Urban-Act
Integrated Urban Climate Action
for Low-Carbon & Resilient Cities

Research Report on Resilient Transport Planning for Climate Change in Xiamen

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Project description
Integrated Urban Climate Action for Low-Carbon and Resilient Cities (Urban-Act)

The Urban-Act project is implemented on behalf of the International Climate Initiative (IKI) of the Federal Government of Germany. Within the Federal Government, the IKI is anchored in the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN).

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Abstract

The rising frequency of climate-related hazard events has markedly increased the vulnerability of Xiamen's urban transport system. Resilience-based transport planning therefore plays a central role in safeguarding residents' safety and mobility and in strengthening the city's capacity to respond to and recover from climate-induced disasters. This study is situated within Xiamen's Disaster Prevention and Mitigation Plan and its Comprehensive Transport Plan. Through field surveys and a baseline assessment, the project team established the current spatial distribution of disaster-prevention and mitigation facilities across the city. A principal finding is a spatial mismatch: facility layouts that have been determined primarily according to the size of the permanent resident population do not align with the spatial distribution of populations exposed under different disaster scenarios. Focusing on heavy-rainfall flood scenarios, the study developed an integrated composite-indicator framework linking disaster-prevention facilities, the transport network, and exposed populations. By combining spatial distribution datasets, population statistics, and facility service-capacity metrics, the framework provides a comprehensive assessment of the city's emergency-response capability and its recovery capacity under disaster conditions. The research comprises three main analytical components—disaster-scenario development, a city diagnostic assessment, and a spatial-resilience evaluation under disaster conditions. Fine-grained resilience monitoring and assessment of Xiamen's transport infrastructure were conducted for heavy-rainfall flood scenarios, and spatial planning measures and regulatory interventions are proposed on the basis of the assessment results to enhance the city's transport resilience.

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1. Preliminary Investigation and Baseline Assessment

To establish a clear baseline for Xiamen's transport facility layout and to support a multi-scalar, in-depth analysis of both current conditions and future plans, the project team carried out systematic field surveys and a baseline assessment. The investigation aimed to identify existing shortcomings, to formulate targeted measures where necessary, to support high-quality implementation of planning actions, to ensure compliance with layout-related indicators specified in higher-level plans, and to clarify the mechanism by which planning indicators are translated into spatial layout decisions. The project's investigative work focused on three principal areas: (1) the current operation and development trends of Xiamen's transport facilities; (2) a survey of planning indicators for disaster-prevention and mitigation facilities; and (3) a review of the planning and layout of peacetime-and-emergency dual-use facilities.

1.1 Survey of the distribution and development trends of Xiamen's transport facilities

Transport facilities are shaped by urban residential and economic activities and therefore reflect the city's jobs–housing structure and travel characteristics. A systematic survey and review of recent changes in Xiamen's transport facilities was undertaken to inform the design of an effective and rational facility layout. The principal findings are presented below:

1.1.1 Population distribution and warehousing/logistics scale in Xiamen

As of the end of 2023, Xiamen's permanent resident population was 5.3270 million. The district-by-district distribution was: Siming 1.0660 million; Huli 1.0010 million; Haicang 0.6220 million; Jimei 1.0960 million; Tongan 0.8950 million; and Xiang'an 0.6470 million. The share of permanent residents living in urban areas was 90.81%. The birth rate was 7.15 per thousand (7.15‰), and the mortality rate was 3.95 per thousand (3.95‰), giving a natural population growth rate of 3.20 per thousand (3.20‰), a year-on-year decline of 0.96 per thousand. The *hukou* (registered) population totaled 3.0208 million, of which 2.6530 million held urban *hukou*—a *hukou* urbanization rate of 87.8%. The two island districts on Xiamen Island—Siming and Huli—together accounted for 1.3582 million registered residents, representing 45.0% of the city's *hukou* population. The *hukou* male population was 1.4635 million and the *hukou* female population was 1.5574 million, corresponding to a sex ratio of 93.97 males per 100 females. Compared with 2022, Xiamen's permanent resident population increased by 19,000 in 2023. The increase was concentrated in off-island districts — Haicang, Jimei, Tongan and Xiang'an — which together contributed 12,000 new residents; the two on-island districts, Siming and Huli, together increased by 7,000.

At the district level, year-on-year increments were as follows: Siming, +2,000; Haicang, +2,000; Tongan, +3,000; and Xiang'an, +2,000. A decline in the natural population growth rate was recorded in 2023, indicating that population growth relied increasingly on net inward migration. During the same period, the urbanization rate rose by 0.62 percentage points, and urban economic activity showed positive growth.

Table 1.1: Key Demographic Indicators by District, Xiamen (2023)
Source: Compiled by author, based on Key Population Indicators by District of Xiamen, 2023

	Permanent Population (in millions)	Birth Rate (‰)	Mortality Rate (‰)	Natural Growth Rate (‰)	Urbanization Rate (‰)
Xiamen	5.327	7.15	3.95	3.20	90.81
Siming District	1.066	7.12	4.65	2.47	100.00
Haicang District	0.622	7.08	3.50	3.58	100.00
Huli District	100.1	7.21	3.51	3.70	100.00
Jimei District	1.096	7.40	3.43	3.97	91.16
Tongan District	0.895	6.71	4.12	2.59	76.23
Xiang'an District	0.647	7.36	4.56	2.80	72.29

Xiamen has developed into a regional multimodal transport hub (land, sea and air) on the southeastern coast and is accelerating construction of an international integrated transport hub and a port-centric national logistics hub. In 2023, the logistics sector achieved total revenue of RMB 171.537 billion. Xiamen Port handled 220 million tons of cargo and recorded container throughput of 12.5537 million TEUs, ranking seventh nationally. Major logistics and port enterprises operating in the city include Xiamen Port Holdings, Sinotrans, COSCO Shipping Logistics, Zhonggu Shipping, JD Logistics, SF Express, Deppon Logistics, ZTO Express and Haitou Supply Chain.

In 2023, Xiamen's postal and express-delivery sector maintained steady growth. Excluding parcel services provided by postal operators, express delivery volume reached 641.198 million items, representing a year-on-year increase of 13.4%. The sector contributed to high-quality development and supported rural revitalization through improvements in last-mile logistics. With respect to rural delivery infrastructure, Xiamen further addressed service gaps and deepened the integrated development of rural passenger, freight and postal services; additionally, measures were taken to promote the extension of express-delivery services into villages and to reduce costs while improving operational efficiency. To date, 147 village-level postal and express service stations have been established, covering 105 administrative villages, with a coverage rate approaching 80%. The number of motorized segments of rural postal routes increased from 7 at the start of the year to 21, and the rural delivery rate rose to 61.8%. A tea express-service demonstration project generated cumulative business revenue of RMB 63.85 million and helped drive nearly RMB 500 million in agricultural product sales.

Integration between the express industry and the manufacturing sector accelerated in 2023. Express services serving manufacturing projects handled 61.4288 million items, accounting for 9.6% of the city's total express volume. The "digitalization + service + manufacturing" integration model supported high-value-added sectors such as optics, microelectronics and hearing aids; over the year this integration contributed to an aggregate industrial output value of RMB 5.168 billion and business revenue of RMB 1.633 billion. According to the Xiamen Postal Administration, total delivery volume in the city's postal industry reached 752.60 million items in 2023, a year-on-year increase of 11.4%. Of this total, intra-city express deliveries amounted to 88.14 million items (down 1.0%), while intercity express deliveries reached 482.505 million items (up 12.4%). Total industry revenue was RMB 9.43 billion, up 8.5% year-on-year, of which express service revenue totaled RMB 8.38 billion, up 6.6%.

Rapid growth in cross-border e-commerce further boosted international express traffic. Xiamen Customs reports that import and export value processed through the cross-border e-commerce supervision platform reached RMB 23.67 billion in 2023, up 65% year-on-year. Correspondingly, international express volume (including Hong Kong, Macao and Taiwan) totaled 70.553 million items, an increase of 50.2% year-on-year. Early-2024 figures indicate continued stability: from January 1 to January 20, 2024, the city averaged 2.45 million deliveries per day and processed approximately 49.02 million items for the period, a year-on-year increase of 35.5%. Delivery demand is expected to rise further ahead of the Lunar New Year; the Municipal Postal Administration will continue to guide express operators to ensure sufficient service capacity and logistics support during the peak season.

A port-oriented development strategy has defined Xiamen's urban model. The central government has designated Xiamen as a regional logistics center for the southeast coast, an international integrated transport hub, and a designated host city for a national logistics hub. The logistics industry is among the first five sectors in Xiamen to surpass RMB 100 billion in annual revenue, and the sector's value-added contribution to GDP reached 9.09%, making it a prominent new driver of economic growth. A π-shaped regional logistics corridor has formed in the city, organized around "one axis and two wings." The "one axis" denotes an east–west logistics corridor composed of National Highway 324 (G324), the Shenhai Expressway and Haixiang Avenue. The "two wings" consist of the principal road and rail corridors that connect logistics clusters at the airport and the seaport. Leveraging a convenient multimodal transport system (sea–land–air–rail), together with policy advantages such as the "One Zone, Multiple Parks" initiative and its strategic position for cross-Taiwan-Strait connectivity and international hub functions, Xiamen is strengthening its outreach to core areas — including the Xiamen–Zhangzhou–Quanzhou subregion — and to thirteen key cities across Fujian, Guangdong and Jiangxi, while deepening cooperation with emerging markets such as the ASEAN economies to enhance regional influence. The city's specialized logistics plan specifies a target total logistics land area of 13.18 km^2 by 2035, equivalent to approximately 2.1% of the city's urban construction land. Planned logistics zones are intended to attract large integrated logistics complexes focused on procurement and trade, centralized distribution and allocation, supply-chain finance, and regional headquarters, thereby concentrating flows of people, goods and capital. A three-tier urban distribution network is being established across the city. Existing public resources — for example, bus terminals and public spaces associated with the four bridges and one tunnel that connect Xiamen Island to the mainland — are being integrated and utilized as urban distribution nodes. Pilot initiatives are underway to explore the use of Bus Rapid Transit (BRT) corridors for overnight deliveries by autonomous vehicles, as part of efforts to resolve the urban "last-mile" distribution challenge.

1.1.2 Scale of Xiamen's transportation infrastructure

The city's transport network has essentially formed an internal–external connectivity pattern with a bay-radial configuration. The completion and commissioning of the Haicang Tunnel have signified the basic formation of the "Two Rings and Eight Radiating Lines" expressway backbone. Key links such as the Xiang'an Bridge and the Xiang'an Airport Expressway are currently under expedited construction. In rural areas, implementation of the national "Four-Good Rural Roads" program has advanced steadily; the total length of operational roads in the city now reaches 2,223 km.

In the public-transit domain, progressive improvements to the bus network have continued. In 2022, in conjunction with the opening of new BRT corridors and metro stations, the transport authority introduced 58 new bus routes and optimized 115 existing routes. Fourteen new feeder routes were added to connect bus services with metro stations, achieving full bus-to-metro coverage at metro stops. At present, the city operates three metro lines, eight BRT corridors and 543 regular bus routes, forming an integrated public-transport system anchored by urban rail and BRT, with conventional buses providing network density and taxis and ride-hailing services functioning as complementary modes. On the rail side, the Haixi (West Coast) railway hub has largely taken shape. The regional rail network follows a "four trunk, two branch" pattern, with the Xiamen–Shenzhen (Xia-Shen), Longyan–Xiamen (Long-Xia), Fuzhou–Xiamen (Fu-Xia) and Yingtan–Xiamen (Ying-Xia) lines as principal trunk routes, supplemented by freight spurs serving Haicang Port and Dongdu Port. The total operating length of this rail system is 146 km.

Air transport has shown marked development. Xiamen's position as a regional aviation hub has steadily consolidated: the airport now serves 122 cities via 175 routes, ranks thirteenth nationally in aviation throughput, and is among the top five Chinese airports for international transfer passenger volume. The city is concurrently advancing a series of major transport-infrastructure projects — including the Third East Passage and upgrades to National Highway G324 — and is laying out hub collection-and-distribution corridors to complete the regional logistics aggregation system. The municipal government has actively promoted the construction of 27 logistics projects to strengthen multimodal connectivity among seaports, airports and rail terminals and to improve logistics-park support facilities. Logistics-node coverage currently reaches 100% at the county/district level, 100% at the township level, and 73.4% at the village level.

Notable progress has also been achieved in China–Europe freight services. Three China–Europe freight routes now operate from Xiamen — Xiamen–Hamburg, Xiamen–Almaty and Xiamen–Moscow — providing connections to 12 countries across Eurasia. A cumulative total of 905 China–Europe trains has been operated, further enhancing Xiamen's role as an international logistics hub.

1.1.3 Scale of Xiamen's disaster prevention and mitigation facilities

In response to the risks posed by extreme climate events, Xiamen aims to establish a comprehensive disaster-prevention and mitigation system. The safety assurance and disaster-resilience capacity of major engineering projects and urban lifeline systems (e.g., power, water, communications and transport lifelines) generally meet the requirements for defense against major disasters, and an institutional system for catastrophic-event response has been largely established. An established urban disaster early-warning and emergency-response mechanism is in place: the emergency-response system is substantially complete and key facilities are equipped with automated emergency-response systems. Urban disaster-relief material depots, hospitals and other protective facilities are sized and sited to meet the demands of major disasters and to provide orderly sheltering and evacuation. From an integrated disaster-prevention perspective, the city coordinates disaster-related spatial planning and facilities across planning levels, identifies and fills resource gaps, and integrates disaster-prevention resources systematically. By rationalizing disaster-reduction assets, upgrading critical infrastructure, and strengthening multisector collaboration, the municipality is building an integrated city–regional safety system characterized by comprehensive monitoring, end-to-end disaster-response procedures, and coordinated prevention and control across the entire territory.

Disaster-prevention zoning in Xiamen is organized into three hierarchical levels (Level I–III), defined as follows. Level I (primary) zones are delineated by district administrative boundaries; these include the island proper and the mainland western, central, northern and eastern zones. Each Level I zone is equipped with central refuge sites, comprehensive medical-rescue institutions, fire-rescue units, material reserves and major evacuation trunk roads that provide external evacuation routes. Level II (secondary) zones are determined according to the principal functional areas set out in the territorial spatial plan. The city has designated 23 Level II zones, each of which has fixed shelters, material-supply facilities and basic rescue capabilities including medical and firefighting services. Level III (tertiary) zones are delineated at the sub-district (street) level; Xiamen has designated 93 Level III zones. Public-service categories addressed by the comprehensive disaster-prevention programme include transportation, lifeline (utility) supply systems, health security, public-space infrastructure and management, fire safety, natural-hazard management and man-made-hazard response.

The city's overall spatial framework for disaster prevention is summarized as "one primary node and three secondary nodes; two axes and two belts; and five Level I zones." Concretely, the southern part of Xiamen Island serves as the principal disaster-prevention node, while the western, central and northern mainland areas serve as secondary nodes. Two ecological protection belts — the northern mountain ecological-protection belt and the coastal ecological-protection belt — function as important separation and protection corridors. The five Level I urban-safety zones are the island proper and the mainland western, central, northern and eastern zones.

Table 1.2: Disaster-Prevention Zoning Tiers
Source: Compiled by author, based on Standard for Urban Comprehensive Planning on Disaster Prevention (GB/T 51327-2018)

Zoning Tier	Population Served	Required Facility Configuration	Management & Implementation Guidance
Level III (tertiary)	30,000–100,000	Permanent evacuation shelters; emergency water intake and storage facilities; emergency access/egress corridors rated at Level II or higher; emergency medical staging areas; dedicated sites for material storage and distribution	Should be coordinated with urban-planning management units and aligned with planning provisions and disaster-prevention measures
Level II (secondary)	200,000–500,000	Centralized shelter(s); municipal/district emergency command center; Level I designated hospitals for emergency support; major disaster-relief material depots; designated emergency standby water sources and emergency water-treatment plants; primary evacuation corridors (Level I); municipal/district-level emergency medical rescue sites and emergency material storage & distribution sites	Should be coordinated with urban-planning management units and aligned with planning provisions and disaster-prevention measures

Evacuation and emergency-transport planning: The external road evacuation network is formed by the Xiarong Expressway, the Shenhai Expressway, the Airport Expressway, the Xiasha Expressway and the Tongnan Expressway. Internal urban evacuation collection-and-distribution is organized around the planned "Two Rings and Eight Radiating Lines" urban expressway network together with the city's primary arterial roads. Rail-based emergency-logistics corridors are formed primarily by the Fuxia High-Speed Rail, the Changxia High-Speed Rail, the Yuchangxia High-Speed Rail and the Jiyongquan branch line. Aviation disaster response is supported by Xiamen Xiang'an New Airport, the comprehensive aviation support base and the Jinwan Heliport, which together constitute the city's aviation emergency-response capability. Urban rail transit can serve as a complementary subsystem to the road-based evacuation network. Waterborne evacuation and logistics make full use of passenger ferry terminals that are integrated with airports, rail hubs and other urban transport interchanges, thereby leveraging sea–air–rail multimodal advantages.

1.2 Survey and assessment of Xiamen's existing transport facilities and facility-layout plans

A structured, multi-stage approach was adopted to obtain accurate parameter values for Xiamen's transport-facility indicators. Prior to fieldwork, proposed survey topics were comprehensively reviewed and screened, and pre-survey consultations were conducted to identify potential logistical and substantive issues. During fieldwork, schedules and survey scopes were adjusted in response to interim findings to ensure collection of valid and comprehensive data. After data collection, technical teams carried out in-depth analyses to clarify identified problems and to isolate their root causes.

1.2.1 Preparation for the low-carbon transport data survey

The low-carbon transport data survey plan was finalized following multiple online and in-person coordination meetings. A definitive set of data requirements and a department-specific survey checklist were produced.

The survey items assigned to the Xiamen Transport Research Institute and the Xiamen Urban Planning & Design Institute were as follows: ① The resilience-related content and indicators embedded in the current Xiamen Territorial Spatial Master Plan (territorial spatial master plan) and the planning methods used to compile those elements. ② The manner in which disaster scenarios were incorporated into the master-planning process, including the procedures for conducting resilience assessments under differing disaster scenarios and the relationships between scenario definitions and planning indicators. ③ The master plan's treatment of the relationship between resilience and emergency response, and the approach to planning and construction of dual-use (peacetime/emergency) public infrastructure. ④ The existence of any dedicated planning or research on emergency logistics, and the availability of data on the current status of associated facilities (for example, material-reserve warehouses, distribution centers and logistics parks). ⑤ For typical climate hazards (sea-level rise, heatwaves, heavy rainfall/flooding, typhoons, etc.), the hazards of greatest concern at the planning level and the hazards judged most likely to affect transport infrastructure.

1.2.2 Survey implementation and principal consultation findings

On-site investigations and consultation meetings were held with relevant municipal departments. The principal outcomes of those consultations are summarized below.

Consultation with the Xiamen Urban Planning & Design Institute: A baseline assessment of urban facility layout was undertaken and two principal planning documents were reviewed: the *Xiamen Integrated Disaster Prevention and Mitigation Plan* and the *Special Plan for the Layout of Dual-Use (Peacetime and Emergency) Public Infrastructure in Xiamen*. These documents address multi-hazard interactions and cascading effects, disaster-vulnerability assessment, the identification and protection of priority facility clusters, hazard-zone risk assessment, system-level disaster-risk-reduction (DRR) planning, and implementation guidance.

Multi-hazard mapping and spatial risk identification: Hazard layers obtained from the Meteorological Center and other monitoring agencies were integrated by the Institute. Primary hazard layers considered include typhoon-vulnerability zones, high-frequency flood areas, geological-hazard potential zones, and seismic-vulnerability zones. Spatial overlay of these layers yields a composite spatial profile of natural-hazard risk across the city.

Disaster-vulnerability assessment and priority enhancement zones: Vulnerability analyses that combine demographic, economic and building-stock susceptibility indicators indicate that built-up areas on Xiamen Island and in mainland districts outside the island exhibit relatively high vulnerability to multiple hazards. Priority enhancement zones have therefore been identified where integrated DRR capacity should be strengthened; in these zones the Institute recommends comprehensive upgrades to disaster-prevention capabilities, together with strategic optimization of shelter locations and emergency facilities.

DRR indicator setting and population planning basis: Comprehensive DRR indicator requirements for Xiamen have been established with reference to applicable DRR standards, technical codes and benchmark cities. The population basis for facility provisioning follows the *Xiamen Territorial Spatial Master Plan (2021–2035)* (submitted for approval): a permanent resident population target of 6.20–6.50 million by 2025 and 7.30–8.00 million by 2035.

Priority facility inventory: A consolidated inventory of key urban and rural facilities requiring protection has been compiled. The inventory classifies key assets into ten categories: emergency command and control; transportation infrastructure; water-supply systems; electrical-power systems; fire and rescue services; shelters; healthcare facilities; emergency material reserves; external relief and mutual-aid logistics; and major hazard sources/facilities.

Integrated DRR systems and targeted facility planning: To enhance engineering resilience across urban and rural lifeline systems, the plan specifies targeted assurance measures. Water-supply assurance includes designation of eight emergency water sources, seven emergency water-treatment plants, and dedicated standby transmission and distribution pipelines. Power-system assurance includes one emergency municipal power dispatch center (existing), two emergency standby power plants (existing), six 500 kV substations (existing), a total of 32 220 kV substations (20 existing, 12 planned), and a total of 24 110 kV substations (15 existing, 9 planned).

Figure 1.1: On-site consultation with the Forest Protection Division, Planning Bureau
Source: Photographed by author during field research

1.2.3 Problems in the development of Xiamen's transport-facility layout and root-cause analysis

Based on field investigations, the project team identified the following problems in Xiamen's transport-facility layout and the underlying causes:

(1) Uneven distribution of warehousing resources and limited surge capacity: Concentration of warehousing facilities in central urban districts has resulted in relatively weak storage and logistics capacity in peripheral and rural areas. Under emergency conditions, this spatial imbalance can create bottlenecks in distribution and dispatch. Existing warehousing and logistics facilities are primarily configured for routine commercial operations; as a result, rapid expansion of storage capacity or temporary repurposing of facilities to meet urgent relief needs is difficult, and the capacity for swift allocation of urgently required supplies is limited.

(2) Aging utility networks and insufficient disaster resilience of supporting infrastructure: Water-supply and power-distribution networks in some areas — in particular at the urban fringe and in rural localities — exhibit significant aging and insufficient maintenance. These conditions increase susceptibility to failures during extreme events and may cause widespread power outages and water-supply interruptions. Certain pipelines, substations and other network components were not designed to accommodate present-day extreme-weather loads, making them vulnerable to typhoon and flood damage; consequent repair times are often prolonged, with adverse impacts on resident welfare and urban operations.

From a spatial-planning perspective, rapid economic development and urban expansion in Xiamen have not been matched by commensurate infrastructure investment and upgrading, particularly in peripheral and rural areas. Rapid urbanization has concentrated resources and facilities in the urban core, leaving outlying zones insufficiently equipped with warehousing, logistics capacity and lifeline infrastructure; this imbalance becomes acute during sudden disasters.

From an institutional perspective, infrastructure projects are commonly implemented in stages and within sectoral silos, with limited cross-departmental coordination. As a result, warehousing and logistics systems, emergency-response sites and lifeline networks have not always been planned and integrated as components of a unified emergency-support system. This fragmentation constrains interoperability and rapid resource mobilization during emergencies.

1.2.4 Recommendations for the development of Xiamen's transport-facility layout

On the basis of the foregoing analysis of facility-layout status and underlying mechanisms, the project team proposes the following recommendations:

(1) Promotion of integrated urban–rural development: An imbalance in infrastructure development between urban and rural areas is one of the principal constraints on the city's overall emergency-response capacity. Promotion of integrated urban–rural development in Xiamen should be pursued, with particular emphasis on increasing investment in rural water-supply and power (electricity), logistics, and emergency-rescue facilities, so as to establish complementary urban–rural infrastructure and enhance the city's overall emergency-response capacity. Further strengthening of the disaster-resilience of critical facilities is required to address the impacts of extreme weather and sudden events; resilience requirements should be incorporated at the design stage, with special attention to the disaster-resilience of water and power networks and of warehousing and logistics facilities to ensure continued operation during disasters. Acceleration of the adoption and pilot deployment of intelligent technologies — including big-data analytics, Internet-of-Things (IoT) systems and real-time dispatch and coordination platforms — is recommended across warehousing, logistics and emergency-rescue operations; such technologies can improve situational awareness, enable real-time dispatch capability, support rapid operational decision-making and increase the efficient allocation of resources.

(2) Strategic measures to resolve facility-layout issues: Strengthening of cross-departmental coordination is essential. Institutional arrangements should be reformed to break down siloed management, to integrate planning for warehousing and logistics, utility networks and emergency response, and to enable seamless information sharing and operational interoperability. Establishment of long-term policy and financing mechanisms is recommended to secure sustainable funding for maintenance, upgrades and replacement of critical facilities; these mechanisms should be accompanied by a regular monitoring and evaluation framework with clear indicators, responsibilities and reporting cycles to ensure effective policy implementation. Promotion of public participation and multi-stakeholder cooperation should be formalized: mechanisms for public consultation and enterprise-government collaboration (including appropriate PPP and incentive models) should be developed to mobilize private and social investment in infrastructure improvements. Such inclusive governance arrangements will help to create a sustained, multi-actor approach to enhancing urban resilience.

1.3 Review of facility-layout indicators in Xiamen's planning system for integrated disaster prevention and mitigation

To clarify the requirements in existing plans and in the city diagnostic assessments for transport indicators related to low-carbon objectives and resilience, the project team reviewed the territorial spatial planning system of Xiamen — including the master (general) plan, relevant special plans and detailed plans — and extracted the indicators and targets in existing plans that are pertinent to low-carbon transport, disaster prevention and facility provisioning.

1.3.1 Facility-layout indicators at the level of the Xiamen Integrated Disaster Prevention and Mitigation Plan

Strategic objectives articulated in the *Xiamen Integrated Disaster Prevention and Mitigation Plan* include the realization of a "Safe Xiamen" and the development of a highly resilient "garden city." The Plan aims to achieve an urban integrated level of disaster prevention that is consistent with socio-economic development. The planning boundary covers the whole Xiamen (Siming District, Huli District, Haicang District, Jimei District, Tongan District and Xiang'an District), with a total area of 1,912 km². The planning horizon extends from 2017 to 2035, with a short-term target year of 2025. The Plan sets a population planning target of 8.00 million permanent residents.

Table 1.3: Comprehensive Disaster-Prevention Indicators

Sources: Compiled by author, based on Xiamen Territorial Spatial Master Plan (2021–2035), Xiamen Comprehensive Disaster Prevention Plan, Xiamen 14th Five-Year Plan for Emergency Management, and master plans of cities including Shanghai and Beijing

<table>
<tr><th></th><th colspan="2">Flood and Tidal Control</th><th>Civil Defense</th><th>Seismic Protection</th><th colspan="2">Firefighting</th><th>Comprehensive Disaster Prevention</th></tr>
<tr><td></td><td>Tidal control</td><td>Flood control</td><td>Per-capita civil-defense facility area (m² per person)</td><td>Per-capita seismic emergency shelter area (m² per person)</td><td>Five-minute fire-and-rescue coverage rate in built-up areas (%)</td><td>Population served per fire-and-rescue station (10,000 persons per station)</td><td>Per-capita emergency shelter area (m² per person)</td></tr>
<tr><td>Current status</td><td>–</td><td>–</td><td>>1</td><td>0.7</td><td>Approximately 90% coverage within the island area Approximately 60% coverage in off-island areas</td><td>20</td><td>1.1</td></tr>
<tr><td>2025</td><td rowspan="2">A 1-in-200-year standard for Xiamen Island, and a 1-in-100-year standard for off-island areas</td><td rowspan="2">A 1-in-50-year return period</td><td>–</td><td>1.0</td><td>–</td><td>–</td><td>1.4</td></tr>
<tr><td>2035</td><td>1.3</td><td>1.5</td><td>100</td><td>12</td><td>2.0</td></tr>
<tr><td>Shanghai (2035)</td><td colspan="2">–</td><td rowspan="4">Specification Requirement: The per-capita civil-defense facility area should exceed 1 square meter</td><td rowspan="4">Specification Requirement: The effective site area should preferably exceed 2,000 square meters, and the per-capita usable shelter area should be greater than 1.5 square meters</td><td>100</td><td><10</td><td>≥2</td></tr>
<tr><td>Xiong'an (2035)</td><td colspan="2">–</td><td>–</td><td>–</td><td>2-3</td></tr>
<tr><td>Beijing (2035)</td><td colspan="2">A 1-in-50-year standard for central and sub-central urban areas, and a 1-in-100-year standard for particularly critical locations</td><td>–</td><td>–</td><td>2.1</td></tr>
<tr><td>Guangzhou (2035)</td><td colspan="2">Core urban area: a 1-in-200-year return period</td><td>–</td><td>–</td><td>1.75</td></tr>
</table>

A two-modal shelter system is delineated in the Plan, comprising (a) facility-based shelters and (b) open-site shelters. Facility-based shelters are further tiered into three levels — central shelters, fixed shelters and emergency shelters — and are to be located by leveraging existing emergency facilities, planned cultural and sports venues, and primary and secondary schools; all facility-based shelters are required to be designed and constructed to seismic-design standards. Open-site shelters are to be arranged in parks, green spaces and other suitable open areas. Planned quantities are: 28 central shelters, 69 fixed shelters, and more than 700 emergency shelters.

Table 1.4: Shelter Classification and Quantitative Controls
Source: Compiled by author, based on Code for Design of Disaster Shelter (GB 51143-2015)

	Net Evacuation Area (ha)	Evacuation Distance (km)	Short-Term Shelter Population (10,000 persons)	Coverage Area (km²)	Permanent Resident Population within Coverage Area (10,000 persons)
Central Shelter Facilities	›	5.0-10.0	10-20	20-50	20-50
Long-Term Fixed Shelter Facilities	5.0-20.0	1.5-2.5	2.3-9.0	3.0-15.0	5.0-20.0
Mid-Term Fixed Shelter Facilities	1.0-5.0	1.0-1.5	0.5-2.3	1.0-7.0	3.0-15.0
Short-Term and Emergency Shelter Facilities	0.2-1.0	0.5-1.0	0.1-0.5	0.8-3.0	0.2-3.5
	No Limitation	0.5	To be determined based on planning and construction		

Emergency medical treatment and material reserves: Adhering to the dual-use (peacetime/emergency) principle, the Plan establishes a hierarchical emergency-medical system organized on a central hospital — emergency hospital — ambulance station model. Planned provisions comprise one municipal emergency medical rescue center; six central hospitals (one per district); 24 emergency hospitals (four per district); and ambulance stations co-located with community health service centers (or street-level health service facilities) to provide timely pre-hospital care and distribution of emergency medical support.

Table 1.5: Inventory of Emergency Power-Supply Facilities
Source: Compiled by author, based on Xiamen Territorial Spatial Master Plan (2021-2035)

	Name of Emergency Power-Supply Power Facility	Disaster-Prevention Requirements
Planned Facilities	Pumped-storage hydropower plant	Designed to seismic fortification intensity 8 degrees.
	500 kV Jimei Substation, 500 kV Xiabei Substation, 500 kV Fengshan Substation	
	12 × 220 kV substations: Linsu, Maqing, Sanshe, Linghu, Xiafeng, Meihe, Yingbin, Hongbi, Cuo, District Government Substation, Fangshan, Xinping	
	12 × 110 kV substations: Yugang, Linhou, Cruise City, Sports, Yanwu, Zhenan, Ganling, Songdou, Fangyang, Chuandong, Beimen, Airport-dedicated Substation	
	500 kV main/transmission lines	Poles and towers shall be designed to a seismic fortification intensity of 9 degrees, with wind-resistance not less than 40 m/s.
	110 kV and 220 kV lines	Overhead line poles and towers shall be designed to a seismic fortification intensity of 9 degrees, with wind-resistance not less than 40 m/s; cables shall be installed in utility tunnels (pipe galleries).

Table 1.6: Inventory of Emergency Water Supply Facilities
Source: Compiled by author, based on Xiamen Territorial Spatial Master Plan (2021-2035)

	Name of Emergency Water Supply Facility Inventory	Disaster-Prevention Requirements
Planned Facilities	Southwestern Fujian Water Resources Allocation Project	Seismic fortification measures shall be implemented to a magnitude 8 standard; dual-circuit power supply shall be adopted at minimum.
	Xitou Reservoir	
	Houxi Water Plant	Seismic fortification measures shall be implemented to a magnitude 8 standard; dual-circuit power supply shall be adopted at minimum. At least two independent water sources and dual transmission channels shall be provided for raw water supply.
	Xiang'an North Water Plant	
	Regional Water Supply Trunk Pipelines	Pipelines shall be installed using the shared utility tunnel method, with high seismic-resistant pipes and joints.
Existing Facilities	Beixi Water Diversion Project	A specialized disaster resilience assessment shall be conducted, and upgrades implemented based on the assessment results.
	Changtai Fangyang	
	Shidou Reservoir	
	Lianhua Reservoir	
	Tingxi Reservoir	
	Hubian Reservoir	
	Gaodian Water Plant	
	Haicang Water Plant	

Table 1.7: Inventory of Emergency Communication Facilities
Source: Compiled by author, based on Xiamen Territorial Spatial Master Plan (2021-2035)

	Name of Emergency Communication Facility	Disaster-Prevention Requirements
Planned Facilities	2 × Telecommunication Hub Buildings	Seismic fortification measures shall be implemented to a magnitude 8 standard; dual-circuit power supply shall be adopted at minimum, and backup power generation equipment shall be installed.
	8 × General Telecommunication Buildings	
	Key Wireless Communication Base Stations	
	Key Communication Assurance Lines	To be laid within shared utility tunnels or integrated communication conduits.
Existing Facilities	5 × Telecommunication Hub Buildings	A specialized disaster resilience assessment shall be conducted, and upgrades implemented based on the assessment results.
	9 × General Telecommunication Buildings	
	Key Wireless Communication Base Stations	
	Key Communication Assurance Lines	
	Tingxi Reservoir	
	Hubian Reservoir	
	Gaodian Water Plant	
	Haicang Water Plant	

1.3.2 Special Plan for the Layout of Dual-Use (Peacetime and Emergency) Public Infrastructure in Xiamen

A major national-level decision — adopted by the Central Committee of the Communist Party of China and the State Council from a strategic perspective that integrates development and security — has established the steady advancement of peacetime–emergency dual-use public infrastructure in super-large and extra-large cities as a priority. Xiamen has therefore actively and steadily advanced exploration of implementation pathways for such dual-use infrastructure in the city, with the aim of reducing the potential impact of newly emerging major epidemics and other sudden public-health or public-security incidents on the central urban area. The Special Plan conforms to the *Guiding Opinions* and concentrates on integrated planning for the peacetime–emergency application scenarios of three facility categories: (a) tourism and residential accommodation with isolation capability; (b) emergency medical and public-health facilities; and (c) suburban large-scale warehousing hubs.

(1) Spatial layout of Xiamen's emergency medical and public-health facilities

Facility designation and intensive-care capacity: Six tertiary general hospitals across the city have been designated as emergency hospitals. These designated hospitals collectively provide 758 intensive-care-equivalent beds (including convertible critical-care beds), representing 14.1% of the city's total authorized bed capacity. This share exceeds the *Guiding Opinions*' minimum threshold of 10% and thereby strengthens the city's capacity to treat critically ill patients during major epidemic events. Twelve cultural and sports venues have been identified for peacetime–emergency dual-use conversion for infectious-disease response; of these, ten will be retrofitted from existing facilities and two will be newly constructed. These venues are designed to be rapidly convertible into Fangcang-type temporary shelter hospitals in emergencies. In addition, a 10.2-hectare site has been reserved as an emergency public-health reserve area for the rapid deployment of temporary shelter hospitals when required. Collectively, these spatial provisions enable expansion of infectious-disease bed capacity to the planned target of 30 beds per 10,000 residents, thereby meeting projected medical demand under severe public-health scenarios. The foregoing layout and reserve arrangements materially enhance Xiamen's emergency medical and public-health preparedness and provide a substantive foundation for scalable response operations in the event of future public-health crises.

(2) Spatial layout of suburban large-scale warehousing hubs

With reference to the scale of the suburban mega-depot base in Pinggu District, Beijing (JD-Pinggu Comprehensive Logistics Hub Industrial Park) and based on calculations of the service population, the Special Plan controls the primary hub site area at 70–90 hectares and reserves an additional 20 hectares for medium- to long-term expansion. Individual auxiliary depots are allocated site areas of 30–50 hectares each, with a controlled floor-area-ratio (FAR) range of 1.5–3.0, in accordance with the *Xiamen Municipal Measures for the Public Transfer of Logistics Land Use Rights* and relevant municipal precedents.

A one-primary, three-auxiliary spatial arrangement has been established. The primary hub is to be newly sited in the periphery of the central urban area and will function, during emergency conditions, as the principal receiving point for external relief supplies entering Xiamen. Auxiliary depots will be positioned at existing logistics parks — for example, Qianchang Logistics Park, JD Asia No.1 (Tongan) and the Southern Fujian Agricultural Products Logistics Center — and will act as intermediate transfer and distribution stations. Urban expressways will serve as high-capacity intra-city transfer corridors to move supplies from the primary hub via auxiliary depots into district-level logistics networks during emergency operations.

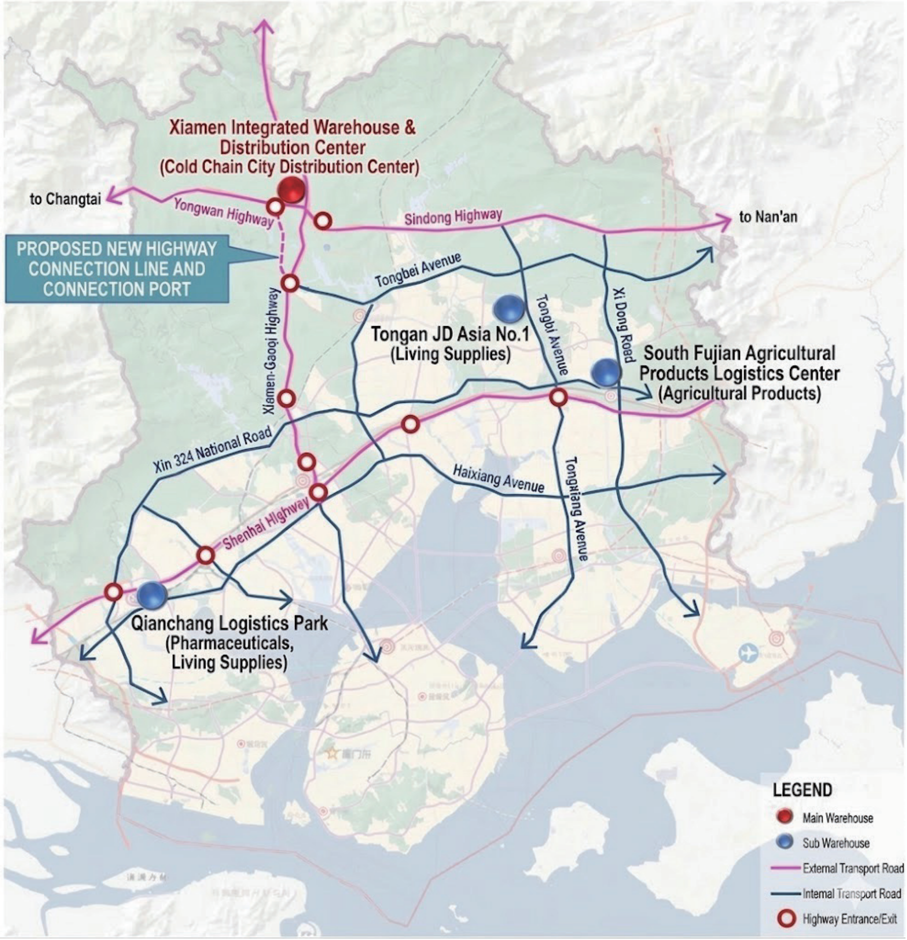

Figure 1.2: Distribution of Peacetime-Emergency Dual-Use Suburban Large-Scale Warehousing Hubs
Source: Compiled by author, based on Special Plan for the Layout of "Dual-Use" Public Infrastructure in Xiamen

1.3.3 Deficiencies in low-carbon indicators within the existing planning framework

1) Absence of formalized resilience-oriented facility-layout planning: Although resilience considerations have been introduced in high-level discussions, no formal resilience-oriented facility-layout plan has yet been adopted by the responsible municipal authorities; the prevailing emphasis remains on comprehensive disaster-prevention and mitigation planning.

2) Failure to incorporate disaster-exposed population distributions into facility siting: Current planning methods typically use the total municipal population as the population basis, but they neglect the spatial distribution of populations that are exposed or vulnerable under specific disaster scenarios.

3) Indicator data acquisition and update challenges: Certain indicator datasets needed for low-carbon and resilience measurement are either sensitive or difficult to obtain, and some available datasets are updated at low frequency. These limitations hinder the feasibility of annual tracking and timely evaluation of indicator performance.

2. Construction of the planning-methodology framework for resilient transportation

2.1 Establishment of an indicator system for resilient transportation

In China's urban-planning practice, the concepts of resilient cities and resilient transportation systems have increasingly informed mainstream planning practice. National-level agencies responsible for natural resources and spatial planning have issued a series of documents relevant to resilience metrics for spatial planning, including the *Urban Assessment Protocol for Territorial Spatial Planning* [1], the *2022 Urban Health Assessment Indicator System* [2], and the *Technical Guidelines for Community Living Circle Planning* [3]. These documents provide methodological guidance and reference indicators for national-level urban and community spatial planning. Current gap in transport-specific metrics: Dedicated research on resilient transportation and the formulation of specific, quantified indicators remain limited. To date, the *Technical Guidelines for Community Living Circle Planning* is the only referenced guideline that proposes transport-related resilience indicators (for example, emergency-access roads and evacuation routes); however, those indicators have not yet been accompanied by quantified measurement methods or thresholds. The relevant candidate indicators are listed in Table 2.1.

Table 2.1: Resilience Indicators at the Municipal Level (China)
Source: Compiled by author, based on National Urban Infrastructure Construction Plan for the 14th Five-Year Plan Period

Indicator	Source
Per-capita effective area of emergency shelters (m^2)	Urban Assessment Protocol for Territorial Spatial Planning [1]
5-minute coverage by fire and rescue services (%)	
Average annual land subsidence (mm)	
Number of geological-hazard sites remediated (or under management) (sites)	
Percentage of flood-control embankments meeting standards (%)	
On-site rainfall retention rate (%)	
Proportion of comprehensive disaster-mitigation demonstration communities (%)	
Proportion of severe waterlogging sites eliminated (severe = significantly disrupt public order/daily life) (%)	2022 Urban Health Assessment Indicator System [2]
Proportion of pervious surface area in the city (%)	
Per-capita effective shelter area (m^2/person)	
Coverage rate of Tier II-and-above hospitals (%)	
Coverage rate of standard and small general fire stations (%)	
Leakage rate of urban public water-supply networks (%)	
Designated emergency access routes	Resilience Indicators for Community Living Circle Planning [3]

At present, many resilience indicators — whether derived from spatial-planning metrics or from transport-resilience assessments — are population-based (that is, reliant on aggregate population figures). A persistent spatial mismatch exists, however, among hazard-prone areas, the populations exposed or vulnerable under specific disaster scenarios, and the geographic distribution of existing transport-resilience infrastructure. Consequently, population-based indicator design often fails to meet practical operational requirements during disaster response.

To support optimization of urban spatial layouts for climate adaptation and to advance climate-adaptive urban development, an indicator framework should be structured around two principal components: (a) climate-risk assessment, and (b) assessment of adaptive capacity. In order to better align transport-resilience planning with the needs of affected populations, indicator design should shift from a purely population-centric approach to a scenario-driven space–facility–group framework.

Table 2.2: Resilient Transportation Indicators
Source: Compiled by author, based on Xiamen Territorial Spatial Master Plan (2021–2035)

		Indicator	Temporal Granularity	Spatial Scale	Unit
Risk Assessment	Space–Facility	Total area of transportation, power, and other critical infrastructure located in high-risk hazard zones	Annual	City / Community	m^2
		Percentage of critical transport-infrastructure area damaged by meteorological hazards	Annual	City / Community	%
	Space–Population	Number of residents in high-risk areas, disaggregated for vulnerable groups (elderly; persons with chronic illnesses; persons with disabilities; pregnant women)	Real-time (rolling updates)	City / Community	
		Area of transport infrastructure destroyed or damaged by disasters (per 100,000 residents)	Annual	City / Community	m^2
Adaptability assessment	Facility	Land area of roads and highways retrofitted or structurally hardened	Annual	City / Community	m^2
		Total land area occupied by emergency material-staging and storage facilities (by spatial unit)	Real-time (rolling updates)	City / Community	m^2
		Total land area allocated for emergency transport infrastructure under specified meteorological scenarios	Annual	City / Community	m^2
		Percentage of population within service catchments of police, fire, and EMS under disaster conditions — defined by 3-km network distance in core urban areas and 10-km network distance in suburban areas	Annual	City / Community	%
		Percentage of designated emergency-route network length that remains passable during meteorological disasters	Annual	City / Community	%

2.2 Meteorological-disaster scenario analysis

Based on case studies, a targeted literature review and stakeholder consultations, a climate-related disaster-scenario analysis framework was developed. The framework comprises three sequential steps — scenario definition, scenario modelling and impact analysis — and is accompanied by a set of associated data and model requirements. As an illustrative case, the framework and the corresponding data-model requirements for heavy-rainfall and flood scenarios are presented in Figure 2.1.

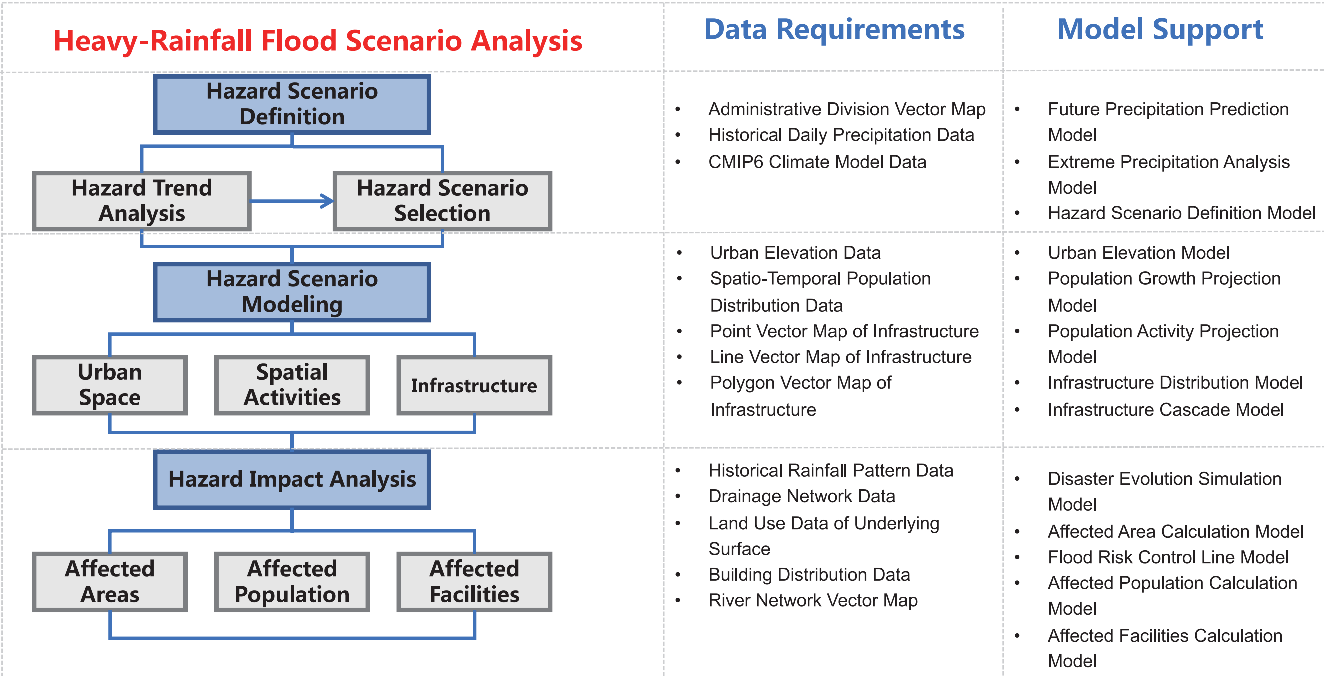

Figure 2.1: Analysis Framework for Heavy Rainfall and Flooding Scenarios
Source: Compiled by author

2.2.1 Disaster-scenario setting

To strengthen the resilience of urban transport systems to climate change and related meteorological hazards, disaster scenarios should be defined on the basis of observed hazard patterns and projected future trends and should integrate methods and datasets from relevant disciplines, including disaster science, meteorology, hydrology and water-resources engineering. Scenario definition should be grounded in a focused hazard-trend analysis and in explicit assumptions about socio-economic and infrastructural change over the planning horizon.

Hazard-trend analysis: Historical datasets relevant to pluvial and fluvial flooding must be assembled — for example, long-term precipitation records, documented flood incidents and losses, flood-risk zoning and inundation maps. For scenario construction, projected datasets should also be compiled in accordance with the planning horizons and anticipated socio-economic pathways; these datasets include projected precipitation time series, population distribution projections (with stated daytime/night-time or resident/commuting population assumptions), and projected urban-infrastructure inventories and footprints. From projected precipitation series (for instance, daily or hourly rainfall sequences over the planning period), a set of extreme-precipitation indicators should be derived — such as annual maximum daily rainfall, the number of heavy-rain days (with an explicitly stated threshold, e.g., ≥X mm/day), and sub-daily intensity measures (e.g., hourly peak rates) — using appropriate extreme-value and trend-analysis techniques.

Scenario selection and specification: Descriptive and extreme-value analyses of historical and projected precipitation series should be performed to identify threshold values for daily or hourly rainfall that correspond to different severity levels. For each planning horizon, scenarios of increasing severity should be defined by progressively higher precipitation thresholds. Each scenario must include a detailed specification of the event characteristics (for example, intensity, duration, spatial footprint and temporal evolution). In multi-hazard contexts, joint occurrence, interdependencies and cascading impacts between hazards should be examined.

2.2.2 Disaster-scenario modelling

Under heavy rainfall and flood scenarios, urban exposure and vulnerability elements are organized into three complementary dimensions — urban space, spatial activities and infrastructure — and disaster-scenario modelling is implemented by integrating elements from these dimensions within geospatial analysis platforms (for example, GIS coupled with hydrodynamic or hydraulic models).

Urban space modelling: The urban-space dimension represents the spatial substrate of social, economic and physical systems. Baseline spatial datasets required include administrative boundaries, city elevation (digital elevation) data, land-use/land-cover information, and flood-risk control lines. Urban-space modelling and simulation are carried out using digital-elevation models and land-use-change models, with consideration of urbanization trends and in conjunction with existing flood-risk prevention and mitigation works.

Spatial-activity modelling: Population density and temporal activity patterns drive exposure and potential losses. Accurate characterization of population distribution and activity patterns under different disaster scenarios is essential. Conventional demographic sources (for example, statistical yearbooks and census bulletins), together with large-scale digital datasets — including online map service logs, social-media indicators, crowdsourced platforms and mobile-app location data — should be used to derive temporal and spatial profiles of population presence and movement for scenario-specific exposure mapping.

Infrastructure representation: The modelling process must comprehensively represent the spatial configuration and functional characteristics of relevant infrastructure. For modelling purposes, infrastructure elements are categorized as point features (for example, emergency shelters, hospitals and fire stations), linear features (for example, road and rail networks, storm-water and water-supply pipelines) and areal features (for example, flood detention/retention basins, coastal wetlands and industrial zones).

2.2.3 Disaster impact assessment

Disaster impact assessment combines defined disaster scenarios with corresponding exposure models to evaluate the development and consequences of heavy rainfall and flood events. Based on simulated inundation depths, the assessment identifies and quantifies the affected areas, population, and facilities.

Inundation-depth analysis: Required input datasets include hydrological data (precipitation, evaporation, and rainfall processes), drainage-network data (drainage pipes, streets, stormwater inlets, pumping stations, and sluice gates), surface data (land use, topography, and building footprints), and boundary-condition data (drainage boundaries, river stages, and tidal levels). By integrating hydrological and hydraulic models, rapid data querying and combined spatial analysis can be performed to produce flood-inundation maps under different scenarios.

Disaster impact analysis: In line with the disaster-scenario modeling framework, the impacts are assessed across three dimensions: affected spatial areas, affected population, and affected facilities. Using GIS-based spatial analysis, flood-depth maps are converted into digital layers for overlay analysis. Through inundation analysis, spatial overlay, and application of vulnerability functions for relevant infrastructure, the spatial distribution and quantity of affected areas, population, and facilities are derived for each scenario.

2.3 Urban transportation resilience monitoring and evaluation

2.3.1 Spatial framework for transportation resilience assessment

Spatial monitoring and evaluation of transportation resilience for a climate-adaptive city are organized around three components: disaster-scenario development, urban assessment (city diagnostic), and spatial resilience evaluation under disaster conditions (Figure 2.2). Based on defined climate-hazard scenarios, the framework assesses the reasonableness of the integrated urban-infrastructure layout and informs dynamic adjustments to planning proposals.

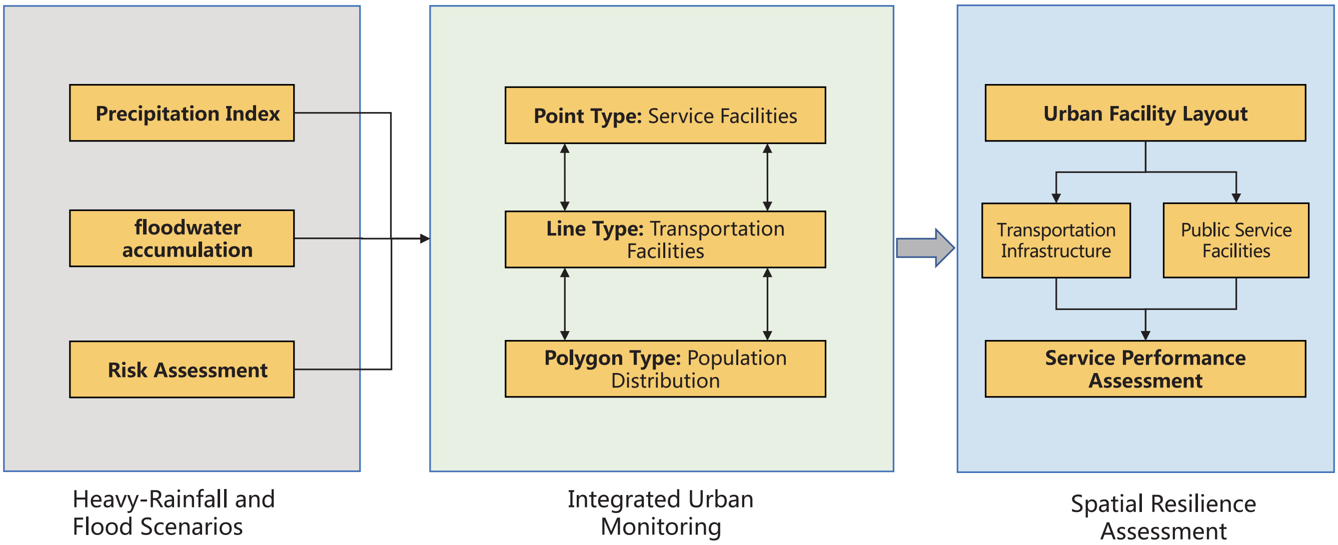

Figure 2.2: Technical Roadmap for Spatial Monitoring and Evaluation of Transportation Resilience in a Climate-Adaptive City
Source: Compiled by author

Indicator construction for a climate-adaptive resilient city is organized across three dimensions — population, infrastructure, and disaster-risk-reduction facilities. Under climate-hazard scenarios, these indicators are used to evaluate the coherence of integrated infrastructure layouts and to guide iterative adjustments of planning schemes. Figure 2.3 schematically presents the relationships among integrated infrastructure planning, spatial distribution, activity demand, and key demographic variables (for example, population density, community distribution, population mobility and the number of affected people). Starting from the integrated infrastructure layout plan, analysis proceeds along two principal streams: general infrastructure and disaster-risk-reduction facilities. For general infrastructure, the road and rail networks influence network performance metrics (for example, capacity, travel times, connectivity and operational reliability). For disaster-risk-reduction facilities, the availability and location of emergency shelters, evacuation and resettlement sites, and material-storage facilities determine levels of emergency service provision. Hazard drivers such as rainfall intensity and surface-water ponding affect infrastructure performance through impacts on drainage capacity and road passability. Climate-hazard scenarios are established from historical meteorological records and from outputs of hydrological and hydraulic flood simulations. Multi-source data are then input to the spatial-resilience assessment module for analysis of the current facility spatial layout. The spatial-resilience assessment module produces, for each scenario, analyses of evacuation capacity and the service catchments of evacuation routes and shelters, network performance metrics (efficiency and connectivity), measures of infrastructure redundancy and diversity, and indicators of physical vulnerability and system robustness (including facility stability, equipment robustness and estimated network damage potential).

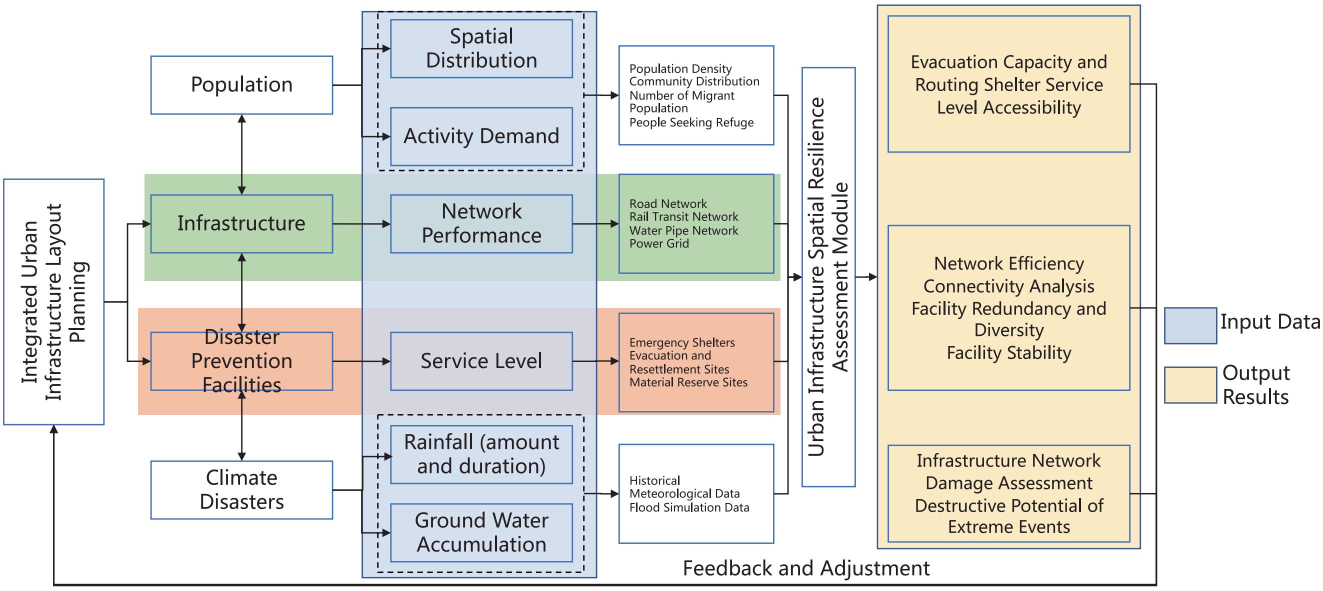

Figure 2.3: Inputs and Outputs for Spatial Resilience Evaluation of Climate-Adaptive Urban Infrastructure
Source: Compiled by author

2.3.2 Spatialized transportation-resilience monitoring method

Based on the *Code of practice for comprehensive disaster prevention planning of territorial space* and relevant urban-infrastructure plans and relevant urban-infrastructure planning documents [4], a spatial layout plan for urban infrastructure is developed with a focus on the city's transport system. The proposed plan is evaluated against existing conditions and is elaborated according to the infrastructure layout typologies of nodes, corridors, and networks. Planning schemes are developed in accordance with key urban-infrastructure development indicators (Table 2.3) and applicable emergency-shelter design standards.

Table 2.3: Urban Infrastructure Layout Planning Indicators
Source: Compiled by the author, based on China Urban Vitality Check and Evaluation Indicator System and Guidelines for the Compilation of Territorial Spatial Master Plans

Category	Planning Indicator	2020 Status
Comprehensive	Share of urban infrastructure construction investment in total social fixed-asset investment (%)	6.65
Transportation System	Completion rate of survey and archival records for urban underground utility (pipe) networks (%)	---
	Urban road-network density (km / km²)	7.07
	Proportion of commuters within an 800-m walking catchment of rail-transit stations (%)	Megacities: 26 Extra-large cities: 17 Large cities: 8

Emergency-access routes at each shelter tier should interconnect and should link to external emergency roads with emergency-support levels equal to or exceeding the shelter's assigned tier. The emergency-support levels and associated requirements for shelters should comply with the specifications provided in Table 2.4. Minimum effective widths for emergency routes are specified as follows: principal disaster-relief routes ≥ 15 m, primary evacuation routes ≥ 7 m, and secondary evacuation routes ≥ 4 m (Table 2.4).

Table 2.4: Emergency-Transport Support Levels and Requirements for Shelter Facilities
Source: Compiled by the author, based on Code for Design of Disaster Shelter (GB 51143-2015)

Emergency-Transport Support Tier	Emergency Access Routes	Number of Shelter Entrances/ Exits (count)
I	Primary disaster-relief artery, or main evacuation routes providing access from two or more directions	≥4
II	Primary disaster-relief artery, main evacuation route, or secondary evacuation routes providing access from two or more directions	≥2
III	Primary disaster-relief artery, main evacuation route, and secondary evacuation routes	≥2

Infrastructure and disaster-prevention plans are revised according to population distribution, defined extreme-event scenarios, and projected change trends. Extreme climate hazards include climate warming, prolonged drought, heavy rainfall and flooding, and sea-level rise. Monitoring elements encompass affected population distribution, effective evacuation area, emergency-shelter population capacity, and emergency evacuation distance (Table 2.5).

Table 2.5: Dynamic Spatial Monitoring Elements for Urban Infrastructure
Source: Compiled by the author, based on China Urban Vitality Check and Evaluation Indicator System and Guidelines for the Compilation of Territorial Spatial Master Plans

Major Element Category	Mid-level Element Category	Reference Indicator(s)
Settlements and facilities	Residential settlements; public-service facilities; buildings and associated facilities	Service catchment area; service population; effective evacuation area; emergency evacuation distance
Transportation	Railways; roads (including highways); transport facilities	Road/rail network density; total route mileage or vehicle-kilometers traveled (VKT); average vehicle speed; commute time
Boundaries and administrative divisions	Municipal-level; district/county-level administrative units	–
Landforms / Topography	Contour lines; elevation; water bodies	Elevation / altitude; water-body area

2.3.3 Methodology for spatially explicit transportation resilience assessment

The spatially explicit assessment of urban transportation resilience is undertaken at three analytical levels — population groups, infrastructure, and public-service facilities. Delivery of services and goods generated by human activities is mediated through the urban transport network; the assessment therefore evaluates the network's overall operational efficiency and, under heavy rainfall–induced flood scenarios, the network's connectivity, redundancy, diversity and accessibility. Quantified indicators for each dimension are combined by a specified weighting scheme to produce a composite spatial-resilience score for the selected flood scenario (Figure 2.4).

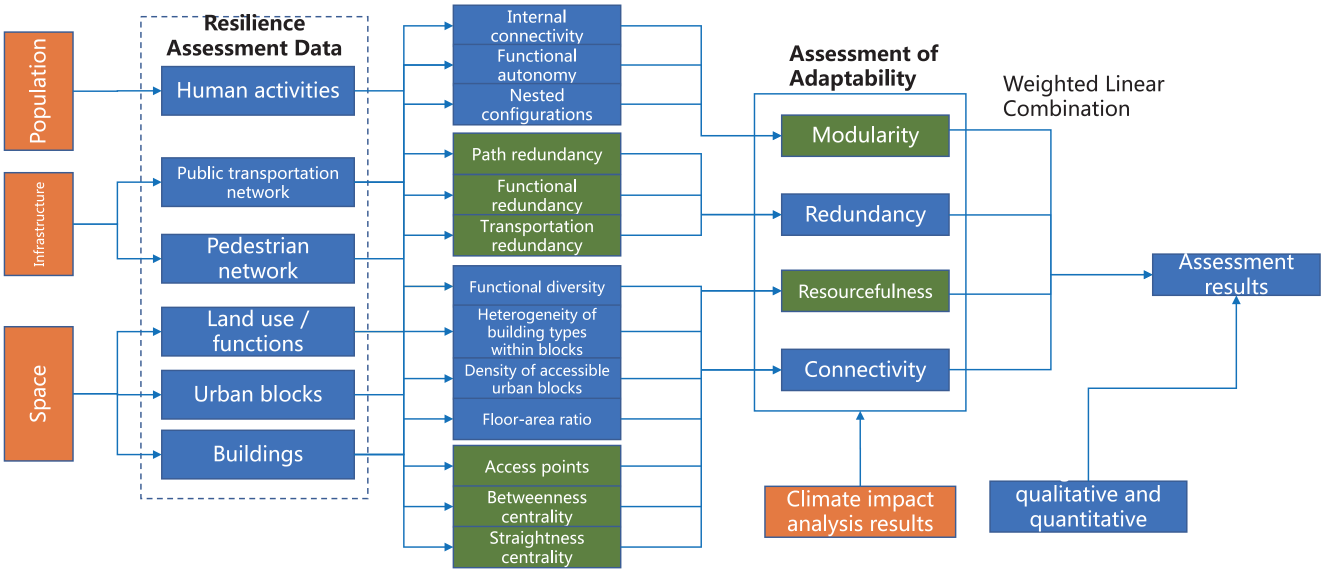

Figure 2.4: Flowchart of the Urban Spatial Transportation Adaptive-Capacity Assessment Procedure

Source: Compiled by author, based on Nel D H. Morphologies of resilience: Towards an approach to the study of urban spatial resilience [D]., 2022

(1) Computation of a parcel-level comprehensive urban flood damage rate

Flood depth–damage functions represent disaster risk vulnerability, describing the relationship between the degree of damage to exposed elements and the inundation depth. Incorporating flood-risk avoidance strategies into urban expansion simulation first requires calculating the comprehensive urban flood damage rate for each parcel within the city. The flood depth–damage functions developed by the Joint Research Centre (JRC) of the European Union for five types of urban land use in Asia—residential, commercial, industrial, transport and infrastructure—are used for this calculation [5]. Computation of the comprehensive urban flood damage rate takes into account extreme future flood conditions and the probability of land parcels being developed for different functional uses; therefore, a series of integrations is performed across various future return periods, flood types and urban land-use classifications. The formula is provided below:

$$\begin{cases} MFD^{rp} = \max\{FD^{rp}_{t,type}\} \\ SLR_{uf} = \dfrac{\sum_{rp} f_{uf}(MFD^{rp}) * RPP^{rp}}{\sum_{rp} RPP^{rp}} \\ SUFR = \sum\limits_{uf} SLR_{uf} * RFP_{uf} \end{cases}$$

Notation: MFD^{rp} = maximum inundation depth associated with return period. $FD^{rp}_{t,type}$ = flood depth in year t for flood type under return period rp. SLR_{uf} = composite (return-period–aggregated) flood-damage rate for urban functional zone uf. f_{uf} = depth–damage function for functional zone uf, mapping inundation depth h to damage fraction (or monetary loss). RPP^{rp} = annual occurrence probability of an event with return period rp, i.e., Prp = 1/rp. SUFR = comprehensive urban flood damage rate (system-level aggregated metric). RFP_{uf} = suitability probability of functional zone uf as output by a Random Forest (RF) model.

(2) Spatial connectivity for urban infrastructure resilience

Connectivity is a measure of a network's resilience to random failures. By analyzing the graph configuration, accessibility, flow and efficiency are assessed and — as the basis for connectivity indicators — normalized to a 0–1 index standard [6]. Betweenness centrality assesses how often a location lies on the shortest path between two given locations, and is calculated using a hybrid metric that minimizes angular choice and metric distance. The formula is as follows:

$$\mathrm{BTW}(x) = \sum_{y \in N} \sum_{z \in R_y} W(y)W(z)P(z)OD(y,z,x)$$

$$\mathrm{OD}(y,z,x) = \begin{cases} 1, \text{if } x \text{ is on the first geodesic found from } y \text{ to } z \\ \frac{1}{2}, \text{if } x = y \neq z \\ \frac{1}{2}, \text{if } x = z \neq y \\ \frac{1}{3}, \text{if } x = z = y \\ 0, \text{Otherwise} \end{cases}$$

The betweenness degree of x is the sum, over origin–destination pairs (y,z), of the shortest geodesic paths from y to z that pass through x. Here, N denotes the entire network; Ry is the evaluation radius; W(y) and W(z) denote the network weights of the end points y and z, respectively; and OD(y,z,x) denotes the terminal link(s) of the geodesic path.

Because the straightness metric enables the comparison of distances between two points, all distance measurements are expressed in meters. In this study, the straightness metric is evaluated on the road network using distance radii of 1,000 m, 1,500 m, and 3,000 m, which approximately correspond to walking times of about 10, 20, and 30 minutes, respectively. The metric is defined as the average ratio of the geodesic (network) path length to the straight-line (Euclidean) distance for all links within the specified measurement radius. The formula is as follows:

$$\mathrm{Div(x)} = \frac{\sum_{y\in R_x} \frac{d_M(x,y)}{CDF(x,y)} W(y)P(y)}{\sum_{y\in R_x} W(y)P(y)}$$

CDF(x,y) denotes the straight-line (Euclidean) distance between the centroids of locations x and y (units: m). dm (x,y) denotes the network (geodesic) distance from origin x to destination y computed under metric M (units: m). W(y) denotes the weight associated with node y; this may represent node-specific attributes such as demand, population, or facility importance (specify exact meaning in the methods). P(y) denotes the proportion of a given polyline (e.g., road segment or path) that lies within the defined measurement radius (i.e., polyline-length-in-radius / total polyline length).

The Gaussian function is used to quantify the number of locations reachable via the network from a given origin within a specified distance or travel-time threshold.

$$A_i = \sum_j l_j e^{(-t_{ij}^2/\beta)}$$

Here, accessibility A is the sum of all available locations l at destinations j reachable within travel time t, weighted by an impedance kernel parameterized by β that reflects travel cost. Figure 2.5 presents a conceptual illustration of the Gaussian function's fractal-penalty application along a multi-modal trip [7]. At the start of a trip, the initially slower rate of decay corresponds to the initial (walking) stage. This is followed by a transition to public transport, where the penalty is larger, and finally by the trip's final leg.

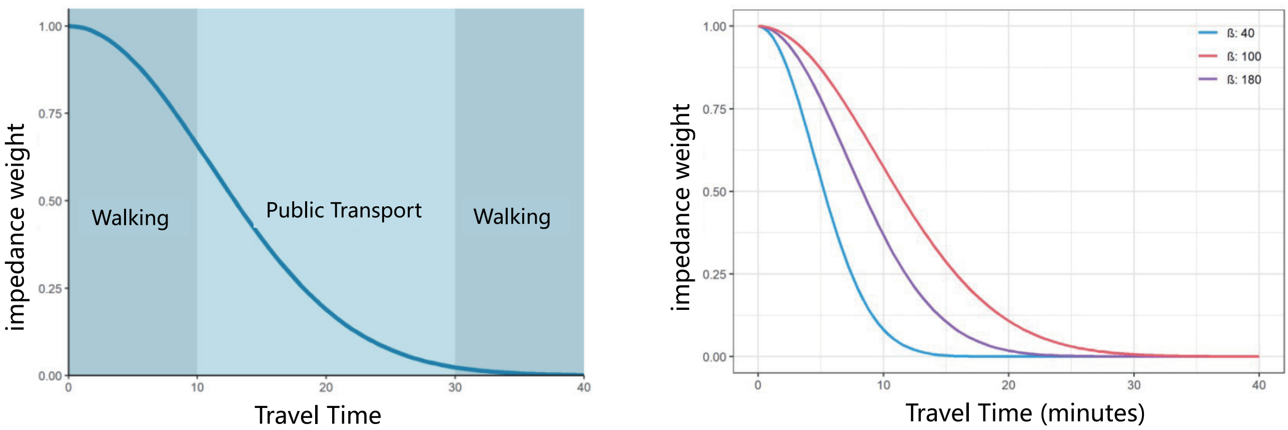

Figure 2.5: Conceptual Visualization of the Fractal Penalty of the Gaussian Function in Multi-Modal Trips
Source: Compiled by author, based on Nel D H. Morphologies of resilience: Towards an approach to the study of urban spatial resilience [D]., 2022

(3) Spatial diversity for urban infrastructure resilience

The diversity index quantifies the relative variety or homogeneity of elements within a given area [8]. The input dataset for this assessment comprises infrastructure types, the transport network, analysis units, and their built volumes (or built-up quantities). Diversity is evaluated using the Mixed-Use Accessibility Index (MXI^A) together with a measure of functional uniformity. To assess functional mix relative to the entire study area, we compute ratios such as (total residential facilities) / (total transportation facilities) and (total disaster-prevention/emergency facilities) / (total transportation facilities).

$$MXI_i^A = \frac{\sum A^{w_L}{}_{j,live} f(t_{ij,live})}{A_{i,total}}; \frac{\sum A^{w_W}{}_{j,aid} f(t_{ij,aid})}{A_{i,total}}; \frac{\sum A^{w_V}{}_{k,visit} f(t_{ij,visit})}{A_{i,total}}$$

Access impedance (threshold) function

$$f(t_{ij}) = \begin{cases} 1 \; for\; tij \le \bar{t} \\ 0 \; otherwise \end{cases}$$

Weighting functions

$$w_{L=1};\; w_{W=\frac{L_T}{W_T}};\; w_{V=\frac{L_T}{V_T}}$$

Variable definitions A: Accessible area (or total accessible opportunities) used in the numerator terms. W_L (appearing in the formula as W_L): Weight applied to the total accessible residential facilities. W_w (appearing in the formula as W_w): Weight applied to the total accessible disaster-prevention / emergency facilities. W_v (appearing in the formula as W_v): Weight applied to the total accessible transportation facilities. t: Total travel time (generalized travel cost) between origin i and destination j. $A_{i,\ total}$: Total weighted accessible area for analysis unit i. L_T, W_T, V_T: Total counts, within the study area, of Residential (L_T), Disaster-Prevention / Emergency (W_T), and Transportation (V_T) facilities, respectively.

(4) Spatial redundancy for urban infrastructure resilience

Spatial redundancy is assessed by evaluating three types of functional redundancy in the urban environment [9]. Required data include the locations of urban facilities (for example, schools, hospitals and emergency services), the evaluation units (parcels or buildings), the pedestrian network and public-transport stops; results for each redundancy type are normalized. An accessibility-based method is applied to delineate, for every location on the primary network, the subnetwork lying within a specified distance. For each distance radius, a separate subnetwork is constructed for each origin, allowing the number of theoretically available alternative routes that can reach that origin within the specified distance to be identified.

$$\mu_i = \sum e_j f(t_{ij}) - \sum v_j f(t_{ij}) + 1$$

Where e denotes the number of links associated with subnetwork element j, v denotes the number of nodes reachable within travel time t between origin i and destination j.

3. Xiamen: Spatial Resilience Evaluation for Emergency Service Facilities

3.1 Study-area selection

Comprehensive datasets for Xiamen — including flood-risk maps, population distribution, emergency shelters and disaster-relief warehouses — were obtained for this study; accordingly, the full municipal area of Xiamen was selected as the study domain for the flood-resilience assessment. Geographic coordinates of the municipality are 24°23′–24°54′ N and 117°52′–118°26′ E. Figure 3.1 shows the municipal administrative divisions: Tong'an District, Xiang'an District, Jimei District, Haicang District, Siming District and Huli District. Use of the entire municipal boundary as the study extent enables a more precise analysis of flood impacts, the distribution of emergency-shelter resources and the current spatial resilience profile, thereby providing a robust data foundation for subsequent analyses.

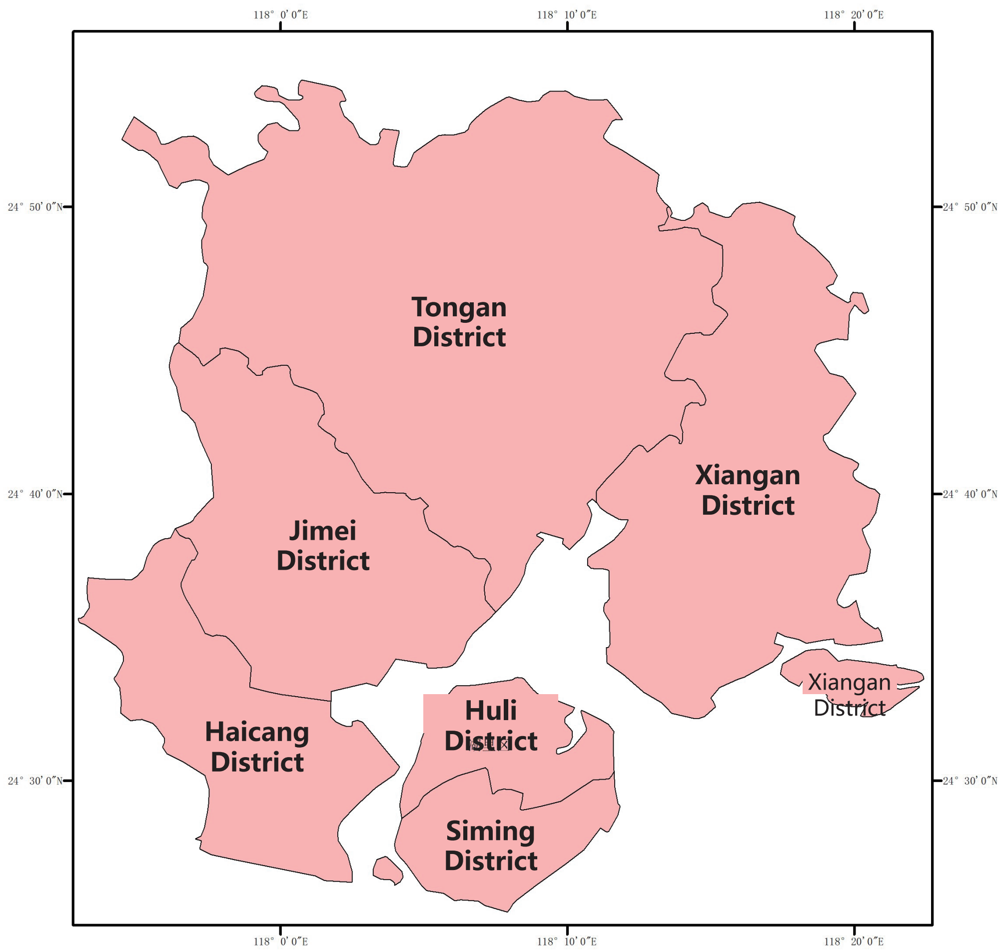

Figure 3.1: Study Area
Source: Compiled by author

3.2 Baseline data

Analysis relied on district-level data for permanent resident population, shelter counts, available shelter area and total shelter capacity across Xiamen's six administrative districts. The objective is to evaluate district-level emergency-sheltering capability and to provide empirical support for optimizing shelter distribution and strengthening emergency response. Figure 3.2 displays population distribution along major thoroughfares across the districts; Jimei District exhibits the highest local population density.

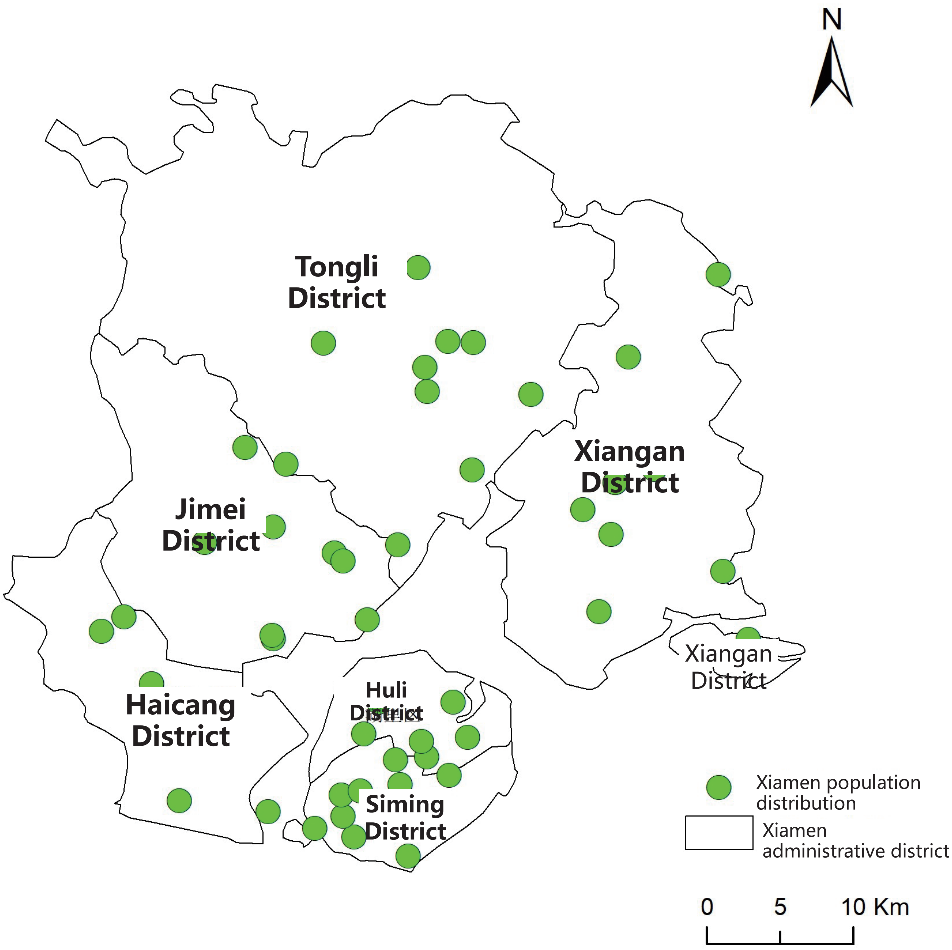

Figure 3.2: Population Distribution along Major Communities in Xiamen
Source: Compiled by author

Figure 3.3 and Table 3.1 present the spatial distribution and quantitative summary of shelters in Xiamen. Tong'an District (179 shelters) and Xiang'an District (158 shelters) report the largest shelter counts, consistent with their larger territorial extents and more dispersed settlement patterns. By contrast, Haicang District (63 shelters) and Huli District (66 shelters) have fewer shelters, which may limit district-level sheltering capacity under extreme events. Jimei District has the largest available shelter area (525,892 m²), supporting a shelter capacity of 103,040 persons.

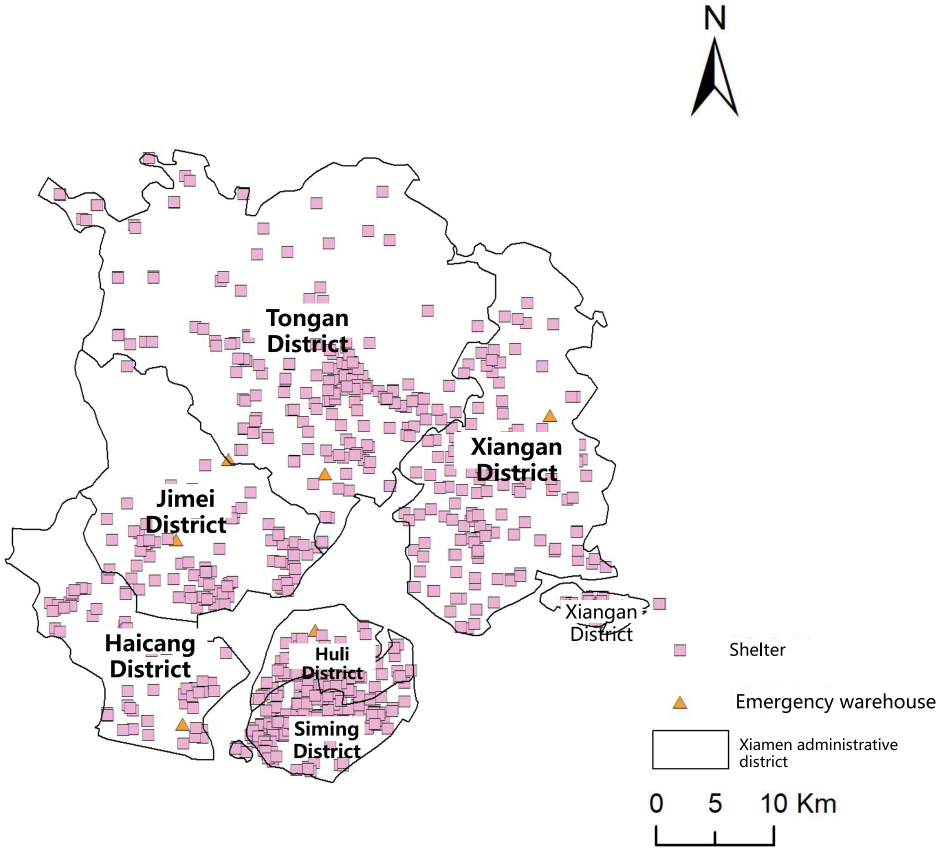

Figure 3.3: Distribution of Emergency Service Facilities in Xiamen
Source: Compiled by author

District-level shelter indicators show the following: Huli District's available shelter area is 235,700 m², corresponding to a shelter capacity of 53,180 persons. Siming District has a substantial aggregate shelter area, but its per-capita shelter allocation is constrained by a relatively large resident population. Tong'an District reports the highest shelter capacity (188,225 persons), representing 21.6% of its resident population — a markedly higher share than in other districts. Huli District's shelter capacity (53,180 persons) represents 5.6% of its resident population, the lowest proportion among the six districts and indicating relatively limited shelter provision. Siming District's shelter capacity (93,522 persons) corresponds to 9.5% of its resident population, substantially lower than typical emergency-shelter benchmarks.

Table 3.1: Population Distribution and Shelter Capacity by Administrative District in Xiamen
Source: Compiled by author

Administrative District	Resident Population (persons)	Number of Shelters	Available Shelter Area (m²)	Capacity (persons)
Haicang District	610,346	63	147,520	89,243
Siming District	983,421	137	371,947	93,522
Huli District	951,122	66	235,700	53,180
Jimei District	1,087,726	89	525,892	103,040
Tongan District	870,813	179	462,510	188,225
Xiang'an District	699,322	158	195,303	123,532

As of 2022, Xiamen's road network consisted of three expressways, three national highways, five provincial highways, forty county-level roads, and an extensive set of township and village roads. Connectivity to and from Xiamen Island is provided by five bridges, two tunnels and one sea dike (seawall). This configuration has resulted in a transport network characterized by internal and external connectivity and a ring-and-radial structure around the bay. The total length of operational roads in the city (excluding natural village tracks) is 2,135.19 km, distributed as follows: national highways — 263.14 km; provincial highways — 223.82 km; county roads — 394.90 km; township roads — 608.97 km; and village roads — 644.36 km. By technical classification, the breakdown is: expressways — 123.51 km; Class I roads — 453.42 km; Class II roads — 212.46 km; Class III roads — 158.65 km; and Class IV roads — 1,187.15 km. Figure 3.4 shows the road-network vector data obtained from OpenStreetMap (OSM).

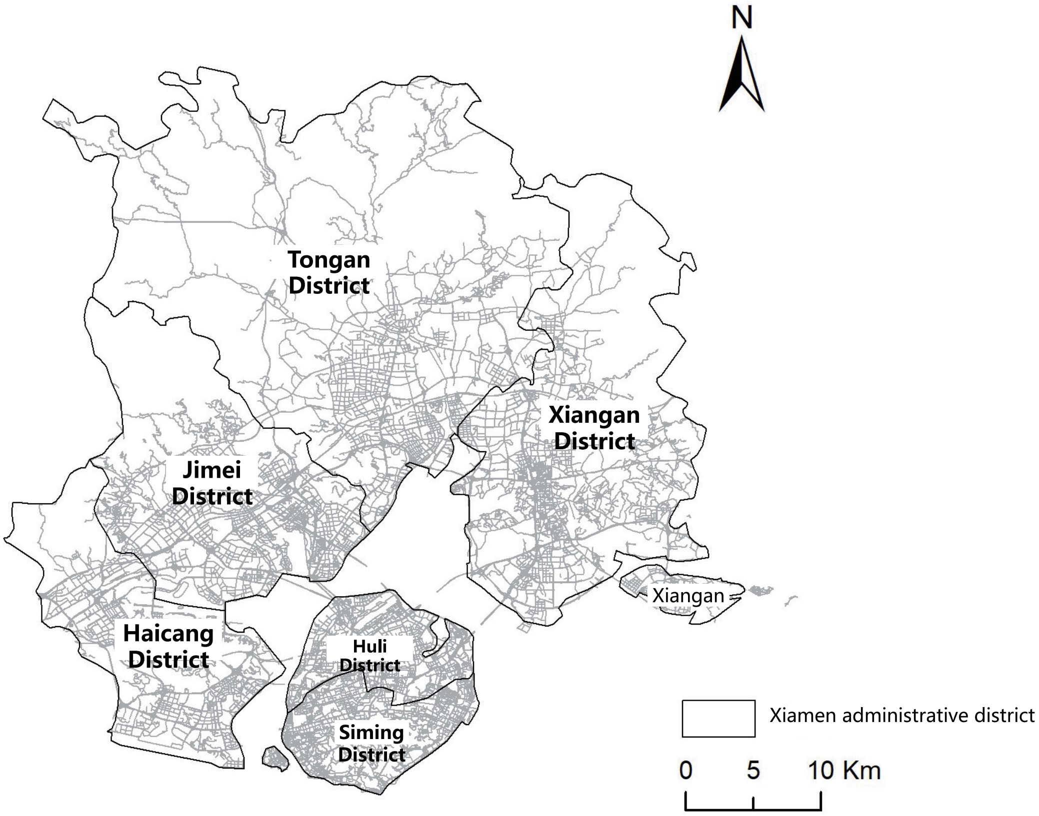

Figure 3.4: Xiamen Road-Network Distribution
Source: Compiled by author

3.3 Construction of heavy rainfall and flood scenarios

A flood-risk model for Xiamen was developed using Geographic Information System (GIS) techniques by integrating historical flood records, topography and geomorphological data, and hydrological conditions. The model produced flood-risk scores for spatial units across the city (Figure 3.5). Flood-risk scores range from 1.3 to 4.37; parts of Tong'an, Jimei and Xiang'an Districts exhibit relatively high scores (darker shading), indicating greater potential flood exposure. Siming and Huli Districts exhibit comparatively low scores (lighter shading), while Haicang and the Gulangyu area display moderate values.

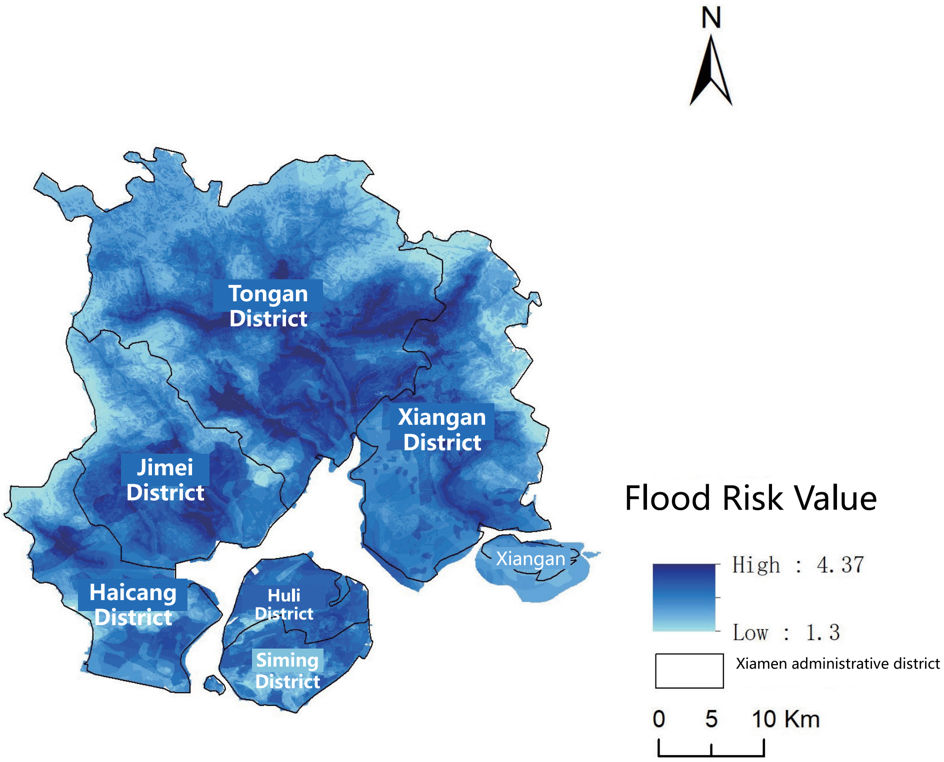

Figure 3.5: Flood-Risk Scores for Xiamen
Source: Compiled by author

Figure 3.6(a) illustrates the potential flood-risk zones identified from the model outputs. Given the observed score range (1.3–4.37), areas with scores ≥ 3 were classified as potential flood-risk zones and are shown with cross-hatch shading. Within these potential zones, random probabilistic sampling was used to generate specific impacted areas; two classes of affected areas were obtained from the sampling procedure, as shown in Figure 3.6(b).

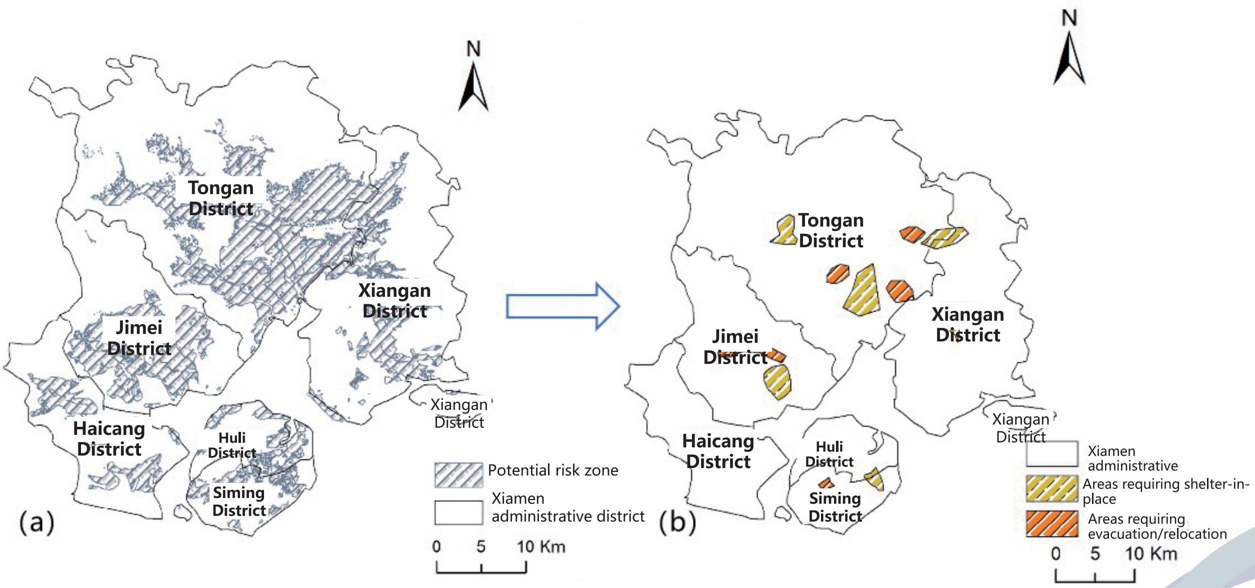

Figure 3.6: Potential Flood-Risk Areas in Xiamen
Source: Compiled by author

Figure 3.7 illustrates the spatial distribution of disaster-risk management resources and population. Shelters (pink squares) are distributed across the city to provide temporary refuge for residents during disasters. Emergency warehouses (yellow triangles) store relief supplies for rapid deployment in emergency situations. Population distribution is shown by green dots, the density of which reflects local population concentrations. Potential risk zones are indicated by cross-hatch shading and denote areas that may face elevated natural-hazard risk, such as flooding and seismic events. The road network is depicted with gray lines, showing primary roads and expressways that are critical for emergency response.

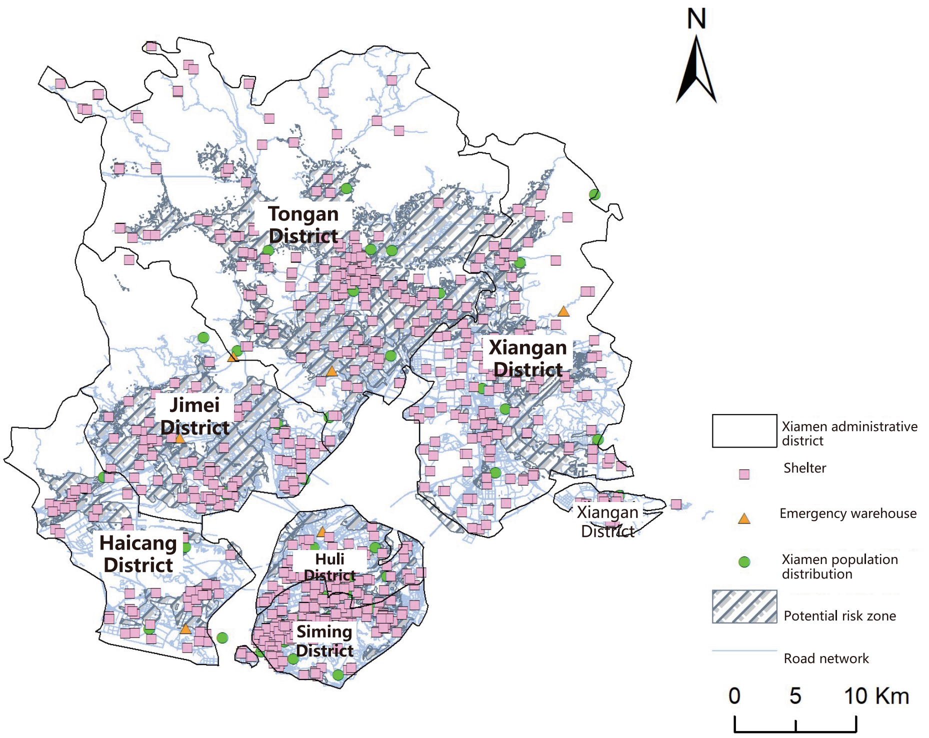

Figure 3.7: Distribution of Facilities and Population Under Potential Flood Risk in Xiamen
Source: Compiled by author

3.4 Resilience assessment of emergency service facilities in Xiamen

Analysis focused on impacts to emergency shelters in Siming, Huli, Jimei, Tong'an and Xiang'an Districts under disaster conditions. The dataset comprised, by district, the number of affected shelters, damaged shelter area, number of persons requiring relocation, and number of persons seeking shelter. The assessment aimed to evaluate the adequacy of shelter layout and the district-level emergency-sheltering capacity, providing empirical support for subsequent optimization.

District-level findings (Table 3.2): Tong'an District was the most severely affected, with 31 shelters damaged — the vast majority of all affected shelters in the city. This may be due to the complex geographical environment of Tong'an District, which is prone to extreme weather events and flooding. Jimei District had 10 affected shelters, second only to Tong'an District, indicating that some of its shelters are located in higher-risk areas. Siming and Xiang'an Districts had 5 and 4 affected shelters, respectively, with relatively minor impacts. Huli District had only 1 affected shelter, representing the least impact among all districts. Tong'an District experienced the largest loss of shelter area, totaling 100,428 m², accounting for the vast majority of lost shelter area city-wide. Such a substantial loss of shelter area could significantly affect the district's emergency-sheltering capacity and warrants particular attention. Jimei District lost 24,215 m² of shelter area; although smaller than Tong'an District, this loss still requires vigilance. Xiang'an and Siming Districts lost 7,847 m² and 4,187 m², respectively, with comparatively limited impact. These results indicate that the high relocation demand in Tong'an and Jimei Districts is largely attributable to complex terrain and uneven shelter distribution. In central districts such as Siming, shelter utilization efficiency is relatively high; however, a mismatch persists between facility capacity and the demand for evacuation.

Table 3.2: Summary of Affected Shelters and Populations under Flood Scenarios
Source: Compiled by author

Administrative District	Number of Damaged Shelters	Damaged Shelter Area (m²)	Population Relocated (persons)	Population Seeking Shelter (persons)
Siming District	5	4,187	380,626	391,230
Huli District	1	200	0	116,890
Jimei District	10	24,215	348,035	394,770
Tongan District	31	100,428	660,540	634,896
Xiang'an District	4	7,847	0	481,766

As shown in Figure 3.8, Tong'an District has the largest population requiring relocation, totaling 660,540 persons, which represents approximately 104% of its shelter-seeking population; this indicates significant pressure on existing shelter capacity and layout. Jimei District's relocation population is 348,035 persons, representing 88.2% of its shelter-seeking population, indicating that shelter capacity is near saturation and that layout adjustment has substantial potential. Siming District's relocation population is 380,626 persons, slightly lower than its total shelter-seeking population; relocation pressure is therefore high, although sheltering needs are largely met. Xiang'an District's shelter-seeking population totals 481,766 persons, and no relocations are required, indicating that the district's shelter layout and capacity are well adapted to the scenario.

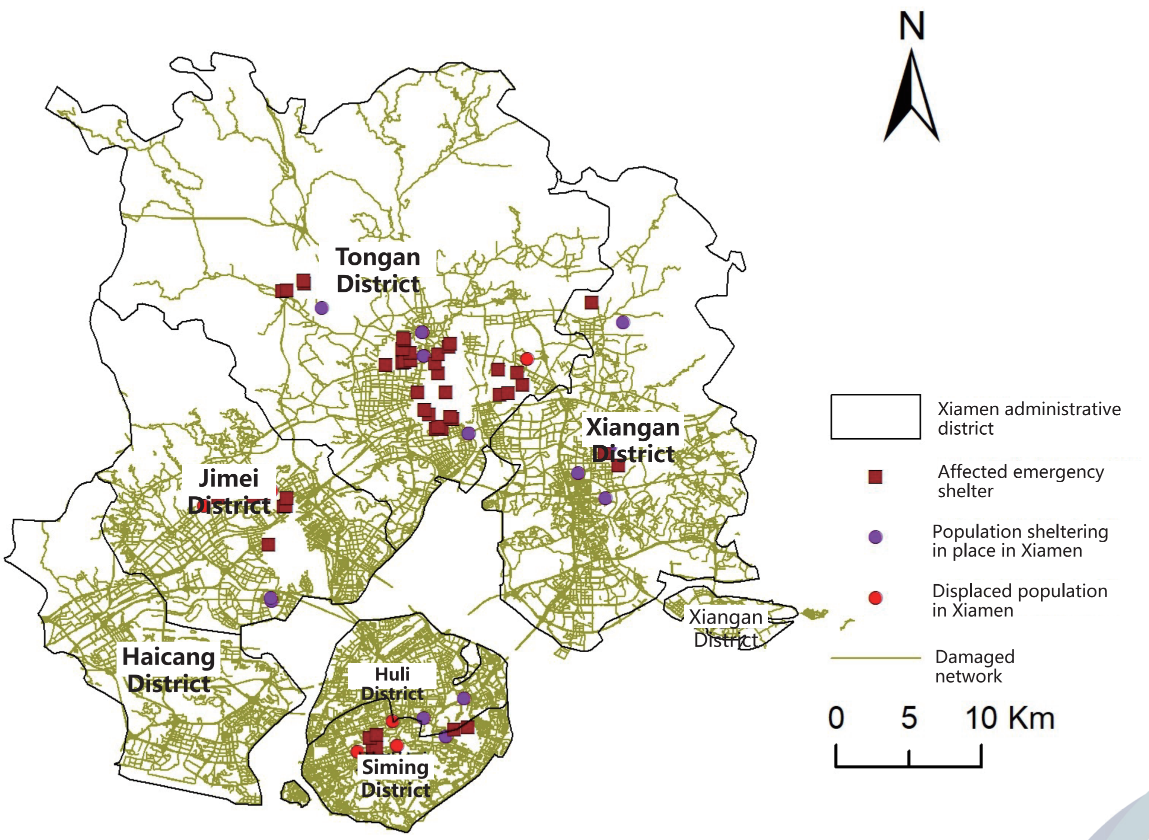

Figure 3.8: Affected Population and Shelter Distribution Under Different Heavy Rainfall and Flood Scenarios
Source: Compiled by author

Figure 3.9 illustrates emergency planning for populations requiring relocation under a flood scenario; relocation points A–I (nine locations) are indicated. Green squares denote shelters that continue to provide services under flood impact. The relocated population is mainly distributed in Tong'an, Jimei, Siming and Huli Districts. Subsequent tables present analyses of shelter service efficiency.

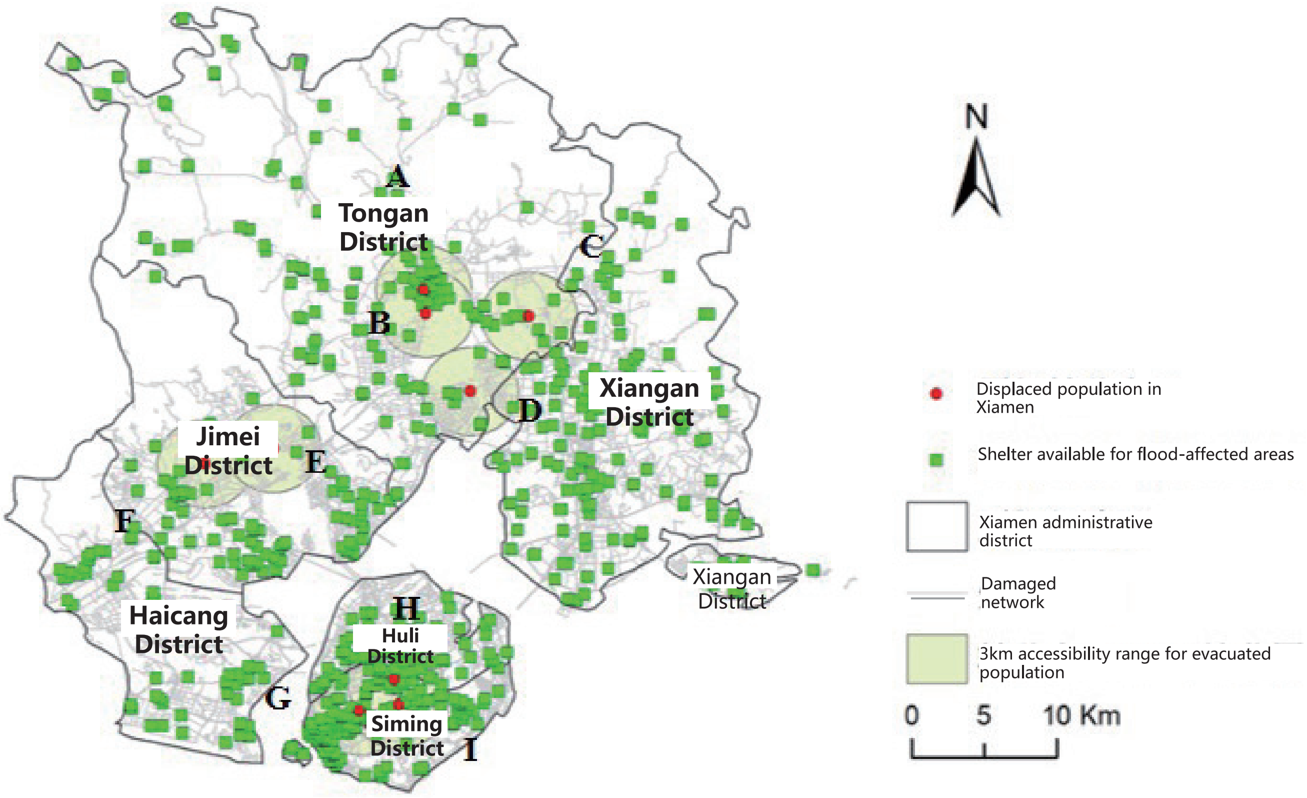

Figure 3.9: Damaged Facilities and Affected Population Under a Flood Scenario
Source: Compiled by author

Figure 3.10 shows the affected-population ratio across administrative districts. The Low affected-population-ratio category (0.00%–12.29%) includes Xiang'an, Huli and Haicang Districts; these areas display relatively low affected-population ratios, which may reflect well-distributed disaster-prevention infrastructure or favorable geographical conditions. The Moderate category (12.29%–14.88%) corresponds to Tong'an District; Tong'an's affected-population ratio is slightly higher than the low-ratio areas but remains within a moderate range, suggesting the need for maintenance of existing measures and potential improvements. The Relatively High category (14.88%–68.88%) includes Jimei and Xiang'an Districts, indicating comparatively large affected-population ratios and highlighting areas where disaster-prevention and mitigation measures could be strengthened. The High category (68.89%–78.48%) is Siming District; Siming's affected-population ratio is the highest, implying pronounced vulnerability that warrants priority attention for disaster-prevention measures such as infrastructure reinforcement and enhanced public preparedness.

Overall, Siming District requires particular attention owing to its high affected-population ratio; Jimei and Xiang'an Districts also warrant attention in order to reduce affected-population ratios. Tong'an, Huli and Haicang Districts display relatively lower ratios but should maintain existing prevention measures and pursue incremental improvements.

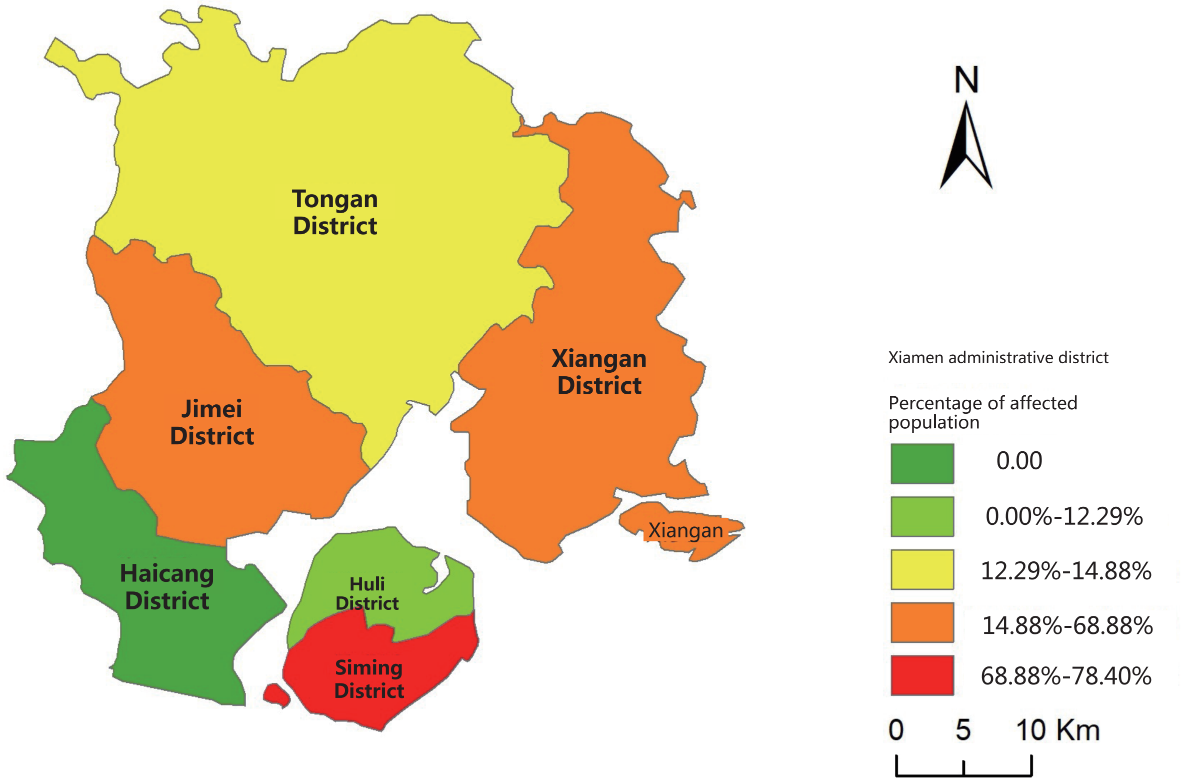

Figure 3.10: Proportion of the Affected Population by Administrative District
Source: Compiled by author

Table 3.3 summarizes the statistics for emergency relocation planning under the flood scenario. There are clear differences in the scale of relocated populations across zones: Zone B has the largest relocated population, followed by Zones E and A; Zones C and H have comparatively smaller relocated populations. Regarding facility capacity within a 3-km radius, Zone H has the largest service capacity, accommodating 40,705 people and satisfying most of its projected relocation demand. Zone F has the smallest facility capacity, which is far from sufficient to accommodate its projected relocated population of 85,771. Similarly, Zones E and G have capacities of 7,700 and 6,090 people, respectively, indicating severely insufficient service capability. Within the 3-km radius, most zones (e.g., F, E, and G) exhibit a clear shortfall in facility capacity, leaving a large proportion of relocated population without adequate local service coverage. This phenomenon is especially pronounced in zones with large relocated populations, such as B and A. In certain zones (notably F, E, and G), projected demand would only be satisfied if the service coverage radius were extended beyond 11 km—far exceeding the 3-km standard. Extending coverage to such distances is likely to reduce relocation efficiency and increase evacuation traffic load during disasters.

Table 3.3: Emergency Planning for Populations Requiring Relocation under the Flood Scenario
Source: Compiled by author

Relocation Population Index	Population Requiring Relocation (Persons)	Facility Service Capacity within 3 km (Persons)	Proportion of Population Whose Needs Cannot Be Met	Minimum Service Radius Required to Meet Demand (km)
A	90,759	29,200	67.83%	8.5
B	115,176	29,250	74.60%	10
C	25,732	8,400	67.36%	6.3

Relocation Population Index	Population Requiring Relocation (Persons)	Facility Service Capacity within 3 km (Persons)	Proportion of Population Whose Needs Cannot Be Met	Minimum Service Radius Required to Meet Demand (km)
E	98,602	7,700	92.19%	11
F	85,771	400	99.53%	11
G	88,246	6,090	93.10%	11.5
H	44,699	40,705	8.94%	3.6
I	80,936	53,160	34.32%	5

3.5 Summary

3.5.1 Conclusions

Assessment indicates that the spatial distribution of emergency service facilities in Xiamen is generally reasonable and, in most circumstances, capable of supporting effective flood response. The existing facilities exhibit strong flood-resilience performance and can maintain effective emergency service delivery during extreme meteorological events. Nevertheless, a degree of spatial unevenness exists, particularly with respect to the siting and allocation of emergency shelters and disaster-relief warehouses.

In areas where facilities are relatively concentrated or unevenly distributed, affected populations may experience delayed access to shelter, rescue, and supply services during flood events. This spatial mismatch warrants careful attention. To further enhance the efficiency of emergency services under flood conditions in Xiamen, future emergency planning should focus on optimizing facility layout and strengthening coordination between districts, thereby improving overall emergency response efficiency and ensuring rapid response and resource allocation during disaster events.

3.5.2 Recommendations

(1) Strengthen inter-district coordination and improve emergency resource allocation efficiency

Under conditions of limited resources, districts within Xiamen should establish inter-district coordination and allocation mechanisms to fully utilize existing emergency service facilities and strengthen overall emergency response capacity. Authorities should develop flexible mechanisms for inter-district resource sharing and reallocation to ensure that emergency resources can be mobilized promptly to support affected areas during disasters. Such mechanisms can help balance resource distribution across districts, avoid excessive concentration or shortage in particular areas, and reduce post-disaster response time. For instance, when the capacity of a shelter or warehouse in one district reaches its limit, resources from other districts can be mobilized to meet the needs of all affected areas, ensuring timely sheltering and rescue for residents.

(2) Optimize shelter layout and strengthen shelter service capacity

Building on existing emergency facilities, Xiamen can further improve shelter planning as follows: 1) Increase the number of shelters in flood-prone areas to avoid people being stranded or experiencing delays in evacuation due to insufficient facilities. Expanding the number of shelters enhances emergency service coverage, disperses population density, and improves efficiency in sheltering; 2) Expand and upgrade existing shelters to increase their capacity, ensuring that larger numbers of affected residents can be accommodated during extreme meteorological events. In densely populated areas, enlarging shelter capacity can reduce overcrowding during evacuation; 3) Improve accessibility of shelters by enhancing transport connections, ensuring that primary evacuation routes remain passable during floods. Evacuation routes should be optimized based on regional traffic conditions to prevent road damage or inundation from impeding movement of people and supplies. Temporary traffic guidance facilities should be established along evacuation routes to enable affected residents to reach shelters quickly and safely.

4. Conclusions and Outlook

4.1 Conclusions

This study integrates urban flood disaster governance with transportation resilience assessment within a comprehensive framework. Focusing on the evaluation and improvement of urban flood resilience levels, the research systematically examined the concept, indicator system, scenario construction, assessment methods, and layout planning. The main conclusions are as follows:

(1) A comprehensive indicator system for assessing urban flood resilience was developed and applied to specific disaster scenarios. By analyzing factors such as service efficiency, accessible range, and facility damage, the study evaluated their effects on transportation resilience under urban flood conditions and identified network configuration effects. Based on the assessment results, evidence-based and theoretical guidance was provided for enhancing urban transportation resilience.

(2) Scenario-based layout planning validated the applicability of the resilience assessment model and confirmed the importance of appropriately siting and distributing emergency service facilities. The results indicate that scientifically informed facility layouts can significantly improve a city's capacity to cope with flood disasters and play a key role in emergency response and resource mobilization. The assessment also revealed limitations in certain optimization measures, providing insights for future studies.

(3) A set of multi-level resilience optimization strategies was proposed, mainly framed from a government-led policy perspective while acknowledging the role of other stakeholders. In practice, a government-led, enterprise-supported, and citizen-participatory model constitutes an important pathway for translating resilience concepts into actionable measures.

4.2 Outlook

Given the complexity of urban systems, the inherent uncertainty of flood hazards, and the broad scope of related research fields, numerous issues regarding urban flood resilience remain to be explored. Future research could proceed along the following lines:

(1) The resilience assessment developed in this study considered only facility layout under a specific disaster scenario and did not account for the influence of other natural hazard scenarios. The assessment dimensions require further expansion and refinement—for example, by incorporating multi-hazard resilience aspects into urban resilience construction. Regarding model parameters, this study analyzed only the configurational effects of service efficiency, accessible range, and facility damage on urban flood resilience; some potential aspects may have been overlooked. The configurational analysis model can therefore be further enriched to strengthen its theoretical foundation.

(2) The temporal scope of this study is relatively short. Future work could extend the analysis over longer periods to reveal changes in urban flood resilience across different temporal stages. Resilience building is inherently dynamic, and because this study used cross-sectional data from a specific disaster scenario, it is difficult to fully explain antecedents and formation processes. Subsequent research could employ multi-temporal dynamic approaches to examine temporal changes in cross-sectional outcomes.

(3) The resilience optimization strategies and safeguard mechanisms proposed in this study are mainly framed from a government perspective. In practice, enhancing urban flood resilience requires multi-stakeholder collaboration following a government-led, enterprise-supported, and citizen-participatory model. Future studies could focus on social actors affected by floods, analyzing their communication, linkages, cooperation, and conflicts throughout the disaster lifecycle. Constructing social-network or multi-agent simulation models to capture the interactive evolution of stakeholder behavior would allow formulation of targeted policy recommendations from the perspectives of key urban flood-resilience stakeholders, including government authorities, residents, enterprises, and volunteers.

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