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Review Article

Research advances on storm resilience of coastal cities in the context of climate change

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Abstract: This paper reviews the research progress on the resilience of coastal cities to typhoon disasters in the context of climate change. It synthesizes advances in theoretical frameworks, quantitative assessment methods, and practical solutions for enhancing resilience to natural disasters. Drawing on complex systems theory, the study conceptualizes disaster resilience and distinguishes it from traditional disaster prevention approaches. The paper examines the strengths and limitations of three primary assessment methods: index systems, scenario analysis, and functional modeling. Furthermore, the study evaluates the adaptability of both structural and non-structural measures to enhance resilience, and it proposes a comprehensive theoretical framework for typhoon resilience in coastal cities. The review also highlights key challenges, including the lack of consensus on theoretical frameworks, unclear mechanisms for assessing resilience to complex natural disasters, and limitations in current multi-hazard assessment approaches. Finally, the paper outlines future research directions, emphasizing the importance of data sharing, the application of big data and artificial intelligence, the development of integrated models, and deeper investigation into resilience mechanisms to support sustainable urban development amid increasing climate uncertainty.

Keywords: Resilience, Disaster Resilience, Resilience Assessment, Storm Disasters

Highlights:

- Proposes a comprehensive framework to assess resilience in coastal cities, integrating both structural and non-structural adaptation strategies in response to compound hazards associated with typhoons.
- Defines disaster resilience through the perspective of complex systems theory, clearly differentiating it from traditional approaches to disaster prevention.
- Compares and evaluates three quantitative assessment approaches: index systems, scenario analysis, and function-based modeling. Each method's advantages and limitations are carefully discussed.
- Identifies key challenges in current research, including the fragmentation of theoretical foundations and the lack of effective tools to assess resilience across multiple, overlapping hazards.
- Suggests future research priorities such as incorporating real-time data, applying artificial intelligence, and strengthening governance mechanisms to improve disaster resilience under intensifying climate conditions.

1. Introduction

Coastal areas are home to more than 50% of developed urban areas, with high population densities and vibrant economies. However, climate change has significantly increased the risks of natural disasters such as sea level rise, storms and extreme rainfall. These threats not only directly threaten the lives and properties of coastal residents but also have serious impacts on infrastructure, socio-economic order and ecological environment (Tian et al., 2023; Vousdoukas et al., 2020). The vulnerability of coastal urban systems is a complex issue where the physical impacts of natural hazards can have ripple effects on supply chains and community livelihood and stability. This suggests that coastal cities are not only physically vulnerable but also represent complex socio-economic-ecological systems where climate impacts can cause systemic failures, requiring a holistic approach to disaster management that goes beyond traditional engineering solutions.

Due to its special geographical location, Vietnam is one of the most vulnerable countries to the impacts of climate change, including storms, floods and inundation (Phan & Ngô, 2013; Vets, 2024). According to the World Bank, Vietnam is ranked as the 13th country in the list of the most vulnerable countries to climate change in 2020 (Vets, 2024). Vietnam has increased from an average of five to seven per year since 2000, often accompanied by high tides and heavy rains that cause severe flooding (Vietnam, 2021). Sea level rise, with an expected increase of 0.5 to 1 meter by the end of this century under the scenario of a global temperature increase of 1.5-2°C, poses a major threat especially to coastal areas such as the Red River Delta, Southeast and Mekong River Delta (Vets, 2024). The degradation of coastal ecosystems such as mangroves also increases community vulnerability (Reed et al., 2015). These consequences not only cause economic losses but also seriously affect livelihoods, especially aquaculture productivity due to rising sea temperatures, salinity intrusion and changes in rainfall patterns (Nguyen et al., 2019).

Faced with these challenges, the Vietnamese Government has proactively implemented national strategies and plans to adapt to climate change and reduce disaster risks (Reed et al., 2015). The National Climate Change Adaptation Plan for the 2021–2030 period, with a vision to 2050, aims to enhance the resilience of natural, economic, and social systems (Dung, 2024). Efforts include strengthening institutions and policies, integrating climate adaptation into national planning, promoting smart agriculture, and enhancing disaster forecasting and early warning systems (Espagne et al., 2021). Vietnam also actively participates in global forums on disaster risk reduction, emphasizing the importance of investing in resilient infrastructure and improving data of risks. However, the application of global risk assessment models to the Vietnamese context is still limited due to differences in loss functions and vulnerability curves, requiring more in-depth research on loss functions suitable for domestic conditions.

Faced with the dual impacts of climate change and rapid urbanization, the concept of “resilience” has emerged as a forward-looking and proactive approach to natural resource management (de Bruijn et al., 2022). This approach integrates disaster risks and socio-economic factors into a comprehensive assessment framework, promoting a shift from reactive response to proactive risk reduction (Abdelhafez et al., 2024). Resilience offers quantitative indicators, serving as both an advanced theoretical framework and a key tool in disaster risk assessment (Cabana et al., 2023). The shift in focus from “vulnerability” to “resilience” reflects a more mature understanding of disaster risk. Vulnerability-based models often emphasize identifying weaknesses and potential damages, leading to reactive protective measures. In contrast, resilience encompasses not only resistance but also the capacity for recovery, adaptation, and transformation. By incorporating socio-economic dimensions, resilience recognizes that disaster impacts are not solely physical but are deeply interconnected with human systems, governance structures, and economic conditions. This shift marks a move from damage prevention to capacity building - enabling systems to absorb, adapt to, and recover from shocks, and even emerge stronger. It is a dynamic approach to capacity enhancement, as opposed to static protection.

Despite notable progress, research on disaster resilience still faces numerous challenges as current findings remain insufficient to support data-driven decision-making for building resilient urban areas. Specifically, the field lacks a unified theoretical framework; mechanisms for assessing storm resilience in complex disaster contexts remain vague; and existing multi-hazard assessment methods are still limited. Determining how to scientifically evaluate urban resilience to natural disasters and enhance adaptive capacity in the face of climate change uncertainties is an urgent task. This study aims to systematize the theoretical foundations, evaluation models, and improvement pathways for storm resilience from a resilience-based perspective. It also seeks to critically examine existing limitations in practical assessments and propose viable solutions. Through this, the research aspires to contribute to the development and real-world application of disaster resilience assessments.

2. Theoretical framework on disaster resilience

The concept of resilience originated in mechanical engineering, where it described the capacity of a material to resist deformation and return to its original form after stress. Over time, this concept has been adapted across various disciplines, including ecology, urban studies, and disaster science. In the context of disasters, resilience refers to the ability of a system to continue functioning during and after a disruption. This includes both resistance to immediate impacts and the capacity for recovery and adjustment over time (Rözer et al., 2022; Tian et al., 2023).

It is important to distinguish resilience from vulnerability. While vulnerability refers to the degree to which a system is exposed and sensitive to harm before a hazard occurs, resilience focuses on how a system responds during and after a disturbance (Cutter et al., 2010; Manyena, 2006). Vulnerability highlights pre-existing weaknesses, whereas resilience emphasizes the strength to absorb impacts, recover functionality, and potentially improve over time. A system with high resilience may still be vulnerable, but its recovery process will be faster, more adaptive, and more sustainable.

The theoretical development of resilience can be described through three major phases. The first phase, known as engineering resilience, focuses on the ability of physical systems to maintain or rapidly regain their original state after a shock. This concept is particularly relevant to infrastructure design, such as buildings withstanding earthquakes or bridges maintaining load-bearing capacity. Research by Rözer and colleagues in 2022, along with findings by Tian et al. in 2023, illustrates the application of this perspective in structural engineering (Rözer et al., 2022; Tian et al., 2023). The second phase is ecological resilience, which emerged from the study of ecosystems. Unlike engineering resilience, ecological resilience does not assume that a system must return to its original state. Instead, it emphasizes the system's capacity to absorb change, reorganize, and maintain essential functions. For example, a wetland recovering from a flood may reorganize its species composition while continuing to provide critical ecological services. Scholars such as Mallick, Vousdoukas, and de Bruijn have contributed to this understanding, showing that resilience includes dynamic processes and the ability to adapt to new conditions (Abdelhafez et al., 2024; Chen & Wang 2023; de Bruijn et al., 2022; Fan et al., 2025; Mallick et al., 2025; Vousdoukas et al., 2020). The third and most recent phase is evolutionary resilience. This perspective highlights learning, transformation, and long-term adaptation in response to disturbance. Rather than aiming to restore the previous condition, evolutionary resilience encourages systems to improve and evolve following a crisis. This approach views disasters not only as threats but also as opportunities for renewal, innovation, and systemic change. Recent studies by Chen and Wang, along with Mallick and others, have emphasized this shift toward adaptive capacity and institutional learning (Chen & Wang 2023; Mallick et al., 2025). Together, these three phases illustrate the growing complexity of resilience theory. Engineering resilience focuses on structural strength and rapid recovery. Ecological resilience introduces concepts of flexibility, feedback, and system-wide adaptation. Evolutionary resilience brings in human behavior, learning, and transformative change. As a result, resilience is now understood as a multi-dimensional concept that requires insights from engineering, natural sciences, social sciences, and economics (Dubey et al., 2025).

This broader view has also been shaped by international policy initiatives. The Sendai Framework for Disaster Risk Reduction, adopted in 2015, expanded the global understanding of risk management. It emphasized the importance of integrating social, economic, and environmental factors into resilience planning. The framework influenced both research and practice by encouraging a shift from vulnerability-focused models to resilience-based strategies. It also demonstrated how global policy can guide and accelerate academic inquiry and practical implementation (Leichenko, 2011).

In current research, resilience is often examined through the lens of human–environment systems (Adger, 2000; Folke, 2006). This approach looks at the interdependence between communities and their ecological or urban surroundings. Resilience can be analyzed at various levels, including cities, neighborhoods, and individuals. Urban resilience has received the most attention, as noted by Meerow and Newell in 2019, accounting for the majority of studies. However, there is increasing interest in community resilience and psychological resilience, especially in response to complex and interconnected risks (Kong et al., 2022; Norris et al., 2008).

This study defines disaster resilience as the combined ability of a system to prevent damage, respond effectively during crises, and adapt to long-term challenges. It includes physical, social, and institutional dimensions. This perspective moves beyond immediate emergency response to consider resilience as part of everyday planning and governance. By embedding resilience into infrastructure design, community development, and policy frameworks, cities and regions can better withstand and grow from future disturbances. This integrated understanding supports a holistic model of disaster risk reduction and sustainable urban development (Ekman, 2023).

Table 1. Classification and Characteristics of the Concept of Disaster Resilience

Classify	Dimensions	Type
Single disaster system (Tian et al. 2023)	Disaster Resilience and Recovery	Physical strength, stability of infrastructure
	Recovery mechanism	Technical measures, technological improvements
Social-ecological system (Mallick, Kour, and Choudhury 2025; Vousdoukas et al. 2020; de Bruijn et al. 2022; Abdelhafez, Mahmoud, and Ellingwood 2024; Chen and Wang 2023; Fan et al. 2025)	Recovery mechanism	Technical measures, comprehensive management, policy support
	System complexity	Resilience, recovery and adaptation of human-environment systems
	System Stability	Infrastructure, economic factors, social factors, ecosystem stability
Complex adaptive systems (Mallick, Kour, and Choudhury 2025; Chen and Wang 2023)	Recovery mechanism	Evolutionary resilience, adaptability, innovation, "sponge city" urban planning
	System complexity	The system's ability to adapt and learn
	System Stability	Dynamic adaptability of multi-dimensional systems, long-term learning process

Table 2. Comparison of Disaster Prevention Systems from a Resilience Perspective

Disaster Prevention Perspective	Traditional Disaster Prevention	Disaster Prevention by Resilience
Disaster prevention goals	Separate prevention units according to administrative management responsibilities, including transportation, electricity, water supply, infrastructure, etc.	Design disaster prevention according to the overall system, emphasizing coordination and linkage between different units in disaster response
Disaster prevention system	Restoring a state of static stability after a natural disaster, focusing on controlling the level of impact of the natural disaster, minimizing loss of life and property, but only has a short-term mitigating effect	Adapt flexibly to natural disasters, emphasize urban functional control and adjust policies early, ensuring the city continues to operate, bringing long-term effectiveness
Disaster prevention education	Professional training is mainly focused on passive response, based on rigid resilience to natural disasters	Encourage broad social participation, towards proactive and flexible response in disaster mitigation

3. Quantitative assessment of resilience to storm disasters

Disaster resilience assessment serves as a bridge between theory and practice, providing scientific guidance for the construction of resilient urban areas through the establishment of a system of indicators and quantitative assessment methods. With the development of resilience theory, the assessment indicator system has expanded from the infrastructure sector to the socio-economic aspect, including direct economic losses, the level of community participation, social networks and governance mechanisms in decision-making (Shahin et al., 2024; Stellacci & Borsoi). However, differences in theoretical frameworks, research objectives and application contexts have led to significant differences in the selection of specific indicators (Valibeigi et al., 2024). Some scholars call for the development of a comprehensive, unified and rational indicator system to analyze the relationship between indicators from a mechanism perspective, thereby improving the reliability and comparability of resilience assessment results (Marolla, 2025).

Resilience assessment methods include qualitative and quantitative assessments. Qualitative assessments, such as survey and document analysis, are gradually being replaced by quantitative methods due to limitations in subjectivity, high data collection costs, and scientific accuracy (Ahamadi et al., 2024). Quantitative assessment methods are classified into three main groups: indicator system analysis, scenario analysis, and function construction (Ros et al., 2024; Zhong et al., 2025) (Table 3).

Table 3. Comparison of quantitative assessment methods for resilience

Classification of methods	System analysis method	Scenario analysis method	Function construction method
Principle of method	Based on the impact factors to measure the resilience of the system	Combining different scenarios to predict future resilience changes	Using historical data to build a simulation function for resilience mechanisms

Advantage	Wide range of applications, can describe multidimensional structure of the system	Consider different possibilities, assess future uncertainty	Simplify and clarify complex resilience mechanisms, simulating real-world conditions
Limitations	The selection of indicators and weighting is subjective.	The scenario combination is subjective, and the calculation process is relatively complicated	Requires high-precision and large-scale input data
Specific measurement method	Delphi method, Analytical Hierarchy Process (AHP), Entropy weighting method, Fuzzy mathematics method, Machine learning model	Numerical Modeling, Regression Analysis, Spatial Analysis using GIS	Statistical Analysis, Complex Network Modeling, Structural Equation Modeling (SEM)

3.1. Method of analyzing the indicator system

The method of analyzing the indicator system establishes a quantitative index framework, providing a theoretical basis for quantitative assessment. Thanks to its comprehensiveness and ease of application, this method is widely used in evaluating disaster resilience (Beccari, 2016; Zhong et al., 2025). Traditionally, the assignment of indicator weights has been highly subjective. However, this issue has been significantly addressed through the application of statistical methods, fuzzy mathematics, and machine learning techniques (De Iuliis et al., 2022; Doshi-Velez & Kim, 2017; Ros et al., 2024).

Evaluation results are verified through accuracy analysis on training and test datasets. However, due to the "black box" problem in machine learning, which limits model interpretability, the scientific validity of the results remains debated. This underscores a fundamental tension in advanced quantitative methods: as models become more sophisticated and accurate (e.g., through deep learning), their internal workings become less transparent (Doshi-Velez & Kim, 2017).

For both scientific research and policymaking, explainability is essential. Understanding why a system is resilient or vulnerable is key to designing effective, targeted interventions. While highly accurate models may offer reliable predictions, they often lack transparency, making it difficult to derive practical guidance for resilience-building. This situation presents a trade-off between predictive power and actionable insight. Looking ahead, an important direction for development involves integrating machine learning algorithms with numerical modeling techniques. Such integration aims to enhance both the transparency and reliability of models, thereby improving their usefulness for decision-making (Alqadhi et al., 2024; Gkontzis et al., 2024).

3.2. Scenario analysis method

This method is based on the results of numerical models driven by physical processes, simulating changes in urban resilience in the future through parameter settings and the combination of different scenarios (Zhong et al., 2025). When integrated with GIS-based spatial analysis technology, this method can visualize the spatial distribution of disaster risk and resilience, making it a mainstream approach in disaster assessment (Bagheri & Liu, 2024).

In Vietnam, scenario analysis-based research primarily focuses on forecasting pressure sources and using models to simulate affected conditions under various disaster intensities in order to develop risk maps (Nguyen et al., 2024). However, integrated assessment models that incorporate socio-economic factors are still in the early stages of development (Nguyen et al., 2021). Although foreign climate adaptation economic models such as DICE (Dynamic Integrated Climate-Economy model), FUND (Framework for Uncertainty, Negotiation, and Distribution), and RCMs (Regional Climate Models), as well as risk assessment models like HAZUS-MH (Hazards U.S. Multi-Hazard) and CLIMADA (CLIMate ADAptation), can serve as references, their direct application in Vietnam has low reliability due to significant differences in loss functions and vulnerability curves compared to local realities (Aznar-Siguan & Bresch, 2019; Dekens, 2023). This highlights a key limitation in applying global or generalized models to specific local contexts.

Loss functions and vulnerability curves are empirical relationships that describe how a system, such as a city or a community, responds to a given hazard intensity. These relationships depend heavily on local building codes, the quality of infrastructure, socio-economic structures, early warning systems, and cultural behaviors (Koks et al., 2019). In the absence of locally calibrated data, even advanced scenario analysis models may generate inaccurate or misleading outcomes. As a result, conducting systematic research on loss functions that reflect Vietnam's specific disaster contexts is essential. Such research not only enhances the accuracy of resilience assessments but also provides a scientific foundation for making more realistic estimates of potential economic losses.

3.3. Method of building evaluation function

Based on mathematical theory, this method employs statistical analysis, complex network models, and structural equations to clarify the interactive relationships among the factors that constitute resilience (Estelaji et al., 2024). At the same time, it uses historical data to forecast future scenarios, addressing the uncertainty and limitations inherent in scenario analysis (Lu et al., 2016). Statistical analysis, a traditional tool in disaster assessment, was initially used to simulate individual disaster phenomena such as storm surges, rainfall, and runoff, as well as to develop vulnerability curves (Xu et al., 2022).

With further research, multihazard analyses have become increasingly common. Methods such as copulas and bivariate extreme value models help evaluate the frequency of complex hazard combinations—for example, extreme rainfall and storm surge, storm surge and extreme runoff, or extreme runoff and sea level rise (Wang et al., 2023; Xu et al., 2019). In model development, complex network modeling and structural equation approaches help examine multidimensional nonlinear relationships among factors, abstracting the resilience problem into mathematical functions for quantitative assessment. This provides a theoretical basis for investigating the evolutionary chains of complex disasters, assessing disaster risks, and understanding resilience mechanisms (Onyeagoziri et al., 2021).

Discuss current challenges in quantitative assessment

The selection of indicators and methods for assessing disaster resilience remains in an experimental phase (Beccari, 2016). Due to limited data availability and unclear operating mechanisms, indicator selection remains subjective. Moreover, the interrelationships among indicators have not been fully examined, resulting in assessment outcomes that are difficult to verify in terms of scientific rigor and reliability (Schipper & Langston, 2015). Although machine learning can help address the issue of indicator interaction and ambiguity in system mechanisms, its transferability and scientific reliability still require further investigation (Zhang et al., 2022).

Currently, pressure source analysis plays a central role in resilience assessments, but socio-economic factors remain insufficiently explored (Cutter et al., 2010). n pressure source analysis, multihazard assessment methods based on copula probability are primarily limited to the bivariate level, and are not yet capable of comprehensively describing complex compound disasters such as "wind–rain–wave–flood" scenarios in the context of tropical storms (Wahl et al., 2015; Xu et al., 2022). Furthermore, when assessing the impacts of climate change, current research tends to separate sea level rise and storm-related disasters as two independent factors, without considering the compound effects of climate change on coastal flood systems (Hao et al., 2018; Moftakhari et al., 2017).

This reveals a critical gap in disaster research and planning. Real-world disasters, particularly in coastal regions, seldom occur as isolated events. For instance, hurricanes often combine wind, rainfall, and storm surges, all of which interact with existing flood conditions and may be further intensified by long-term sea level rise. These interactions are nonlinear and can trigger cascading failures that exceed the sum of individual hazard impacts. Although bivariate analysis marks a methodological advancement, it remains insufficient to capture the full range of synergistic or antagonistic effects that arise from simultaneous hazards. The phenomenon of "compound disasters" represents a core challenge to building effective coastal (Wahl et al., 2015; Zscheischler et al., 2018).

Future research must comprehensively integrate diverse data sources, examine the mechanisms of interaction among indicators, and address the scientific challenges inherent in constructing robust indicator systems. In addition, it is essential to improve assessment methods and develop models that can accurately represent the complex interplay of multiple factors influencing resilience. Addressing this issue is both urgent and critical for advancing the field.

4. Adaptation measures to enhance disaster resilience

Globally, countries are gradually optimizing disaster mitigation strategies, positioning resilience building as a core objective in responding to the negative impacts of climate change on coastal cities. Resilience-enhancing measures can be divided into two main groups: technical and non-technical measures.

4.1. Technical measures

Engineering measures, such as breakwaters and dams, have long been widely implemented as effective means of combating storm surges and floods (Watson et al., 2024). However, rising sea levels and the increasing frequency of super typhoons have posed major challenges to coastal protection structures and drainage systems (Seneviratne et al., 2021). These infrastructures are typically designed to handle high-probability but low-impact events, and are thus inadequate in addressing ultra-extreme events (Hallegatte et al., 2013). Superstorms accompanied by storm surges and extreme rainfall can exceed the design standards of these structures, resulting in infrastructure failure, increased disaster risks, and diminished resilience (Aerts et al., 2014).

Raising protection standards to cope with rare and high-intensity extreme events is not only economically unfeasible, but may also negatively impact coastal ecosystems (Temmerman et al., 2013). This reveals a fundamental limitation of relying solely on hard infrastructure in a dynamically changing climate. As climate change intensifies, “design events” (e.g., 100-year floods) become more frequent or more severe, requiring ever higher and more costly structures. This creates an unsustainable arms race with nature. Moreover, such structures frequently disrupt natural coastal processes, leading to unintended consequences such as erosion in adjacent areas, habitat degradation, and reduced ecosystem services. These indirect effects can ultimately weaken the overall resilience of coastal systems (Wang & Marsooli, 2021). This highlights the need to move beyond static, defense-oriented strategies toward more adaptive and ecologically integrated approaches.

4.2. Non-technical measures

To address the above challenges, non-technical measures are increasingly being emphasized in research due to their flexibility and environmental compatibility (Raymond et al., 2017). These measures focus on utilizing or restoring natural ecosystem functions to deliver multiple benefits such as flood control and coastal erosion protection (Narayan et al., 2017; Temmerman et al., 2013). For instance, restoring wetlands and mangroves not only mitigates storm impacts by absorbing waves and storm surges, but also improves water quality and provides habitats for biodiversity (Spalding et al., 2014). This underscores the concept of “co-benefits” or “multi-functional solutions.” Unlike hard infrastructure that serves a single purpose, nature-based solutions (NBS) often deliver multiple ecosystem services in addition to disaster protection. This makes them more cost-effective over the long term, more adaptable to changing conditions, and more sustainable (Kabisch et al., 2016). They contribute to ecological health, climate change mitigation (e.g., carbon sequestration), and even socio-economic benefits such as ecotourism and fisheries (Cohen-Shacham et al., 2016). This integrated benefit profile makes them a superior choice for long-term resilience strategies.

In addition to ecological solutions, land use planning and the adjustment of building standards to reduce human and property exposure in high-risk areas are also effective strategies for disaster risk reduction (Neumann et al., 2015; UNDRR, 2019). During the prestorm phase, early warning systems and risk assessment tools can help policymakers and the public better prepare and enhance their capacity to respond to extreme weather events (Basher, 2006; Coughlan de Perez et al., 2015).

In conclusion, from a resilience perspective, integrating basic protection measures, ecological infrastructure, emergency management, and disaster warning systems into a multi-layered risk reduction strategy can enhance the climate adaptation capacity of coastal cities. This study focuses on compound storm-related disaster risks in coastal areas and proposes a resilience-based risk reduction framework for coastal urban environments (Hino et al., 2017). Among these, rising sea levels represent long-term challenges driven by climate change, while tropical storms, storm surges, and heavy rainfall are short-term impacts of extreme weather events on urban areas. Solutions such as upgrading sea dikes and underground drainage systems reflect advancements in traditional disaster prevention infrastructure, whereas ecological buffer zones and evacuation areas exemplify green infrastructure development. At the same time, integrating early warning systems and rational urban spatial planning constitutes technical interventions to strengthen urban resilience—towards the ultimate goal of sustainable disaster risk reduction.

5. Research Prospects on Disaster Resilience

In the context of climate change and the growing frequency of extreme weather events, enhancing the resilience of coastal cities has become a central priority in global urban planning and disaster risk reduction strategies. Resilience-building efforts are no longer confined to strengthening physical infrastructure; they also involve non-structural measures such as land use planning, the restoration of natural ecosystems, and the use of real-time data for early warning and risk governance.

Broadly, these solutions can be categorized into three core layers: (1) physical defenses through engineered infrastructure, (2) adaptive and flexible ecological systems, and (3) governance tools and data systems that support responsive action and long-term planning (See Figure 1). Integrating these three layers in a coordinated manner enables coastal cities not only to minimize short-term impacts from disasters like storms and floods but also to improve their capacity to adapt to long-term changes, such as sea level rise.

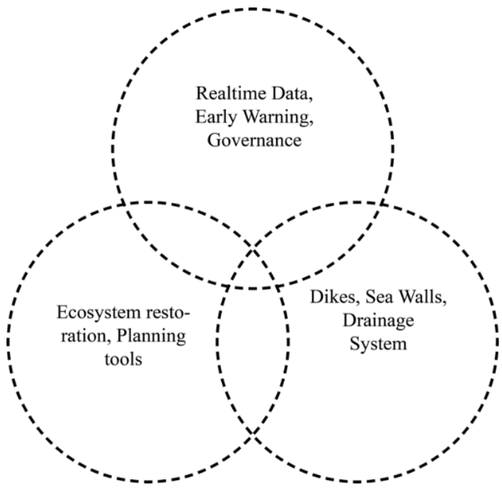

Figure 1. Integrated layers of resilience solutions

5.1. Share historical data on natural disasters

In the quantitative assessment of urban resilience, feasibility and consistency in data collection are major challenges. Although observational data on disaster stressors such as typhoons are relatively complete, significant gaps remain in key indicators such as early-stage disaster losses and population casualties. Inconsistencies in statistical standards across data sources also affect the accuracy of resilience assessment results (Abu Baker, 2025).

The national disaster risk census launched in 2020 has compiled data on affected populations and disaster histories, established a foundational national disaster risk database, and introduced the "Temporary Regulations on the Management of the National Disaster Risk Database," laying the groundwork for sharing historical disaster data (Díaz-Vilariño & Balado, 2024). To strengthen the proposed resilience framework, future research should emphasize the creation of interoperable data-sharing platforms supported by legal and institutional frameworks. These should integrate historical, observational, and real-time disaster data from multiple sectors to enhance assessment precision.

The emphasis on legal regulations, rights protection, and data security underscores the critical role of data governance. Without clear policy frameworks, legal guidelines, and trust mechanisms, data sharing will remain fragmented—despite technological advances (Hrvoje et al., 2025). Effective data governance ensures data quality, accessibility, ethical usage, and long-term sustainability—all foundational for reliable quantitative assessment.

At the policy level, it is necessary to address gaps in legal frameworks for data management while safeguarding the rights of data providers and users. At the practical level, strengthening database security and privacy protection, alongside establishing long-term data update and maintenance mechanisms, will foster greater cooperation in disaster data sharing across relevant authorities.

5.2. Apply real-time data from multiple sources

Building on traditional observation and data collection, the development and application of real-time data from multiple sources provide a new quantitative approach to resilience assessment (Goodchild & Glennon, 2010). The integration of multi-temporal remote sensing data can improve the monitoring of typhoon dynamics, clarify the formation and dissipation processes, and provide accurate spatiotemporal information for disaster response (Voigt et al., 2007).

Real-time data from social media opens new avenues for collecting information on disaster situations, while mobile phone location data can accurately capture individual behavioral patterns, playing a crucial role in evacuation and rescue planning (De Albuquerque et al., 2015; Lu et al., 2012). For data-scarce areas, integrating technologies such as deep learning, multispectral remote sensing, natural language processing, and trajectory analysis enables the accurate extraction of useful information from emerging data sources. This integration has become a key research direction in disaster assessment modeling (Lai et al., 2022; Rahmati et al., 2019).

To deepen the discussion of real-time data integration, the review should include case studies. For example, Taiwan's Central Weather Bureau integrates radar, satellite, and social media feeds to provide early warning alerts, while Indonesia's InAWARE platform (Indonesia All-hazard Warning, Analysis, and Risk Evaluation) combines hazard maps, population data, and social media for situational awareness. Although these sources offer unprecedented insights into disaster dynamics and human behavior in real time, they come with inherent challenges. Social media data can be noisy, biased, or inaccurate, requiring advanced filtering and validation techniques (Imran et al., 2015). Mobile data raises significant privacy concerns. Process standardization is essential, as integrating such disparate, often unstructured, and rapidly generated data streams presents a complex technical challenge (Resch, 2013). The potential lies in improving situational awareness and enabling dynamic response; the risks lie in data quality, ethical implications, and the computational complexity of integrating and interpreting such diverse inputs.

However, given the variability in accuracy and temporal resolution across data sources, standardizing processing to ensure data consistency and comparability is a critical step toward improving the reliability of assessment outcomes (Kryvasheyeu et al., 2015).

5.3. Developing a model for assessing resilience to integrated natural disasters

Coastal cities are affected by overlapping disaster factors, while traditional assessment methods primarily focus on individual natural hazards and fail to fully account for the complexity of compound disasters (Zscheischler et al., 2018). Identifying key disaster drivers, developing simulation technologies for assessment, and enhancing response capacity are essential to ensuring the safety of coastal cities (Laino & Iglesias, 2024).

Based on the integration of data from multiple sources, the coastal compound flooding process—resulting from the interaction of hydrological, oceanic, and meteorological factors—can be dynamically simulated (Muis et al., 2016). At the same time, multidimensional impact factors such as economic conditions, social structures, environmental variables, response capacity, and climate adaptability are incorporated into the quantitative assessment model (Koks et al., 2015). The review should better describe the proposed resilience framework referenced earlier. A conceptual model or figure illustrating its components—data input, compound hazard interaction, socio-ecological feedback loops, and output indices—would enhance clarity. This move is not simply about adding more variables; it requires a fundamental shift from static, single-hazard models to dynamic, multi-hazard, and interdisciplinary models. "Dynamic simulation" implies capturing feedback loops and cascading effects over time. Integrating socio-economic and adaptive factors marks a transition from purely physical models to integrated human–environment systems models (Gill & Malamud, 2014). This represents a significant leap in complexity, requiring interdisciplinary model development and validation against real-world compound disaster events.

In particular, the model must be validated against historical events and continuously optimized to improve forecasting capacity—ultimately enabling storm resilience assessment from a climate adaptation perspective (Vousdoukas et al., 2018). Methodologically, in addition to expanding research on joint probability distributions and multi-scenario numerical simulations, attention should be given to the application of deep learning in disaster assessment (Rahmati et al., 2019). At the same time, developing simplified and generalizable assessment methods will help make the model a practical tool for policymakers and managers in addressing complex disaster challenges (Wens et al., 2019).

5.4. Research on resilience mechanisms to storm disasters

Currently, research primarily focuses on theoretical frameworks and quantitative assessments, while the mechanisms influencing resilience to natural disasters remain underexplored (Meerow & Stults, 2016). In the future it is necessary to develop a comprehensive inventory of influencing factors, identify key variables, and thoroughly examine the interactions among indicators in order to address the limitations of the current indicator system, including the absence of a unified classification framework and the presence of overlapping or redundant indicators(Cutter et al., 2010). This is a core task in clarifying the mechanisms of disaster resilience.

Given the complexity of resilience mechanisms, it is necessary to engage experts from multiple disciplines including disaster science, climatology, urban planning, sociology, and economics. The human–land system approach can serve as an integrated assessment framework to develop comprehensive solutions that help coastal cities cope with storm-related risks and climate change (Liu et al., 2007; Turner et al., 2003). To enhance this section, the review should contrast resilience mechanisms through comparative analysis. For example, how Rotterdam's multifunctional green infrastructure compares to New York's zoning reforms in increasing storm resilience.

In addition, resilience governance should be integrated into mechanism studies by analyzing the effectiveness and interrelationships of adaptation measures, thereby identifying pathways to enhance holistic resilience (Pelling & Manuel-Navarrete, 2011). This underscores that even with advanced theoretical frameworks, accurate assessments, and effective adaptation measures, successful resilience-building ultimately depends on how these measures are implemented and governed. "Resilience governance" refers to the institutional arrangements, policies, decision-making processes, and stakeholder collaborations that enable a system to adapt and transform (Ahern, 2011). Without effective governance, even the most advanced scientific insights may fail to translate into practical actions or long-term improvements. This not only provides a scientific foundation for disaster preparedness but also supports the development of "sustainable and resilient" city models, such as sponge city urbanization (Chan et al., 2018).

6. Conclusion

In the context of climate change, the frequency of storms is increasing, posing significant challenges to the sustainable development of coastal cities. This study has synthesized both domestic and international research progress on theoretical frameworks, quantitative assessment methods, and pathways to enhance disaster resilience. From the perspective of complex systems, the study analyzed key aspects of the disaster resilience theoretical framework, the indicator assessment system, and recovery mechanisms, while also clarifying the concept of disaster resilience. The study also reviewed resilience assessment methods, comparing the strengths and limitations of the three main approaches: the indicator system method, the scenario analysis method, and the function construction method as applied in real-world assessments. Additionally, it synthesized adaptation pathways to improve current resilience. Based on an analysis of the appropriateness of both structural and non-structural solutions, the study proposed a disaster prevention framework for coastal cities to enhance resilience to compound storm-related hazards.

Overall, current research has not yet reached a consensus on a theoretical framework; the mechanisms for assessing resilience to compound storm-related disasters remain unclear, and the integrated assessment methods that account for multiple types of hazards and influencing factors are still in their infancy. In particular, the integration of socio-economic factors into scenario analysis and function modeling in quantitative assessments remains limited, which hinders the ability of such assessments to serve as a reliable basis for resilience-based disaster risk reduction decision-making. This constitutes a critical self-assessment of the field, implying that even with theoretical and methodological advancements, resilience research findings often lack the robustness, precision, or comprehensiveness required by policymakers to support concrete, high-stakes decision-making. This gap may stem from data limitations, model complexity (e.g., interpretability issues), or the inability to fully capture real-world socio-economic dynamics. It highlights a disconnect between academic findings and practical applicability.

In the future, research should focus on establishing disaster data-sharing mechanisms and making full use of Big Data and Artificial Intelligence (AI) to improve the collection and coordination of early-stage disaster information. Emerging data sources should also be explored to support more effective resilience assessments. Guided by a logical progression from theoretical inquiry to model building, resilience evaluation, and strategic planning, future studies should adopt interdisciplinary methods and apply multidimensional data analysis, treating the human–environment system as a single, integrated subject of assessment. Within the broader context of climate change, it is important to investigate how compound storm-related disasters operate across different levels in coastal cities. This includes conducting detailed resilience assessments and designing context-specific adaptation strategies. Such an approach will help reveal the evolving relationship between human systems and storm events, clarify their interactions and feedback loops, and ultimately provide a scientific basis for developing risk reduction measures that are both resilience-focused and climate-responsive.

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