Response Mechanisms and Construction Strategies for Urban and Rural Environments Under Cascading Typhoon Disasters

—A Case Study of Hongqiao in Yueqing City

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Abstract: The “cascading effect” of typhoons refers to the chain reaction and interaction of multiple factors that amplify disaster losses, posing severe challenges to urban and rural environments in affected regions. Reducing risks and enhancing resilience through appropriate construction has become a critical goal for sustainable human settlements. Following a technical pathway of “response mechanisms—disaster dynamics—construction strategies,” this empirical study focuses on the cascading “typhoon—rainstorm surge—urban flooding” process in the Hongqiao watershed of Yueqing City. The study interprets the three-tier drivers of cascading disasters—coastal and land-based foundations, watershed characteristics, and urban-rural spatial patterns—while establishing a governance-oriented “process control” approach. Aiming for a balance between disaster and peace-time objectives, the study develops urban-rural construction units that integrate “hydrology—topography—needs” synergistically. It unveils response mechanisms for urban-rural environments under cascading typhoon disasters, identifies the nonlinear dynamics of typhoon-triggered disasters, and formulates adaptable strategies for constructing resilient urban-rural environments. The findings aim to provide technical methods and strategic pathways for disaster-adaptive construction in typhoon-prone regions.

Keywords: cascading typhoon effects; urban-rural environment; response mechanisms; disaster dynamics; construction strategies

1. Introduction: The Need for Resilient and Secure Development Amid Cascading Typhoon Disasters

1.1 Background: The Challenge of the “Cascading Effects” of Wind, Rain, Flood, Tide, and Waterlogging

Statistics from the World Meteorological Organization (WMO) show that between 1970 and 2019, 38% of global deaths and 38% of economic losses were related to tropical cyclones, making them the leading cause among all hydrometeorological disasters. In recent years, compound extreme disasters triggered by typhoons have caused significant losses in affected areas, with Zhejiang Province being the hardest hit. In 2019, Typhoon “Lekima” (No. 1909) made landfall, and despite the overall high water levels in almost all rivers, reservoirs, and sluice gates in the Jiaojiang River Basin, heavy rainfall still occurred in Taizhou City. A total of 16 weather stations reported rainfall exceeding 500 mm, and 95.5% of stations had rainfall exceeding 100 mm. All weather stations in Linhai City, located at the Jiaojiang River estuary, recorded an average rainfall of 337.2 mm, becoming the center of the extreme rainfall, forcing the entire urban area to be used for water storage. In 2020, Typhoon “Hagibis” (No. 2004) rapidly intensified near the coast, with wind, rain, and tide all meeting head-on to directly hit Wenzhou. In 2021, Typhoon “In-Fa” (No. 2106) lingered over land for a record-breaking 95 hours. In 2022, Typhoon “Meihua” (No. 2212) caused rainfall exceeding 300 mm in as many as 70 towns and streets in Ningbo, coinciding with astronomical high tides, leading to widespread waterlogging. In 2023, Typhoon “Doksuri” (No. 2305) caused extensive urban waterlogging and mountain flash floods in Fujian and Zhejiang, and its residual circulation moved north, triggering flooding in even larger areas. The combined impact of wind, rain, tide, flood, and waterlogging from typhoons indicates that under the intensified climate change and changing trends in typhoon activity, such initial events can trigger subsequent chain reactions with strong interactions between multiple factors. This leads to risks expanding continuously in time and space, causing cumulative disaster losses amplified by the “cascading effect,” which has become the true depiction of the impact of typhoons on urban and rural environments today.

Faced with the challenges brought by urbanization and various uncertainties, the focus on risk prevention and maintaining dynamic safety has become a key goal for human settlement development. In 2021, China’s “14th Five-Year Plan” was the first to incorporate “coordinating development and safety” into its socio-economic development guiding ideology, making safe development one of the core requirements for guiding China’s future economic and social development. In November 2023, President Xi Jinping emphasized the importance of “comprehensively promoting the construction of resilient and safe cities” during his inspection of Shanghai, highlighting the prominent role of resilience and safety in urban planning, construction, and management. Therefore, actively responding to the new urbanization strategy, constructing resilient and safe national territorial space, and actively mitigating the increasing risks of natural disasters has become a top priority in the development of urban and rural environments.

1.2 Review: Research Trends on Typhoon “Cascading Effects”

In recent years, with a deeper understanding of the interconnectedness and complex impacts between disaster events, the “cascading effects” of typhoons have received increasing attention. Research in this area has focused on cascade scenario analysis, disaster condition calculations, disaster risk and resilience quantification, and adaptive planning methods. Some scholars have used historical disaster or hydrological data to innovate models, enhancing explanations of the complexity and cross-scale nature of typhoon “cascading effects,” aiming to improve the accuracy of decision-making related to disaster risk management. Some scholars have explored flood-wind coupling models, correlations between typhoons and flooding, encounters of floods and storm surges, typhoon-flood-geological disaster chains, and multi-threats from typhoons, heavy rain, and astronomical tides, deriving disaster mechanisms and risk probabilities for urban infrastructure such as embankments, drainage systems, bridges, industrial equipment, and lifeline engineering under multi-disaster coupling conditions, and proposing corresponding engineering optimization schemes. Others have quantified the probability of disasters, risk distribution, economic losses, and resilience in specific regions using statistical data. However, due to data accessibility limitations, the results are mostly presented at global, regional, basin, or urban scales and tend to construct resilience assessment systems from economic, social, perceptual, and infrastructure dimensions, followed by the development of macro-scale disaster reduction strategies.

In the field of spatial disaster-adaptive construction planning, the relationship and positive interaction between social and natural processes have received increasing attention. For example, following Hurricane Sandy, the Dutch firm H+N+S proposed a construction vision of “coexistence with the bay” in Nassau County, New York, developing an adaptive framework based on five types of bayland landforms, such as sandbars, tidal islands, wetlands, streams, and mountains, using the dynamics of landform formation as a spatial intervention mechanism, providing urban design strategies in accordance with hydrological and geomorphological laws. In China, some scholars have also proposed dynamic flood and waterlogging adaptability planning methods to ensure the normal operation of cities during typhoon impacts, rather than relying solely on horizontal resilience measures to provide macro-level disaster reduction strategies. At the same time, some scholars have pointed out the need to focus on cross-scale construction of resilient cities to address the cross-scale challenges posed by the “cascading effects” of typhoons, in response to the UN’s disaster reduction strategy of establishing multi-level disaster reduction mechanisms. However, existing research still pays insufficient attention to an in-depth analysis of the key driving factors and development processes of the “cascading effects” of typhoons, and it remains difficult to provide precise guidance for prevention, adaptation, and mitigation practices in affected areas. The resilience and safety of urban and rural environments should not rely solely on localized optimization and transformation under specific technologies or focus merely on fine-tuning risk identification. Instead, it should be based on clarifying the non-linear relationships exhibited by the “cascading effects” and understanding precise response mechanisms and construction methods, to facilitate a balance between normal construction and the mitigation of extreme disaster risks while ensuring spatial compatibility.

1.3 Research Path and Significance

The occurrence and development of the typhoon “cascade effect” involve different spatial scales, ecosystems, and the interaction between urban-rural construction systems. As part of a larger ecosystem, urban and rural environments should seek a holistic approach to human-environment collaboration for disaster adaptation and reduction. Based on this, this research takes the Hongqiao group in Yueqing City as a case study to reveal the response mechanisms of spatial construction in mitigating typhoon cascade risks, analyze the nonlinear mechanisms of the disaster cascade process, and explore precise pathways for local practices. The goal is to provide new research and practical approaches for small-scale disaster prevention spaces in the Yangtze River Delta region, while also inspiring thinking about how disciplines such as urban planning, architecture, and landscape architecture can accommodate the rigid demands of risk prevention and control, ultimately opening up new development paths for various fields.

2. Overview of the Study Area

2.1 Research Object: Hongqiao Watershed Urban Group in Yueqing City

Yueqing City, a county-level city under the jurisdiction of Wenzhou, Zhejiang Province, is located on the northern wing of Wenzhou and is one of the pilot areas for Zhejiang's high-quality development and common prosperity demonstration zone. The city's GDP has consistently ranked first in Wenzhou. The city lies to the west of the Yandang Mountain range and faces the Leqing Bay to the east. The Yandang Mountains divide the city into several small independent river basins, and the study area is located in the Hongqiao watershed, with a basin area of 236.28 km². The watershed is surrounded by mountains, with two main water sources: Danxi and Meixi. After merging, these rivers form a complex water network, with tidal channels connected to artificial freshwater reservoirs and river channels, draining into Leqing Bay via the Donggan and Xigan rivers. The Hongqiao watershed urban group, with Hongqiao town as the core, is one of the three major urban groups in Yueqing's overall land spatial plan for 2021–2035, alongside the Liubai and Lecheng groups (see Figure 1).

2.2 Cascade Disaster Process: Typhoon—Rain Flood Surge—Urban Waterlogging

Over the past 40 years, typhoons that have made landfall in Wenzhou and Taizhou account for 75% of the total typhoons in Zhejiang Province. Yueqing, located at the border of Wenzhou and Taizhou, has always been on the front line of such impacts. Although the number of fatalities and collapsed buildings caused by strong winds has significantly decreased, waterlogging after typhoons remains a common occurrence. Yueqing's water safety guarantee in the 14th Five-Year Plan analyzes issues with the water safety system, noting that the combination of high tide levels and heavy rainfall often causes urban waterlogging, and the drainage capacity of the Hongqiao urban area is still insufficient 【23】. The "Yueqing Flood Disaster Prevention Plan" highlights that the area is historically prone to flash floods triggered by heavy rainfall accompanying typhoons 【24】. Thus, the "Typhoon—Rain Flood Surge—Urban Waterlogging" cascade disaster process can be summarized as a coupling of heavy rain, mountain floods, and storm surges under the typhoon's influence, resulting in waterlogging. In light of the objective reality that "flooding is unavoidable and unmanageable" 【23】, it is urgent to clarify the causes of disaster and explore their interconnections.

3. Response Mechanisms for Urban and Rural Environments in Typhoon "Cascade Effects"

Since the 13th Five-Year Plan, counties like Yueqing have raised higher requirements for resilient safety and flood prevention. By the 14th Five-Year Plan, these requirements have become more systematic and refined, with an emphasis on combining disaster prevention with development (see Table 1). At the same time, the focus of national spatial planning has gradually shifted towards detailed planning. Therefore, combining safety development planning with national spatial planning to establish response mechanisms for the typhoon “cascade effect” is one of the key premises for proposing suitable urban and rural construction methods.

3.1 “Sea-Land Base—Watershed Characteristics—Urban-Rural Space” Three-Level Scale Explanation of the Disaster Cascade Process

Different ecological and social processes operate at different spatial scales, and scale conversion is a key perspective for understanding cross-scale processes. The “Typhoon—Rain Flood Surge—Urban Waterlogging” cascade process exhibits significant spatial scale degradation: At the macro scale, energy conversion during typhoon landfall is influenced by the physical interaction between the ocean and land; at the meso scale, the hydrological coupling laws of rain, floods, and surges are closely related to watershed characteristics; and at the micro scale, urban waterlogging is the feedback of urban-rural spaces to hydrological coupling laws. Currently, the interconnections between various national land spaces, including urban, ecological, agricultural, and marine spaces, are becoming increasingly tight 【25】. Therefore, understanding the typhoon disaster mechanism and analyzing driving factors requires integrating the multidimensional and cross-scale perspectives of sea-land base, watershed characteristics, and urban-rural space.

3.2 “Process Control” Cascade Risk Governance Approach

Under the interaction with the sea-land base, the energy conversion of a typhoon is irresistible, and the only option is to avoid it. However, the hydrological coupling laws of rain, floods, surges, and the occurrence of urban waterlogging are the result of a fierce collision between the “water entering and people entering” process. Although the hydrological coupling laws are constrained by watershed characteristics and cannot be avoided, they can still be partially mitigated through ecological restoration, water engineering infrastructure, and structural adjustments in the urban-rural environment construction system. Therefore, the key to mitigating typhoon cascade risks lies in establishing a governance system guided by “process control,” promoting the consumption and transfer of hydrological sub-process energy, and delaying the coupling of hydrological sub-processes to effectively guide the planning and construction of urban and rural environments.

3.3 Urban and Rural Environmental Construction Units with “Hydrology–Geomorphology–Demand” Coordination Under the Goal of Disaster Mitigation

The geomorphological texture varies, and so do the hydrological conditions. Some geomorphological units can promote hydrological processes, while others can alleviate them. Therefore, geomorphological units that help mitigate hydrological subprocesses actually serve as natural carriers for “process control” in the construction system. The direction of hydrological subprocesses can be used as a basis to anchor geomorphological units. By combining urban and rural construction development needs, through spatial layout and functional structural reorganization, the texture of geomorphological units can be enhanced, and the energy of hydrological subprocesses can be dissipated, forming a coordinated “Hydrology–

Geomorphology–Demand” urban and rural environmental construction unit (Figure 2). This, in turn, helps regulate the traversing properties of typhoon hydrological subprocesses in all directions, delays the encounter of subprocesses, and creates a cooperative pattern that protects the internal and downstream urban and rural environments, complementing the spatial governance layer for disaster prevention and reduction.

4. Collaborative Strategy for Urban and Rural Environmental Construction Units in Hongqiao, Yueqing City

4.1 Resilient Port Area Maintaining the Tidal Flat Reduction Effect

4.1.1 Underwater Slopes and the Closure Topography of Yueqing Bay Promote Storm Surge

Typhoon storm surges are local sea surface oscillations or non-periodic abnormal rises caused by strong winds and pressure changes associated with a typhoon passing over the sea. The increase in water level is typically the result of a combination of wind stress, low-pressure rise, and astronomical tide rise. However, the coastal and topographical features of Yueqing Bay also promote the increase in water level due to storm surges. The average slope of the underwater accumulation slopes in the Zhejiang offshore area is only 1‰, and the inclination is very slight. The underwater accumulation slopes near Wenzhou have a depth of less than 20 meters but extend 20-50 km in width. The reduction in offshore water depth causes waves to slow down, wave height to increase, and tide levels to rise. At the same time, Yueqing Bay has a typical closing topography, and as the storm surge progresses into narrower areas, the restricted water flow space leads to further increases in tide levels. Statistical data show that the highest historical tide recorded at the nearest Sha Gangtou station in the Hongqiao group reached 4.57 meters, caused by Typhoon “Tanmei” in 2013.

4.1.2 Expansion of Port Area Intensifies Tidal Energy Concentration

The maximum tidal range in Yueqing Bay can reach 8.34 meters, and the measured maximum tidal range at Sha Gangtou station is 7.95 meters. The conversion between gravitational potential energy and kinetic energy is intense, resulting in high water energy. Since 2000, the coastal tidal flats in Yueqing Bay have been gradually converted into port construction land, and tidal creeks have been interrupted by new ponds and sluices. The waterways inside the ponds have been channeled, and the tidal creeks outside the ponds have developed more slowly due to reduced hydrodynamics. The once abundant tributary creek system has degraded, making it difficult to play its role in dissipating tidal surge and wave energy, and when affected by storm surges, the embankment suffers greater stress. Meanwhile, the rise and fall of storm surge waters can erode and hollow out the embankment, further reducing the stability of the embankment structure. Despite ongoing upgrades to the embankment structure, the fundamental issue of intensified concentration of storm surge energy remains unresolved.

4.1.3 “Resilient Port Area” Regeneration of Tidal Flow Channels

The current controlled detailed plan for the first expansion area of Yueqing Bay Port has overturned the comprehensive reclamation of coastal tidal flats and has planned a surface water network. Therefore, each port area module divided by the water network can be planned with independent surrounding standard embankments to form tidal surge resistance modules. This breaks the traditional tidal protection paradigm by opening the internal water network as tidal flow channels, returning the space to tidal surges and tides, thus providing multiple pathways to disperse pressure. At the same time, drawing on the Bolsa Chica lowland ecological restoration project in Orange County, California, through strategies such as pre-filling sandbars, dredging tidal pools, creating artificial islands, and reinforcing embankments, the tidal flow channels that were opened have reinforced the full tidal influence, creating favorable conditions for salt marsh growth and dune stability, and maximizing the integration of ecological space and tide reduction disaster prevention space. In the future, the construction of the “Resilient Port Area” in Yueqing will need to deeply understand the regeneration mechanisms of tributary creek systems and salt marshes, reserve tidal pools, and use spatial substitution strategies to offset the occupation of tidal flat resources by port construction, optimizing the organization of spatial elements and promoting the energy dissipation and water storage functions during disaster times, maintaining the sediment balance and biodiversity of Yueqing Bay.

4.2 “Port-City Ecological Compartments” Reshaping Nearshore Diversion Functions

4.2.1 Changes in Nearshore Profile Order Alter Confluence Direction

In the nearshore area of the Hongqiao group, thanks to the presence of low hills, traditional settlements were located on the slopes, with reclaimed farmland in the middle and tidal flats and tidal creeks retained as flexible lowest planes, forming a profile order that facilitates water flow diversion. Currently, with the development of the Hongqiao group’s port and industrial areas, some farmland has been converted to or planned as commercial and industrial zones. The newly planned land parcels, roads, and embankments have high construction standards and elevations, inevitably creating slight height differences between the old and new surfaces. Meanwhile, as the flood protection function of the old embankments gradually shifts towards the function of levees and secondary road networks, issues of settlement and deformation are common. Even longstanding embankments, such as the Victory and Friendship embankments, have sunk by 80-100 cm, making it difficult for them to continue protecting internal farmland from external floods. When the tidal level in the estuary drainage is blocked by high tide, surface runoff in the nearshore area is easily gathered into the farmland surrounded by old embankments or into the central flat land to the northwest.

4.2.2 “Port City Ecological Compartment” Converging Local Self-Elimination

With the implementation of Phase 1 expansion in the port area, the nearshore area will retreat to become the buffer zone between the Hongqiao urban core and the port area, emerging as an important block for the integration of port-city development, the emergence of new business models, and the upgrading of lifestyles. There is a need to reshape the profile order, create microtopographies for guiding converging flows to self-eliminate on site, mitigate the transfer of flood risks to farmland and central plains, and form the significance of regional compartments. The specific construction strategies are as follows:

1. **Reshaping Elevation of Multiple Profiles**

Although the traditional profile order from land to sea has been disrupted, there are still opportunities to reshape elevation from other profiles. For example, by demolishing and relocating the short-sided old ponds, the space can be released for water bodies or submergible ecological wetlands, forming a construction model similar to polders. This would increase the probability of the plot connecting with the outer river. The newly created water bodies or wetlands need to connect with the existing water network, specifically linking to the truncated rivers and cooperating with dredging efforts to enhance the overall water retention capacity of the network.

2. **Boundary Limitation**

As the rear boundary, the Shenhai Expressway has high construction standards. Small-scale low-impact development facilities such as rainwater flood buffers, grass ditches, and retention ponds can be integrated along the expressway on both sides. The traffic roundabouts can serve as larger-scale disaster reduction green spaces, acting as hydrological management hubs to connect the drainage network and low-impact development facilities. Additionally, the rainwater management system along the Shenhai Expressway can become a channel linking the East and West Gan rivers, promoting the upgrade of river water retention capacity.

3. **Empowering Grey Spaces**

In the constructed port industrial area, there are many idle spaces and urban lawns. Due to the homogeneity of the population and land use types, these grey spaces do not currently serve the purpose of improving the ecological environment or enhancing urban quality. These spaces can be transformed into sunken areas for disaster management purposes, combined with the core positioning of the Yejing Bay leisure and cultural tourism belt to create cultural nodes. In normal times, these spaces can provide leisure and resting areas for port workers and visitors, while in emergencies, they can be converted into water storage spaces, connected to underground developments through stormwater channels and infiltration technologies.

4.3 Stimulating the Collaborative Flood Control of Sloped Land through “Mountain Encircling Guard Barriers”

4.3.1 Complex Terrain Intensifies Typhoon Rainstorm Magnitude, Catchment Features Drive

Flash Floods

Zhejiang’s mountainous terrain is steep and complex. As typhoons approach the land, the mountains lift and obstruct the near-surface airflow of the typhoon, forcing water vapor to rise and condense, slowing the typhoon’s movement and intensifying precipitation. Meanwhile, the airflow convergence effect in the valleys promotes small- and medium-scale convection and local vortices, further intensifying the typhoon rainstorms in the complex terrain. Therefore, the typhoon rainfall in Zhejiang often sharply increases after landfall.

The mountain range surrounding the Hongqiao group presents a surrounding spatial layout: the west is dominated by high mountains, and the east consists of low hills over 200 meters in elevation. The surrounding slopes overall are steeper than 25%, with short, fast-flowing mountain streams in the west. In contrast, the east lacks perennial rivers, and the convergence process typically occurs through slope surface runoff. During heavy rainstorms, flash floods rush into the central plain from all directions.

The runoff coefficient refers to the ratio of runoff depth (R) to average precipitation depth (P) within a given time period, denoted as α. For a closed watershed, since $R < P$, $\alpha < 1$. A larger runoff coefficient α indicates that precipitation is less absorbed by the soil, increasing the load on drainage systems during heavy rain. The runoff coefficient for the Hongqiao watershed is 0.7, meaning approximately 70% of rainfall is converted into surface runoff, and the watershed surface has limited infiltration capacity. For example, during the impact of Typhoon Lekima in 2019 and Typhoon Higos in 2020, the Hongqiao watershed experienced rainfall of 341.1 mm and 257.7 mm, respectively, generating runoff volumes of approximately 5.65 million m^3 and 4.26 million m^3, triggering flash floods.

4.3.2 Delayed Planning of Upstream Flood Retention

To prevent upstream mountain floods, the Hongqiao group primarily relies on the 1968-built Danxi Reservoir and various dams along the route. However, the complexity of the upstream Meixi terrain far exceeds that of Danxi, making flood management more difficult. The Meixi upstream is essentially a small-scale basin unit with valleys distributed around it. The west side of the mountain foot features small flood fans, while the east exhibits river bends before the Meixi valley. Due to the differing geomorphological features and hydrological conditions, relying solely on river-based water infrastructure cannot effectively control the mountain floods in the Meixi basin. Additionally, with recent rapid development of the cultural and tourism industry in the area, river channelization and drainage infrastructure have accelerated, further weakening flood retention capacity. Targeted flood retention planning has rarely been explored.

4.3.3 Highlighting the Imperviousness of Sloped Land and Insufficient River Water Surface Area

The land use types in the Hongqiao group present a multi-layered nested structure from outer to inner, including forest land, garden land, sloped village settlements, farmland, and urban areas on the central plain. Particularly in the mountain valleys, forest, garden, village, and farmland areas, with land leveling and agricultural upgrades, a terraced landscape has formed that can absorb and store rainwater. However, with the ongoing industrialization and urbanization, road hardening and extensive construction of industrial parks have increased surface imperviousness, further weakening the already fragile mountain flood retention pattern.

Currently, the Hongqiao group is strengthening the connectivity of the mountain rivers. Rivers like Lehong Tang River, Shifan Mountain River, Henghe River, and Dongpai River have connected various radial water systems, largely completing the mountain river system. This helps repair the mountain flood retention pattern to some extent. However, the overall grade of the mountain rivers remains low, with a total water surface area of only about 0.73 km², which still lacks sufficient redundancy to effectively mitigate flash floods during heavy rainstorms.

4.3.4 "Mountain-ringed Defensive Barrier" Dual-layer, Dual-reservoir, Multi-tier Spatial Co-governance

The mountain-ringed space between the Hongqiao group's mountainous region and the central plain features diverse landforms. It is necessary to organize the spatial structure with a flood detention approach, using a holistic perspective to form a "mountain-ringed defensive barrier," with corresponding adjustment strategies shown in Figure 6.

Under conditions of scattered valleys and alluvial fan surfaces, efforts should be made to extend and elevate useful space. In terms of extension, identify single-layered areas of existing mountain-ringed rivers, revitalizing the original water network and upgrading the single-layer mountain-ringed rivers to a dual-layer system, which can help supplement the insufficient water storage areas. Regarding elevation, supplement the mountain-ringed rivers upstream of Meixi Basin, activating the flood detention potential of the basin and creating a "dual-reservoir" structure with the Danxi Reservoir to reduce downstream pressure during the flood season after Meixi and Danxi release water. Based on this, the collaborative flood detention function of four land-use types within the mountain-ringed space—gardens, built environment, farmland, and small water bodies—should continue to be constructed. Following the principles of "point layout, vertical development" in Zhejiang's sloping rural areas, architectural design should be limited to building boundaries, adapt to the terrain to create a staggered layout, and use elevated or semi-underground ground contact methods. This will retain the terraced texture of surrounding gardens and farmland, while small water bodies can delay flood runoff through strategies like straightening curves and increasing storage space.

In conclusion, despite the multiple factors in the Hongqiao group that drive heavy rainfall and flash floods, the spatial structure and construction methods can still be adjusted to create a "dual-layer, dual-reservoir" water regulation pattern, and a multi-tier texture where the “garden—building—farmland—water” process jointly participates in reducing the threat of flash floods downstream.

4.4 Activating Disaster Reserve Space through a “Water-sensitive Network”

4.4.1 Construction Goal: Occupying Waterfront Space on the Central Plain

The waterfront space in the central plain of the Hongqiao group is flat, well-connected, and a key area for spatial urbanization. Using 30-meter fine surface cover data from 1985–2020, trends in the changes of land-use types along the waterfront were calculated, showing that urban and rural built environments have appropriated low-lying paddy fields and ecological resources, causing a loss of flood retention and water storage functions. Over the past 35 years, land use changes in the 10m, 30m, and 50m waterfront areas have shown consistent patterns: the area of paddy fields decreased by 4.35 km^2, 7.5 km^2, and 10.5 km^2, respectively; forest land decreased by 0.4 km^2, 1.06 km^2, and 1.71 km^2, respectively; and built environments increased by 2.79 km^2, 6.07 km^2, and 9.28 km^2, respectively. In the 50m waterfront, the extent and distribution of the growth of built environments match the goals of urban expansion: from 1995–2005, the urban center expanded fully relying on the core waterfront; from 2005–2015, the construction of urban gateways such as highway exits, high-speed rail stations, and ports encroached on the waterfront; and from 2015–2020, the construction of the longitudinal industrial artery Hongnan Road and the industrialization boom in rural areas further encroached on the peripheral waterfront.

4.4.2 Weak River Flow and Retention Capacity

The river system in the Hongqiao watershed is generally underdeveloped, with many low-level ponds and rivers in the central plain. The topography and micro-depressions of these rivers, which should dissipate the energy of the water, are naturally insufficient, lacking features such as deep pools, shoals, river bends, concave riverbeds, oxbow lakes, and sediment traps. This makes it difficult to absorb rain, flood, and stagnation water. Additionally, small natural highlands along the riverbanks are scarce, and settlements in the central plain are poorly sited, often subject to waterlogging and flooding.

The encroachment of built environments further depletes the already limited natural retention and protective capacity of the waterfront, making it difficult to buffer extreme disaster events like typhoons. For example, during the impact of Typhoon Hegbi in 2020, the emergency flood storage capacity of the Hongqiao watershed’s central plain was only 2.5 million m^3, while rainfall of 4.97 million m^3 occurred in just three days. Furthermore, the 1-hour maximum rainfall recorded at the Shifan station was 117 mm, and at the Puqi station, it was 101 mm. These two stations alone generated around 5.07 million m^3 of rain in just one hour. Meanwhile, the storm surge coincided with high tide in Yueqing Bay, exacerbating the situation. All rivers in the Hongqiao watershed exceeded their warning levels by 6:20 AM on the fourth day, causing significant waterlogging and severe flooding.

4.4.3 “Water-sensitive Network” Combined Retention Layers

In the future, slower typhoon movement will lead to even more intense rainfall, and the increase in storm surge intensity as typhoon centers move closer to the coast will worsen the convergence of rain, floods, and tides. The Hongqiao group, with its weak natural water retention and protective ability, must strengthen the construction of a water-sensitive infrastructure network to maximize the activation of reserve space and reduce the pressure on drainage systems.

In line with the national spatial planning for Hongqiao, the “water-sensitive network” can be constructed through the combination of five subsystems: rivers, G-class green spaces and open areas, non-indoor spaces in A/B/M-class land uses, micro S-class transportation spaces, and pocket spaces in R-class residential areas. By adjusting the spatial structure and organizing hydraulic facilities based on different space types and hydrological conditions, the system can better absorb floodwaters. In rivers, human intervention can enhance sediment transport and water flow diversion, increasing the dynamism of river topography and restoring the river’s self-regulation ability to flood.

The “water-sensitive network” overlaps spatially with resilient port areas, port-city ecological barriers, and mountain-ringed defensive barriers, but focuses more on refining site-scale corrections, which can consolidate their collective impact on dissipating water energy. Additionally, the overlay pattern of the “water-sensitive network” has topological significance in scaling. The planning and design approach can expand to the entire watershed and delve into any specific site, community, or rural area. This concept enables the transformation of isolated spaces into network nodes, which can be converted into floodwater storage during disasters and serve daily functions like living, transportation, and recreation, making these areas resilient, accessible, attractive, and interconnected.

5. Conclusion

To address the challenges posed by the cascading effects of typhoons on urban and rural environments, this study uses the example of the urban and rural clusters in the Hongqiao watershed in Yueqing City. It analyzes the “Typhoon-Rain-Flood-Tide-Inland Flood” cascading process, explaining three key points of the environmental response mechanism:

1. By utilizing a three-level scale of “Marine-Land Surface—Watershed Characteristics—Urban and Rural Space,” we gather information to understand the system characteristics and ecological-social processes at each level, such as the ocean, land, watershed, and urban-rural areas. This helps clarify the interactions between typhoon disasters and the various systems, strengthening the explanation of the typhoon’s cascading effects.

2. Defining the “Process Control” approach for cascading risk governance, which aims to promote the consumption and transfer of hydrological sub-process water energy during typhoons, delay the encounters and coupling of hydrological sub-processes, and slow down the urban and rural construction’s reinforcement of hydrological coupling patterns.

3. Constructing urban and rural environmental building units under the integrated “Hydrology—Geomorphology—Demand” goal, focusing on practical, problem-oriented strategies. This aims to balance disaster risk governance with sustainable development goals and spatial compatibility.

Based on these findings, combined with quantitative analysis and field surveys, the study clarifies the nonlinear disaster evolution mechanism of typhoons in the Hongqiao cluster. It analyzes the cross-scale spatial elements and organizational issues affecting coastal storm surge energy accumulation, offshore confluence disorder, hill flood runoff, and the lack of central flat land storage space. Accordingly, the study develops urban and rural environmental building units such as “Resilient Port Areas,” “Port-City Ecological Barriers,” “Mountain Encompassing Barriers,” and “Water-Sensitive Networks,” along with appropriate strategies. It establishes collaborative patterns between units to mitigate the coupling effects of rain, flood, and tide-induced inundation, offering guiding and reference value for disaster adaptation activities in urban and rural environments in typhoon-prone regions.

Notes:

1. Data from the Taizhou Water Information Center. [link]

2. Data from the “China Meteorological Disaster Yearbook (2004-2021),” China Typhoon Network, and relevant Zhejiang Provincial documents.

3. Data from the “Yueqing City Seawall Construction Plan (2020-2030).” [link]

4. Data from the Yueqing Water Conservancy Bureau.

5. Data from the Chinese Academy of Sciences Aerospace Information Innovation Research Center. [link]

6. Data from Wenzhou City, August 2020 water rainfall information. [link]

References:

[1] WMO. WMO atlas of mortality and economic losses from weather, climate, and water extremes (1970-2019). [link]

[2] Ding, Y. “Meihua” disaster intensity level, Ningbo Daily, 2022.

[3] Ministry of Emergency Management, Report on national natural disaster situation, 2023. [link]

[4] Wei, J. Coupling and cascading risks: Complex causes of evolving societal risks, Journal of Learning, 2019.

[5] UNDRR. Scoping study on compound, cascading, and systemic risks in Asia-Pacific, 2024. [link]

[6] The People's Republic of China, The 14th Five-Year Plan for National Economic and Social Development, and 2035 Vision, 2023. [link]

[7] Tang P., Zhong W., Wen J., et al. Developing and understanding cascading effects scenarios of typhoons in coastal megacities from system perspectives for disaster risk reduction: A case study of Shenzhen, China, International Journal of Disaster Risk Reduction, 2023, 92: 103691.

[8] Zhang Z., Lu Y., Hu D., et al. Across-scale modeling framework for simulating typhoon-induced compound floods and assessing emergency response in urban regions, Ocean and Coastal Management, 2023, 245.

[9] Lan, M. Typhoon-induced multi-disaster mechanisms and risk quantification in coastal industrial clusters, University of Science and Technology of China, 2022.

[10] Xu, W., Liu P., Huang P., et al. Joint risk analysis of typhoon-induced flood and tide in the Pearl River Basin, Hydrology, 2023, 43(2): 110-114.

[11] Yang, H., Ye, G., Zhou, G., et al. Analysis and optimization of urban drainage and flood control systems under the encounter of rain, flood, and tide, Science & Technology and Engineering, 2019, 19(21): 271-277.

[12] Snaiki, R., Wu, T., Whittaker, A. S., et al. Hurricane wind and storm surge effects on coastal bridges under a changing climate, Transportation Research Record, 2020, 2674(6): 23-32.

[13] Xie, L., Zhou, P., Yang, H., et al. Resilience paradigms of coastal lifeline infrastructure under climate change: A case study of Ningbo City, Urban Planning Journal, 2022 (S2): 81-88.

[14] Wang, Q. Typhoon simulation and wind disaster risk research in coastal areas of China under climate change, Zhejiang University, 2022.

[15] Wang, T., Wu, S., Gao, J., et al. Evaluation of regional typhoon-flood-geological disaster chain reduction capacity, Disaster Science, 2022, 37(4): 193-200.

[16] Xu, H., Lian, J., Bin, L., et al. Study on joint distribution of multiple typhoon disaster-causing factors, Geographical Sciences, 2018, 38(12): 2118-2124.

[17] Zeng, P., Su, C., Fang, W., et al. Damage assessment of typhoon-induced secondary flooding based on high-precision building type data: A case study of Haikou City, Disaster Science, 2022, 37(4): 155-165.

[18] Wang, Q., Zhao, G., Zeng, J. From "opposition" to "unity": Exploring urban land development paths that balance socio-economic development and ecological protection, Urban Planning, 2022, 46(12): 110-120.

[19] Rebuild by Design. Living with the Bay, 2022. [link]

[20] Chen, B., Li, Y. Resilience-oriented evaluation of adaptive transformation planning for high-density coastal cities: A case study of Shenzhen's Mangrove Bay area, Urban Planning Journal, 2023 (4): 77-86.

[21] Guo, R., Wang, Z., Qiu, Z., et al. Adaptive strategies for human settlements under typhoon-induced inland flooding disaster mechanisms: A study based on the Zhejiang coastal plain, Western Human Settlements and Environment, 2022, 37(6): 52-58.

[22] Peng, X., Jiang, H., Huang, D., et al. Resilient spatial strategies for adapting to typhoon climate in the Guangdong-Hong Kong-Macau Greater Bay Area urban cluster, Urban Development Research, 2019, 26(4): 55-62.

[23] Yueqing City People's Government. Water security guarantee "14th Five-Year Plan" for Yueqing City, 2023. [link]

[24] Yueqing City People's Government. Announcement of the Mountain Flood Disaster Prevention Plan for Yueqing City, 2024. [link]

[25] Pan, H., Dai, S., Zhao, Y., et al. Urban resilience and spatial planning for climate change adaptation, Academic Forum on Urban Resilience, 2021, (5): 1-10.

[26] Dai, S., Liu, T., Gao, X., et al. National land space disaster reduction planning system and implementation mechanism, Urban Planning Journal, 2023 (1): 48-53.

[27] Guo, R., Wang, Z., Zheng, Y., et al. Conceptual recognition and construction strategies for flood disaster adaptation in human settlements from a nested perspective, New Architecture, 2022 (6): 129-133.

[28] Yan, W., Ren, J., Zhang, S., et al. Resilient urban planning in Shanghai: Key issues, overall framework, and planning strategies, Urban Planning Journal, 2022 (3): 19-28.

[29] Li, S., Zeng, J., Zhu, Y., et al. Typhoon storm surge disasters in Zhejiang, 1949-2020, Beijing: Ocean Publishing House, 2021.

[30] Cao, C., Cai, F., Zheng, Y., et al. Analysis of seabed terrain characteristics and profile types in China's offshore waters, Journal of Central South University (Natural Science Edition), 2014, 45(2): 483-494.

[31] Cai, F. China Offshore Marine Atlas, Seabed Terrain, Beijing: Ocean Publishing House, 2016.

[32] Editorial Committee of China's Gulf Chronicles. China Gulf Chronicles (Volume 6: Southern Zhejiang Bays), Beijing: Ocean Publishing House, 1993.

[33] Xia, R., Han, Z., Xu, T. Hydrodynamics and sedimentary environment characteristics of Yueqing Bay, Waterway and Port, 2014(5): 503-508.

[34] Wetlands Recovery Project. Bolsa Chica Wetlands Restoration, 2023. [link]

[35] Chen, L., Xu, Y. Review of extreme typhoon rainfall in China, Meteorology and Environmental Science, 2017, 40(1): 3-10.

[36] Lou, X., Ma, H., Huang, X., et al. Analysis of the extreme precipitation caused by Typhoon "Lekima" in Zhejiang, Meteorological Science, 2020, 40(1): 78-88.

[37] Wang, K., Li, Y., Gao, L., et al. The impact of Zhejiang's topography on the nature of typhoons: A case study of Typhoon "Lekima" (No. 1909), Marine Forecasting, 2022, 39(1): 11-20.

[38] Yu, Z., Ji, C., Dong, M., et al. Statistical study on the multi-scale amplification characteristics of typhoon rainstorms in Zhejiang, Meteorology, 2017, 43(12): 1496-1506.

[39] Yueqing City Water Conservancy and Hydropower Bureau. Yueqing City Water Conservancy Records, Nanjing: Hohai University Press, 1994.

[40] Knutson, T.R., McBride, J.L., Chan, J., et al. Tropical cyclones and climate change, Nature Geoscience, 2010, 3(3): 157-163.

[41] Patricola, C.M., Wehner, M.F. Anthropogenic influences on major tropical cyclone events, Nature, 2018, 563(7731): 339-346.

[42] Wang, S., Toumi, R. Recent migration of tropical cyclones toward coasts, Science (American Association for the Advancement of Science), 2021, 371(6528): 514-517.