

Article

Bridging Subjective and Objective Dimensions of Resilience: A Space Syntax Approach to Analyzing Urban Public Spaces

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Abstract

Public spaces are fundamental spatial units within cities, serving as essential venues for residents' daily activities and as resilient environments for responding to emergencies. They play a crucial role in enhancing urban resilience and promoting sustainable urban development. However, existing research predominantly focuses on objective spatial entities, often neglecting users' behavioral and psychological perceptions. Studies that incorporate perceived resilience typically necessitate extensive, time-consuming, and costly fieldwork. To address these gaps, this study innovatively integrates space syntax into the Public Space Resilience (PSR) analytical framework, thereby bridging the subjective and objective dimensions of resilience in the evaluation process. A comprehensive resilience measurement framework is developed, linking 'material entities', 'spatial perception (via space syntax)', and 'spatial resilience'. Using the Yuzhong Peninsula in Chongqing, China, as a case study, this research employs indicators such as integration, connectivity, and comprehensibility to quantitatively evaluate PSR. Based on the findings, this study also proposes strategies and recommendations to enhance PSR. The results contribute to both a practical measurement method and a theoretical framework for advancing PSR in urban planning and design.



Academic Editor: Grigorios L. Kyriakopoulos

Received: 27 March 2025

Revised: 6 June 2025

Accepted: 25 June 2025

Published: 27 June 2025

Citation: Li, Y.; Wang, M.; Wang, B.; Liang, Y. Bridging Subjective and Objective Dimensions of Resilience: A Space Syntax Approach to Analyzing Urban Public Spaces. *Sustainability* **2025**, *17*, 5937. <https://doi.org/10.3390/su17135937>

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Keywords: spatial perception; space syntax; resilience; public space

1. Introduction

The term 'resilient public space' refers to a systematic spatial network that integrates urban emergency functions, including green spaces, plazas, and various public open space systems [1]. As a critical component of urban infrastructure, public spaces not only facilitate residents' daily social interactions, leisure activities, and transportation but also play a pivotal role in responding to emergencies and enhancing urban resilience [2]. Research has demonstrated that optimizing spatial configurations and fostering social interactions within public spaces can significantly enhance a city's capacity to manage emergencies, thereby facilitating recovery and supporting sustainable development. Although public spaces play crucial roles during disasters, their potential remains underutilized due to planning approaches that inadequately consider user perceptions and behavioral habits. For instance, during the 2008 Wenchuan earthquake in China, the absence of effective spatial disaster contingency planning impeded timely evacuations and safe access to public spaces, exacerbating the loss of lives and property. Similarly, in the 2010 Chilean earthquake, disaster-affected individuals established temporary camps in urban public

spaces. However, many chose locations near roads for commercial convenience, leading to localized congestion and the underutilization of spaces farther from roadways, as these did not align with user behavior patterns [3]. These shortcomings reflect a failure in disaster contingency planning to fully account for the accessibility of public spaces and the behavioral patterns and needs of their users. To more effectively leverage public spaces in disaster response, it is essential to optimize their planning and design to enhance resilience.

Assessing the public spaces resilience (PSR) has emerged as a critical area of research in urban planning and disaster management. Such assessments aid in identifying weaknesses in urban disaster responses and inform targeted improvement strategies. However, existing research on PSR predominantly emphasizes the physical characteristics of these spaces, focusing on objective factors such as spatial layout and functional zoning. For instance, Li et al. [4] evaluated the risk and resilience of urban underground public spaces across natural, economic, social, and physical dimensions. Similarly, objective assessment methods typically rely on spatial analyses and traditional technical approaches. For example, Lu et al. [5] utilized literature reviews and comprehensive analyses to construct a theoretical framework for urban spatial resilience, while French et al. [6] and Suleimany et al. [7] identified factors influencing PSR through systematic reviews and expert interviews. However, these studies primarily infer the functionality of public spaces based on their physical attributes, neglecting the behavioral and psychological perceptions of users. This limitation impedes research findings from fully capturing the actual role of public spaces in disaster response. With the integration of multiple disciplines and advancements in new technologies, resilience research has increasingly shifted towards quantitative analysis and behavior-oriented approaches [8]. Scholars have begun to examine PSR from the perspective of users' perceptions. For instance, Jones L. et al. [9] proposed a subjective self-assessment resilience score (SERS) based on questionnaire data, while Ensor J. E. et al. [10] combined family interviews with participatory qualitative methods to evaluate resilience. However, such studies often rely on extensive datasets and involve complex analytical frameworks, which can make them challenging to implement on a wide scale. Consequently, developing a straightforward yet precise framework for assessing PSR, which integrates both the physical attributes of a space and user perceptions, has emerged as a crucial area of research. Space syntax, a tool adept at quantitatively analyzing the relationship between spatial physical structures and users' behavioral perceptions, offers significant advantages. By utilizing syntactic indicators such as spatial integration, connectivity, and comprehensibility, it elucidates how spatial configurations affect user behaviors and perceptions. This approach provides a systematic and quantitative framework for evaluating PSR from a perceptual standpoint. In comparison to traditional measurement frameworks, space syntax not only captures the interaction between space and behavior more accurately but also facilitates implementation and reduces reliance on extensive datasets.

This study selects the Yuzhong Peninsula in Chongqing Municipality as a case study area and employs space syntax to construct a comprehensive framework for measuring PSR that bridges the subjective (spatial perception) and objective (material entities) dimensions of resilience. Space syntax effectively elucidates the relationship between physical spatial structures and users' behavioral perceptions, offering a systematic and quantitative tool for assessing PSR. The objectives of this study are threefold: (1) to clarify the concept of PSR; (2) to develop an integrated measurement framework for PSR that bridges subjective and objective dimensions; and (3) to propose evidence-based strategies and recommendations aimed at enhancing PSR.

The subsequent sections are organized as follows: Section 2 reviews relevant literature and outlines the conceptual framework; Section 3 delineates the study area, data sources, and

research methodology; Section 4 presents the analysis results; Section 5 provides an in-depth discussion of the findings; and Section 6 concludes the study with concluding remarks.

2. Literature Review and Conceptual Framework

2.1. Literature Review

2.1.1. The Connotation of PSR

The term “resilience” originates from the Latin word “resilio”, meaning “to return to the initial state”. Initially, resilience theory was primarily used to describe a system’s ability to recover and adapt to external shocks. Over time, as the concept of resilience has been explored and applied across various disciplines, its definition has expanded. Resilience now encompasses not only a system’s ability to recover but also its capacity for adaptability and adjustment in the face of uncertainty [11]. In urban spatial research, resilience theory has been applied primarily in two domains: spatial resilience in landscape ecology and urban resilience in urban studies [12].

Nystrom et al. [13] introduced the concept of “spatial resilience” in their study of the Great Barrier Reef, defining it as the ability of a system to reorganize after disturbances while maintaining its basic ecosystem functions. Cumming [14] further refined the concept of spatial resilience, describing it as the manner in which changes in internal and external variables across different spatial and temporal scales affect a system’s resilience. This resilience is influenced by the system’s composition, spatial structure, and scale. Studies by various scholars have highlighted that factors such as spatial connectivity, layout, heterogeneity, and diversity play a crucial role in determining spatial resilience [12,15,16]. Allen C. R. [17] summarized spatial resilience as the role of spatial attributes in feedback regulation, which relies on the asymmetry, connectivity, and information exchange of complex systems. Urban spatial resilience represents a novel integration of resilience theory with urban spatial research and can be understood as the capacity of an urban spatial system to withstand changes and disturbances while maintaining the stability of its core functions. The resilience characteristics of spatial elements—such as robustness, adaptability, flexibility, diversity, and connectivity—enable systems to recover swiftly and adjust to dynamic conditions [12].

Building on the concepts of resilience and urban spatial resilience, and incorporating the attributes of public spaces, this study defines urban PSR as the capacity of urban public spaces to sustain their normal functions, rapidly restore their original state, and proactively adapt to external disturbances or uncertainties, including environmental, social, and economic impacts. This definition underscores the dynamic resilience of urban public spaces and provides theoretical support for their essential role in disaster management.

2.1.2. Measuring PSR

To effectively assess PSR, scholars have developed measurement frameworks and indicator systems that encompass various dimensions. For instance, Li et al. [4] evaluated the resilience of urban underground public spaces across four dimensions: natural, economic, social, and physical structure. Their indicators included aspects of the natural environment, economic environment, and the facilities and equipment available. However, relying solely on the physical structure of spatial entities to infer the functionality of public spaces frequently overlooks users’ behavioral perceptions, leading to biased conclusions and an inadequate representation of the role of public spaces in addressing extreme scenarios [18]. Ensor et al. [10] assessed the PSR from the perspective of social interaction using participatory qualitative methods, including surveys, observations, and household interviews. Their evaluation criteria included pedestrian flow, frequency of use, and diversity of activities. However, methods that emphasize spatial perception generally necessitate large datasets,

which can escalate research complexity and time costs. Consequently, current measurement methods still face limitations in data acquisition and evaluation criteria [7,9].

Space syntax, a topology-based spatial analysis method, addresses certain limitations of existing approaches. It partitions space according to the local perceptual range of moving individuals and employs tools such as axial maps to simulate the structural relationship between locally perceived space and the overarching spatial structure [18]. Currently, synthesis methods have been developed for constructing road networks and urban areas with optimized topological configurations [19,20]. Research has demonstrated that the spatial syntactic axial model aligns well with users' perceptual cognitive maps, effectively reflecting their spatial perceptions [21,22]. This model has been utilized in various contexts, including the design of pedestrian-friendly green and blue spaces [23], the evaluation of the experiential quality of historical streets [24], and the planning and simulation of spatial forms [25]. While quantitatively analyzing the structural layout and spatial permeability of public spaces, space syntax also effectively elucidates the relationship between physical spatial structures and users' behavioral perceptions, thereby reducing reliance on large datasets. Consequently, as a multidimensional spatial analysis tool, space syntax provides a novel perspective for comprehensively measuring the resilience of public spaces and facilitates more nuanced and accessible resilience assessments.

2.2. Conceptual Framework

Physical space constitutes the objective environmental foundation of a city and serves as a fundamental pre-requisite for spatial resilience. However, in emergencies or crises, it is only the material spatial information perceived by individuals that can effectively contribute to resilience responses [26,27]. Perceived space serves as a crucial link between individuals and physical environments, encapsulating subjective interpretations while transforming tangible spatial information into actionable insights. This process of translation greatly impacts individuals' capacity to respond to risks. Within the framework of resilience planning for urban public spaces, space syntax provides valuable tools and methodological support for connecting material and perceived spaces. It empowers planners to comprehend the needs and expectations of space users, effectively pinpoint vulnerable areas within urban settings, and design urban spaces that prioritize human-centered approaches [28].

Space syntax theory posits that human behavior is intrinsically linked to the structural characteristics of physical urban spaces. The material spatial structure of a city influences individuals' mobility and behavioral patterns, which subsequently shape their spatial perceptions. These perceptions and behaviors, in turn, directly contribute to the spatial layout and form of the city [29]. Space syntax employs tools such as the axis model to quantitatively represent physical space by dividing the urban spatial structure into interconnected networks of axes. These networks simulate how individuals perceive and navigate space [21,22]. Key metrics, such as integration, connectivity, and comprehensibility, are calculated for each axis to translate spatial structure into insights regarding human perception and behavior. For instance, integration measures the accessibility of a location within the overall spatial structure. Highly integrated spaces are typically perceived as easily accessible and convenient, whereas spaces with low integration may be regarded as difficult to reach. These perceptions influence the functional and social dynamics of urban areas.

Modern urban planners increasingly recognize how urban space fundamentally influences both individual and collective behaviors, leveraging these insights as key determinants of effective urban planning [28]. The application of space syntax enables the connection between the objective structure of physical space and the subjective perceptions and behaviors of individuals. This translation transforms material spatial data into perceptual imagery, thereby influencing human responses to risks. By leveraging this approach,

planners can construct more resilient internal spatial structures, gain a deeper understanding of the needs and expectations of users, and promote human-centered urban design. Ultimately, this methodology enhances the resilience of urban public spaces, ensuring that they are better equipped to adapt to and recover from crises.

In urban public space planning, the optimization of material spaces into perceptual spaces that align more closely with individuals' behavioral patterns and cognitive pathways can significantly enhance the resilience of public spaces during unforeseen events [26]. As illustrated in Figure 1, material space serves as the objective environmental foundation, while perceptual space offers subjective behavioral support for individuals. Together, these elements constitute a support system for urban PSR. Within this framework, the syntactic model translates physical space—characterized by spatial morphological attributes such as position, direction, and distance in the objective dimension—into perceptual space, which is influenced by sensory and cognitive processes in the subjective dimension. This translation facilitates the inference from the 'visible' to the 'invisible' [21]. By calculating syntactic parameters such as integration, connectivity, and comprehensibility, space syntax not only quantifies individuals' cognitive pathways and perceptual processes but also reveals their correlation with the resilience attributes of public space. Specifically, integration measures spatial accessibility, determining whether individuals can quickly identify safe evacuation areas during emergencies, and is directly linked to the robustness of public space. Connectivity reflects the permeability of space, indicating the redundancy of public spaces—that is, whether alternative spaces can functionally compensate when certain areas become inaccessible. Comprehensibility assesses the extent to which individuals can cognitively understand a space, reflecting the adaptability of public spaces to behavioral patterns. This parameter relates to the ability of public spaces to provide psychological and physical security during disasters or emergencies. In the context of natural disasters or crises, the accessibility, permeability, and cognitive ease of public spaces are crucial for enabling individuals to rapidly adapt to changes in their spatial environment. Therefore, enhancing the flexibility of subjective spatial cognition is essential for improving spatial resilience [2,12].

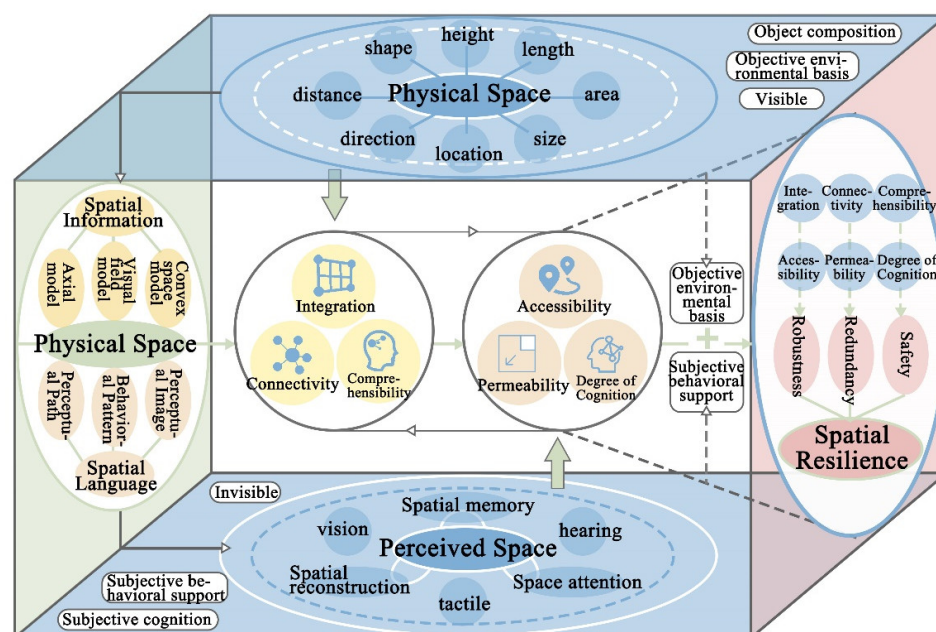


Figure 1. Theoretical framework diagram.

This framework introduces a novel approach that integrates both subjective and objective dimensions for measuring PSR. It not only provides a quantitative tool but also serves as a practical planning basis for de-signing highly resilient urban public spaces. By leveraging the

space syntax model, we can assess urban PSR and propose targeted strategies to enhance their human-centered qualities, thereby fostering more resilient urban environments.

3. Methods and Materials

3.1. Study Area

In this paper, we focus on the public space of Yuzhong Peninsula in Chongqing Municipality, which is situated at the confluence of the Yangtze River and the Jialing River. This narrow east-west peninsula is flanked by water to the east, south, and north. Yuzhong Peninsula is characterized by high population density and a mountainous terrain, resulting in a complex urban system marked by interlocking and meandering roads arranged in a free-form layout. The rapid pace of urban development, combined with the erosion caused by modern capital, has led to a significant decline in both the quantity and quality of public spaces on the peninsula, creating potential safety hazards. Furthermore, current global climate change has exacerbated the risks of extreme weather events, such as floods, high temperatures, and droughts, which threaten urban survival and development. Man-made disasters also represent a critical aspect of urban safety. Given that the urban peninsula is directly affected by these disasters, it is essential for public space planning to incorporate resilience strategies to effectively address and mitigate these risks.

The concept of public space originates from sociology and political philosophy, and is gradually used in urban planning and design disciplines, but at present there is no unified and clear definition of it at home and abroad. Public space in the narrow sense refers to the outdoor space for public use by urban residents in their daily life and social life. It includes streets, squares, parks, sports venues and so on. The broad concept can be extended to the space of public facility land, such as city center area, commercial area, urban green space, etc. Public spaces that are open, accessible and available to the public can be used to achieve urban resilience. In this paper, urban public space refers to any outdoor space in a city that is completely open and accessible to the public, mainly including squares, parks, sports venues, etc. in cities. Based on the analysis of Points of Interest (POI) data, a total of 33 major public spaces on the Yuzhong Peninsula were identified through a comparison of satellite images and supplementary field research. As illustrated in Figure 2, these existing public spaces are widely distributed across the Yuzhong Peninsula, with a notable concentration around the vicinity of 23# Bashu Middle School Zhangjia Garden Campus and 4# Square 2.

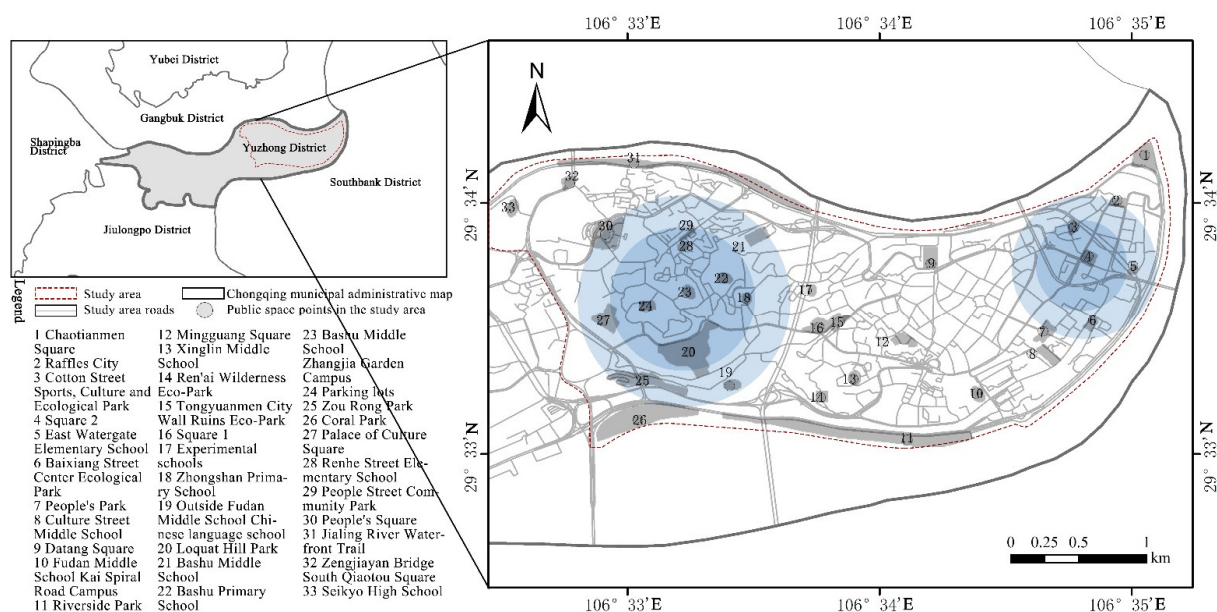


Figure 2. Scope of the study.

3.2. Data Collection

This study primarily utilizes road network data and Points of Interest (POI) data for the Yuzhong Peninsula. The road network information for 2023 was sourced from the OpenStreetMap (OSM) platform (<https://www.openstreetmap.org>, accessed on 9 December 2024) and validated using real satellite imagery (<http://www.gscloud.cn>, accessed on 13 December 2024) to exclude disconnected roads. OSM provides a publicly accessible vector base map of streets that is more accurate and convenient than traditional field mapping and satellite mapping methods. The POI data was extracted from the website, with duplicate entries and erroneous data, including incorrect coordinates, removed. POIs represent real geographic entities and include essential information such as names, addresses, categories, and other basic attributes [30]. The data sources are widely available, accurate, and updated in real-time, which not only reduces research costs but also enhances the accuracy and timeliness of the data analysis (Table 1).

Table 1. Data source.

Data Type	Data Content	Data Source
Vector data	Road; Administrative boundaries	OSM website 2023 (https://www.openstreetmap.org , accessed on 9 December 2024); 1:250,000 national basic geodatabases (https://www.webmap.cn , accessed on 12 December 2024)
POI data	Public space POI data	OSM website 2022 (https://www.openstreetmap.org , accessed on 9 December 2024)

3.3. Methods

This study integrates fundamental information, including road network data, digital image data, and survey data, by constructing a multi-source database. It builds upon existing scholarly research [31] by employing DepthmapX0.8.0 syntax software to delineate the axes of the Yuzhong Peninsula's Road network. This process translates the spatial structure of the Peninsula into an axial model and calculates key spatial syntactic parameters. Building on this foundation, ArcGIS spatial analysis technology was employed to superimpose and analyze the urban space integration, connectivity, and comprehensibility indicators derived from the space syntax analysis model with the geographical distribution points of public space. The analysis results effectively characterize the robustness, redundancy, and security of PSR, thereby facilitating a comprehensive, multi-level, and multi-variable evaluation of PSR.

Space syntax serves as a critical methodological foundation for this study. Among its commonly employed analytical approaches—convex space, axial, and visual field analysis—the axial model is particularly well-suited for urban environments characterized by dense, linear arrangements of buildings or clusters of buildings [32]. This model effectively captures the ‘spatial skeleton’, which is essential for understanding spatial perception, illustrating how individuals internalize, store, and process spatial information [21]. Axes represent the longest and most direct lines of sight within a spatial system, correlating with both spatial structures and human behavioral pathways within those spaces. The axial model translates spatial configurations into topological operations, generating syntactic parameter indices such as integration, connectivity, and comprehensibility. These indices quantitatively describe attributes of spatial resilience. By applying the axial model of space syntax, this study calculates and analyzes the parameters of integration, connectivity, and comprehensibility to characterize spatial accessibility, penetration, and cognitive understanding within perceptual space. These indicators correspond to key resilience attributes: robustness, redundancy, and security, respectively, as outlined in Table 2.

Table 2. Space syntax parameter description.

Parametric Indicators	Calculation Formula	Syntactic Parameter Paraphrasing	Resilience in Public Spaces	Analyze Features
Global Integration I_i Local Integration G	$I_i = \frac{D_n(n-2)}{2(D_m-1)}, G = \frac{I_i}{D_n}, \text{ where,}$ $D_m = \frac{\sum_{i=1, j=1, i \neq j}^n d_{ij}}{n-1}$ $D_n = \frac{2\{n[\log_2(\frac{n+2}{3}-1)]+1\}}{(n-1)(n-2)},$ i denotes the ith space; I_i denotes the global integration of the ith space; n denotes the total number of axes of the public space structural system; D_n is a standardized parameter; D_m is the average depth. the equations for D_n and D_m are: where, i denotes the ith space; j denotes the jth space; d_{ij} denotes the depth and represents the shortest topological distance between the ith and jth points of the connection.	The degree of integration indicates the degree of aggregation or dispersion of a node from other nodes. The global integration degree reflects the ease of reaching each other between the nodes in the overall space, while the local integration degree represents the relationship between a certain space node and other space nodes within a few steps of topological distance. The higher the degree of integration, the higher the accessibility between system nodes.	This metric indicates the capacity of a spatial node to be accessed by other nodes within the overarching system topology. Locations with higher integration levels tend to attract more individuals and are utilized to evaluate whether evacuees can swiftly reach a safe location, thereby illustrating greater robustness and the ability to endure disasters.	Accessibility Robustness
Connectivity C_i	$C_i = k$ i denotes the ith space; C_i denotes the connectivity of the ith space; and k denotes the number of spaces directly connected to the i space.	This metric indicates the number of spatial connections within the system node space. A system node with more connections to other nodes will have a higher connection value, resulting in improved spatial connectivity within the system.	This indicates the number of nodes connected to a spatial node. A higher number of connections enhances the permeability of a space within the system. Resilient public spaces must exhibit permeability, which implies that they should be accessible to the public and possess both physical and functional connections to urban environments.	Permeability Redundancy
Comprehensibility R^2	$R^2 = \frac{[\sum (C_i - \bar{C})(I_i - \bar{I})]^2}{\sum (C_i - \bar{C})^2 \sum (I_i - \bar{I})^2}$ where C_i, $\bar{C}$ are the connectivity and its average value; I_i, $\bar{I}$ are the global integration and its average value.	Indicates the relationship between local space and overall space, and the difficulty of perceiving the overall spatial structure from the local space.	The comprehensibility of a space significantly enhances individuals' ability to perceive and understand it. A comprehensible environment facilitates navigation, thereby aiding people in finding their way. As the clarity of a space increases, so too does the sense of safety it provides; in contrast, a confusing space tends to evoke feelings of insecurity.	Degree of Awareness Security

3.3.1. Integration and Spatial Accessibility, Robustness

Integration refers to the degree of aggregation or disaggregation of a space in relation to other spaces, serving as a primary covariate for quantifying spatial accessibility [12]. A higher degree of integration is associated with increased spatial relatedness and accessibility. Research indicates that accessibility significantly influences public space safety during disasters; enhanced accessibility improves centrality, strengthens public perception, and facilitates the attraction of agglomerated flows [33,34]. Spaces characterized by a high degree of integration demonstrate greater robustness, defined as the capacity to withstand sudden and unpredictable disasters. This robustness serves as a criterion for evaluating the ability of evacuees to swiftly reach safe locations. The calculation formulas of global integration degree (I_i) and local integration degree (G) are Equations (1) and (2):

$$I_i = \frac{D_n(n-2)}{2(D_m-1)} \quad (1)$$

$$G = \frac{I_i}{D_n} \quad (2)$$

where, i denotes the i th space; I_i denotes the global Integration of the i th space; n denotes the total number of axes of the public space structural system; D_n is a standardized parameter; D_m is the average depth. the equations for D_n and D_m are Equations (3) and (4):

$$D_m = \frac{\sum_{i=1, j=1, i \neq j}^n d_{ij}}{n-1} \quad (3)$$

$$D_n = \frac{2\{n[\log_2(\frac{n+2}{3}-1)]+1\}}{(n-1)(n-2)} \quad (4)$$

where, i denotes the i th space; j denotes the j th space; d_{ij} denotes the depth and represents the shortest topological distance between the i th and j th points of the connection.

3.3.2. Connectivity and Spatial Permeability, Redundancy

Connectivity is defined as the number of spaces neighboring a given space. A higher level of connectivity enhances the options perceived by the crowd and increases the spatial permeability of that area [33]. The degree of connectivity is a significant indicator of redundancy within a resilient city. Redundancy refers to the presence of diverse spaces that fulfill the same or similar functions, a well-connected network, and the presence of alternative spaces that can serve as substitutes for one another in the event of destruction [35]. This redundancy ensures that the crowd can evacuate to shelters in the shortest possible time, both efficiently and safely. Resilient public spaces must be permeable; they should not only be accessible to the public but also be physically and functionally well connected to the broader urban environment [16]. The formula for connectivity (C_i) is (5):

$$C_i = k \quad (5)$$

where, i denotes the i th space; C_i denotes the connectivity of the i th space; and k denotes the number of spaces directly connected to the i space.

3.3.3. Comprehensibility and Spatial Cognition, Safety

Comprehensibility pertains to the interrelation between local and overall space, highlighting the challenges of spatial cognition when perceiving the overall environment from a localized viewpoint. A higher level of comprehensibility enhances an individual's ability to perceive space effectively [15]. As a person navigates through a space, their perception

is influenced by its comprehensibility; greater comprehensibility is associated with more pronounced effective and purposeful behaviors, thereby improving the efficiency of space utilization. Moreover, an individual's perception of a space significantly affects their sense of safety; enhanced perception fosters feelings of security, whereas confusion within a space can lead to feelings of insecurity and panic. The value of comprehensibility is quantified on a scale from 0 to 1, where $R^2 \geq 0.5$ indicates a high level of space comprehensibility, and $R^2 < 0.5$ signifies a low level. The formula for the comprehensibility (R^2) (6):

$$R^2 = \frac{[\sum (C_i - \bar{C})(I_i - \bar{I})]^2}{\sum (C_i - \bar{C})^2 \sum (I_i - \bar{I})^2} \quad (6)$$

where, $C_i, \bar{C}$ are the connectivity and its average value; $I_i, \bar{I}$ are the global integration and its average value.

4. Results and Analysis

4.1. Robustness of Space

The average global integration degree of the Yuzhong Peninsula is 0.712, indicating that the overall spatial accessibility and robustness of the peninsula are relatively low [36]. In the axial model, warmer colors signify higher integration, which corresponds to better accessibility and greater robustness, while cooler colors denote lower integration, indicating poorer accessibility and diminished robustness. According to Figure 3a, the public space exhibiting the highest degree of integration within in the study area is 4# Square 2, followed by 7# People's Park, 15# Tongyuanmen City Wall Ruins Eco-Park, and 16# Square 1. These highly integrated spaces exhibit strong robustness characteristics. In contrast, the public space with the lowest degree of integration, 14# Ren'ai Wilderness Eco-Park, indicates that the robustness of this area is comparatively weak.

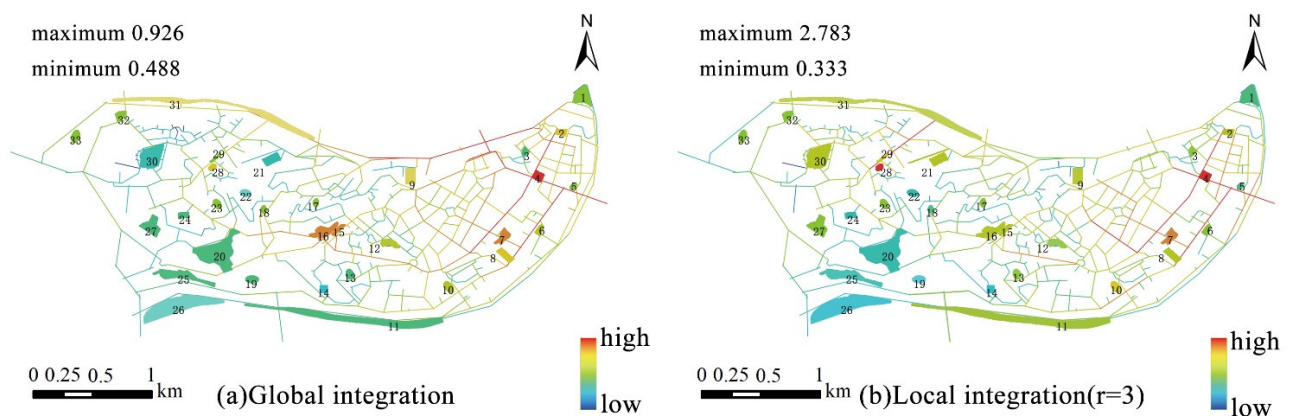


Figure 3. Analysis of global integration degree and local integration degree of public space in Yuzhong Peninsula.

The average local integration degree ($r = 3$) of the Yuzhong Peninsula is 1.506, which is significantly higher than the global integration degree. This finding indicates that the region possesses a superior self-organizing structure. As illustrated in Figure 3b, there is considerable overlap between spaces with high global and local integration degrees. Notably, 4# Square 2 and 7# People's Park, which exhibit the highest global and local integration degrees, are the most accessible spaces on the peninsula. These spaces are relatively well-connected to their surrounding areas, easily perceived, and can serve as important refuge public spaces. A comparison of global and local integration degrees reveals that 21# Bashu Middle School and 11# Riverside Park exhibit low global integration

degrees but high local integration degrees. Although the overall accessibility to these spaces is poor, individuals in the surrounding local area perceive them more strongly, thereby making them significant nodes for local activities and evacuation. This demonstrates their robustness and ability to withstand disasters.

4.2. Redundancy of Space

The connectivity value of the Yuzhong Peninsula ranges from 1 to 11, with an average value of 3.727, indicating that the spatial permeability of the peninsula is relatively weak and the redundancy is low. The standard deviation is 4.892, which reflects the degree of dispersion within the data, with a value exceeding 1 signifying a higher level of variability. This suggests that the spatial connectivity of the Peninsula is characterized by significant dispersion, resulting in an uneven overall distribution. As illustrated in Figure 4a, the public spaces exhibiting the highest connectivity values include 28# Renhe Street Elementary School, 4# Square 2, and 30# People's Square. These spaces are distinguished by their numerous intersections with other spaces and their strategic positioning at junctions where main roads converge with side roads leading to essential urban nodes. Their strong connections to surrounding spatial elements, marked by high redundancy, enhance the flexibility and adaptability of their spatial functions. In contrast, the public space with the lowest connectivity value is the 24# Parking Lots, which exhibits poor permeability and minimal redundancy with adjacent spaces.

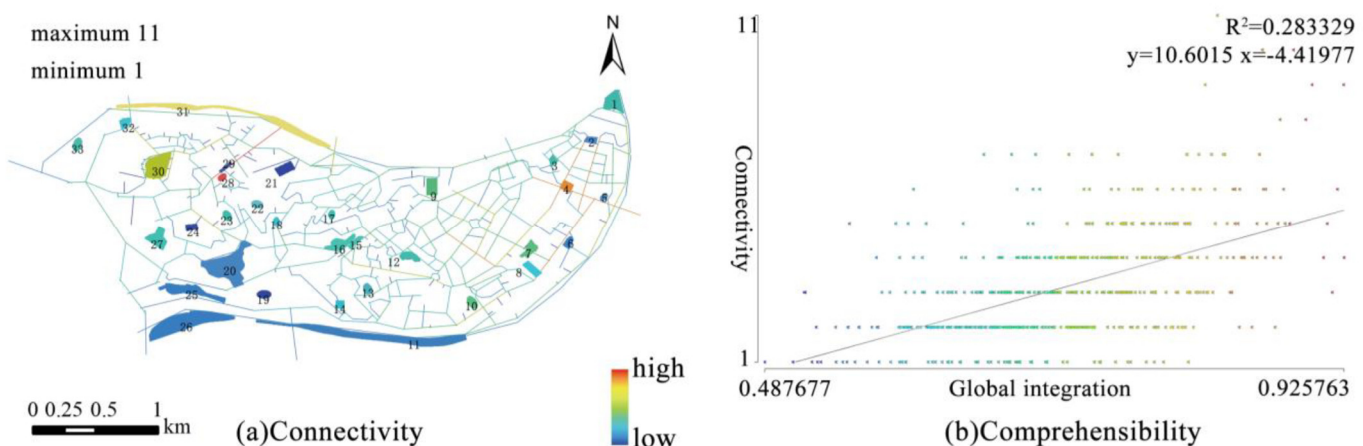


Figure 4. Analysis of connectivity and comprehensibility of public space in Yuzhong Peninsula.

4.3. Safety of Space

Comprehensibility was analyzed through an XY scatterplot, with global integration and connectivity selected as the two datasets for regression linear analysis in Depthmap software (Figure 4b). The X-axis represents the global integration of the Yuzhong Peninsula, while the Y-axis represents connectivity, with R^2 indicating comprehensibility. The analysis results reveal that the intelligibility of the Yuzhong Peninsula is only 0.283, indicating a weak correlation between the local space and the global space of the peninsula. This suggests that people's awareness of this space is low and that spatial safety is inadequate. Consequently, individuals' spatial perception of the peninsula is poor, making it challenging to understand and navigate the space. This difficulty can lead to disorientation and spatial confusion during evacuation, ultimately resulting in insufficient psychological safety and adversely affecting the peninsula's resilience.

4.4. Comprehensive Resilience of Urban Public Space

As shown in Table 3, the average levels of robustness and redundancy serve as benchmarks: values exceeding the average are classified as high resilience, while those below

the average are categorized as low resilience. The comprehensibility parameter (R^2) is also included, with $R^2 < 0.5$ indicating low resilience. By incorporating the dimensions of robustness, redundancy, and safety, the resilience characteristics of public spaces in the study area can be systematically classified. A public space is deemed high resilience if all three indicators are high, or if two indicators are high and one is low. Conversely, the classification of ‘two lows and one high’ denotes medium resilience, while ‘all three lows’ indicates low resilience. The analysis reveals that 30.3% of the public spaces in the study area exhibit high resilience, enabling them to effectively meet the needs of residents across various scenarios. Public spaces with medium resilience make up 39.4%, which may show deficiencies in robustness or spatial redundancy, indicating a need for further optimization of their functional layout. Low-resilience public spaces comprise the remaining 30.3%, characterized by limited accessibility and safety, as well as poor overall adaptability and risk resistance. Overall, while high and medium resilience public spaces are predominant, the significant proportion of low-resilience spaces highlights the necessity for targeted interventions aimed at optimizing the layout and spatial configuration of public spaces in the Yuzhong Peninsula. Specifically, prioritizing improvements in low-resilience spaces is essential for achieving a comprehensive enhancement in the resilience of urban public spaces.

Table 3. Integrated resilience statistics for public space.

Public Space	Robustness	Redundancy	Safety	Comprehensive Resilience Level
4 Square 2	+	+	—	High
7 People’s Park	+	+	—	High
16 Square 1	+	+	—	High
15 Tongyuanmen City Wall Ruins Eco-Park	+	+	—	High
28 Renhe Street Elementary School	+	+	—	High
31 Jialing River Waterfront Trail	+	+	—	High
2 Raffles City	+	+	—	High
10 Fudan Middle School Kai Spiral Road Campus	+	+	—	High
17 Experimental schools	+	+	—	High
21 Bashu Middle School	+	+	—	High
8 Culture Street Middle School	+	—	—	Medium
6 Baixiang Street Center Ecological Park	+	—	—	Medium
12 Mingguang Square	+	—	—	Medium
29 People Street Community Park	+	—	—	Medium
5 East Watergate Elementary School	+	—	—	Medium
18 Zhongshan Primary School	+	+	—	Medium
33 Seikyo High School	—	+	—	Medium
1 Chaotianmen Square	—	+	—	Medium
23 Bashu Middle School	—	+	—	Medium
11 Riverside Park	—	+	—	Medium
30 People’s Square	—	+	—	Medium
27 Palace of Culture Square	—	+	—	Medium
3 Cotton Street Sports, Culture and Ecological Park	—	+	—	Medium
32 Zengjiayan Bridge South Qiaotou Square	—	—	—	Low
9 Datang Square	—	—	—	Low
19 Outside Fudan Middle School Chinese language school	—	—	—	Low
25 Zou Rong Park	—	—	—	Low
13 Xinglin Middle School	—	—	—	Low
24 Parking lots	—	—	—	Low
20 Loquat Hill Park	—	—	—	Low
22 Bashu Primary School Zhangjia Garden Campus	—	—	—	Low
26 Coral Park	—	—	—	Low
14 Ren’ai Wilderness Eco-Park	—	—	—	Low

Note: “+” indicates that the value is above the average, while “—” indicates that the value is below the average. The resilience levels of public spaces are categorized as follows: High resilience: Combinations of “+ + +” or “+ + —”; Medium resilience: Combination of “+ — —” or “— + —”; Low resilience: Combination of “— — —”.

This study further utilized Geographic Information Systems (GIS) to spatially visualize and analyze the comprehensive resilience of public spaces in the Yuzhong Peninsula, elucidating the intrinsic relationship between the PSR and urban spatial structure from a spatial perspective. The analysis results (Figure 5) indicate that high-resilience spaces are predominantly located in the northern part of the Yuzhong Peninsula and along the eastern riverfront. These spaces exhibit high accessibility, strong spatial permeability, and are easily perceptible to users. Their locations are memorable and navigable, enabling them to effectively serve as emergency evacuation points during disturbances. Medium-resilience spaces are irregularly distributed in the central and southern regions of the peninsula. While these spaces demonstrate moderate adaptability, their spatial utilization rates and functionalities require enhancement. In contrast, low-resilience spaces are concentrated in the southern and parts of the western regions of the peninsula. These areas suffer from poor accessibility, weak spatial permeability, and low comprehensibility, rendering them less attractive and underutilized. Characterized by single-use environments, these spaces are susceptible to becoming ‘resilience weak points’ during extreme events or environmental changes. Overall, the PSR in the Yuzhong Peninsula is relatively low, exhibiting an uneven spatial distribution. Some low-resilience areas create ‘resilience depressions’, that impede the overall resilience of the peninsula. In the absence of a scientifically informed optimization of the layout and spatial design of urban public spaces, the city’s resilience may further deteriorate, limiting its capacity to confront potential challenges posed by climate change and urban development. Therefore, priority should be given to upgrading low-resilience public spaces by enhancing their robustness, increasing redundancy, and ensuring safety, thereby improving the overall resilience of public spaces in the Yuzhong Peninsula.

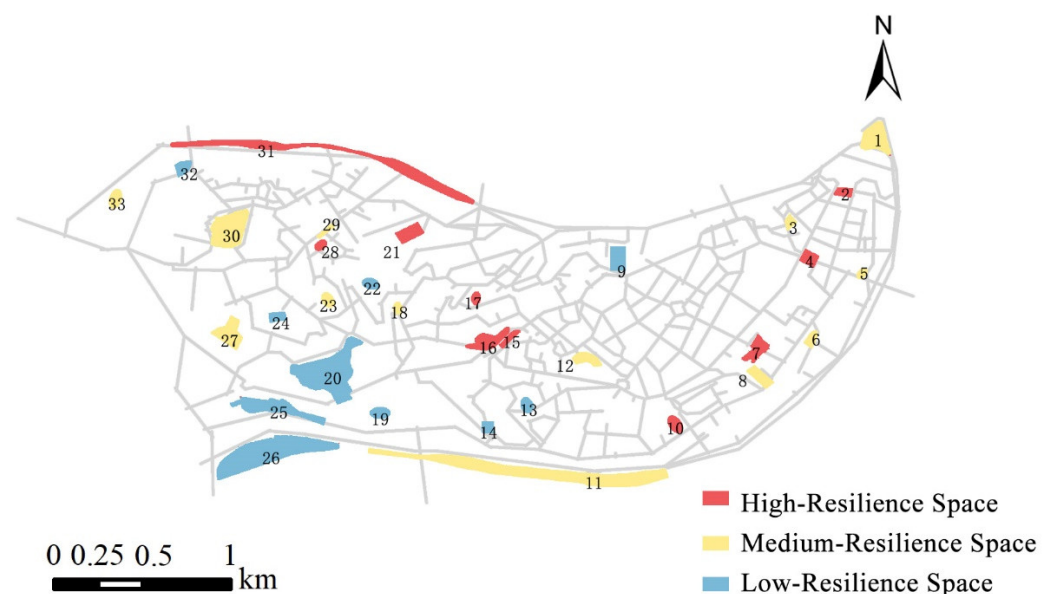


Figure 5. Comprehensive Resilience Analysis of Public Space in Yuzhong Peninsula.

5. Discussion

5.1. Validation of Space Syntax Measurement Results

This study presents an innovative application of the space syntax method to bridge subjective and objective dimensions of resilience into the research on measuring urban PSR, thereby enhancing the theoretical framework of urban resilience studies. To ensure the accuracy of the space syntax measurement results, on-site investigations were conducted to calibrate the resilience measurements of public spaces in the Yuzhong Peninsula.

5.1.1. Verification of Spatial Robustness, Redundancy and Safety

On-site investigations indicate that public spaces with high integration values, such as 4# Square 2, 7# People's Park, and 15# Tongyuanmen City Wall Ruins Eco-Park, are distinguished by their accessible and well-structured road networks. These spaces benefit from robust connections between side roads and main roads, which enhance their ability to attract, gather, and disperse crowds. Consequently, they play a crucial role in facilitating emergency evacuations. In contrast, the space with the lowest integration value, 14# Ren'ai Wilderness Eco-Park, faces notable accessibility challenges. Field research indicates that the park's elevated location on a mountain requires visitors to walk a considerable distance from the base to access the site, which deviates from typical travel patterns. Additionally, inadequate access roads, combined with road congestion and disorder caused by parking lot encroachments, considerably hinder the park's accessibility. These factors not only prolong evacuation times but also increase the risks associated with crowd movement. The alignment of these findings with the space syntax measurement results reinforces the notion that integration effectively reflects the robustness characteristics of public spaces.

Public spaces with high connectivity values, such as 28# Renhe Street Elementary School, 4# Square 2, and 30# People's Square, are primarily located at the intersections of major traffic arteries and branch roads that lead to significant urban nodes. These locations provide multiple spatial path options and demonstrate a high level of redundancy. In contrast, the 24# Parking Lot exhibits the lowest connectivity value. Field research indicates that this space is accessible via only one narrow and winding main road, which obstructs visibility and creates a long, confined corridor. These observations align with space syntax measurements, thereby confirming the reliability of connectivity as a quantitative indicator of redundancy.

The low comprehensibility of public spaces in the Yuzhong Peninsula, as indicated by space syntax measurements, is further corroborated by field research. The weak correlation between local and global spaces often results in users becoming disoriented within these public spaces. The intricate distribution of behavioral pathways, coupled with a diminished sense of direction, compels users to navigate repeatedly in search of entrances and exits, thereby increasing psychological stress and feelings of insecurity. These findings underscore the influence of low comprehensibility on spatial perception, further reinforcing the measurement results.

5.1.2. Verification of Comprehensive Urban PSR

High-resilience public spaces, such as 4# Square 2, located in the eastern part of the peninsula, exhibit strong accessibility to the surrounding road network, with well-coordinated connections between branch roads and main roads. These attributes facilitate convenient access for crowds and promote frequent utilization of the space, making such spaces highly effective for emergency evacuation. This observation highlights robust PSR, which is consistent with the findings from the space syntax analysis. Medium-resilience spaces, exemplified by 12# Mingguang Square located in the central area of the peninsula, were identified through field research as having suboptimal road layouts and low overall spatial utilization in their surroundings. Nevertheless, these spaces exhibit a certain degree of adaptability and activity in daily life, attracting a significant number of residents for regular use. Low-resilience spaces are predominantly found in the southern and western regions of the peninsula, such as 14# Ren'ai Wilderness Eco-Park. These areas are characterized by inadequate road access and low pedestrian traffic, which impede their ability to meet daily needs and fulfill emergency evacuation requirements. These findings are consistent with the results obtained from the space syntax measurements. Overall, the outcomes of the field research largely support the findings derived from the

space syntax method. This consistency indicates that space syntax effectively measures the comprehensive PSR by bridging subjective and objective dimensions of resilience, while also conserving time and resources. Consequently, it serves as a scientific and reliable analytical tool, providing a theoretical foundation for the study of PSR.

5.2. Theoretical and Practical Implications

This study innovatively applies space syntax to integrate subjective and objective dimensions of resilience in the investigation of PSR, thereby expanding the theoretical framework of urban resilience research. Unlike conventional studies that predominantly adopt an objective perspective [5,7], this research incorporates users' spatial perception into the resilience measurement framework, thereby exploring the formation of PSR from the perspective of spatial perception. This approach strengthens the theoretical linkage between the subjective and objective aspects of resilience. While previous studies frequently depend on household interviews and questionnaires to evaluate resilience from a perceptual standpoint [9,10], this study leverages space syntax to uncover the intricate relationship between spatial perception and urban PSR. By employing syntactic metrics such as spatial integration, connectivity, and comprehensibility, this research quantifies spatial resilience and develops a measurement framework that links "material entity—spatial perception (via space syntax)—spatial resilience". This method provides a more precise and quantifiable approach for investigating spatial resilience, thereby introducing a novel paradigm for the study of PSR.

From a policy perspective, the research findings have substantial practical implications for enhancing urban PSR. This study employs space syntax to quantify resilience, thereby enabling urban managers to more precisely identify vulnerable areas and formulate targeted optimization strategies. The results demonstrate that the degree of integration and connectivity exerts a significant influence on PSR, indicating that enhancing overall accessibility and permeability of public spaces is a critical approach to improving PSR. Urban planning policies should prioritize optimizing spatial layouts in public areas to enhance their adaptability and resilience during emergencies. While the policy proposed by Suleimany M. et al. [7] to provide services through governmental and non-governmental organizations may offer short-term improvements in urban resilience, it frequently requires sustained resource investment and does not address the root causes of the issues. This study's methodology elucidates the spatial distribution of challenges through quantitative indicators, allowing for the optimization of spatial layout structures at their root, thereby enhancing the adaptability and resilience of urban public spaces in emergencies. Consequently, future urban planning policies should emphasize the application of space syntax indicators to structurally reinforce urban resilience. This approach not only offers innovative ideas for planning practice but also presents a more economical and effective pathway to enhance resilience in cities with limited resources.

The results of the study indicate that the PSR of the Yuzhong Peninsula is at a moderate level. Key factors contributing to this resilience include the region's complex mountainous topography, high building density, and insufficient access points to public spaces. These findings align with previous research [37,38]. High-resilience spaces identified through fieldwork are predominantly situated in areas characterized by high integration, connectivity, and comprehensibility. This finding reinforces the scientific validity and practical applicability of space syntax as a tool for assessing PSR. In light of the increasing frequency of extreme climate events, the substantial presence of low-resilience public spaces on the peninsula not only undermines the city's overall risk resistance but also introduces new challenges and requirements for optimizing the spatial configuration of public spaces and enhancing urban resilience. In response to this analysis, the study proposes several countermeasures aimed at improving the resilience of urban public spaces:

- Enhancing the Accessibility and Robustness of Public Spaces

Enhancing the accessibility of public spaces facilitates easy access for individuals to neighboring areas in response to disturbances and ensures the smooth arrival of rescue personnel and materials. A sustainable and robust physical environment is crucial for reinforcing the resilience of public spaces, serving both as a guarantee for the life and health of the population and as a foundation for emergency rescue operations. Analysis of global and local integration indicates that the accessibility of public spaces on the east side of Yuzhong Pen-insula is high, while that on the south and west sides is relatively low, resulting in a diminished capacity for gathering and evacuating individuals. It is recommended to strengthen construction of the road network on the peninsula, organize mixed-use roads, and open interrupted and winding routes. Additionally, improving the barrier-free design of public spaces will enhance convenience and accessibility for the public. As illustrated in Figure 6, it is advisable to increase the connectivity between 20# Loquat Hill Park and the adjacent roads to improve road accessibility; appropriately widen the road connecting 25# Zou Rong Park and 30# People's Square, increase the number of entrances and exits, and install accessible ramps to ensure that individuals can quickly enter public spaces for refuge during emergencies.

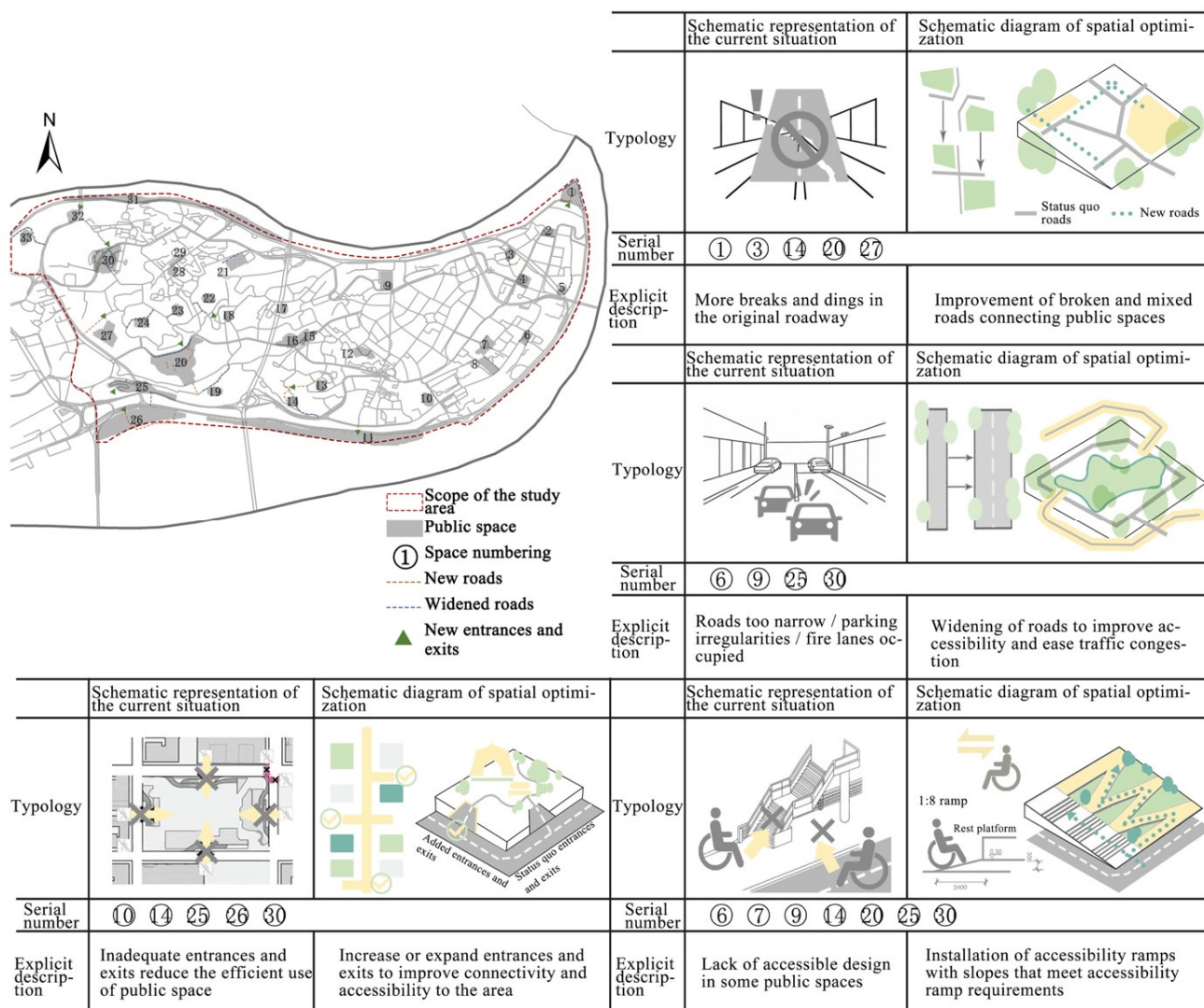


Figure 6. Optimizing Countermeasures for Robustness in Public Spaces.

- Systematic Optimization of Public Space Layout to Enhance Redundancy

To enhance connectivity between urban public spaces, it is essential to ensure smooth traffic flow while fostering a pedestrian-friendly environment through a human-centered approach. This involves minimizing interference between pedestrians and vehicles, thereby improving the connectivity of pedestrian spaces. By leveraging the city's natural environment to design greenways that link various public spaces, we can create a spatial topology characterized by points, lines, and planes, ultimately establishing a comprehensive public space system. Currently, the overall connectivity of the Yuzhong Peninsula is inadequate, with dense buildings limiting the spatial permeability of public spaces. It is advisable to develop public spaces in accordance with the mountainous terrain, thereby enhancing the visual appeal of these spaces and creating diverse spatial layers (Figure 7). Additionally, maintaining effective interfaces with the surrounding redundant spaces will help prevent the underutilization of public space resources. This approach will also improve crowd perception during emergencies, address their needs for disaster avoidance, and facilitate subsequent rescue operations.

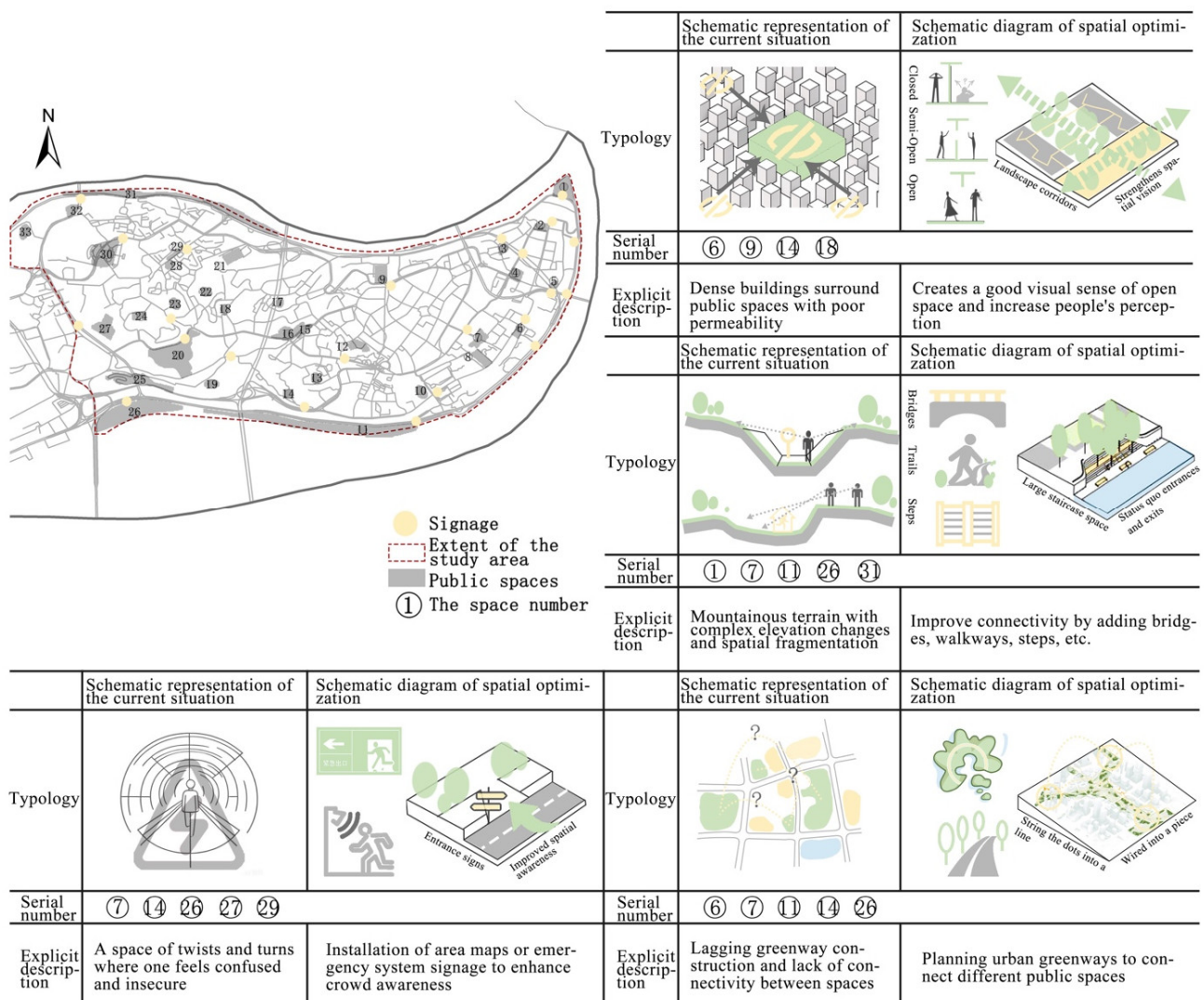


Figure 7. Countermeasures to enhance redundancy and safety in public space.

- Sorting Out the Yuzhong Peninsula Street Network to Ensure Safety

The comprehensibility of the Yuzhong Peninsula is currently low, and the correlation between connectivity and integration is weak. Consequently, the public's perception of

the spatial system within the Peninsula is diminished due to its geographical location, which adversely affects the resilience of each public space. The mountainous terrain further complicates this issue, as the roads connecting public spaces are often winding or sloped. This irregularity disrupts individuals' perception of the space, leading to feelings of confusion and insecurity. To address these challenges, it is recommended to plan and construct a street network characterized by a clear hierarchy, simple forms, and complete shapes that provide directionality. For public spaces situated in areas with dense road networks and poor navigational clarity, such as 26# Coral Park and 7# People's Park, the installation of area maps or emergency signage is advisable. This would enhance visual permeability and ensure spatial accessibility, thereby improving overall spatial comprehensibility (Figure 7). By leveraging the mountainous terrain, it is possible to foster a strong sense of spatial visualization, allowing the public to develop a distinct and effective perception of urban public spaces.

6. Conclusions

PSR is significantly influenced by both subjective and objective factors. Studies that focus exclusively on the physical structure of these spaces frequently neglect the behavioral and psychological perceptions of users, leading to findings that inadequately capture the critical role of public spaces in disaster response. Research that incorporates perceived resilience often requires extensive fieldwork, which can be time-consuming and costly. Consequently, this study bridges the subjective and objective dimensions of resilience by developing a novel measurement framework based on the interrelationship between 'physical entity—spatial perception (via space syntax)—spatial resilience'.

An empirical study was conducted in the Yuzhong Peninsula of Chongqing, China, with results validated through field research. The main conclusions of the study are as follows: (1) The average global integration value of the Yuzhong Peninsula is 0.712, indicating low robustness. Public spaces within the peninsula have poor connectivity and inadequate accessibility. To improve this, a spatial perceptual order should be established to enhance public space accessibility. (2) In the connectivity analysis diagram, most public spaces exhibited cold colors, indicating weak spatial permeability and low redundancy. This limited interconnection among spaces highlights the necessity to enhance the efficiency of public areas and to improve spatial permeability by fostering greater visual and spatial recognition. (3) The comprehensibility value of the peninsula is 0.283, indicating a poor connection between local and global spaces. This lack of spatial clarity compromises security and diminishes the perceptibility of public spaces to users. To mitigate this issue, measures such as the installation of regional maps and emergency response markers are recommended. (4) The overall resilience level of the Yuzhong Peninsula is relatively low, with medium-resilience spaces constituting the largest proportion. High-resilience and low-resilience spaces each account for 30.3%, highlighting an uneven spatial distribution of resilience. Future initiatives should prioritize enhancing the PSR by optimizing spatial layouts and improving the robustness, redundancy, and security of low-resilience spaces to more effectively address environmental changes and urban development challenges.

The results demonstrate that bridging subjective and objective dimensions of resilience into the measurements of PSR through space syntax yields a more refined and efficient tool, offering a novel paradigm for resilience research. This study has verified the validity and adaptability of this measurement framework, indicating its potential for broader application in cities worldwide. The findings provide a scientific foundation for urban planning decisions, enhance the ability of urban public spaces to respond to extreme climatic conditions, and offer both theoretical and practical guidance for achieving resilient urban development.

While this study introduces innovative approaches to PSR research, it has several limitations. First, the scope of the study is confined to the Yuzhong Peninsula in Chongqing, China, which may not represent the characteristics of other cities or different types of spaces. This limitation could impact the generalizability of the conclusions drawn. Future research could extend the framework developed in this study to various urban environments to validate its applicability. Second, this study primarily relies on space syntax for quantitative analysis and does not fully account for the influence of social and psychological factors. Future studies could adopt interdisciplinary approaches that integrate methods from psychology and sociology to explore the deeper factors influencing PSR. Lastly, with the advancement of big data and artificial intelligence technologies, future research could incorporate real-time data and more precise modeling techniques. This would facilitate a more comprehensive understanding of spatial resilience mechanisms, ultimately contributing to the promotion of urban resilience and sustainable development.

Author Contributions: Conceptualization, Y.L. (Yunyan Li), M.W. and B.W.; Methodology, Y.L. (Yunyan Li); Software, M.W.; Validation, Y.L. (Yunyan Li), M.W. and B.W.; Formal analysis, Y.L. (Yunyan Li); Investigation, B.W.; Resources, Y.L. (Yuchen Liang); Data curation, M.W.; Writing—original draft preparation, M.W.; Writing—review and editing, B.W.; Visualization, Y.L. (Yuchen Liang); Supervision, B.W.; Funding acquisition, Y.L. (Yunyan Li) and B.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the National Natural Science Foundation of China (52478042, 42101200), the Social Science Planning Project of Chongqing Municipality (2023NDYB83), the Fundamental Research Operating Expenses of the Central Universities and Colleges (NO. 2024CDJXY014), and Postdoctoral Fellowship Program of CPSF (NO. GZC20233314).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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