, systematicness, and comparability of the indicators [74].

While the constructed indicator system is region-specific to Shanghai, it offers a template for resilience evaluation in other regions [75]. Regions with differing natural resource endowments or socio-political environments may require restructured matrices and revised indicators to ensure relevance and validity.

The process resilience indicator system developed in this study includes three levels [76]:

Goal Level: Represents the ultimate evaluation objective of the entire system, which is the overall resilience performance of the city in response to disasters. This level reflects the city's adaptability, response, and recovery capabilities comprehensively.

Criteria Level: Refines and decomposes the goal level, highlighting the key factors influencing process resilience. By breaking down process resilience into different core dimensions, such as risk prevention and control, emergency command, and extreme defense, this study ensures the systematic and scientific nature of the indicator system.

Sub-Criteria Level: Further refines the criteria level into more specific subsystem indicators [77] to evaluate each criterion in detail. These indicators were developed based on the results of structured expert interviews with disaster management specialists from Shanghai's 16 districts [78]. They cover various aspects, from facility safety to emergency response capabilities, providing a comprehensive assessment of each influencing factor's specific performance.

The relationships between each level are detailed in Table 8, which outlines the comprehensive evaluation system for process resilience.

Table 8. Comprehensive Evaluation System for Process Resilience.

Evaluation Level	Primary Indicator	Secondary Indicator
Comprehensive Evaluation of Process Resilience Indicators	Risk Prevention A2	Safety of Critical Facilities B4 Operational Safety B5 Key Risk Management B6
	Emergency Command A6	Effectiveness of Emergency Plans B15 Emergency Command and Dispatch B16 Emergency Rescue Operations B17
	Extreme Defense A7	Extreme Scenario Preparedness B18 Extreme Emergency Support B19 Recovery and Reconstruction Mechanism B20

4.3.2. Establishing the Safety Evaluation Matrix for Urban Resilience

The judgment matrix is a tool used to describe and evaluate the relative importance of indicators within each level [79]. In this study, the judgment matrix was constructed through a structured expert evaluation process involving 2–3 risk management experts for urban safety from each of Shanghai’s 16 districts. These experts were selected based on their knowledge of local disaster management practices and their familiarity with the city’s unique risk profile. During the interviews, experts were asked to compare the importance of indicators pairwise using a standardized questionnaire, which was designed to ensure consistency across evaluations. The pairwise comparison data were then aggregated to form the judgment matrix for each level of indicators [80]. This approach ensured both the comprehensiveness and objectivity of the evaluation system. The judgment matrix is in Table 9 [81]:

Table 9. Judgment Matrix Scale Method.

No.	Level of Importance	Scale Value
1	Elements a_i and a_j are equally important	1
2	Element a_i is slightly more important than a_j	3
3	Element a_i is more important than a_j	5
4	Element a_i is strongly more important than a_j	7
5	Element a_i is extremely more important than a_j	9
6	Element a_i is slightly less important than a_j	1/3
7	Element a_i is clearly less important than a_j	1/5
8	Element a_i is strongly less important than a_j	1/7
9	Element a_i is extremely less important than a_j	1/9
10	Compromise scale between the above two levels	2, 4, 6, 8
11	Reciprocal scale for the compromise between the above two levels	1/2, 1/4, 1/6, 1/8

We begin with the sub-criteria level, comparing the indicators under the same criterion pair by pair to assess their relative importance and construct the judgment matrix. Each matrix is developed using the scale method outlined above, combined with expert opinions and literature data to determine the relative importance values (a_{ij}) for each comparison, ensuring the objectivity and scientific validity of the evaluation. Below are the judgment matrices for A_2 , A_6 , and A_7 .

$$A_2 = \begin{bmatrix} 1 & 1/2 & 3 \\ 2 & 1 & 5 \\ 1/3 & 1/5 & 1 \end{bmatrix} \quad (1)$$

$$A_6 = \begin{bmatrix} 1 & 1 & 3 \\ 1 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{bmatrix} \quad (2)$$

$$A_7 = \begin{bmatrix} 1 & 4 & 3 \\ 1/4 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{bmatrix} \quad (3)$$

To ensure the consistency of the judgment matrix, we followed these steps:

Calculation of the Maximum Eigenvalue (λ_{max}): For each judgment matrix, we calculated the maximum eigenvalue (λ_{max}) using MATLAB. This value is used for consistency testing. If the judgment matrix is perfectly consistent, λ_{max} should equal the matrix order (n).

Calculation of the Consistency Index (CI): Since judgment matrices may not achieve perfect consistency, we introduce the Consistency Index (CI) to measure the degree of deviation. The formula for CI is

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

A CI value of 0 indicates perfect consistency in the judgment matrix.

Calculation of the Consistency Ratio (CR): To further evaluate the consistency of the judgment matrix, we use the Random Index (RI), which depends on the matrix order. In this study, we use CR as the criterion for consistency validation:

$$CR = \frac{CI}{RI} \quad (5)$$

If the CR value is less than 0.10, the judgment matrix is considered to have acceptable consistency. Otherwise, the matrix needs to be adjusted based on expert opinions to ensure it passes the consistency test.

The validity of the obtained numerical weights was ensured through a systematic process. After constructing the judgment matrix, calculated weights were compared with original pairwise comparison data to ensure alignment with expert judgments. Any inconsistencies identified (e.g., $CR > 0.10$) were resolved through iterative consultations with experts. This rigorous validation process guarantees that the derived weights accurately represent expert opinions and meet scientific standards for consistency and objectivity [82].

4.3.3. Indicator Weight Outputs and Hierarchical Total Ranking

The judgment weights were generated through a combination of expert consultations and structured evaluations. Experts provided pairwise comparisons of indicators during interviews, which were then used to construct the judgment matrices.

We developed statistical software to address the calculations required, streamlining the weight computation process and reducing the workload [83]. Using statistical software (MATLAB R2024b), we constructed the matrices and calculated the weights of each indicator, determining the total hierarchical ranking weights for the system.

4.3.4. Hierarchical Total Ranking and Consistency Test Results for Process Resilience Indicators

After constructing the judgment matrices based on expert evaluations, we used MATLAB to calculate the maximum eigenvalue (λ_{max}) and perform consistency tests, including the CI and CR calculations. These steps validated the alignment of the computed weights with the experts' initial input, ensuring that the results accurately reflected their judgments. This process highlights the integration of qualitative expert opinions with quantitative analytical methods.

The calculated weights were then compared to the original pairwise comparison data to ensure that the results accurately reflected the experts' inputs. In cases where inconsistencies ($CR > 0.10$) were identified, the judgment matrix was revised in consultation

with the experts to align the results with their intended evaluations. This iterative process ensured that the final weights were both scientifically valid and reflective of expert opinions.

The weight values and consistency test results for the process resilience indicators are shown in Table 10.

Table 10. Weights and Consistency Test Results for Process Resilience Indicators.

Evaluation Level	Criterion Indicator Weight	Alternative Indicator Weight	
Comprehensive Evaluation of Process Resilience Indicators (P)	A2: 0.6	B4: 0.3090	$CI = 0.0018$, $RI = 0.58$, $CR = 0.0032$
		B5: 0.5816	The judgment matrix meets consistency requirements
		B6: 0.1095	
	A6: 0.2	B15: 0.4434	$CI = 0.0091$, $RI = 0.58$, $CR = 0.0158$
		B16: 0.3874	The judgment matrix meets consistency requirements
		B17: 0.1692	
	A7: 0.2	B18: 0.6301	$CI = 0.0539$, $RI = 0.58$, $CR = 0.0930$
		B19: 0.2184	The judgment matrix meets consistency requirements
		B20: 0.1515	

The numerical weights derived in this study are specific to Shanghai's urban context, reflecting its unique socioeconomic, geographical, and disaster management characteristics. However, the resilience framework and methodology can be adapted to other megacities with similar profiles by recalibrating the weights based on region-specific data and expert consultations. Future studies should test the applicability of these weights in different regions to evaluate their robustness and potential for broader use [8].

4.3.5. Comprehensive Scoring Based on Hierarchical Structure

To evaluate the overall score for urban disaster resilience, this study calculates the scores for functional resilience, process resilience, and system resilience, and then weights them according to their respective weights (45% for functional resilience, 35% for process resilience, and 20% for system resilience). The weighted sum yields the comprehensive score, as shown in Table 11. The scores for each type of resilience are based on the performance of each level's indicators and their corresponding weights [84], ensuring a comprehensive and objective evaluation.

Table 11. Scores and Weights for the Three Types of Resilience.

Type	Individual Score	Weight	Weighted Score
Functional Resilience	59.98	45%	26.991
Process Resilience	69.55	35%	25.438
System Resilience	62.9	20%	12.58
Total			65.009

The formula for calculating the comprehensive urban disaster resilience score is

$$S = w_1 S_{B_1} + w_2 S_{B_2} + w_3 S_{B_3}$$

where w_1 , w_2 , w_3 are the weights for functional resilience, process resilience, and system resilience, respectively, and S_{B_1} , S_{B_2} , S_{B_3} are the corresponding scores for each criterion level. The final comprehensive score is 65.009.

The calculated scores represent a comprehensive evaluation of Shanghai's disaster resilience. The weighting system is adaptable for similar metropolitan contexts with appropriate recalibration based on local expertise.

5. Policy Recommendations

Building on the urban disaster resilience indicator system developed in this study, the following recommendations are proposed to enhance disaster resilience and guide urban development and risk management in Shanghai:

1. Enhancing Comprehensive Disaster Prevention Capabilities

Strengthen key infrastructure resilience to ensure functionality during and after disasters.

Develop region-specific risk management plans that account for internal vulnerabilities and external risks.

Leverage modern technologies, such as big data and IoT, for real-time disaster monitoring and efficient emergency response [85].

2. Promoting Community and Collaborative Governance

Foster partnerships between government, communities, and private sectors to create a shared responsibility framework for disaster preparedness and mitigation [86].

Conduct public education programs to enhance societal awareness of disaster risks and response capabilities.

3. Advancing Smart Urban Development

Upgrade aging infrastructure to meet modern resilience standards [87].

Implement intelligent disaster management systems that integrate risk monitoring, early warning, and emergency resource allocation.

4. Optimizing Full-Cycle Disaster Management

Strengthen prevention measures through accurate disaster forecasting and scenario-based emergency drills.

Enhance post-disaster recovery mechanisms, ensuring the rapid restoration of core urban functions [88].

5. Strengthening Regional and Global Cooperation

Promote resilience collaboration within the Yangtze River Delta and other regions by sharing best practices and standardizing resilience indicators.

Facilitate the development of integrated disaster management systems that address cascading and compounded disaster risks [89].

6. Establishing a Dynamic Resilience Evaluation Mechanism

Regularly update the resilience indicator system to reflect evolving urban conditions and integrate lessons learned from disasters.

Use evaluation results to drive the formulation and improvement of urban planning and disaster risk reduction strategies.

6. Conclusions

It is impossible for a city to be completely free of disasters; therefore, enhancing urban resilience to reduce disaster risk, increase public risk awareness, and decrease urban vulnerability is essential for promoting sustainable urban development.

This study approaches the topic from the perspective of urban disaster resilience. It first reviews the concepts of disaster risk and resilience, analyzing and summarizing the compounded disaster scenarios and their impacts on affected entities in Shanghai.

Additionally, based on these urban disaster resilience dimensions, the study applies a disaster management model and risk management process to analyze process resilience, and a systems approach to analyze system resilience. Using Hall's three-dimensional model,

the study constructs a model for urban disaster resilience. Finally, a three-level indicator system for urban disaster resilience in Shanghai is established, covering functional, process, and system resilience.

The findings of this study contribute to a deeper and more comprehensive understanding of the characteristics and dimensional elements of urban disaster resilience. In the future, through evaluation-driven construction, cities can achieve a deeper understanding of their resilience structures and develop more rational disaster prevention and mitigation plans based on the attributes of urban resilience.

7. Discussion and Limitations

7.1. Connection with Expanded Practices and Generalizability

The practical application of resilience indicators in Shanghai highlights the following key aspects:

Clear Structure: The structural elements of the indicator system align with both historical and contemporary academic logic and have been validated through multiple reviews. The nine primary indicators ensure a reliable framework through 2035. Secondary and tertiary indicators are designed based on the current status and guided by staged government objectives, making them practical for planning and regular management [90].

Practical Relevance: This version of the indicator system emphasizes core disaster resilience capabilities, reflecting the objectives and capacity-building requirements outlined in Shanghai's "14th Five-Year Emergency Management Plan" and "Comprehensive Disaster Prevention Plan". Each primary indicator is a reflection of current conditions and specific requirements [73].

Dynamic Updates: During the 2025–2035 implementation period, the indicators can be dynamically adjusted or iteratively updated based on actual conditions (e.g., retaining the indicators but adjusting their degree of rigor). Secondary and tertiary indicators can be revised in line with medium- and long-term plans, with suggested revisions every five years for secondary indicators and annual updates for tertiary indicators at the municipal level.

This study presents an urban disaster resilience indicator system specifically designed for Shanghai as a prototypical metropolis. The two- and three-tier indicators reflect Shanghai's unique socio-cultural attributes, including its high population density, significant economic activity, and relatively low direct exposure to disasters. These attributes highlight the urgency and necessity of developing a comprehensive resilience system tailored to such environments.

While rooted in Shanghai's local context, the proposed framework aligns with global best practices [91] in urban resilience, such as integrating comprehensive risk assessments, resilience-oriented planning, and leveraging advanced technology for disaster risk management. The structured approach of functional, procedural, and systemic resilience indicators provides a universal framework that other megacities can adapt. Future comparative research [92] could expand the framework's generalizability by systematically examining its applicability in different metropolises.

1. Regional Adaptations: Extending resilience evaluations to smaller administrative units within cities (e.g., districts or neighborhoods) to provide finer-grained insights.

2. Dynamic Data Integration: Exploring automated data collection and dynamic monitoring systems to enhance the accuracy and timeliness of resilience evaluations.

3. Indicator Decomposition: Investigating methods to decompose complex indicators into actionable subcomponents for targeted resilience-building efforts.

4. Collaborative Applications: Developing frameworks that facilitate collaboration among regions to address transboundary disaster risks.

7.2. Limitations

While this study contributes to the understanding of urban disaster resilience, several limitations exist:

1. Specific Applicability of the Indicator System

The indicator system is designed for predictable natural disaster scenarios with mild variations. Under intensified climate change effects leading to more frequent and severe disasters, the framework may require substantial adjustments to maintain its validity [93].

2. Regional Differences and Resource Endowments

The framework's effectiveness may be limited in regions with significantly different natural resource endowments, ecological environments, or socio-cultural dynamics. Adapting the system to such areas may require a comprehensive re-evaluation of its structure and components [90].

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