Network Science and Complex Systems
https://nscs-journal.org

Relationship of Resilience Investment Rules and Routing Diversity to Recovery Speed in Coastal Infrastructure Networks

Alice Ng*

Department of Electrical and Electronic Engineering, Faculty of Engineering, Hong Kong Polytechnic University, Hong Kong, Hong Kong SAR, China

Corresponding author: alice.ng@polyu.edu.hk

Abstract

Coastal infrastructure networks represent a critical backbone of modern urban economies, yet they are increasingly vulnerable to severe weather events and climate-driven hazards. As the frequency of disruptive incidents escalates, evaluating network robustness alone is no longer sufficient; understanding the determinants of post-disaster recovery speed has become paramount. This study provides a comprehensive investigation into how resilience investment rules and routing diversity jointly explain the variance in recovery speed across complex coastal infrastructure systems. By conceptualizing infrastructure as interconnected spatial graphs, this research evaluates diverse resource allocation strategies alongside topological variations characterized by multi-path routing redundancy. Through extensive simulation of hazard scenarios such as storm surges and hurricanes, the analysis demonstrates that targeted resilience investments based on node vulnerability significantly accelerate functional restoration compared to uniform or purely centrality-based hardening. Furthermore, high routing diversity is shown to act as a crucial buffer during the initial phases of disaster impact, allowing networks to maintain baseline operations while physical repairs are executed. The findings indicate a synergistic relationship between strategic financial investment and topological design, suggesting that coastal urban planners must integrate both dimensions to optimize recovery trajectories. This paper provides actionable insights for civil engineers and policymakers tasked with safeguarding coastal communities against an increasingly volatile climate future.

Keywords: Coastal Infrastructure; Recovery Speed; Resilience Investment; Routing Diversity; Network Topology

1. Introduction

1.1 The Growing Imperative of Coastal Infrastructure Resilience

Coastal regions across the globe are experiencing unprecedented rates of urbanization and economic development, transforming them into vital hubs of international trade, tourism, and human habitation. Consequently, the infrastructure networks that support these regions including power grids, water distribution systems, telecommunications, and transportation logistics have grown exceedingly complex and highly interdependent. However, this dense concentration of critical infrastructure is situated in environments inherently prone to devastating natural hazards such as hurricanes, typhoons, tsunamis, and progressive sea-level rise. When these complex networks fail under the stress of extreme environmental forces, the resulting disruptions cascade rapidly across regional and national boundaries, leading to catastrophic socioeconomic losses. The traditional engineering paradigm heavily emphasized designing infrastructure to resist failure, a concept broadly defined as robustness. While robustness remains a fundamental design criterion, the magnitude of contemporary climate hazards frequently exceeds design thresholds, making total failure prevention an economically and physically impossible goal. Acknowledging this reality, academic and professional engineering communities have fundamentally shifted their focus toward resilience, prioritizing the ability of a system to absorb shocks, adapt to degraded conditions, and rapidly restore its intended functionality [1]. In this context, recovery speed has emerged as the defining metric of resilience, dictating how quickly a community can return to a state of normalcy or establish a new functional baseline following a destructive event.

1.2 Determinants of Post-Disaster Recovery Speed

The velocity at which an infrastructure network recovers from a disruptive shock is not merely a function of the disaster's severity, but rather the outcome of complex interactions between the physical topology of the network, pre-disaster mitigation strategies, and post-disaster operational management. Two critical determinants that have garnered significant academic interest are resilience investment rules and routing diversity. Resilience investment rules refer to the established policies, algorithms, and prioritization schemes that dictate how limited financial and physical resources are allocated to strengthen specific components of the infrastructure before a disaster occurs, or how repair resources are distributed in the aftermath. Due to strict budgetary constraints, it is impossible to maximally harden every component of a regional power grid or transportation network. Therefore, planners must rely on specific rules ranging from uniform resource distribution to highly targeted investments based on node centrality or historical vulnerability to maximize the return on resilience investments. Conversely, routing diversity is a fundamental topological property of the network itself. It describes the availability of multiple independent pathways through which critical services, such as electricity, data, or vehicular traffic, can flow between sources and destinations. Networks with high routing diversity can bypass damaged nodes and links by redistributing operational loads through surviving parallel corridors. The interplay between proactive resilience investments and inherent routing diversity dictates the trajectory of the recovery curve, yet the precise mechanisms through which these two factors complement or substitute each other remain underexplored in standard civil engineering literature [2].

1.3 Scope and Objectives of the Research

The primary objective of this comprehensive study is to systematically explain how variations in resilience investment rules and levels of routing diversity interact to determine the overall recovery speed of coastal infrastructure networks subjected to simulated disaster events. By constructing a robust analytical framework that models infrastructure systems as complex spatial graphs, this research aims to isolate the individual and combined effects of strategic resource allocation and topological redundancy. First, this paper explores different paradigms of resilience investment, comparing strategies that prioritize highly connected components against those that prioritize highly vulnerable components located in exposed coastal zones. Second, the study quantifies the impact of routing diversity on the initial drop in network performance and the subsequent rate of functional restoration. Third, the research seeks to uncover any synergistic effects, attempting to answer whether superior routing diversity can compensate for suboptimal investment strategies, or if precise investment can overcome the limitations of a rigid, low-diversity network topology. By addressing these critical questions, this paper seeks to provide theoretical advancements in the field of infrastructure resilience while offering practical, actionable frameworks for urban planners and utility operators tasked with optimizing disaster preparedness and recovery protocols in vulnerable coastal environments.

2. Literature Review and Theoretical Background

2.1 The Evolution of Infrastructure Resilience Analysis

The concept of resilience in the context of critical infrastructure has evolved significantly over the past two decades. Early studies predominantly borrowed from ecological definitions, emphasizing a system's ability to return to equilibrium after a disturbance. However, as infrastructure systems are fundamentally engineered rather than naturally occurring, researchers recognized the need for a more operationalized definition. Modern interpretations of infrastructure resilience conceptualize it as a multi-dimensional capability encompassing four distinct phases: preparation, absorption, recovery, and adaptation. Extensive literature has documented that while absorption represents the immediate robustness of the physical assets, recovery is a dynamic, time-dependent process that profoundly impacts the long-term viability of the affected population. Studies investigating post-disaster trajectories often utilize the resilience triangle metric, which calculates the area of lost functionality over time [3]. Minimizing this area requires accelerating the recovery speed. Previous investigations have shown that recovery speed is highly sensitive to the initial state of the network and the availability of repair resources [4]. Despite the growing body of literature on recovery modeling, many existing models treat the pre-disaster investment landscape and the topological configuration of the network as static, independent variables, failing to capture how proactive financial decisions shape the physical pathways available during the critical restoration phase.

2.2 Paradigms of Resilience Investment Rules

In the domain of disaster risk management and infrastructure planning, resilience investment rules serve as the foundational logic for allocating scarce capital. The literature identifies several dominant paradigms for pre-disaster mitigation and post-disaster restoration. A widespread approach relies on network centrality metrics, where planners allocate maximum funding to harden components that possess the highest degree, betweenness, or closeness centrality. The underlying assumption is that preserving the most highly connected nodes will inherently protect the systemic integrity of the entire network [5]. Another prominent paradigm focuses on exposure-based or vulnerability-based allocation. In this framework, resources are directed disproportionately toward assets located in high-risk geographic areas, such as low-lying coastal zones susceptible to storm surges, regardless of their topological importance within the broader network. Studies evaluating these rules often utilize optimization algorithms to find the theoretical maximum resilience for a given budget [6]. However, a significant gap in the literature is the assumption that investment outcomes are uniformly deterministic. In reality, the efficacy of an investment rule is heavily mediated by the nature of the hazard. A centrality-based investment strategy may perform exceptionally well during a localized equipment failure but might fail catastrophically during a massive coastal inundation that indiscriminately destroys multiple peripheral nodes, isolating the hardened central hubs. Consequently, researchers are increasingly calling for comparative analyses that test multiple investment rules against spatially correlated hazard models typical of coastal environments.

2.3 The Concept and Mechanics of Routing Diversity

Routing diversity represents a critical topological attribute derived from complex network theory and graph theory. In the context of infrastructure, it refers to the multiplicity of physically distinct paths available to transport a continuous flow of resources such as electricity, water, or data from supply generation nodes to demand consumption nodes [7]. A network with minimal routing diversity typically exhibits a tree-like topology, where the removal of a single parent node instantly disconnects all downstream children. Conversely, a network with high routing diversity resembles a dense mesh, characterized by high clustering coefficients and numerous redundant edges. During a disruptive event, high routing diversity provides immediate functional buffering. When primary transmission lines or main arterial roads are severed, the system can automatically or manually reroute flows through secondary and tertiary pathways. This capability significantly reduces the initial loss of system performance. Furthermore, literature suggests that routing diversity dramatically alters the requirements for recovery speed [8]. If a highly diverse network can maintain seventy percent of its baseline functionality post-disaster by utilizing alternative paths, the urgency and speed required for physical repairs are entirely different than in a network that immediately drops to twenty percent functionality. Despite its recognized importance, routing diversity is often expensive to build and maintain, requiring extensive land acquisition and significant capital expenditure for redundant assets that remain underutilized during normal operations.

2.4 Identifying the Research Gaps in Coastal Contexts

While both resilience investment strategies and routing diversity have been studied independently, their interactive effects remain a significant gap in the contemporary literature, particularly within the specific context of coastal infrastructure systems [9]. Coastal networks face unique geospatial challenges; the hazards they encounter, such as hurricanes and tsunamis, do not impact nodes randomly. Instead, these hazards exhibit strong spatial correlation, sweeping from the coastline inward and systematically destroying infrastructure along an identifiable geographic gradient. Many theoretical models of network resilience rely on random node deletion or targeted attacks on high-degree nodes, which fail to accurately simulate the spatially progressive nature of coastal disasters. Furthermore, existing studies rarely explore whether advanced topological designs can offset the risks of poor investment decisions, or conversely, whether sophisticated, algorithm-driven investment rules can compensate for legacy infrastructure systems burdened with low routing diversity. Addressing this interaction is critical because municipal planners rarely have the luxury of building entirely new, highly diverse networks from scratch. They must optimize operational recovery by applying modern investment rules to aging, rigid topologies. By analyzing these variables concurrently under simulated spatially correlated hazards, this study addresses this critical gap, providing a more holistic explanation of what truly drives recovery speed in coastal environments.

3. Methodology and Analytical Framework

3.1 Network Representation and Topological Design

To systematically investigate the interactions between investment rules and routing diversity, this study employs a rigorous simulation framework grounded in complex network theory. The coastal infrastructure system is abstracted as a set of spatial graphs consisting of nodes representing critical facilities such as power substations, pumping stations, and telecommunication hubs, and edges representing the physical linkages such as transmission lines, water pipelines, and fiber optic cables. To ensure the findings are generalizable while remaining relevant to coastal geographies, synthetic networks were generated using spatially constrained algorithms. The generation process bounds the nodes within a defined rectangular coordinate system, where one boundary represents the coastline. To test the effects of routing diversity, the algorithm generated three distinct topological variants for the same set of spatial nodes. The first variant is a minimal spanning tree topology, representing extreme low routing diversity where exactly one path exists between any two nodes. The second variant is a moderate diversity topology, generated by adding a fixed probability of connections between geographically adjacent nodes, creating localized loops. The third variant is a highly diverse mesh topology, which incorporates long-range connections and multiple redundant pathways traversing different geographic corridors. These variations allow for the isolation of routing diversity as an independent experimental variable while holding the spatial distribution and number of operational nodes constant.

3.2 Simulating Spatially Correlated Coastal Hazards

A critical requirement of this methodology is the realistic simulation of coastal hazards, which differ fundamentally from random equipment failures. This study develops a spatially correlated hazard model designed to mimic the impacts of a severe storm surge accompanied by hurricane-force winds. The hazard is initiated at the coastal boundary of the simulation space and propagates inland. The intensity of the hazard diminishes as a function of the distance from the coastline and the elevation of the terrain, which is synthetically mapped onto the coordinate system. Each node and edge within the network is assigned an initial fragility curve, dictating its probability of failure given a specific level of hazard intensity. Nodes located directly on the coastline experience maximum intensity, resulting in a near-certain probability of failure unless previously mitigated through resilience investments. As the simulated storm surge moves inland, the probability of failure decreases. To capture the stochastic nature of natural disasters, the hazard model is executed over thousands of Monte

Carlo iterations. During each iteration, the physical state of every node and edge is evaluated based on its specific failure probability, resulting in a unique post-disaster damage state. This robust probabilistic approach ensures that the analysis of recovery speed is not biased by a single, idiosyncratic damage scenario but represents a statistically significant expectation of performance under severe coastal stress.

3.3 Formulation of Resilience Investment Rules

Prior to the initiation of the simulated hazard, the analytical framework applies different resilience investment rules to the network. These rules represent the strategies policymakers use to allocate a fixed budget to harden infrastructure components, thereby reducing their fragility and probability of failure during the disaster. The budget is intentionally constrained to ensure that only a subset of the network can be protected. This study evaluates three distinct investment rules. The first is the Centrality-Based Investment Rule. Under this protocol, the simulation calculates the betweenness centrality for every node, which measures how frequently a node acts as a bridge along the shortest path between two other nodes. The fixed budget is exclusively allocated to harden the top percentile of nodes with the highest betweenness centrality scores. The second approach is the Vulnerability-Based Investment Rule. This protocol ignores network topology entirely and allocates funding based strictly on geographic exposure. Nodes closest to the coastal boundary, which face the highest anticipated hazard intensity, receive priority hardening. The third approach is the Uniform Distributed Investment Rule, which acts as a baseline control. Under this strategy, the budget is spread equally across all nodes in the network, providing a marginal, uniform reduction in failure probability across the entire system. By testing these three distinct strategies, the methodology can precisely measure how proactive financial decision-making alters the starting point of the post-disaster recovery phase.

3.4 Operationalizing Routing Diversity and Flow Redistribution

Following the impact of the simulated hazard and the resulting component failures, the network's immediate surviving functionality must be quantified before recovery begins. This is achieved through a flow redistribution algorithm that evaluates routing diversity in real time. The model defines performance based on the total volume of service successfully delivered from supply nodes to demand nodes. When an edge is destroyed, the flow algorithm attempts to find an alternative continuous path through the surviving topology. In networks with low routing diversity, the destruction of a critical arterial edge typically results in a complete loss of service to downstream demand nodes, as no alternative paths exist. In contrast, networks with high routing diversity trigger complex rerouting behaviors. The algorithm evaluates the remaining capacity of parallel edges and redistributes the flow accordingly. If the redistributed flow exceeds the physical capacity constraints of the secondary edges, cascading failures are triggered, simulating the real-world phenomenon of overloaded power lines or severely congested evacuation routes. The post-disaster functionality score is calculated as the ratio of successfully delivered flow after the hazard event to the maximum flow delivered under normal baseline conditions. This calculation isolates the immediate buffering effect provided by routing diversity before any physical repair interventions are launched.

3.5 The Recovery Speed Simulation Engine

The core of the methodology is the dynamic recovery simulation engine, which tracks the restoration of network functionality over a discrete time horizon. The recovery process is modeled as the sequential repair of damaged nodes and edges by a finite number of dispatchable repair crews. The simulation proceeds in daily time steps [10]. At each step, a central repair algorithm prioritizes the damaged components based on their potential to reconnect the largest number of disconnected demand nodes to the supply source. Once a component is assigned a repair crew, it requires a specific number of time steps to be restored, after which it becomes fully operational and available for flow redistribution [11]. Recovery speed is formally quantified using two distinct metrics. The first metric is the Time to Complete Restoration, representing the total number of time steps required for the network to reach one hundred percent of its pre-disaster functionality. The second, more nuanced metric is the Restoration Integral, which calculates the cumulative area under the recovery curve. A larger Restoration Integral indicates that the network regained significant functional capacity very early in the recovery timeline, even if the final few peripheral nodes took weeks to repair. By tracking these metrics across all combinations of network topologies, investment rules, and hazard scenarios, the simulation engine generates a massive, multidimensional dataset that can definitively explain the drivers of recovery speed in coastal infrastructure networks.

4. Results and Comprehensive Discussion

4.1 Evaluating the Efficacy of Resilience Investment Rules

The extensive simulation results reveal profound differences in recovery speed driven by the choice of pre-disaster resilience investment rules. When subjected to the spatially correlated coastal hazard, the baseline scenario without any investment demonstrated severe initial degradation and an unacceptably protracted recovery timeline. Implementing the Uniform Distributed Investment Rule provided only marginal improvements. Because the coastal storm surge exerted forces that vastly exceeded the slightly improved tolerances of the uniformly hardened nodes, the coastal assets still failed en masse. Consequently, the uniform strategy resulted in a highly inefficient allocation of capital, yielding a slow and staggered recovery curve.

In stark contrast, the highly targeted strategies yielded complex, divergent outcomes. The Centrality-Based Investment Rule proved surprisingly ineffective against the specific nature of coastal hazards. Because high-centrality nodes are often located geographically inland acting as major distribution hubs the investment successfully protected these hubs. However, the unprotected coastal nodes, which included vital generation and intake facilities, were obliterated. The repair crews were forced to spend immense time clearing and reconstructing the coastal periphery from scratch before the protected central hubs could actually distribute any service.

The clear optimal strategy for maximizing recovery speed was the Vulnerability-Based Investment Rule. By heavily hardening the nodes directly on the coastline, this strategy prevented the destruction of critical supply entry points. Although some central and peripheral inland nodes failed due to the residual wind and storm effects, the survival of the coastal frontline meant that repair crews could rapidly progress inland, systematically reconnecting surviving inland segments to the protected supply sources.

Table 1: Comparison of Recovery Metrics Across Different Investment Rules (Averaged Over 5000 Simulations on Moderate Diversity Topology)

Investment Rule Strategy	Initial Post-Disaster Functionality	Total Time to Complete Restoration	Restoration Integral Score
No Investment (Baseline)	22.4 Percent	45 Days	12450
Uniform Distributed	28.1 Percent	39 Days	14200
Centrality-Based	31.5 Percent	35 Days	15800
Vulnerability-Based	54.2 Percent	18 Days	28450

As detailed in Table 1, the Vulnerability-Based strategy not only preserved more than double the initial functionality compared to the baseline but also reduced the total time to complete restoration by more than half. The exceptionally high Restoration Integral Score indicates that the vast majority of consumer demand was met very early in the recovery phase, highlighting that understanding the spatial nature of the hazard is far more critical than relying on topological centrality metrics when allocating financial resources in coastal zones.

4.2 The Mitigating Impact of Routing Diversity

The analysis of routing diversity isolated its profound capacity to alter the fundamental physics of network recovery. In scenarios featuring the minimal spanning tree topology, representing low diversity, the destruction of any node completely halted the flow of services to all subsequent branches. Recovery in these low-diversity environments was agonizingly linear; repair crews had to fix the damaged parent node before any downstream repairs could have a functional impact. There was no capability to bypass damage, leading to massive bottlenecks in the restoration of societal services.

Conversely, the highly diverse mesh topology fundamentally altered the recovery trajectory. When the coastal hazard swept through, destroying a significant swath of infrastructure, the high density of redundant pathways immediately engaged. The flow redistribution algorithms consistently found alternative, albeit circuitous, routes to maintain service to demand nodes located behind the damage zone. This buffering effect meant that the initial post-disaster functionality remained remarkably high. More importantly, it allowed the repair algorithms immense flexibility. Repair crews did not have to follow a strict sequential path; they could tackle repairs in parallel across multiple geographic zones because the redundant pathways allowed isolated pockets of repaired infrastructure to immediately integrate with the surviving global network.

Table 2: Influence of Routing Diversity on Recovery Speed Under Vulnerability-Based Investment

Network Topology Variant	Pre-Disaster Redundancy Ratio	Functionality Maintained at Day 1	Time to Reach 90 Percent Functionality
Minimal Spanning Tree	1.00	18.5 Percent	28 Days
Moderate Diversity	1.45	54.2 Percent	12 Days
High Diversity Mesh	2.80	79.4 Percent	4 Days

Table 2 clearly demonstrates that routing diversity is arguably the most potent driver of rapid recovery. The high diversity mesh network was able to reach ninety percent functional restoration in just four days, compared to twenty-eight days for the low-diversity tree. This outcome emphasizes that the topological design of the infrastructure creates a structural ceiling on how fast recovery can theoretically proceed, regardless of the sheer number of repair crews deployed.

4.3 Synergistic Dynamics and Strategic Trade-offs

A critical objective of this research was to identify whether routing diversity and resilience investments substitute for or complement one another. The simulation data provides a conclusive answer: they operate synergistically but serve distinct temporal functions in the disaster timeline. High routing diversity is an immediate shock absorber. It requires no activation time and passively maintains system continuity in the minutes and hours following the hazard. However, diversity alone cannot repair destroyed physical assets. Resilience investment rules, particularly vulnerability-based hardening, dictate the survival of critical source nodes that feed the diverse pathways.

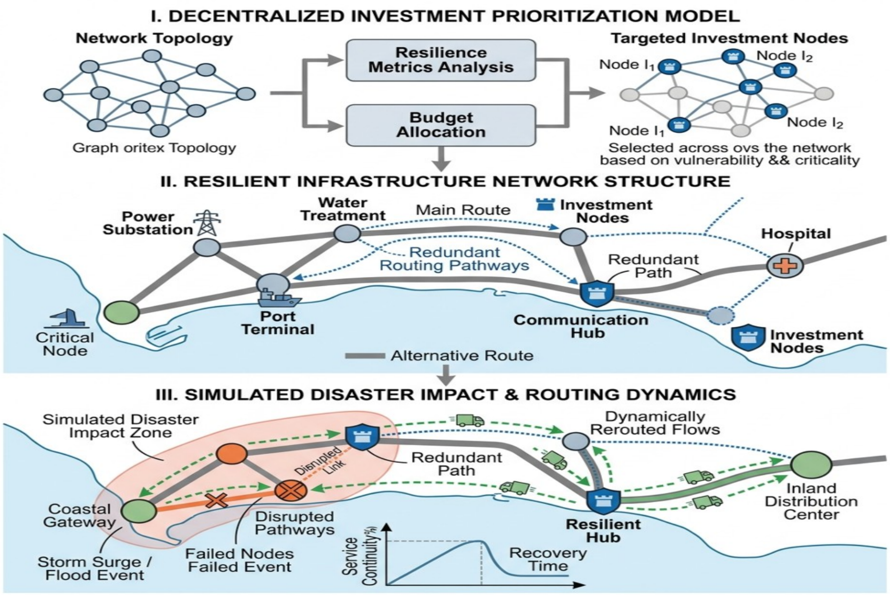

Figure 1: Comprehensive Schematic of Coastal Infrastructure Network Resilience Modeling

If a highly diverse network lacks vulnerability-based investment, the coastal hazard may destroy all the primary source nodes. In this scenario, having hundreds of redundant inland pathways is entirely useless because there is no fundamental service to distribute. Alternatively, a network with perfect vulnerability-based investment but low routing diversity remains highly brittle; if an unpredicted localized failure occurs inland, the entire downstream branch dies. Therefore, the optimal recovery speed was consistently observed only in scenarios that combined high topological routing diversity with aggressive, spatially targeted resilience investments [12]. The data indicates that urban planners should view these two mechanisms as necessary halves of a holistic resilience strategy. Investments secure the vital anchors of the system, while diversity guarantees that the services generated by those anchors can navigate the chaos of a post-disaster landscape to reach the populace in need.

5. Conclusion and Policy Implications

5.1 Summary of the Analytical Findings

This comprehensive academic investigation has systematically explored the intricate mechanisms through which resilience investment rules and routing diversity govern the recovery speed of coastal infrastructure networks. By employing an advanced simulation framework that integrates spatial graph theory, probabilistically modeled coastal hazards, and dynamic recovery algorithms, the research has quantified the profound impact of pre-disaster planning on post-disaster outcomes. The findings definitively demonstrate that conventional investment strategies, such as uniform resource distribution or topology-based centrality hardening, are fundamentally ill-suited for the unique spatial threats posed by coastal hazards like storm surges. Instead, vulnerability-based investment rules, which prioritize the fortification of geographically exposed frontline nodes, yield massively superior recovery speeds. Furthermore, the study confirms that high routing diversity acts as an essential topological catalyst for rapid restoration. Redundant pathways not only prevent catastrophic initial losses in system functionality but also provide indispensable flexibility for repair crews, allowing parallel restoration efforts that bypass localized devastation. Ultimately, the fastest and most robust recovery trajectories are achieved exclusively when targeted financial hardening is seamlessly integrated into a highly diversified network architecture.

5.2 Strategic Recommendations for Coastal Infrastructure Management

The insights derived from this study offer highly actionable policy implications for municipal planners, civil engineering consortiums, and government oversight agencies responsible for coastal infrastructure. First, utility operators must abandon uniform budget allocations and transition to highly targeted, spatially informed investment paradigms. Vulnerability assessments must prioritize the geographic source of the threat over the mathematical centrality of the network node. Funding must be aggressively directed toward hardening assets physically located within predicted inundation zones. Second, infrastructure master plans must mandate strict minimum criteria for routing diversity in all new developments. The construction of single-pathway dependencies should be strictly prohibited in coastal zones. Furthermore, municipal governments should incentivize the retrofitting of legacy infrastructure to create deliberate redundant loops, transforming brittle tree-like structures into resilient localized meshes. Policymakers should recognize that while building redundant pathways involves significant upfront capital expenditure, this cost is overwhelmingly justified by the catastrophic economic losses averted during the accelerated post-disaster recovery phase.

5.3 Acknowledgment of Limitations and Future Directions

While the simulation framework provides robust, statistically significant conclusions, it is important to acknowledge certain theoretical constraints. The current model assumes that repair resources, such as specialized crews and replacement components, are continuously available and do not suffer from localized supply chain disruptions caused by the hazard itself. In reality, massive coastal disasters often destroy the very transportation infrastructure required to move the repair crews, creating complex inter-network dependencies. Future research should aim to construct coupled, multi-layer network models where the recovery speed of the primary network, such as the power grid, is dynamically constrained by the real-time operational status of the secondary network, such as the regional highway system. Additionally, incorporating dynamic human behavioral models detailing how populations evacuate and consequently shift infrastructure demand during the recovery phase would provide an even more realistic measure of community resilience. Despite these limitations, the fundamental principles established in this study regarding the critical synergy between strategic vulnerability investment and topological routing diversity provide a vital foundation for the future of resilient coastal engineering.

References

1. Zhao, R.; Cai, J.; Luo, J.; Ran, Y.; Gao, J.; Xu, Y. Joint Beam Hopping and Resource Allocation for Load Balancing and Interference Avoidance in Multi-LEO Satellite Networks. In Proceedings of the ICC 2025—IEEE International Conference on Communications, Montreal, QC, Canada, 8–12 June 2025; pp. 958–963.

2. Fastiggi, M.; Meerow, S.; Miller, T.R. Governing urban resilience: Organisational structures and coordination strategies in 20 North American city governments. Urban Stud. 2021, 58, 1262–1285.

3. Viana, J.; Farkhari, H.; Gil Jiménez, V.P. Securing 5G and Beyond-Enabled UAV Links: Resilience Through Multiagent Learning and Transformers Detection. IEEE Access 2025, 13, 153993–154007.

4. Ayyappan, V.; Bruno, M.A. Applying Machine Learning to Optimize Resource Allocation & Maritime Wireless Mobile Network. J. Wirel. Mob. Netw. Ubiquitous Comput. Dependable Appl. 2025, 16, 406–416.

5. Kim, S.; Andrew, S.A.; Ramirez de la Cruz, E.; Kim, W.-J.; Feiock, R.C. Impacts of Local Government Perceptions of Disaster Risks on Land Resilience Planning Implementation. Land 2024, 13, 1085.

6. Kunreuther, H., & Pauly, M. V. (2006). Rules rather than discretion: Lessons from Hurricane Katrina. Journal of Risk and Uncertainty, 33, 101–116.

7. Ministry of Land, Infrastructure, Transport and Tourism. National Land Numerical Information Download Site. Available online: https://nlftp.mlit.go.jp/ksj/index.html (accessed on 29 August 2024).

8. Lin, G.; Xiao, Y.; Yu, S.; Yu, K.; Liu, J. Constrained Probabilistic Routing with RouterRL: A General Packet-Level Network Simulation Framework. IEEE Trans. Netw. Sci. Eng. 2026, 13, 2604–2622.

9. Li, S.; Wu, Q.; Wang, R. Efficient Packet Routing in Ultra-Dense LEO Satellite Networks via Cooperative-MARL with Queuing Theory Model. In Proceedings of the 2025 IEEE Wireless Communications and Networking Conference (WCNC), Milan, Italy, 24–27 March 2025; pp. 1–6.

10. Nguyen, T.T.H.; Kim, T. Proximal Policy Optimization for Up/Downlink Time Slots Allocation in 5/6G Dynamic TDD Networks. KSII Trans. Internet Inf. Syst. 2025, 19, 259–278.

11. He, H.; Yang, X.; Mi, X.; Shen, H.; Liao, X. Multi-Agent Deep Reinforcement Learning Based Dynamic Task Offloading in a Device-to-Device Mobile-Edge Computing Network to Minimize Average Task Delay with Deadline Constraints. Sensors 2024, 24, 5141.

12. Cui, Z.; Qamar, F.; Kazmi, S.H.A.; Zainol Ariffin, K.A.; Safdar, G.A.; Ur Rehman, M.H. A Review of Multi-Agent Deep Reinforcement Learning for Resource Allocation in beyond 5G Network Slicing: Solutions, Challenges and Future Research Directions. PeerJ Comput. Sci. 2026, 12, e3728.