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Inter-Organizational Collaboration under Cascading Typhoon Risks: Evidence from the Yangtze River Delta, China

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Abstract

Under the cascading effects of typhoon disasters, it is difficult for a single region or department to cope independently with complex risks, making cross-regional emergency collaboration a practical need for regional governance. However, existing studies have paid insufficient attention to the joint analysis of typhoon cascading-risk propagation structures and organizational collaboration relationships. Based on historical typhoon event data, this study constructs a typhoon disaster cascading-effect network for the Yangtze River Delta and identifies key nodes, disturbance impacts, and coverage overlap relationships in the disaster propagation process. It also constructs a cross-regional emergency organizational collaboration network and uses the QAP method to analyze the effects of spatial relationships, hierarchical relationships, system affiliation, and economic disparity on the formation of collaborative relationships. The results show that the cascading propagation of typhoon disasters presents clear centralization characteristics, with risks mainly diffusing through nodes related to critical infrastructure such as transportation, water conservancy, power, and communications. At the level of organizational collaboration, cross-provincial ties and system affiliation significantly promote the formation of collaborative relationships, while within-province vertical relationships show a relatively weaker tendency to form collaborative ties in contexts with larger economic disparities. This study provides empirical evidence for understanding risk propagation characteristics and organizational collaboration conditions in regional emergency response under cascading typhoon risks.

Keywords

Typhoon Disasters, Cascading Effects, Inter-Organizational Collaboration, Complex Networks, Regional Emergency Governance

1. Introduction

Typhoons are among the most destructive natural hazards worldwide. They are often accompanied by strong winds, heavy rainfall, and storm surges, but most damage is caused by secondary hazards such as floods and landslides (Pandey & Liou, 2022). Within China, southeastern coastal regions are among the areas most severely affected by typhoons, especially highly urbanized regions such as the Yangtze River Delta. This region has high population density and concentrated economic activities, and its urban systems are complex and interdependent. The failure of a local component often triggers chain reactions, causing the secondary impacts of typhoon disasters to be continuously amplified within the system (Zheng et al., 2024). For example, after Super Typhoon Lekima made landfall in Zhejiang Province in 2019, persistent heavy rainfall triggered secondary disasters such as floods and landslides across several provinces and municipalities in the Yangtze River Delta. In total, 14.02 million people were affected, 15,000 houses collapsed, 11,370 hectares of farmland were damaged, and direct economic losses reached CNY 51.53 billion (Zhang et al., 2021). These severe losses reflect the cross-system and cross-regional cascading characteristics of typhoon disasters in the Yangtze River Delta, creating an urgent need to identify their risk propagation patterns and key nodes.

To address this complex evolutionary process, recent studies have begun to use the complex network approaches to analyze disaster propagation processes and their structural characteristics (Hu et al., 2022; Wang et al., 2022). This approach usually abstracts disaster events as nodes and represents triggering or influence relationships between events as links, thereby transforming a disaster chain into a measurable propagation network and identifying key pathways in risk diffusion (Valdez et al., 2020). On this basis, structural indicators such as degree centrality and betweenness centrality are commonly used to assess the connectivity and path-control role of nodes, providing a basis for identifying structurally critical events in disaster propagation (Hu et al., 2022). However, these indicators mainly identify key nodes from direct connections and shortest-path control. They provide limited explanation of how far the influence of a given event can be transmitted or whether the influence ranges of different events overlap. Especially in highly urbanized regions, typhoon disasters often continue to propagate along multiple types of infrastructure and social functional units. The role of key nodes is reflected not only in their connections and path-control positions, but also in their subsequent influence ranges and overlapping risks. Therefore, based on existing structural indicator analysis, this study further identifies key nodes and their potential impacts in the cascading evolution of typhoon disasters in the Yangtze River Delta from the perspectives of propagation process and influence range.

Cascading disaster networks reveal how risks diffuse, whereas organizational collaboration networks reflect how governance actors respond to such cross-boundary risks. The impacts of typhoon disasters often cross multiple systems and regions, and their risks are transmitted and continuously amplified across different domains (Pescaroli & Alexander, 2016). Such cascading impacts mean that disaster response is often no longer confined to a single department or region, but simultaneously involves multiple functional systems and local actors. Traditional department- or jurisdiction-based emergency approaches often struggle to integrate information collection, resource allocation, and action coordination when facing cross-boundary risks (Sun et al., 2024). In China's current disaster management system, this problem is reflected in the long-standing division of responsibility among relatively independent departments for different types of disasters, while cross-departmental information sharing and capability coordination remain constrained by institutional and organizational boundaries (Wu et al., 2020). In the context of cross-boundary diffusion of cascading typhoon disasters, this segmented management structure further increases the cost of inter-organizational coordination and affects the efficiency of joint response (Kapucu & Garayev, 2016; Parker et al., 2020). Therefore, understanding the governance of typhoon disasters at the regional scale requires attention not only to risk propagation pathways and key node identification, but also to the collaborative tie structure among emergency organizations.

Disaster response usually involves the joint participation of multiple organizations, and identifying participating actors alone is insufficient to explain how emergency collaboration operates. Earlier studies understood disaster response as a relational process among multiple organizations, emphasizing that emergency action depends on information exchange and resource coordination among organizations (Comfort et al., 2005). On this basis, related studies further analyzed organizational ties in disasters from a network perspective, pointing out that emergency collaboration depends not only on which organizations participate, but also on whether collaborative ties are formed among organizations and what roles these ties play in response (Butts et al., 2012; Cai et al., 2023). In collaboration networks, different ties perform different functions. Vertical collaboration mainly reflects command and coordination between higher- and lower-level governments or departments, whereas horizontal collaboration more often reflects coordination and cooperation among organizations at the same level or with related functions (Kapucu & Garayev, 2011; Kapucu & Garayev, 2016). Based on cases of floods in China, Li et al. (2023) found that the preparedness stage relies more on horizontal ties, while the response stage relies more on vertical ties, further indicating that the two types of relationships play different roles in disaster response. However, existing studies mostly discuss vertical and horizontal collaboration within a single region or the same administrative system, whereas typhoon disaster response in the Yangtze River Delta also involves within-province and cross-provincial ties. Understanding collaboration solely from the vertical and horizontal dimensions is therefore insufficient to fully explain its cross-regional differences. Accordingly, this study combines hierarchical relationships and spatial scope to classify collaborative relationships into four types: cross-provincial horizontal, cross-provincial vertical, within-province horizontal, and within-province vertical. Relationship types can explain the forms in which collaboration appears, but they are still insufficient to explain why these relationships are formed. Regarding the formation of collaborative relationships, Bodin & Nohrstedt (2016) and Nohrstedt et al. (2018) explain organizational cooperation from the perspectives of resource dependence, shared tasks, and institutional environments, showing that collaborative relationships are influenced by these conditions. In the context of this study, these conditions can be transformed into two testable factors: system affiliation is used to reflect whether organizations have similar functional tasks and institutional rules, while economic disparity is used to reflect differences in the resource bases of the regions where organizations are located. Based on this, this study further examines the effects of system affiliation and economic disparity on the formation of collaborative relationships.

Given the above research background and gaps, this study focuses on the following core questions: 1) In the context of the Yangtze River Delta, what cascading structural characteristics are presented by the propagation chains of typhoons and their secondary disasters? Which key nodes play major roles in risk diffusion? 2) In cross-regional disaster contexts, what collaborative relationships are formed among multi-level organizations in the Yangtze River Delta, and what organizational and regional factors influence them?

This study makes three main contributions. First, it supplements the dynamic diffusion and overlapping risk characteristics that traditional structural indicators cannot directly present, enabling key node identification to further consider subsequent influence ranges and risk overlap relationships. Second, it analyzes collaboration patterns from the two dimensions of hierarchical relationships and spatial scope, comparing differences between vertical and horizontal collaboration and between within-province and cross-provincial collaboration. Finally, this study transforms system affiliation and economic disparity into testable variables and analyzes the effects of functional similarity and regional resource differences on the formation of collaborative relationships, thereby providing empirical evidence for understanding the conditions of inter-organizational collaboration in cross-regional disaster governance.

2. Literature Review

2.1. Disaster Chains and Cascading Effects

Research on disaster chains provides an important perspective for understanding the cascading effects of typhoons. Existing studies have shown that typhoon impacts can be transmitted to urban infrastructure and social systems through secondary events such as floods, landslides, and infrastructure damage, leading to multi-stage associations and continuous amplification of disaster impacts (Green et al., 2025; Han & Tahvildari, 2024; Xu et al., 2023). On this basis, scholars have begun to construct typhoon disaster chains for specific regions or typical scenarios and to identify key links that are more likely to trigger subsequent impacts. For example, Wang et al. (2022) assessed the risk of typhoon disaster chains in the

Guangdong-Hong Kong SAR-Macao Greater Bay Area, while Tang et al. (2023) constructed cascading-effect scenarios based on historical typhoon cases in Shenzhen and analyzed the triggering relationships among cascading events. These studies have advanced the analysis of typhoon disaster impacts from direct loss assessment to the identification of event chains and key links. However, systematic analysis is still lacking on the regional cascading propagation characteristics revealed by multiple historical typhoon samples. For cross-provincial and highly urbanized regions such as the Yangtze River Delta, it remains necessary to further identify the propagation structure of typhoon disaster chains and their key nodes.

After disaster chains are identified, a further question is how to transform triggering relationships between events into analyzable relational structures. Complex network methods represent disaster events as nodes and triggering or influence relationships between events as links, making it possible to analyze disaster propagation processes from the perspectives of node positions, path relationships, and overall connectivity. Hu et al. (2022) constructed cascading networks of typhoon disasters in Japan and the Philippines and combined degree centrality, betweenness centrality, edge betweenness, and global efficiency to identify disaster propagation routes and vulnerable paths. Tang et al. (2023), based on historical typhoon cases in Shenzhen and expert judgment, identified hazard transition relationships and used a directed weighted network to analyze key disaster events and key transition relationships. These studies show that complex network methods can transform typhoon disaster chains from chain-based descriptions into measurable relational structures, providing a quantitative basis for identifying key links. However, existing analyses mainly rely on centrality, edge betweenness, and overall network indicators to evaluate node connectivity, path-control roles, and network efficiency. Insufficient attention has been paid to the subsequent diffusion ranges of key nodes along directed chains and to the overlap relationships among the influence ranges of different key nodes. Therefore, based on the construction of disaster chain networks, this study further examines the subsequent diffusion ranges of nodes and coverage overlap relationships, in order to supplement the limited explanatory capacity of traditional centrality indicators for the range of cascading impacts.

2.2. Inter-Organizational Collaboration Networks

Research on disaster collaboration networks takes organizations and their ties as the objects of analysis, in order to examine the structural characteristics, dynamic changes, and governance functions of organizational relationships in emergency response. Existing studies emphasize that disaster response depends on information flows and resource coordination among multiple organizations (Comfort et al., 2005), and that organizational collaboration and resource flows are dynamically coupled across different emergency stages, thereby affecting resource allocation and response efficiency (Sun et al., 2024; Tao & Zhang, 2023). Accordingly, the focus of related research has shifted from identifying participating actors to analyzing how ties are formed among organizations and how these ties function.

Within collaboration networks, vertical collaboration and horizontal collaboration are important dimensions for understanding the functions of organizational relationships. Vertical collaboration mainly occurs among governments or departments at different levels, emphasizing command transmission, resource dispatch, and responsibility implementation. Horizontal collaboration more often occurs among governments at the same level, functional departments, or related organizations, emphasizing information sharing, task cooperation, and resource complementarity (Kapucu & Garayev, 2011; Kapucu & Garayev, 2016). Existing studies further point out that collaboration structures in disaster contexts adjust between vertical and horizontal relationships as disaster stages and task demands change (Aung & Lim, 2021; Li et al., 2023). Therefore, vertical and horizontal relationships are not only differences in organizational hierarchy, but also reflect different coordination modes and response functions in disaster management.

However, distinguishing collaborative relationships only from the perspectives of vertical and horizontal relations is still insufficient to fully explain cross-provincial disaster response contexts such as the Yangtze River Delta. Research on cross-boundary crisis governance points out that when disaster impacts cross administrative boundaries, emergency cooperation involves both command and support across different levels and information sharing and joint action among same-level organizations in different regions (Bignami et al., 2024; Blondin & Boin, 2020; Chen et al., 2022). Therefore, collaborative relationships in typhoon disaster response in the Yangtze River Delta need to consider both hierarchical relationships and spatial scope. At the same time, whether collaborative relationships are formed is also affected by organizational tasks, institutional rules, and resource conditions. Bodin & Nohrstedt (2016) and Nohrstedt et al. (2018) explain organizational cooperation from the perspectives of resource dependence, shared tasks, and institutional environments, providing a basis for analyzing the formation of collaborative relationships. In the context of this study, system affiliation can be used to reflect whether organizations have similar functional tasks and institutional rules, while economic disparity reflects differences in the resource bases of the regions where organizations are located. Accordingly, this study classifies collaborative relationships into four types: cross-provincial horizontal, cross-provincial vertical, within-province horizontal, and within-province vertical, and further examines the effects of system affiliation and economic disparity on the formation of collaborative relationships.

3. Research Methods

The methodological arrangement adopted in this study is shown in **Figure 1**. It focuses on the analysis of propagation structures and the mechanisms of collaborative relationship formation under cascading risk scenarios of typhoon disasters. The specific methods used in each stage are introduced in sequence below.

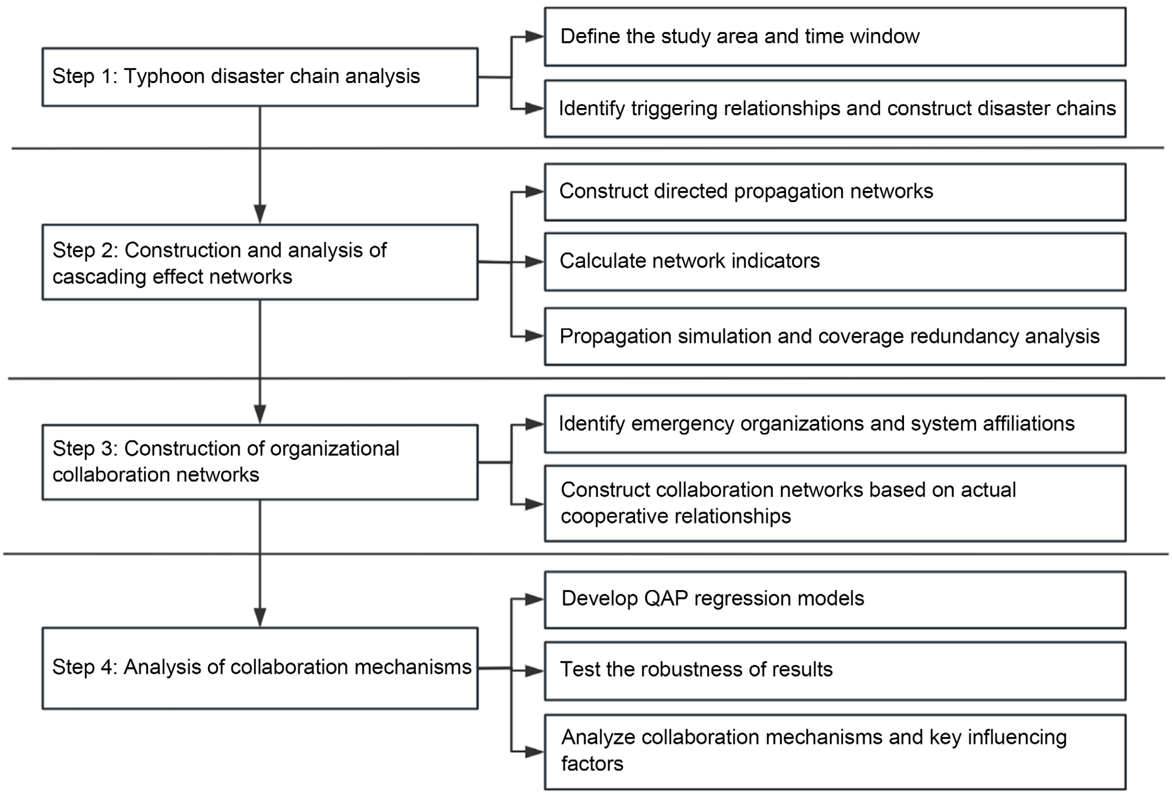

Figure 1. Research framework.

3.1. Construction and Analysis of Typhoon Disaster Cascading-Effect Networks

3.1.1. Disaster Chain Analysis

Before analyzing the cascading effects of typhoon disasters, it is necessary to identify the triggering relationships among different hazard factors. Regional disaster system theory holds that disaster processes are usually chain-like processes formed through the interaction of triggering hazards, hazard-forming environments, and affected elements (Thomas et al., 2020). Within this framework, a typhoon disaster chain can be expressed as:

$$dsChain = \left\langle hzEvent^{init}, hzEvent^{sec}, dsAfB, hzFmEnv \right\rangle$$

where $hzEvent^{init}$ represents the typhoon and its direct hazard factors; $hzEvent^{sec}$ refers to secondary events triggered by it; $dsAfB$ refers to affected social and infrastructure units; and $hzFmEnv$ represents the environmental conditions on which hazard evolution depends. The basic unit of a disaster chain is a hazard transition, that is, one hazard acts on a vulnerable element and triggers a new hazard (Pescaroli & Alexander, 2016). Multiple hazard transitions connected in sequence can represent the evolutionary pathway of typhoon disasters within urban systems (Tang et al., 2023).

3.1.2. Network Construction

After clarifying the basic links of the typhoon disaster chain, this study uses complex network methods to model disaster events and their triggering relationships. Specifically, disaster events identified in each typhoon cascading-effect scenario are encoded as nodes, with event identification based on explicit descriptions in disaster reports and related news reports. If the textual materials describe a disaster event as being triggered, caused, or intensified by another event, a causal triggering relationship is considered to exist between the two, and a directed edge from the former to the latter is established accordingly.

A coding protocol was used to reduce the subjectivity of event extraction and causal-link identification. First, the textual materials were screened to identify disaster phenomena, infrastructure failures, social-function disruptions, and socioeconomic impacts, which were then coded as disaster nodes according to their substantive meanings. Second, a directed edge was established only when the material explicitly indicated a triggering, causal, or intensifying relationship between two events, using expressions such as “caused by”, “triggered”, “led to”, “resulted in”, or equivalent Chinese expressions in official reports and news materials. For example, if a local report stated that persistent rainstorm caused urban waterlogging and then led to traffic interruption, the coding generated two directed edges: “rainstorm → urban waterlogging” and “urban waterlogging → traffic interruption”. The initial coding was completed by the first author and then reviewed by the research team. Ambiguous cases were discussed and revised according to the original textual evidence until agreement was reached.

In addition, to reflect the stage-based characteristics of propagation in network analysis and visualization, this study takes typhoon events as source nodes and applies the breadth-first search (BFS) algorithm to the disaster cascading-effect networks. It traverses reachable nodes layer by layer and records the shortest path length from each node to the source node. In propagation network analysis, the shortest path length from a node to the source node is usually used to characterize its relative position in the disaster propagation process, thereby reflecting the triggering sequence of nodes in the disaster chain (Brandes, 2001). Accordingly, the propagation process is divided into three stages: early stage (d = 0 - 1), middle stage (d = 2 - 3), and late stage (d ≥ 4), in order to clarify the propagation timing characteristics of different events in the disaster chain.

The cutoffs of d = 0 - 1, d = 2 - 3, and d ≥ 4 were used to distinguish direct or near-direct impacts, intermediate secondary impacts, and more distant downstream consequences in the cascading process. Nodes with d = 0 - 1 mainly represent the typhoon event itself and its immediate hazard factors; nodes with d = 2 - 3 usually correspond to secondary infrastructure damage or functional disruptions; and nodes with d ≥ 4 indicate impacts transmitted through longer chains. This classification is not intended to represent strict chronological intervals, but to provide a comparable topological representation of propagation stages across the four provincial-level networks.

3.1.3. Node-Level Network Measures

Based on network construction, this study uses typical node indicators to identify structurally critical events in the propagation process.

1) Degree centrality. The degree centrality of a node reflects its direct connectivity. In a directed network, degree centrality is divided into two forms: in-degree and out-degree. In-degree indicates the extent to which a node is affected by upstream influences, while out-degree indicates its potential role in downstream propagation. The sum of in-degree and out-degree can be used to identify key events with stronger triggering or propagation roles. Its formal definition is as follows:

$$DC_i = k_i^{in} + k_i^{out}$$

2) Betweenness centrality. Betweenness centrality measures the bridging role of a node on shortest paths and can reflect an event's capacity to control propagation pathways. The higher the betweenness centrality value, the more likely the event is to appear in the middle of multiple key pathways and occupy a hub position in the evolution of the disaster chain. It is defined as follows:

$$BC_i = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}}$$

3.1.4. Impact Evolution and Node Coverage Analysis

To overcome the limitation that traditional static indicators can only reflect the topological position of nodes, this study introduces impact evolution and node coverage analysis methods to further characterize the diffusion range and overlapping risks of disturbances in typhoon disaster cascading networks.

1) Impact evolution. The cascading diffusion of typhoon disasters shows a clear pattern of directed transmission from upstream to downstream, while network centrality indicators have difficulty reflecting this directed diffusion process. Therefore, this study adopts a disturbance propagation method to quantify the cumulative and diffusion effects of node influence in the network (Banerjee et al., 2020; Li et al., 2018). First, the initial coverage impact value (NodeScore) is calculated according to the downstream reachable range of each node:

$$NodeScore_i = \frac{|D(i)|}{N-1}$$

where $NodeScore_i$ denotes the initial coverage impact value of the node i, $D(i)$ is the set of nodes reachable from the node i along the shortest directed paths, and N is the number of nodes in the network. A higher $NodeScore$ indicates that the node can affect a wider downstream range. Then, cumulative propagation is conducted for T rounds from upstream to downstream, and the $t+1$ round is obtained by accumulating upstream influence from the previous round:

$$d_i^{(t+1)} = d_i^{(t)} + \sum_{j \in pred(i)} d_j^{(t)} \cdot NodeScore_j, t = 0, \cdots, T-1$$

where $pred(i)$ is the set of all upstream nodes pointing to the node i, and the initial value is set as $d_i^{(0)} = NodeScore_i$. The intensity in the T round, $d_i^{(T)}$, is recorded as the node's disturbance impact value (Disturbance Value). The larger this value is, the stronger the comprehensive effect of the node in accumulating upstream influences and transmitting them to subsequent pathways during cascading propagation.

2) Node coverage analysis. After clarifying the global influence of nodes, node coverage analysis is further conducted to identify overlapping disaster risks caused by the overlap of multiple nodes' coverage ranges. Such overlapping risks are a key cause of amplified losses from cross-regional typhoon disasters in the Yangtze River Delta, and their accurate identification can support cross-regional collaborative early warning. In complex network research, Jaccard similarity is often used to measure coverage relationships between nodes (Chung et al., 2019). This study selects the top 10 key nodes ranked by disturbance impact value and calculates the Jaccard similarity between their pairwise reachable node sets:

$$J(A,B)=\frac{|A\cap B|}{|A\cup B|}$$

where A and B are the reachable sets of two nodes, respectively. Ultimately, a higher similarity value indicates a greater degree of overlap between node coverage ranges and a stronger risk that the two events will overlap within the same propagation range.

3.2. Construction and Analysis of the Organizational Collaboration Network

3.2.1. Network Construction

To reveal the cross-departmental collaboration characteristics of the study region in responding to typhoon disasters, this study takes government departments and related institutions participating in disaster emergency management as network nodes, covering organizations at the central, provincial, and municipal levels. Collaborative relationships are identified based on joint actions in typhoon preparedness and emergency response. If two organizations have explicit cooperation in disaster response, an undirected edge is established between them, thereby forming the organizational collaboration network. At the same time, different nodes are classified according to their functional systems, so that same-system and cross-system ties can be compared in subsequent analysis.

3.2.2. Variable Specification

The dependent variable in this study is the undirected organizational collaboration network, which is set as an N × N matrix. If two organizations have a cooperative relationship in the process of typhoon disaster response, the matrix element is recorded as 1; otherwise, it is recorded as 0.

The explanatory variables are divided into two categories: relational attributes and organizational attributes. Relational attributes include the following two dimensions. First, administrative hierarchical relationship: if two organizations belong to different administrative levels, the value is recorded as 1 in the vertical relationship matrix; if they are at the same level, the value is recorded as 1 in the horizontal relationship matrix. Second, spatial relationship: if two organizations belong to different provinces, the value is recorded as 1 in the cross-provincial relationship matrix; if they belong to the same province, the value is recorded as 1 in the within-province relationship matrix. On this basis, this study constructs four types of relationship matrices, namely cross-provincial horizontal, cross-provincial vertical, within-province horizontal, and within-province vertical, to represent the spatial ties and hierarchical attributes between organizations. Organizational attributes include: 1) Whether the organizations belong to the same system, with the matrix assigned a value of 1 for organizations in the same system; 2) Economic development disparity, measured by the difference in per capita GDP between the regions where the two organizations are located, from which a symmetric matrix is generated.

Central-level organizations were treated separately in the construction of spatial and economic-disparity matrices. These organizations were coded as a national-level category rather than as belonging to Shanghai, Jiangsu, Zhejiang, or Anhui. For dyads involving central-level organizations, the spatial relationship was identified according to the unified coding rule used for the QAP matrices, and the per-capita GDP value of central-level organizations was represented by a national-level reference value to keep the GDP-gap matrix complete. Therefore, the spatial and GDP-gap variables should be interpreted mainly as relational measures for comparing territorial and economic differences among organizations, rather than as direct measurements of the local economic condition of central-level organizations.

3.2.3. Quadratic Assignment Procedure (QAP) Analysis

This study uses the Quadratic Assignment Procedure (QAP) regression method to test the effects of relational attributes and organizational attributes on the formation of collaborative relationships. This method obtains robust significance tests by permuting matrix rows and columns and repeatedly calculating regression results, thereby addressing the problem of non-independent observations in network data (Dekker et al., 2007). In the baseline model, the organizational collaboration matrix is used as the dependent variable, and the relational attribute and organizational attribute matrices are used as explanatory variables to construct a linear regression model.

To verify the reliability of the estimation results, this study conducts three types of robustness tests. The first is a sample perturbation test, in which some collaborative edges are randomly removed and the regression is repeated multiple times to assess the sensitivity of the results to individual samples. The second is an explanatory-variable substitution test, in which the continuous per capita GDP gap is transformed into a binary high-GDP-gap grouping variable divided by the sample median. Specifically, GDP1-0 is coded as 1 when the per-capita GDP gap between the two organizations' regions is above the sample median, and 0 otherwise. This substitution is used to examine whether the baseline model is sensitive to an alternative measurement of regional economic disparity. The third is an organizational-attribute substitution test, in which system affiliation is replaced by the administrative rank gap between departments, in order to assess whether the model remains stable under changes in the specification of organizational attributes.

To explore the moderating effects of structural conditions on the formation of collaborative relationships, this study constructs interaction models, mainly including two types. First, for moderation by system affiliation, interaction terms are constructed between system affiliation and each of the four types of collaboration variables, in order to test whether organizational system affiliation strengthens or weakens the effects of specific collaborative relationships. Second, for moderation by economic disparity, interaction terms are constructed between the per capita GDP gap and the four types of collaboration variables, in order to identify the moderating effect of economic heterogeneity on the mechanisms of collaborative structure.

4. Case Study

4.1. Study Area

This study selects the Yangtze River Delta region as the case for analysis. The Yangtze River Delta is located along the eastern coast of China and at the estuary of the Yangtze River. It covers Shanghai Municipality, Jiangsu Province, Zhejiang Province, and Anhui Province, and is one of the most densely populated and highly urbanized urban agglomerations in China. The region is characterized by low and flat terrain, a dense river network, and a subtropical monsoon climate. Because it is located along the main tracks of typhoons originating from the northwest Pacific, the region is directly affected by approximately two to three typhoons each year on average. Historically, multiple typhoon events have caused cross-system and cross-regional cascading effects in this region under extreme weather conditions. For example, Typhoon In-fa in 2021 moved slowly and followed a complex track, causing prolonged heavy rainfall. This led to severe waterlogging in many areas of Jiangsu, Zhejiang, and Shanghai, and resulted in large-scale evacuation and infrastructure disruptions. Therefore, studying the cascading effects of typhoons and cross-regional collaboration in the Yangtze River Delta is of great significance.

4.2. Data Sources and Sample Construction

This study uses the period from 2015 to 2024 as the study period, and the data include two parts: typhoon disaster data and organizational collaboration data. The typhoon disaster data are mainly based on disaster reports issued by flood-control, typhoon-prevention, and meteorological authorities in Shanghai, Jiangsu, Zhejiang, and Anhui, combined with mainstream media reports and post-disaster summary materials. Ten typhoons with relatively large local impacts are selected as study samples for each provincial-level area. The direct hazard factors of each typhoon, such as rainstorms, strong winds, and storm surges, as well as the secondary impacts triggered by them, such as urban waterlogging, facility damage, and evacuation, are systematically collected and organized to construct the typhoon disaster dataset.

The typhoon samples were selected according to three criteria. First, the typhoon occurred during 2015-2024 and affected at least one provincial-level area in the Yangtze River Delta. Second, the event caused observable secondary or derivative impacts, such as urban waterlogging, infrastructure damage, traffic interruption, evacuation, or economic loss, which were reported in official bulletins, disaster reports, post-disaster summaries, or mainstream media sources. Third, sufficient textual information was available to identify triggering relationships among disaster events. The sample was constructed at the provincial-level impact scale rather than only by unique typhoon names. When a single typhoon affected more than one provincial-level area, it was treated as a separate province-event observation if province-specific disaster processes and triggering relationships could be identified from local materials. This rule was adopted to capture regional differences in cascading effects under the same typhoon event.

The organizational collaboration data are derived from publicly available government documents, emergency drills and joint-action reports, and news materials corroborated by multiple sources. Through a systematic review of these materials, 76 organizational nodes are ultimately identified, covering key departments at the central, provincial, and municipal levels, including meteorology, water conservancy, emergency management, transportation, and electric power. A total of 243 pairs of collaborative relationships are extracted and organized into the organizational collaboration dataset used in this study.

5. Results

5.1. Results of Typhoon Disaster Cascading Effects

5.1.1. Analysis of Network Structural Characteristics

Based on the collation and coding of case data from the four provincial-level regions, Gephi was used to visualize the typhoon disaster cascading-effect networks of Shanghai, Jiangsu, Zhejiang, and Anhui, as shown in **Figure 2**. Each node in the network represents a disaster event directly or indirectly triggered by a typhoon event. Node shapes distinguish different event types, including natural hazards, infrastructure damage, loss of social functions, and socioeconomic impacts, while node colors indicate propagation stages. The figure illustrates the triggering and transmission relationships among different types of events across propagation stages.

Table 1 presents the top five disaster events ranked by total degree centrality, reflecting their direct propagation roles in the network. Overall, strong wind, rainstorm, and road waterlogging repeatedly appear across multiple regions, suggesting that these events have widespread triggering effects. Differences are also observed across regions. In Shanghai, tornadoes and falling objects are prominent high-degree risk events; in Jiangsu, flood and power facility damage reveal the vulnerability of water-related hazards and the power system; in Zhejiang, road destruction and river backflow reflect the interaction between water-related hazards and transportation; and in Anhui, high-degree events are concentrated in road destruction and traffic interruption. Therefore, disaster prevention and mitigation should focus on these high-frequency triggering events to prevent them from evolving into larger-scale chain reactions.

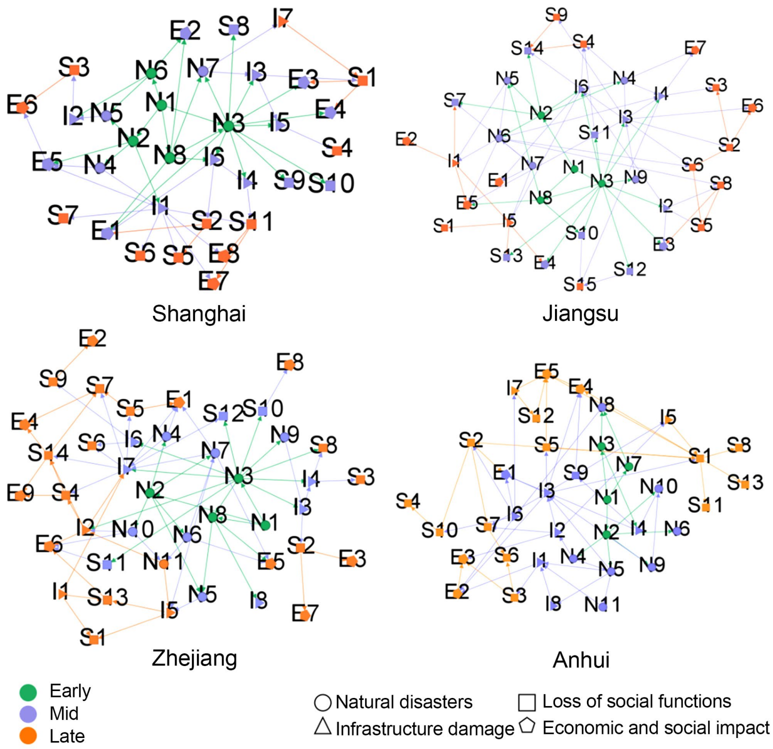

Figure 2. Typhoon disaster cascading-effect networks of Shanghai, Jiangsu, Zhejiang, and Anhui.

Table 1. Top 5 nodes by total degree centrality.

		Shanghai			Jiangsu	
No.	Code	Node label	Total DC	Code	Node label	Total DC
1	N3	Strong wind	0.3235	N3	Strong wind	0.1806
2	I1	Road waterlogging	0.2059	N6	Flood	0.1389
3	N8	Tornado	0.1471	I6	Road waterlogging	0.1250
4	N2	Rainstorm	0.1176	I3	Power facility damage	0.111
5	I6	Falling objects	0.1176	N2	Rainstorm	0.0972
		Zhejiang			Anhui	
No.	Code	Node label	Total DC	Code	Node label	Total DC
1	N3	Strong wind	0.1463	I3	Road destruction	0.1389
2	I7	Road waterlogging	0.1463	S1	Traffic interruption	0.1250
3	I2	Road destruction	0.0854	N2	Rainstorm	0.0833
4	N2	Rainstorm	0.0732	N5	Flood	0.0833
5	N7	River backflow	0.0732	I6	Power facility damage	0.0833

Table 2 lists the top five nodes ranked by betweenness centrality in the typhoon disaster cascading-effect networks of the four provincial-level regions, reflecting the bridging role of disaster events in propagation pathways. The results show that road waterlogging repeatedly appears across multiple regions, indicating that this event is not only common but also often determines whether other disasters can continue to propagate along the chain. Each region also shows its own vulnerable links. In Shanghai, traffic congestion and road facility damage have relatively high betweenness values, reflecting the key role of the transportation system in urban operations. In Jiangsu, flood, water conservancy facility damage, and power facility damage reflect the impacts of water-related hazards on infrastructure. In Zhejiang, road destruction, river backflow, and water conservancy facility damage play important roles in propagation. In Anhui, traffic interruption and power supply interruption are vulnerable links in disaster propagation.

Table 2. Top 5 nodes by betweenness centrality.

	Shanghai			Jiangsu		
No.	Code	Node label	BC	Code	Node label	BC
1	N3	Strong wind	0.0204	N6	Flood	0.0351
2	I1	Road waterlogging	0.0156	I6	Road waterlogging	0.0250
3	N2	Rainstorm	0.0089	I5	Water conservancy facility damage	0.0230
4	I4	Road facility damage	0.0085	I3	Power facility damage	0.0194
5	S11	Traffic congestion	0.0071	N5	Above-warning water level	0.0193
	Zhejiang			Anhui		
No.	Code	Node label	BC	Code	Node label	BC
1	I7	Road waterlogging	0.0379	I3	Road destruction	0.0552
2	I2	Road destruction	0.0180	S1	Traffic interruption	0.0496
3	N3	Strong wind	0.0152	I6	Power facility damage	0.0295
4	I5	Water conservancy facility damage	0.0128	S2	Power supply interruption	0.0278
5	N7	River backflow	0.0106	N5	Flood	0.0241

5.1.2. Propagation Simulation and Coverage Overlap Analysis

Table 3 shows the top five key nodes ranked by disturbance impact value in the disturbance propagation simulation for the four provincial-level regions, reflecting the comprehensive influence of different disaster events in the cascading diffusion process. Overall, road waterlogging, flood, and road destruction appear across multiple regions, indicating that they are often important links driving further cascading diffusion. In Shanghai, nodes such as greenhouse damage, tree collapse, and falling objects have relatively high disturbance impact values, reflecting the important role of strong-wind-related events in the diffusion of subsequent impacts. In Jiangsu, communication equipment damage and road waterlogging indicate that information transmission and transportation are vulnerable to disruption. In Zhejiang, storm surge and road destruction reflect the association between coastal risks and the transportation system. In Anhui, road destruction, flood, and debris flow highlight the risks associated with mountainous water-related hazards and transportation corridors. If these nodes are not mitigated in time, they may further expand the influence range of the disaster chain.

Table 3. Top 5 nodes by disturbance propagation impact value.

	Shanghai			Jiangsu		
No.	Code	Node label	Disturbance Value	Code	Node label	Disturbance Value
1	E1	Greenhouse damage	0.0851	I6	Road waterlogging	0.0651
2	N7	Tree collapse	0.0760	I4	Communication equipment damage	0.0648
3	I6	Falling objects	0.0760	E5	Fishery facility damage	0.0560
4	N3	Strong wind	0.0704	S10	Scenic spot closure	0.0489
5	I3	Power facility damage	0.0542	N6	Flood	0.0489
	Zhejiang			Anhui		
No.	Code	Node label	Disturbance Value	Code	Node label	Disturbance Value
1	I7	Road waterlogging	0.0717	I3	Road destruction	0.0770
2	N8	Storm surge	0.0647	N5	Flood	0.0719
3	I2	Road destruction	0.0587	N10	Debris flow	0.0624
4	S12	School suspension	0.0489	N4	Urban waterlogging	0.0444
5	I3	Power facility damage	0.0446	S1	Traffic interruption	0.0440

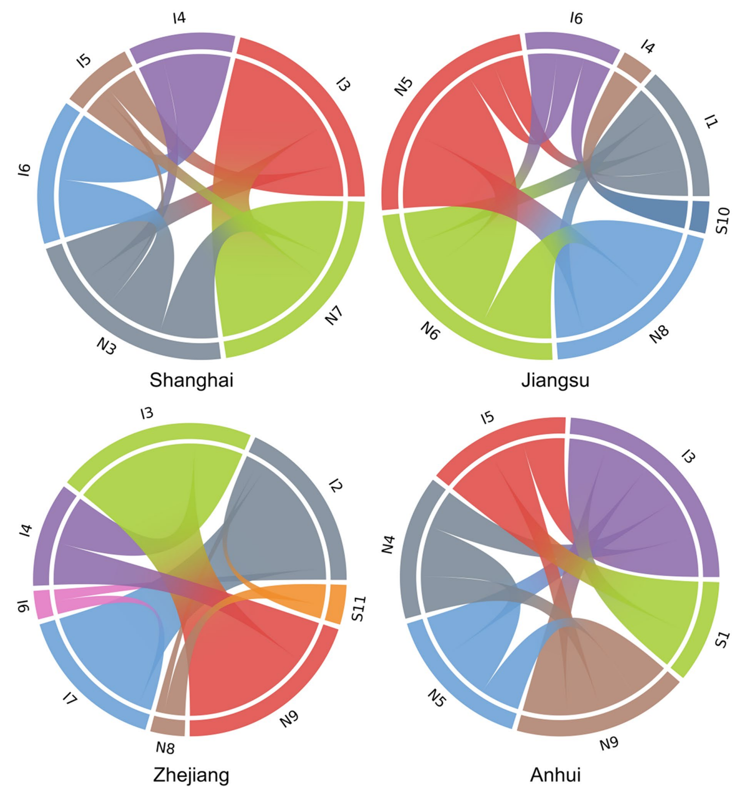

Figure 3. Chord diagram of node coverage similarity in the four provincial-level regions (top 10 node pairs).

Figure 3 shows the node pairs with the highest coverage similarity in the network. During cascading propagation, some high-frequency risks tend to appear simultaneously or interact with each other. In Shanghai, tree collapse-power facility damage and road waterlogging-road facility damage appear jointly in multiple propagation pathways, indicating that strong winds can easily trigger multiple types of facility and environmental damage. In Jiangsu, the highly overlapping node combinations of flood-above-warning water level, flood-dike breach, and above-warning water level-dike breach reflect the cascading superposition of water-related hazards. In Zhejiang, node pairs such as road waterlogging-road destruction and traffic interruption-traffic congestion reveal a close linkage between declining road accessibility and structural damage. In Anhui, road destruction-traffic interruption and debris flow-flood constitute the main coverage combinations, indicating that topographic conditions are more likely to amplify disaster overlap effects.

5.2. Results of the Organizational Collaboration Network

5.2.1. Network Structure

The multi-department emergency collaboration network constructed for the four provincial-level regions is shown in Figure 4. Each node in the figure represents an organization participating in emergency management, and the lines indicate the collaborative relationships established between organizations in typhoon response. In the network, central-level organizations are represented by blue nodes, provincial-level organizations by orange nodes, and municipal-level organizations by green nodes.

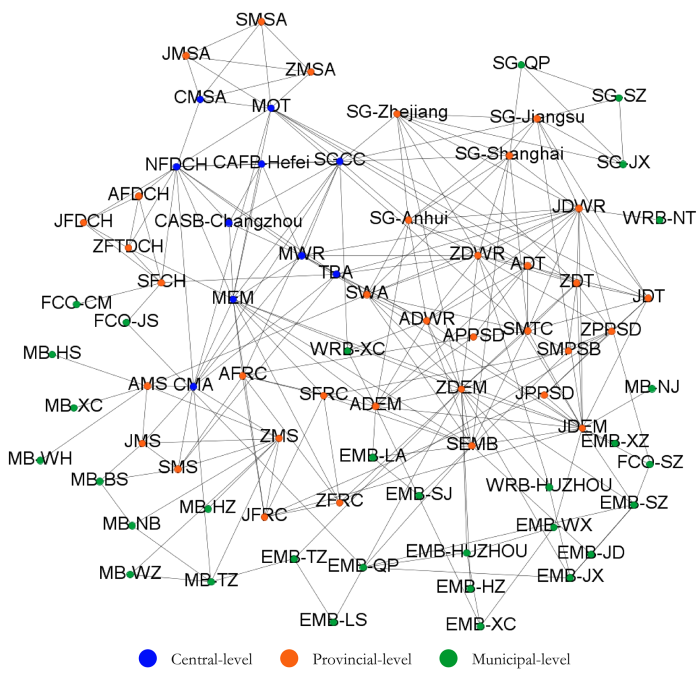

Figure 4. Multi-department emergency collaboration network of the four provincial-level regions.

5.2.2. Testing the Influencing Factors of Collaborative Relationships

To further identify the key factors associated with the formation of inter-organizational collaborative relationships, this study uses the QAP method to analyze the organizational collaboration matrix. Table 4 reports the bivariate QAP correlation results. These results provide a preliminary description of the association between each explanatory matrix and the organizational collaboration matrix. Because the correlation analysis does not control for other relational and organizational factors, the results in Table 4 should be interpreted only as bivariate associations rather than evidence of independent effects.

Table 4. QAP correlation analysis results.

Independent Variable	Correlation	P-Values
Cross-provincial horizontal	0.079***	0.000
Cross-provincial vertical	0.077***	0.001
Within-province horizontal	0.004	0.462
Within-province vertical	−0.034*	0.050
GDP Gap	−0.040**	0.048
Same System	0.124***	0.000

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

To further examine the independent effects of different relational and organizational factors, QAP regression was conducted by including all explanatory matrices in the same model. As shown in Table 5, both cross-provincial horizontal and cross-provincial vertical relationships show significant positive effects, indicating that cross-regional ties are associated with a higher likelihood of collaborative relationship formation after controlling for other factors. System affiliation also shows a significant positive effect, suggesting that functional consistency is an important condition for establishing ties between organizations. In contrast, the coefficient of within-province vertical collaboration is negative, indicating that hierarchical proximity within the same province does not necessarily translate into observable collaborative ties. The per capita GDP gap also shows a significant negative coefficient in the baseline model, suggesting that greater economic disparity may make collaborative relationships more difficult to form. Overall, cross-regional ties and system affiliation are the main facilitating factors, whereas within-province vertical ties and economic disparity should be interpreted as conditional constraints rather than uniformly stable inhibitory factors.

Table 5. QAP regression analysis results.

Variable	Unstd. Coef.	Std.Coef.	Significance
Intercept	0.082	0.000	
Cross-provincial horizontal	0.119***	0.073***	0.001
Cross-provincial vertical	0.174***	0.080***	0.001

Continued

Within-province horizontal	0.017	0.010	0.285
Within-province vertical	−0.080**	−0.031**	0.028
GDP Gap	−0.000**	−0.042**	0.032
Same System	0.103***	0.123***	0.000
R^2		0.030	

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

To verify the reliability of the research results, this study conducts robustness tests based on three schemes: sample perturbation, explanatory-variable substitution, and organizational-attribute substitution. Table 6 presents the results of the robustness regressions. The positive effects of cross-provincial collaboration remain relatively consistent across different specifications. However, the negative coefficient of within-province vertical collaboration is not significant in all robustness models, although its direction is generally consistent with the baseline regression. In addition, the GDP-gap grouping variable is positive in the substitution model, whereas the continuous GDP gap is negative in the baseline model. This discrepancy indicates that the overall effect of economic disparity is sensitive to variable operationalization. The continuous variable captures the linear magnitude of economic disparity, while the binary grouping variable only distinguishes high-gap and low-gap dyads and loses within-group variation. Therefore, the robustness tests support the stability of the main collaboration-type variables, whereas the overall effect of economic disparity should be interpreted cautiously rather than as a uniformly robust inhibitory effect.

Table 6. Robustness test results of QAP regression.

Variable	5% Edge Deletion Run1	5% Edge Deletion Run2	5% Edge Deletion Run3	GDP Gap Grouping	Hierarchical Difference Substitution
Intercept	0.0756	0.0767	0.0760	0.0648	0.0893
Cross-provincial vertical	0.1744*	0.1316*	0.1324*	0.1561*	0.1642*
Within-province vertical	−0.0756	−0.0767	−0.0759*	−0.0720*	−0.0836
Cross-provincial horizontal	0.1127*	0.1115*	0.1241*	0.0991*	0.1338*
Within-province horizontal	0.0034	−0.0109	0.0030	0.0187	0.0144
GDP-gap grouping variable				0.1730*	
Same System (sys)				0.0619*	
GDP Gap (continuous)					−0.0000*
Hierarchical Difference (level)					0.1146*
R^2	0.012	0.009	0.010	0.040	0.019

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. In the GDP Gap Grouping model, GDP1-0 is coded as 1 if the per capita GDP gap between two organizations' regions is above the sample median, and 0 otherwise.

On this basis, the further interaction-term tests in Table 7 reveal differentiated mechanisms. The interaction between the per capita GDP gap and within-province vertical ties is negative and weakly significant, suggesting that economic disparity may reduce the tendency of higher- and lower-level organizations within the same province to form observable collaborative ties. This finding should be interpreted as a conditional tendency rather than a uniformly stable effect. Among the interaction terms for system affiliation, only cross-provincial horizontal collaboration shows a significant positive effect, indicating that cross-provincial departments within the same system are more likely to form cross-regional cooperation because of consistency in functions and rules.

Table 7. Regression results of mechanism analysis.

Collaboration Type	Same System × Type	Significance	GDP Gap × Type	Significance
Cross-provincial horizontal	0.269***	0.000	0.000	0.127
Cross-provincial vertical	0.103	0.118	−0.000	0.456
Within-province horizontal	−0.112	0.146	−0.000	0.282
Within-province vertical	0.009	0.588	−0.007*	0.085
R^2	0.035		0.020	

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

6. Discussion

6.1. Cascading Effects of Typhoon Disasters

At the node level, events with high degree centrality, such as strong wind, rainstorm, flood, and road waterlogging, are important triggering nodes in the disaster chain. These disasters mostly originate from the primary hazard factors during the typhoon landfall stage and have widespread impacts on multiple systems (Cai et al., 2018). Their occurrence not only causes direct losses, but may also activate multiple downstream propagation links. At the same time, nodes such as road waterlogging, traffic congestion, water conservancy facility damage, and power interruption show prominent betweenness centrality, indicating that they serve as cross-system connectors in the propagation process (Pescaroli & Alexander, 2016). Once such nodes are disrupted, originally independent disaster processes may become connected, thereby forming cross-sectoral and cross-system amplification effects (Valdez et al., 2020). Although the key disaster nodes vary across regions, they generally reflect the joint influence of geographical exposure and infrastructure layout on disaster propagation. Coastal cities are mainly characterized by strong-wind- and drainage-system-related disasters, regions with dense river networks are mainly characterized by floods and water conservancy facility damage, while areas with more undulating terrain are prone to key nodes such as road destruction and traffic interruption (Mortensen et al., 2024; Son et al., 2025).

The disturbance propagation simulation results further explain the above structural characteristics from a dynamic perspective. High-impact nodes are mostly concentrated in components related to critical infrastructure, such as transportation, water conservancy, electric power, and communication, indicating that the diffusion of typhoon disasters has clear characteristics of spatial concentration and functional dependence. These nodes are located at key interconnection points among critical infrastructure systems, and their disruption may lead to simultaneous damage to information, transportation, and energy systems (Zheng et al., 2024). In compound disaster networks, this key-node-driven propagation mechanism suggests that a small number of high-impact nodes may substantially affect the range and direction of risk transmission. Gill and Malamud (2016) also pointed out that the functional dependence of complex disaster systems strengthens the amplification effect of key nodes, causing risk diffusion to show clear asymmetric characteristics.

The coverage analysis results reveal the overlapping characteristics among disaster propagation pathways. Node pairs with high coverage similarity show that the downstream influence ranges of some key nodes clearly overlap, indicating that multiple types of disasters do not evolve completely independently. Such highly overlapping pathways mean that different systems may be affected simultaneously when disturbed, thereby increasing the possibility of joint failures (Pescaroli & Alexander, 2016). From a resilience perspective, this structure weakens the buffering capacity of the region and makes risks more likely to be amplified in high-density urban environments (Cutter, 2016). Therefore, identifying and intervening in these highly overlapping pathways is an important direction for improving regional disaster resilience and controlling cascading diffusion.

6.2. Organizational Collaboration Network

The QAP regression results show that cross-provincial collaboration is an important factor associated with the establishment of ties among organizations. Collaboration across administrative boundaries helps improve the efficiency of information sharing and alleviates the fragmentation problem caused by local governments acting independently (Kapucu et al., 2010). The advancement of regional integration policies has also been shown to promote the formation of cross-regional governance networks. For example, in fields such as emergency management and environmental regulation, formalized cross-provincial collaboration mechanisms can improve the efficiency of resource dispatch and action coordination (Lei et al., 2023). The recent development trend of the Yangtze River Delta is consistent with this pattern. The wider adoption of joint early-warning, joint-drill, and information-sharing mechanisms has laid an institutional foundation for the formation of collaborative ties among departments across provinces. In addition, the significant positive effect of same-system affiliation indicates that collaborative relationships are more likely to form when departments have similar functions and consistent rules. This is consistent with the study by Roiseland & Traetteberg (2024), which shows that consistency in institutions and responsibilities can reduce communication costs and enhance the willingness for inter-organizational coordination. In disaster governance, same-system departments usually have coordination advantages because they share professional language and correspond to similar tasks (Kapucu et al., 2010).

The interaction-term tests further reveal differentiated mechanisms in the formation of collaborative relationships. The results suggest that the per capita GDP gap may have a negative association with within-province vertical ties, indicating that when economic levels differ greatly, the tendency to form publicly observable collaborative ties in within-province vertical relationships may become weaker. This finding should be understood in relation to the specific structure of within-province vertical collaboration, rather than a universal inhibitory effect of economic disparity across all collaborative dyads. As shown in the robustness tests, the overall GDP-gap coefficient is sensitive to the measurement form of economic disparity. Therefore, this study interprets economic disparity as a conditional factor that may constrain collaboration in particular relational contexts. By contrast, the interaction term between cross-provincial horizontal collaboration and same-system affiliation shows a significant positive effect, indicating that departments within the same system may be more likely to establish collaborative mechanisms in cross-regional cooperation because of consistency in functions and norms (Lian et al., 2025). In cross-jurisdictional contexts, the coordination advantages brought by institutional consistency may be more apparent, which is consistent with the theoretical expectation of Roiseland & Traetteberg (2024) that institutional isomorphism reduces the cost of cross-regional collaboration. Overall, the mechanism analysis reveals the heterogeneous roles of institutional consistency and economic disparity across different collaboration dimensions: the former is mainly related to the formation of cross-regional horizontal cooperation, while the latter is associated with a lower tendency toward collaboration in within-province vertical ties under certain conditions. For governance practice, this indicates that vertical coordination based solely on administrative hierarchy is insufficient to explain and support coordinated response in complex disaster contexts. More attention should therefore be paid to the influence of regional resource differences on organizational collaboration.

7. Conclusion

By constructing a typhoon disaster cascading-effect network for the Yangtze River Delta and combining propagation simulation with coverage analysis, this study identifies key triggering nodes and high-impact links in the propagation process of typhoon disasters. The results show that events such as strong wind, rainstorm, flood, and road waterlogging have relatively high structural importance in the cascading network. Risk diffusion depends on a small number of key nodes and coupled system components, exhibiting centralized and asymmetric propagation characteristics. Meanwhile, the QAP analysis based on the organizational collaboration network shows that cross-provincial ties and system affiliation significantly promote the formation of collaborative relationships, whereas within-province vertical relationships do not show a higher tendency to form collaborative ties. The continuous GDP-gap result suggests that economic disparity may constrain collaboration, but this finding should be interpreted cautiously because the substitution test indicates sensitivity to the measurement of GDP disparity.

The main contribution of this study lies in examining both the cascading propagation of typhoon disasters and organizational collaboration networks. It identifies key nodes and highly overlapping pathways in risk diffusion, and also reveals the structural conditions of organizational collaborative relationships in cross-regional disaster response. In practice, the findings suggest that regional disaster prevention and response systems should pay attention to interlinked risks in key sectors such as transportation, water conservancy, electric power, and communication, and further improve institutionalized cooperation mechanisms in cross-provincial information sharing, joint early warning, and resource coordination. For regions with large economic disparities, resource compensation and collaborative incentive mechanisms may be needed to reduce potential structural constraints in vertical collaboration.

This study also has certain limitations. The propagation simulation and collaboration analysis are based on existing network structures. Although they can show the potential pathways of disaster diffusion, they do not fully reflect the temporal evolution and emergency response processes in real disaster events. At the same time, the collaboration data mainly come from publicly available materials, which may not fully cover actual ties among various organizations. In addition, this study mainly identifies whether collaborative relationships exist between organizations, but does not further distinguish collaboration intensity, collaboration quality, or changes in relationships across different emergency stages. Future research can combine richer cases, time-series data, and process-based materials to reveal the interaction mechanisms between disaster propagation and governance collaboration in greater depth, thereby providing more reliable support for regional risk governance and resilience building.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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