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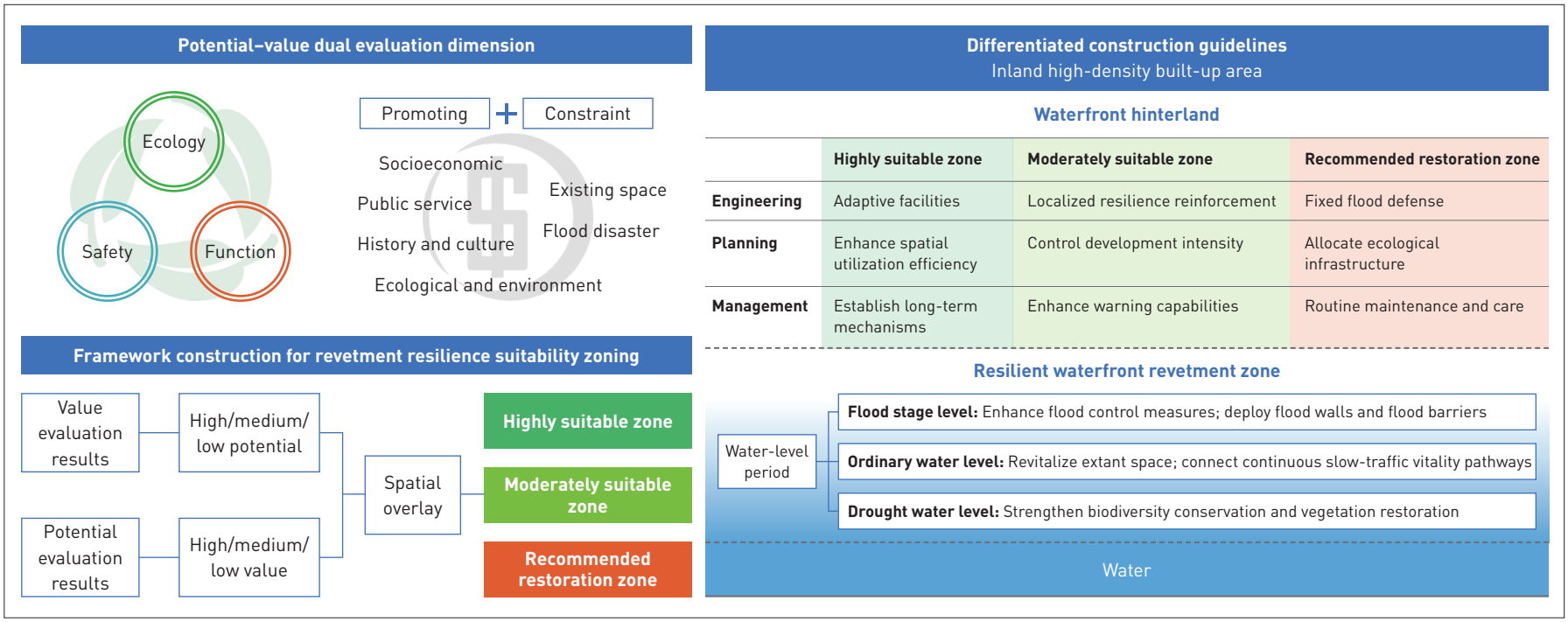
Potential–Value Evaluation of Waterfront Revetment Zones in High-Density Urban Areas for Resilience Enhancement

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GRAPHICAL ABSTRACT



ABSTRACT

As China's urbanization shifts from scale expansion toward qualitative and fine-grained development, waterfront revetment zones in high-density urban areas increasingly require both the regeneration of existing spaces and ecological restoration. Traditional revetment engineering, however, typically prioritizes flood control and drainage at the expense of ecological integrity. Meanwhile, higher flood-protection standards have left some waterfront areas vacant or underused, intensifying the spatial tension between rigid safety constraints and multi-dimensional development needs. To address this challenge, this study integrates the principles of spatial equilibrium and marginal decision-making from public finance to develop a resilience-oriented, potential–value evaluation framework. The framework defines construction potential in terms of safety, ecological, and functional resilience, and construction value in terms of socioeconomic, historical and cultural, ecological and environmental, and public-service dimensions. Both construction potential and value are classified and overlaid using the analytic hierarchy process–entropy weighting method (AHP–EWM) and geographic information system (GIS) spatial overlay analysis. Applied to Fengqituo and Jiulongpo District in Chongqing, this study delineates three spatial suitability zones based on comparative advantages: highly suitable zones,

moderately suitable zones, and recommended restoration zones. Accordingly, it proposes a development-guided and restoration-prioritized differentiated management pathway alongside water-level-responsive construction guidelines. The results indicate that the framework effectively quantifies the resilience supply capabilities and demand intensities of specific spatial units, thereby striking a dynamic balance between disaster prevention baselines and spatial efficiency. Ultimately, the framework translates macro-resilience concepts into operational spatial planning strategies, providing an analytical tool for the optimal allocation and fine-grained governance of waterfront resources in high-density urban settings.

KEYWORDS

High-Density Urban Areas; Waterfront Revetment Zones; Resilience Enhancement; Potential–Value Evaluation; Spatial Equilibrium Theory; Marginal Effect; Differentiated Management

HIGHLIGHTS

- Applies public finance to potential–value evaluation, resolving flood safety–development trade-offs
- Reveals revetment–hinterland responses across water levels, driving spatiotemporal synergies
- Delineates three suitability zones to support fine-grained differentiated waterfront governance

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1 Introduction

Urban waterfronts are terrestrial-aquatic ecotones that possess both ecological and socioeconomic values[1–2]. The governance of waterfront revetment zones is undergoing a transition from single-purpose drainage infrastructure to composite systems that balance safety, ecological, and social values[2–3]. With the rise of ecological revetments and resilient city concepts, an international consensus increasingly emphasizes restoring land-water exchange functions by relying on natural ecological processes, while firmly safeguarding the flood control baseline[4–7].

Nature-based and integrated flood-risk management is widely applied in Europe and North America. For instance, New York City integrates flood infrastructure with wetland parks, and projects along the Hudson River illustrate how such designs enhance community socio-ecological resilience[8–9]. European practice also emphasizes integrated flood-risk management, as exemplified by London's multi-tiered gray–green infrastructure strategy encompassing a prevention–defense–mitigation–response framework[10–11]. Similarly, the Netherlands shifted its paradigm toward coexisting with water through the Room for the River Programme, while the "Living Shorelines" project within Rotterdam's Kop van Zuid port area redevelopment combined flood protection and ecological functions by integrating diverse natural elements[12]. High-density Asian cities focus on multi-functional facility integration within limited spatial confines, such as Japan's "Super Levees" and Singapore's "ABC (Active, Beautiful, Clean Waters) Waters Programme," combining flood-protection requirements with public open-space functions[13]. These international approaches to multifunctional integration and integrated risk management are relevant to the regeneration and ecological restoration of waterfronts in China's high-density urban areas. They also correspond to China's current shift toward quality-oriented and fine-grained urban development.

China's revetment zone planning is shifting from an engineering-led to an ecology-prioritized paradigm, as exemplified by Shenzhen Mountain–Sea Vistas project, ecological governance of clean small watersheds in Shanghai, and Liangma River restoration in Beijing. However, existing practices do not sufficiently address the unique human–land conflicts and spatial constraints of local high-density urban areas[14–15]. This creates a gap in technical pathways for translating macro concepts into specific revetment renewal strategies, operational spatial classification methods, and well-defined planning management units[16–17].

Although the classic "4R" (robustness, redundancy, rapidity, and resourcefulness) framework is widely recognized as describing core attributes of resilient systems, translating this broad framework into specific planning parameters remains difficult[18–20]. In China, existing evaluation frameworks provide limited support for comprehensive waterfront governance because they lack spatial adaptability[20–21]. This limitation has three main sources.

First, disciplinary barriers fragment evaluation standards, as water conservancy, ecological assessment, and spatial planning departments focus respectively on flood control efficiency, shoreline sensitivity, and functional layout; this discipline-specific approach segments an integrated waterfront system to separate assessment indicators. Second, a static perspective dominates current evaluation practices, with insufficient analysis of the coupled spatiotemporal responses of hydrological, climatic, and social processes; this prevents evaluation results from capturing changes in revetment performance during floods or providing guidance for long-term adaptive management[22–23]. Third, engineering infrastructure is often assessed separately from its surrounding environment rather than from an integrated governance perspective.

Although existing studies recognize spatial gradients in urban waterfront and delineate water-level fluctuation, flood-buffer, and urban-transition zones for differentiated retrofitting[6,20,24], conventional evaluations often sever engineering facilities from their surroundings. This overlooks the continuous gradient from the water body through the resilient revetment zone and urban hinterland to inland high-density built-up areas[25]. Traditional practices narrow the revetment zone to a rigid physical barrier, concentrating engineering measures within its boundaries and disrupting safety, ecological, and functional supply–demand feedback between the revetment and its hinterland. As the frontline of flood defense, the revetment zone serves as the supply side of resilience and security, directly determining the flood-prevention baseline. Conversely, the urban hinterland above the flood-control elevation, where economic activities are concentrated, acts as the vitality-driving demand side. Without quantitative tools to coordinate supply and demand, safety and development are treated as supposing goals, leaving revetment resilience construction isolated from the diverse and flexible needs of hinterland development[25–26].

To address the tension between safety and development stemming from a lack of quantitative supply–demand tools, current practices primarily explore two pathways: first, multifunctional use through the three-dimensional integration of gray–green infrastructure in core built-up areas; second, near-natural restoration that "exchanges time for space" through ecological succession in areas subject to advance planning control or water-level fluctuation zones with natural buffering capacity[27–28]. However, indiscriminate functional intensification in high-density areas can transfer rather than reduce disaster risk. Therefore, optimizing resource allocation requires assessing revetments together with their hinterlands through a systematic framework that integrates resilience supply potential with multi-dimensional demand value. Only by quantifying the comparative advantages and safety thresholds of each spatial unit, while accurately delineating multifunctional compatibility boundaries and tiered management pathways, can resource mismatch be reduced and existing waterfront resources be allocated more effectively.

2 Theoretical Potential–Value Evaluation Framework and Evaluation Methodology

To address aforementioned challenges, this research establishes a potential–value evaluation framework of waterfront revetment zones in high-density urban areas. Waterfront revetment zone planning in high-density urban areas aims to address climate risk impacts and to optimize resource allocation under rigid constraints, drawing its theoretical foundations from public finance as well as environmental and resource economics. The flood control, ecological regulation, and cultural services provided by these zones are public goods susceptible to the "tragedy of the commons" or underinvestment driven by market failures, which manifest as the excessive encroachment on and erosion of public ecological and landscape resources by high-density development. These phenomena justify government planning interventions and further drive the practical need for systematic, interdisciplinary value evaluations of waterfront spaces[24]. Although the traditional engineering-led paradigm guarantees safety, it frequently induces negative externalities such as ecological degradation and loss of spatial value[29–31]. Grounded in the extension of cost–benefit analysis within spatial planning, this study develops a potential-value evaluation framework.

Under this framework, construction potential measures the resilience-related public service supply capacity of a specific spatial unit across safety, ecological, and functional dimensions, whereas construction value characterizes the intensity of its multi-dimensional demand benefits across socioeconomic and public-service dimensions. Specifically, the potential evaluation identifies highly efficient supply zones with low costs and high returns, while the value evaluation focuses on high-demand areas with significant marginal benefits, together supporting equilibrium decision-making for spatial resource allocation.

2.1 Principles of Spatial Equilibrium and Marginal Decision-Making

At the core of the framework of this research are the principles

of spatial equilibrium and marginal decision-making. According to welfare economics, when the marginal social benefit (MSB) of any spatial unit x within the waterfront revetment zone equals its marginal social cost (MSC), spatial resource allocation achieves a Pareto-optimal state:

$$\mathrm{MSB}(x) = \mathrm{MSC}(x). \tag{1}$$

When this condition is satisfied, the net social benefit (NSB) is maximized, which can be expressed as:

$$\mathrm{NSB} = \int_0^{Q^*} \mathrm{MSB}\,(q) - \mathrm{MSC}(q)\,\mathrm{d}q, \tag{2}$$

where Q^* represents the optimal total resource allocation and q is a continuous variable of allocation quantity. Applying this principle to spatial allocation in high-density urban areas aims to achieve functional configurations with the highest MSB under limited land and resource constraints. This study introduces the ratio of MSB to MSC as a key decision variable; thus, for any two spatial units i and j to be compared, resource allocation must satisfy:

$$\frac{\mathrm{MB}_i}{C_i} = \frac{\mathrm{MB}_j}{C_j} \forall i, j, \tag{3}$$

where MB_i and MB_j represent the MSBs brought by resilience construction or spatial development in units i and j, respectively, such as risk reduction, ecological improvement, and economic gains; while C_i and C_j represent the corresponding MSCs, including construction, ecological opportunity, and relocation costs. The economic implication of this equation is that, under an optimal allocation, the MSB generated by an additional unit of public investment, including capital budgets, land quotas, and ecological resource inputs, should be equal across spatial units. If the ratio of MSB to MSC for a specific unit is relatively high, it implies that resources are under-allocated at this location, necessitating prioritized investment; conversely, resource allocation may be excessive.

This study translates this economic reasoning into a tiered spatial evaluation framework. A rational allocation of revetment zones lies within an equilibrium interval where MSB is greater than or equal to MSC, beyond which social welfare losses occur. Specifically, the construction potential dimension corresponds to the MSC, identifying spaces with low marginal costs and high marginal resilience benefits, whereas the construction value dimension corresponds to the MSB, identifying spaces with high marginal use benefits. These two dimensions exhibit a trade-off along the waterfront-to-inland spatial gradient.

2.2 Indicator System

This study organizes the multi-objective assessment into tiers of supply and demand. Specifically, the evaluation of construction potential focuses on the revetment zone proper as the primary riverfront interface, primarily measuring its flood-control robustness, ecological water-holding capacity, and shoreline functional supply elasticity under hydrological stress. Conversely, the construction-value evaluation extends to the closely connected waterfront hinterland, assessing the economic, cultural, and public-service demands under flood-protection conditions. Through spatial supply–demand mapping, this indicator system ensures that the measurements support the coordinated, integrated governance of the city and its shoreline.

2.2.1 Indicator System for the Construction Potential of Resilient Waterfront Revetment Zones

The national standard *Guidelines for Safety and Resilience City Evaluation* (GB/T 40947–2021) broadly aligns with mainstream academic frameworks emphasizing attributes such as robustness, redundancy, rapidity, and resourcefulness, with a focus on safety, ecology, and function[5,32–33]. Accordingly, this study integrates these 4R resilience attributes into each criterion (Table 1), structuring evaluation around safety, ecological, and functional resilience[34–38].

Table 1: Evaluation indicator system for the construction potential of resilient waterfront revetment zones

Criterion	Sub-criterion	Indicator	Resilience attribute
Safety resilience potential	Flood control safety	Elevation	Robustness
		Historical high-water level recurrence interval	Robustness
		Current flood control facilities	Robustness
		Minimum emergency-response travel time	Resourcefulness, Rapidity
	Engineering construction safety	Slope	Robustness
		Aspect	Robustness
		Foundation bearing capacity	Robustness

(Continued)

Table 1: Evaluation indicator system for the construction potential of resilient waterfront revetment zones (Continued)

Criterion	Sub-criterion	Indicator	Resilience attribute
Ecological resilience potential	Water retention and carbon sequestration	Vegetation coverage	Redundancy
		Retained wetland resources	Redundancy
		Proportion of natural shoreline length	Redundancy
	Ecological stability	Soil erosion	Rapidity
Functional resilience potential	Urban characteristics	Preserved buildings	Resourcefulness
		Important landmarks	Resourcefulness
		Landscape resource richness	Redundancy
		Visual importance	Rapidity
	Functional supporting facilities	Hinterland functional richness	Redundancy
		Human activity intensity	Resourcefulness
		Current development intensity	Resourcefulness

Indicator selection draws on established measures, such as elevation, slope, vegetation cover, and shoreline proportion[23,36–39], while incorporating indicators tailored to the spatial characteristics of revetment zones, including minimum emergency response time, visual importance, and hinterland functional diversity. The resulting evaluation system comprises 3 criteria, 6 sub-criteria, and 18 indicators.

2.2.2 Indicator System for the Construction Value of Resilient Waterfront Revetment Zones

The evaluation system for the construction value of resilient waterfront revetment zones examines how revetment interventions may affect broader urban value. It covers socioeconomic, historical and cultural, ecological and environmental, and public-service dimensions while incorporating constraints from existing development and flood hazards, this study develops an evaluation framework that supports both systematic evaluation and practical application (Table 2).

Among facilitating factors, socioeconomic value is quantified through indicators such as land use types, distance to commercial centers, the number of bus and metro stations, and floor area ratio[40–41]; historical and cultural value is evaluated based on architectural heritage stock and chronological characteristics[42]; ecological and environmental value is characterized by the number of parks and squares, distance to the riverbank, and environmental quality[43]; and public-service value is measured by the number of educational and medical facilities[44]. Regarding constraint factors,

Table 2: Evaluation indicator system for the construction value of resilient waterfront revetment zones

Criterion	Indicator
Socioeconomic value	Land use type
	Distance to commercial center
	Number of bus stations
	Number of metro stations
	Plot ratio
Historical and cultural value	Quantity of historical buildings
	Age of historical buildings
Ecological and environmental value	Number of parks and squares
	Distance to the riverbank
	Vegetation ecological quality
	Number of middle schools
Public-service value	Number of primary schools
	Number of kindergartens
	Number of hospitals
Existing-development constraint	Development cost
Flood-hazard constraint	Flood loss

the constraints of extant space and flood disasters are quantified by development costs and flood losses, respectively[45]. This system integrates composite dimensions, including public service supply–demand matching and historical and cultural space resilience, providing a multi-dimensional evaluation perspective for the sustainable development of revetment zones in high-density urban areas.

2.2.3 Indicator Weighting, Composite Scoring, and Classification

Using GIS-based spatial overlay, this study cross-overlays the classified construction potential and construction value results in a dual-axis matrix at the grid-cell scale to identify the comparative advantages of each unit and delineate suitability zones, thereby informing differentiated strategies and potential Pareto improvements in spatial resource allocation. The corresponding formula is as follows:

$$U_{\mathrm{A}}(S') \geq U_{\mathrm{A}}(S) \wedge U_{\mathrm{B}}(S') \geq U_{\mathrm{B}}(S)\ , \tag{4}$$

where U_A represents the comprehensive utility function of highly suitable construction zones, which measures both social welfare and spatial development benefits; U_B represents the comprehensive utility function of moderately suitable construction zones; while S and S' characterize the dynamic configuration states of waterfront spatial resources before optimization and after Pareto improvement, respectively.

Grounded in the logic of spatial equilibrium, a resilience-oriented technological roadmap for the potential–value evaluation is established. On the supply side, the potential evaluation encompasses flood control engineering safety, water retention and carbon sequestration, ecological stability, and supporting functions to identify key priorities for coordinated city–shore restoration. On the demand side, the value evaluation coordinates economic, cultural, environmental, and public livelihood benefits while factoring in the constraints of existing development and flood hazards, aiming to achieve multi-dimensional supply–demand alignment[27–28,31].

This study adopts a combined weighting model that integrates the analytic hierarchy process (AHP) and the entropy weight method for multi-objective measurement. Specifically, subjective weighting distills expert knowledge and experience across multiple disciplines, including urban planning, hydraulic engineering, and ecological restoration. Concurrently, objective weighting utilizes indicator information entropy to reduce subjective bias, combining subjective and objective weights at a 6:4 ratio to quantify multi-dimensional resilience supply capabilities and demand benefit intensities. To address the rigid constraints of flood safety in high-density urban areas, the safety resilience criterion layer is assigned additional weight within the construction potential evaluation. Upon calculating the composite scores on a 100-point scale for each spatial grid cell, a K-means clustering algorithm (K = 3) is introduced for objective classification, mapping construction potential and construction value into three discrete levels of high, medium, and low.

2.3 Suitability Zoning Framework for Resilient Waterfront Revetment

Based on the spatial overlay of the potential–value evaluation results, this study established a suitability zoning framework for resilient waterfront revetment (Fig. 1), dividing the waterfront space into three distinct types of coordinated regulation units. Highly suitable zones combine favorable ecological conditions, stable flood-control conditions, and high socioeconomic and cultural value; these areas may be prioritized to support ecological restoration and functional enhancement through revetment retrofitting. Moderately suitable zones have advantages in one dimension but face diminishing marginal benefits, making it advisable to adopt low-intervention measures, such as minor revetment regeneration, vegetation replenishment, and functional replacement, to progressively enhance resilience. Recommended restoration zones are subject to binding land–development or cultural–heritage constraints; these areas should rely primarily on passive restoration, supplemented by minimal engineering interventions to maintain the flood-control baseline, thereby coordinating ecological conservation and disaster-prevention resilience. This framework provides differentiated planning guidance connecting the revetment zone proper with non-flooded terrestrial hinterlands, providing a planning framework for the refined governance and coordinated management of waterfront resources in high-density urban areas.

2.4 Research Area and Data

To validate the applicability of the potential–value evaluation framework across different development stages of high-density urban areas, this study selects Fengqituo in the Chongqing High-tech Zone and Jiulongpo District for empirical analysis (Fig. 2). Both sites represent typical high-density waterfront zones characterized by complex topography and landforms, subject to severe seasonal water-level fluctuations in the upper Yangtze River, periodic impoundment and drawdown from the Three Gorges Reservoir, and sudden drought–flood alternations induced by overlapping

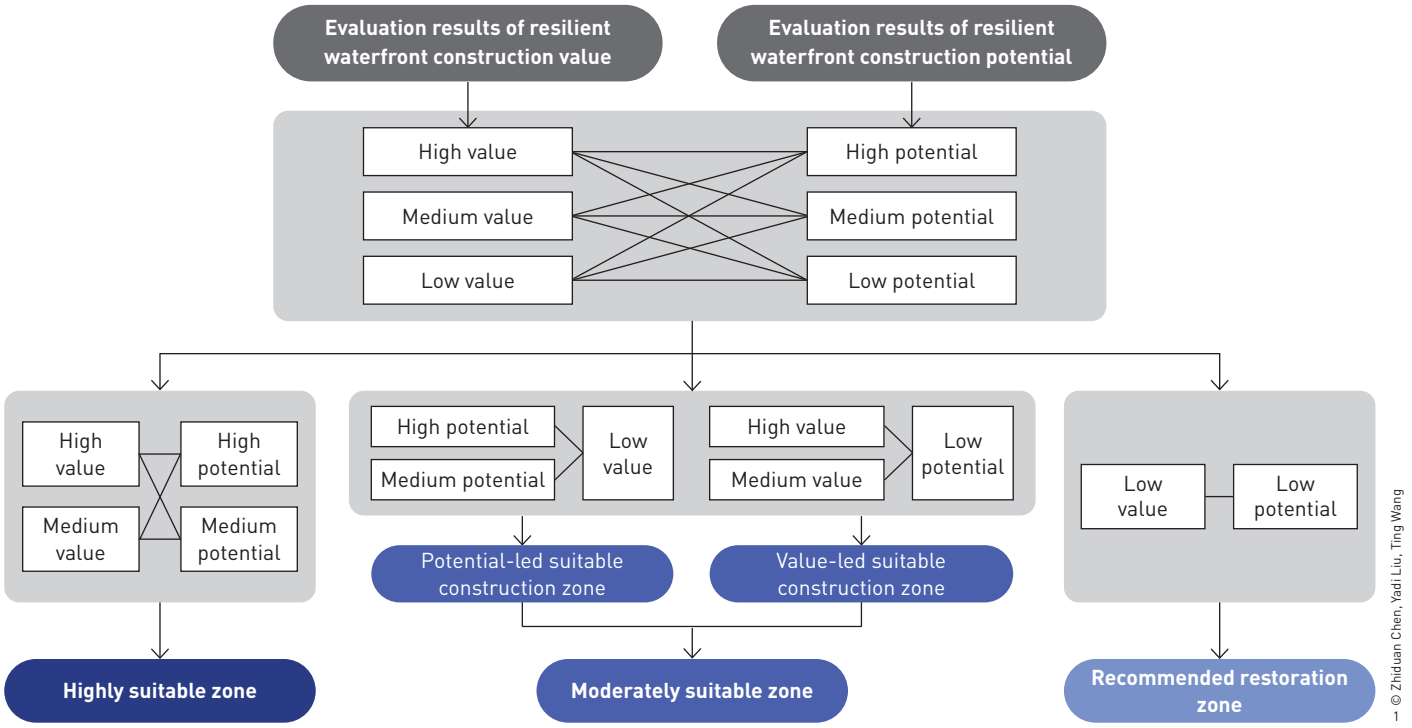


Fig. 1 Suitability identification scheme for resilient waterfront revetment zone construction.



Fig. 2 Study areas of Fengqituo (left) and Jiulongpo District (right), mapped based on the public detailed planning drawings of Liangjiang New Area and Jiulongpo District in Chongqing from Chongqing Municipal Bureau of Planning and Natural Resources.

geo-hydrological factors such as high-intensity mountain rainstorms[46–47]. Specifically, Fengqituo, a planned development area spanning 160 hm^2, features an excellent ecological condition but faces intense future development pressures, representing advance control and proactive ecological planning scenarios. Conversely, Jiulongpo District, a mature built-up area covering 330 hm^2, exhibits high development density and significant flood vulnerability, representing regeneration of an existing area under disaster-prevention constraints. Together, these two cases constitute representative samples for urban resilience enhancement research.

From March to July 2021, the research team conducted multiple field surveys along the “Two Rivers and Four Banks” area in Chongqing and consulted relevant local departments responsible for urban planning, water conservancy, and municipal design to collect and integrate multiple datasets. These include Chongqing’s territorial spatial survey data from 2020 to 2022 (baseline year: 2020) provided by the Chongqing Municipal Bureau of Planning and Natural Resources; the ALOS World 3D Digital Elevation Model (DEM, Version 3.2, 30 m resolution), acquired from the JAXA Earth Observation Research Center in May 2021); historical flood disaster records from 1998 to 2021 (standardized to the base year 2022), provided by the Chongqing Water Resources Bureau and the Flood Control and Drought Relief Headquarters; and multi-source Point of Interest (POI) data (2022 Version) acquired from

Amap in May 2022. To ensure spatial consistency across evaluation units, this study employed GIS vector resampling and bilinear interpolation algorithms to resample and match all data sources to a uniform 10 m × 10 m spatial analysis grid. On this basis, raw data were converted into the evaluation indicator values listed in Tables 1 and 2 using spatial analysis tools: topographic indicators (e.g., slope and catchment area) were extracted from the DEM via hydrological analysis modules; land-use attributes and protective infrastructure indicators were derived through vector overlay and buffer analysis of the territorial spatial survey data; hazard-bearing element density indicators were computed via kernel density estimation of POI data; and historical flood records were spatially interpolated onto grid cells to establish the hazard baseline indicators.

3 Empirical Analysis of the Potential–Value Evaluation Results

3.1 Spatial Characterization of the Potential–Value Evaluation Results

Based on the evaluation model and clustering method, this study calculated the composite scores and classified the construction potential and construction value for each grid unit in Fengqituo and Jiulongpo District (Tables 3–5). The results for both areas show distinct spatial patterns and substantial overlap (Figs. 3, 4).

The potential evaluation results indicate that high-potential zones in both study areas exhibit a distinct pattern of clustering along core axes or hubs. Specifically, Fengqituo's high-potential zones (12.52 hm^2) are concentrated along urban development corridors such as Binjiang Road, where sound ecological safety coexist with transportation advantages. High-potential zones in Jiulongpo District (10.68 hm^2) cluster around transport hubs like the Chongqing South Railway Station, featuring relatively stable

Table 3: Identification results for construction potential and construction value in Fengqituo and Jiulongpo District

Study area	Construction potential			Construction value		
	High	Medium	Low	High	Medium	Low
Fengqituo	75.2–100	62.1–75.1	0–62.1	75.2–100	62.1–75.1	0–62.1
Jiulongpo District	73.8–100	60.5–73.7	0–60.5	73.8–100	60.5–73.7	0–60.5

Table 4: Indicators and combined weights for construction potential in Fengqituo and Jiulongpo District

Indicator	Combined weight	Indicator	Combined weight
Elevation	0.12	Proportion of natural shoreline length	0.06
Historical high-water level recurrence interval	0.12	Soil erosion	0.06
Current flood control facilities	0.12	Preserved buildings	0.02
Minimum emergency response travel time	0.06	Important landmarks	0.02
Slope	0.06	Landscape resource richness	0.02
Aspect	0.06	Visual importance	0.04
Foundation bearing capacity	0.06	Hinterland functional richness	0.04
Vegetation coverage	0.04	Human activity intensity	0.04
Retained wetland resources	0.04	Current development intensity	0.02

Table 5: Indicators and combined weights for construction value in Fengqituo and Jiulongpo District

Indicator	Combined weight	Indicator	Combined weight
Land use type	0.06	Distance to the riverbank	0.04
Distance to commercial center	0.02	Vegetation ecological quality	0.03
Number of bus station	0.02	Number of middle school	0.02
Number of metro station	0.04	Number of primary school	0.02
Plot ratio	0.06	Number of kindergarten	0.03
Quantity of historical building	0.14	Number of hospital	0.03
Age of historical building	0.06	Development cost	0.1
Number of park and square	0.03	Flood loss	0.3

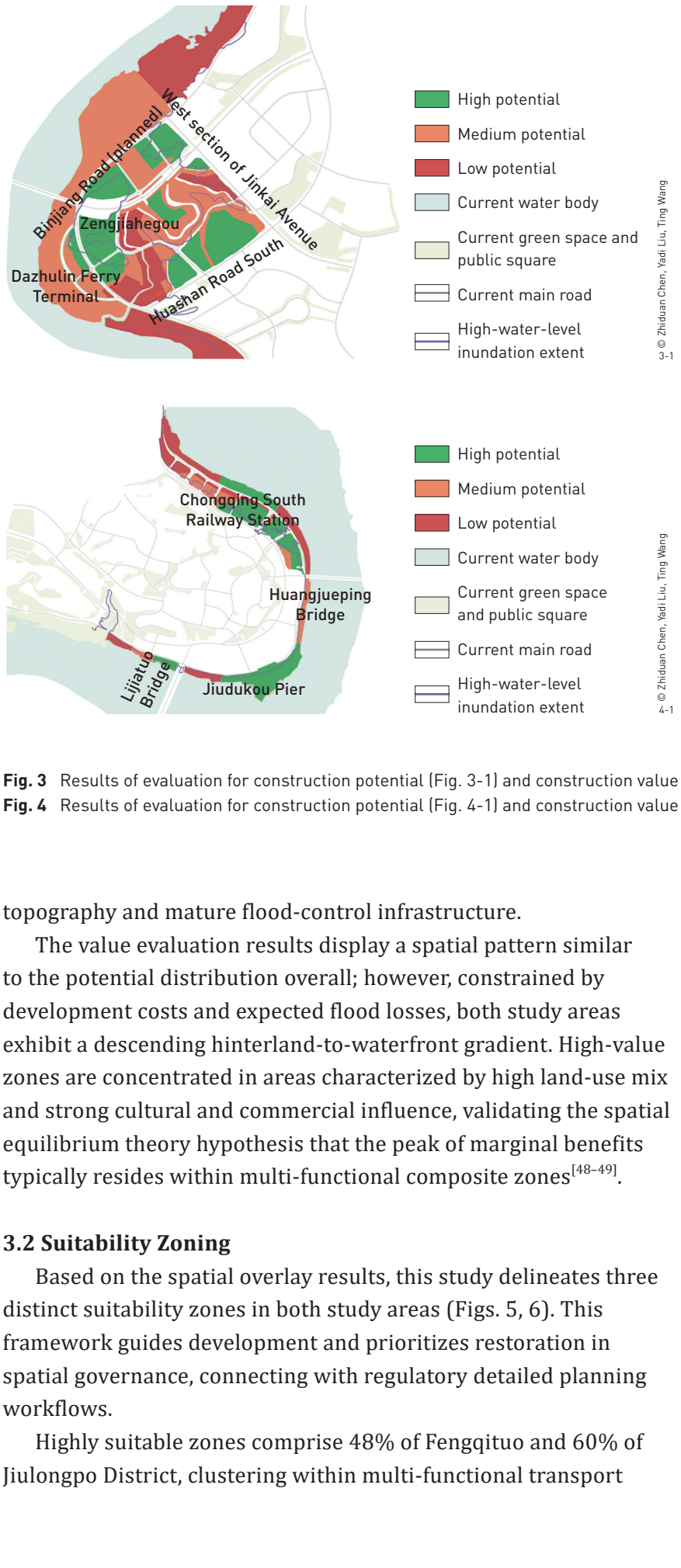


Fig. 3 Results of evaluation for construction potential (Fig. 3-1) and construction value (Fig. 3-2) of resilient waterfront revetment in Fengqituo.
Fig. 4 Results of evaluation for construction potential (Fig. 4-1) and construction value (Fig. 4-2) of resilient waterfront revetment zones in Jiulongpo District.

topography and mature flood-control infrastructure.

The value evaluation results display a spatial pattern similar to the potential distribution overall; however, constrained by development costs and expected flood losses, both study areas exhibit a descending hinterland-to-waterfront gradient. High-value zones are concentrated in areas characterized by high land-use mix and strong cultural and commercial influence, validating the spatial equilibrium theory hypothesis that the peak of marginal benefits typically resides within multi-functional composite zones[48–49].

3.2 Suitability Zoning

Based on the spatial overlay results, this study delineates three distinct suitability zones in both study areas (Figs. 5, 6). This framework guides development and prioritizes restoration in spatial governance, connecting with regulatory detailed planning workflows.

Highly suitable zones comprise 48% of Fengqituo and 60% of Jiulongpo District, clustering within multi-functional transport hubs such as the Dazhulin Ferry Terminal and the Chongqing South Railway Station to generate positive externalities including industrial linkage and land value appreciation[50–52]. For these areas, planning frameworks should promote the mixed-use layout of residential, commercial, and public service functions under strict flood-control engineering constraints. Furthermore, planning controls should explicitly integrate specific technical resilience requirements for elevation-adaptive, multi-level waterfront landscapes and activity spaces into land-leasing conditions and site-level detailed planning.

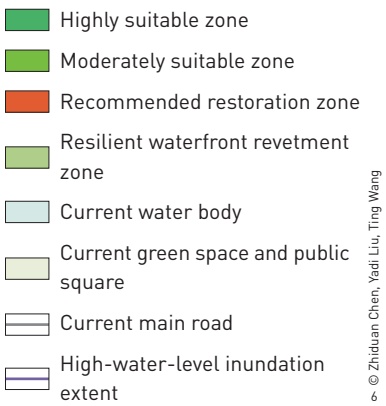
Moderately suitable zones comprise 28% of Fengqituo and 25% of Jiulongpo District, largely situated in spatial transition zones between highly suitable and recommended restoration areas that advantage in certain aspects advantages but face diminishing comprehensive marginal benefits. To govern these areas, planning strategies prioritize low-cost micro-regeneration, progressively enhancing overall disaster-prevention efficiency through targeted facility reinforcement and vegetation replenishment. This approach





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Fig. 5 Suitability zoning construction scheme for resilient waterfront revetment in Fengqituo.
Fig. 6 Suitability zoning construction scheme for resilient waterfront revetment in Jiulongpo District.

allows a moderate level of development while satisfying medium-risk flood-control standards.

Recommended restoration zones comprise 24% of Fengqituo and 15% of Jiulongpo District, clustering within areas covered by historical and cultural protection redlines, e.g., the Anti-Japanese War Relic Site of Zengjiahegou, as well as in ecologically sensitive areas. Under Chongqing's "Two Rivers and Four Banks" flood-control guidelines, which generally prohibit new permanent buildings in high-risk zones, this framework preferentially designates these areas as public open spaces (e.g., parks, squares). Hard engineering interventions should be minimized, with near-natural restoration and ecological conservation as the core functions.

Grounded in the evaluation framework, the proposed suitability zoning scheme supports the reuse of existing waterfront land through resilient spatial design while maintaining flood protection. Although quantifying the precise economic benefits and marginal construction costs of revetment retrofitting requires more detailed subsequent engineering parameters, its potential for spatial release and practical feasibility have been initially verified. For instance, the first phase of Jiulongpo District shoreline governance project, spanning approximately 6.8 km and implementing the strategies developed in this study, is now complete and open to the public. The project features a multi-level pathway system adapted to seasonal water levels, incorporating vitality, water-accessible, and resilient paths. This infrastructure transforms the disaster-restricted shoreline into a continuous public landscape and vibrant space, providing a practical reference for the application of the evaluation framework.

3.3 Differentiated Management Pathways and Water-Level-Responsive Construction Guidelines

Based on the potential–value evaluation and suitability zoning, this study establishes a differentiated management pathway that guides development while prioritizing restoration, alongside water-level-responsive construction guidelines for the revetment zone proper.

At the zonal management level: Highly suitable construction zones prioritize value multiplication under strict flood safety, explicitly integrating resilience criteria into land-leasing conditions and detailed planning to encourage mixed land use. Moderately suitable construction zones focus on low-cost resilience reinforcement, progressively enhancing disaster-prevention and ecological capabilities through micro-regeneration, vegetation replenishment, and adaptive facilities. Recommended restoration zones strictly adhere to rigid disaster-prevention constraints, focusing on nature-based restoration and ecological conservation, preferentially serving as public open spaces while minimizing hard engineering interventions.

At the water-level-responsive level: To address the severe seasonal water-level fluctuations characteristic of Chongqing's waterfronts, dynamic adaptive designs are implemented along the revetment zones to balance ecological vitality with flood control. During drought water-level periods, priority is given to habitat conservation and vegetation restoration to enhance wetland biodiversity and landscape quality. During ordinary water-level periods, existing waterfront land is revitalized by strengthening ecological stability and connecting continuous slow-traffic vitality pathways. During flood stage periods, resilient flood-defense infrastructure—such as automatic lifting floodwalls and flood barriers—is deployed to guarantee safety while maintaining visual landscape quality and dynamic spatial recovery.

4 Conclusions and Discussion

This study addresses the challenge of coordinating safety and development in waterfront revetment zones in high-density urban areas. Drawing on spatial equilibrium and marginal decision-making principles from public finance, it constructs and tests a resilience-oriented potential–value evaluation framework. The findings indicate that this framework helps overcome the limitations of traditional single-dimension static assessments and provides an operational approach for the refined governance of urban waterfront spaces.

At the theoretical level, this study develops a potential–value evaluation framework for spatial resource allocation. By treating the waterfront as a socio-ecological system that integrates natural processes and human activities, this framework identifies the spatial relationships among multi-dimensional objectives; by jointly assessing the construction potential of ecological safety and resilience supply against the construction value of socioeconomic and public services. The comprehensive evaluation results map regional comparative advantages, providing an analytical tool for examining the relationship between safety and development.

At the methodological level, this study develops a differentiated intervention pathway based on suitability zoning. Empirical findings indicate that high-potential and high-value spaces are typically concentrated in locations such as transport hubs and multi-functional integration zones. The spatial overlay of the evaluation results guides development and prioritizes restoration across three distinct zonal management categories. Highly suitable construction zones prioritize value enhancement subject to safety requirements, promoting mixed-use land layouts and functional integration while prioritizing spatial quality enhancement and renewal. Moderately suitable construction zones emphasize low-cost resilience improvements, progressively upgrading overall disaster-prevention and ecological functions through micro-renewal measures such as vegetation replenishment and facility retrofitting. Finally, recommended restoration zones are subject to binding constraints by prioritizing resilience conservation driven by natural processes; these areas leverage nature-based solutions to coordinate disaster-prevention resilience with ecological baselines.

At the planning level, this study proposes a water-level-responsive revetment strategy and a closed-loop planning management mechanism. Revetment governance should shift from rigid defenses toward dynamic adaptive designs that reconcile ecological vitality with flood control, thereby revitalizing existing spaces while safeguarding safety baselines. Implementation frameworks must embed evaluation zones and technical resilience parameters into regulatory and site-level detailed planning, establishing a management process that connects area-wide evaluation with project-level governance.

While this study establishes the potential–value evaluation framework and verifies its scientific rigor across both built-up area regeneration and new urban area pre-control scenarios, certain limitations remain in this exploratory work. Due to project data constraints and the scope of this research, the model has not yet incorporated weight sensitivity analyses or spatial autocorrelation tests. Furthermore, the framework relies primarily on static weights tailored to the specific characteristics of high-density urban areas in Chongqing, leaving the dynamic feedback of water-level fluctuations and climate change not fully represented. Consequently, evaluation standards and weight allocations would need to be calibrated to regional contexts; for instance, coastal applications require strengthened storm-surge defense metrics, historic cities may require higher heritage protection priorities, and the model must further integrate long-term climate impacts such as an increased frequency of extreme rainfall.

Future research could be advanced in three directions. First, a system dynamics model could be integrated to simulate the spatio-temporal responses of revetment infrastructure to water-level fluctuations and climate stress. Second, machine learning algorithms could support the development of dynamic weight optimization models to achieve adaptive adjustments in indicator weight allocation. Third, cross-city comparative case studies utilizing multi-source remote sensing data could be conducted to enhance the generalizability and transferability of this framework.

Competing interests | The authors declare that they have no competing interests.

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面向韧性提升的高密度城区滨水护岸带潜力-价值评价

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摘要

在新型城镇化由规模扩张向品质提升和精细化转型的背景下，中国高密度城区滨水护岸带已步入存量更新与生态修复并重的高质量发展阶段。然而，传统护岸工程重防洪排涝、轻生态保护；同时，随着防洪标准的提高，部分滨水地区面临用地闲置与资源利用不充分的困境，防洪刚性约束与多维发展需求之间的空间矛盾日益突出。为打破安全与发展的二元对立，研究引入公共财政学空间均衡与边际决策原理，构建韧性导向的潜力－价值双评价理论框架。该体系涵盖强调安全、生态与功能韧性的建设潜力，以及兼顾社会经济、历史文化等多维度的建设价值，综合运用层次分析法-熵权法（AHP-EWM）与地理信息系统（GIS）空间叠加实现双维综合分级。以重庆凤栖沱与九龙半岛为例，基于比较优势将空间划分为高度适建、一般适建与建议修复3类分区，提出开发引导、修复优先的差异化管控路径及水位响应型建设指引。研究表明，该体系能有效量化空间单元的韧性供给与需求强度，实现防灾底线与空间效能的动态平衡。研究将宏观韧性理念转译为可操作的规划管控策略，为高密度城区滨水资源的优化配置与精细化治理提供了创新工具支撑，对推动城市滨水区的精细化治理具有重要意义。

关键词

高密度城区；滨水护岸带；韧性提升；潜力-价值双评价；空间均衡理论；边际效应；差异化管控

文章亮点

- 基于公共财政学构建潜力-价值双评价，打破安全与发展的二元对立
- 解构护岸带与腹地在不同水位下的响应机制，实现水陆时空协同与价值重塑
- 划定3类韧性适宜性分区，提供高密度滨水精细化治理路径

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