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Resilience Enhancement Paths Assessment Based on City Networks Synergistic Response Under Disaster Strike—A Case Study of Yangtze River Delta City Cluster

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Abstract: In the face of increasingly polarized disasters, interregional synergistic emergency responses have become a mainstream means of enhancing disaster response and recovery. Given the holistic and networked nature of city clusters under regional synergy, it is necessary to fully consider the balance between the overall region and individual cities when analyzing regional resilience enhancement. Taking the Yangtze River Delta (YRD) city cluster as the study area, this study proposes three resilience enhancement paths under the perspective of network synergy, including promoting the resource allocation of cities, strengthening the development of inter-city transportation systems, and improving the integration of sub-metropolitan areas. The dynamic resilience status of the whole city cluster system and each individual city under three enhancement paths are compared based on synergistic network simulation. Firstly, the optimal resilience model is for each city to allocate 60% of its resources for self-recovery and invest 40% of its resources for other recovery. Secondly, among the existing transportation planning policies, railway development will more significantly enhance YRD's resilience. Thirdly, for the resilient impact of the integration of the six metropolitan areas, the Shanghai metropolitan area has the most significant influence.

Keywords: city cluster network; regional synergy; resilience enhancement paths; YRD city cluster

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1. Introduction

Regional urban systems are facing an increasing number of threats and disruptions from both natural and human-made disasters [1–3], resulting in potential economic losses and failure of sustainable development [4–6]. The concept of "resilience", which refers to the ability of a region to anticipate, prepare for, respond to, and recover from a disturbance [7,8], has gained increasing attention as a valuable strategy for managing uncertainties in regional development environments [3,9]. Strengthening regional planning and management to enhance regional resilience is essential for sustainable regional development.

In the context of regional integration development, cities are no longer isolated systems within regions, and intra-regional links between cities are becoming increasingly close, resulting in highly integrated regions such as city clusters [10]. These city cluster regions are usually centered on one or more megacities, with at least three or more large cities as

constituent units, and they contain complex population, information, and resource flow relationships within them, which can be abstractly viewed as a complex urban network model [11,12]. This complex city cluster network enhances the efficiency of the region's operations based on better resource flows and provides a foundation for regional synergy, which are both significant for disaster response. Therefore, it is necessary to consider overall resilience from a regional synergy perspective for the development planning of city cluster regions. Regional synergy can be interpreted as regional cooperation or interaction to jointly inhibit and mitigate risks, and the entire region, as well as each sub-region, can benefit from regional synergy [13]. The concept of regional synergistic development has become a key element, where the closer connectivity between cities and the resulting city network evolution lead to the enhancement of resilience for the entire city cluster [14].

As a multi-hazard-prone country, the Chinese Government is a strong advocate of building resilient regions. The 14th Five-Year Plan (2021–2025) of China proposes the idea of "building resilient cities, improving urban governance, and strengthening risk prevention and control in mega-cities", integrating the construction of resilient cities into the national strategic planning system. To achieve the goal of resilience building, in 2018, China's State Council explicitly emphasized the implementation of the regional coordinated development strategy, which is regarded as one of the major national strategies in the new era. The Yangtze River Delta (YRD) city cluster has been positioned as a pilot region for a new model of city cluster-driven regional development to promote integration and interactive development between regional segments. In 2021, the large-scale COVID-19 epidemic in Shanghai, which resulted in insufficient regional supplies, further highlighted the criticality and necessity of enhancing regional resilience in the YRD region [15].

This study explores the status of resilience enhancement in the YRD city cluster to cope with disasters under different synergistic response paths. First, building on our previous study, we propose a resilience measurement method for the YRD city cluster, considering the coupled effects of disaster risk propagation and synergistic recovery. Second, leveraging complex network theory and regional synergistic emergency response theory, we propose a mechanism for resilience enhancement through synergistic evolution at the levels of nodes, edges, and sub-networks. Furthermore, the three synergistic response paths for resilience enhancement align with practical planning measures, such as adjusting urban resource allocation, developing inter-city transportation systems, and integrating sub-metropolitan areas within the city cluster. Finally, we compare the effectiveness of resilience enhancement in the YRD city cluster under different synergistic paths using simulation-based analysis. These results provide detailed insights into the regional resilience and sustainable development of the YRD city.

The subsequent sections of this paper are organized as follows. Section 2 provides a literature review. Section 3 introduces the study region and the basic data. Section 4 elucidates the simulation analysis framework for city cluster resilience enhancement under different network synergistic paths. Sections 5 and 6 present simulation results under different scenarios and provide discussions and suggestions for the sustainable development and resilience enhancement of the YRD city cluster. Section 7 summarizes the entire article.

2. Literature Review

2.1. Regional Resilience Enhancement of City Cluster

The increase or perceived increase in the number of shocks and disruptions, such as natural disasters, has led to a growing interest in regional resilience [16]. Since the 1980s, the concept of resilience, which emphasizes characteristics such as robustness, redundancy, and adaptability, has gradually entered the field of urban disaster reduction and has become a consensus choice for countries worldwide to cope with risky disasters [17]. Programs

and initiatives such as the "Making Cities Resilient Campaign" and the "100 Resilient City Project" have emerged [18,19], alongside resilient city strategies like the "London City Resilience Strategy 2020" and "One NYC 2050". These strategic plans for urban resilience enhancement have significantly contributed to building and strengthening the resilience of individual cities.

However, regions are never isolated; instead, they can affect each other [20]. The expanding development of regional integration, particularly the emergence of city clusters, has further facilitated this interconnectedness of cities. As a result, the risk conditions faced by each city within a city cluster not only include its own potential risks but also involve external inputs from other cities [21]. The resilience of individual cities alone cannot meet the needs of enhancing the resilience of the entire city cluster system, which requires further consideration.

Existing studies on the resilience of the city clusters have mainly focused on exploring differences among cities within the clusters to identify cities with low resilience and propose city areas for improvement. For example, in a study of the resilience of the Chengdu-Chongqing City Cluster, Gou et al. [22] constructed the Functional Resonance Analysis Method by integrating five primary indicators (society, economy, infrastructure, environment, and government) to measure the resilience of cities over time and compare them on a spatial scale. This approach advocates that managers focus on less resilient cities. However, this spatial comparison of resilience overlooks the impact of interactions among cities within a city cluster. A holistic approach to resilience enhancement, which considers internal interactions between cities and maximizes the measurement and discussion of resilience, remains to be proposed.

2.2. Regional Resilience Enhancement from the Perspective of City Network

In the context of economic globalization and regional integration, cities and regions have entered a new phase of networked development, which has spurred the emergence of an urban network research paradigm [23]. Network modeling is seen as a promising approach that can effectively analyze the influence of city interactions within the city cluster system. Scholars have depicted city networks at different scales based on data related to infrastructure, economic links, factor flows, and multiple relationships [24]. They have then conducted research on the characteristics of the region's spatial pattern, temporal evolution patterns, growth momentum mechanisms, externalities, and spillover effects from a network perspective, revealing the interactions between cities within the region [25–28]. For example, Wu et al. [29] constructed a spatial network of green total factor productivity for China's three major coastal city clusters (Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta) based on the gravity model. They traced the centralities and subgroups of each network by conducting social network analysis and then investigated the socioeconomic factors correlating with the green total factor productivity interrelation between cities.

These studies provide a methodological foundation for quantifying the impact of interactive relationships in city cluster regions. However, the resilience of city cluster regions under interaction relationships is more complex, emphasizing multidimensionality and systematicity [30,31]. Therefore, it is necessary to improve the complex modeling of factor circulation networks in city clusters in response to external strike perturbations further to better describe resilience.

Furthermore, in the measure of regional resilience for city networks, most scholars still characterize it as a specific capability attribute through network indicators such as degree, betweenness, and clustering [32–34]. Wang et al. [35] took a step further by adding

actual weights to the network model, attempting to characterize the actual characteristics for better resilience measurement.

However, these network indicator-based characterizations of resilience conceptualize resilience only as a level of a region's capacity, which hardly satisfies the definition of resilience as the ability of a region to anticipate, prepare for, respond to, and recover from the entire process of a disturbance [36]. In fact, in the face of external perturbations, closely connected city clusters are more intensively influenced by each inner city within the region, with synergistic relationships existing. The city cluster network system will also evolve synergistically under perturbations, and its resilience will fluctuate dynamically. Thus, it is necessary to further explore regional resilience from a dynamic perspective [37], applying advanced modeling techniques to quantify the dynamic interrelations and feedback loops among resilience factors. Evaluating the resilience of regions to adapt, resist, and recover from strikes through techniques such as modeling network nodes or edge disruptions will be a promising direction [38].

2.3. Regional Resilience Enhancement Under Regional Synergy

With the increasing interconnectedness of cities within regions, regional synergistic integration at the scale of city clusters has become an important mode of economic development [39]. The main goal of regional synergistic integration in city clusters is to enhance the free flow of production factors through intergovernmental collaboration and to promote industrial synergies, cooperation, and resource sharing among constituent cities in neighboring geographic regions [40]. Previous studies have shown that inter-city synergy promotes the free flow of regional factors, reshapes the pattern of regional factor allocation, and impacts urban land-use efficiency [41]. For instance, Liu et al. [42] developed a theoretical framework of regional synergy and economic growth and measured the synergy between every two cities among 285 cities in China. Their findings illustrate that the synergy between different regions can enable system optimization, achieving a $1 + 1 > 2$ effect and generating new growth potential.

Regional synergy not only promotes regional economic growth and productivity but also provides a pathway for responding to external shocks, such as disasters and enhancing regional resilience [43]. The theory of regional synergy for emergency response requires cities in the region to treat shared disaster risks as common tasks, promote resource integration, and implement unified dispatch, which is essential for disaster recovery [44]. For example, in response to the COVID-19 pandemic, cities in China carried out coordinated emergency responses, such as coordinating medical resources, harmonizing management models, and sharing data, which significantly slowed the spread of the epidemic and reduced disaster losses [45]. In contrast, during the 2005 Hurricane Katrina disaster in the United States, the dysfunctional relationship between state and local governments and the failure to establish effective synergistic networks among cities led to catastrophic consequences [46].

Although many scholars have emphasized the need to strengthen regional synergies to cope with external shocks, such as disasters, and to enhance regional resilience, there are few quantitative studies on the benefits of regional synergies in terms of resilience. The concept of regional synergies remains largely theoretical. Further quantitative analysis of regional synergies using simulation and modeling methods for city cluster resilience is necessary.

2.4. Gap Summary

From the above literature review, three major gaps for regional resilience enhancement can be identified that this study attempts to address:

- The city cluster is the product of a high degree of regional development integration. Enhancing the resilience of the entire city cluster will benefit the entire region, with spillover effects for each city. Exploring the resilience of the entire city cluster system under the influence of city interactions is a necessary but underexplored task.
- Resilience studies based on city networks provide insights for analyzing resilience under the influence of internal interactions within the city cluster. However, most studies still define resilience as the ability of a specific indicator, which fails to characterize the entire process of resistance, absorption, and recovery inherent in the concept of resilience. Advanced simulation modeling techniques are needed to quantify the dynamic interrelationships among resilience factors after disaster strikes.
- The concept of regional synergy has been widely recognized as an important approach to enhancing resilience, but it is still primarily discussed in policy and reporting contexts. More in-depth research is needed on the dynamic changes in performance and the quantification of resilience enhancement in the city cluster system under regional synergy.

3. Study Area and Basic Data

3.1. Study Area and Regional Characters

As shown in Figure 1, the YRD city cluster is located in the southeastern coastal region of China, where cities are economically developed and densely populated. According to the National Bureau of Statistics of China (2024), the YRD city cluster generates 21% of the country's GDP with about 2% of the country's land area. However, within the YRD city cluster, there are significant differences in the economic development levels and emergency medical resource reserves of various cities, which have been proven to be an important basis for regional resilience against disaster strikes [47]. Overall, the economy and resource levels of the eastern region are relatively developed, while the cities in the western region, especially in Anhui Province, are relatively underdeveloped. These disparities in spatial economy and resources further highlight the necessity of a regional synergistic response.

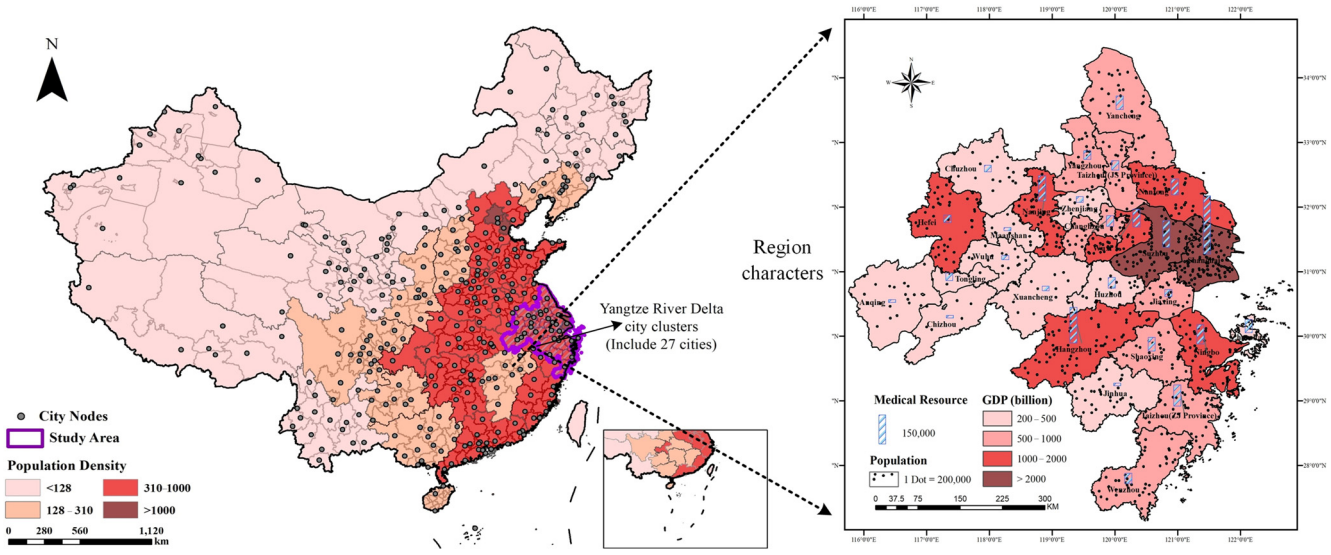


Figure 1. Study area and regional characters.

3.2. Resilience Enhancement Paths of YRD City Cluster

With the promulgation of the Outline of the Plan for the Integrated Development of the Yangtze River Delta Region in 2016, the following three paths are seen as effective evidence for enhancing regional synergy and enhancing YRD city cluster regional resilience.

3.2.1. Adjustment of Resource Allocation

The adjustment of resource allocation in a city cluster implies a more rational distribution of limited resources. In the recovery process of the city cluster system following a disaster, the resources of a city are limited and fixed, and the rational allocation of these resources across cities will significantly improve resilience [48]. There are two ways to allocate the resources of each city. One is to retain resources within the city to ensure the stability of its own resilience, which is referred to as resources used for self-recovery. The other mode is to allocate resources for regional synergy and deployment to support the resilience recovery of other cities, which is referred to as resources used for other recovery. For the YRD city cluster system, the entire region is regarded as a network model with synergistic relationships. When one city suffers from a disaster impact, the adjustment of resource allocation ensures the promotion of system resilience recovery. When each city operates under the optimal resource allocation mode, the performance of the city cluster will reach its peak, enhancing the efficiency of resource supply and contributing to resilience enhancement.

3.2.2. Transportation System Development Impact

More convenient transportation can greatly reduce the challenges of inter-city resource synergy and improve regional resilience under disaster impact [49,50]. According to the Outline of the Development Plan for the Yangtze River Delta Region Integrated Development [51], both the railway and highway systems in the YRD city cluster have been significantly upgraded in recent years (as shown in Table 1), with a total of nine railway and eight highway projects, covering 51 cities. These improvements will further enhance the resilience of the YRD city cluster in the event of a disaster strike.

Table 1. Railway and highway development plans in YRD city clusters.

Type of Transportation	Transportation Projects	Cities Involved[1]
Railway development	North Yanjiang High Speed Railway	SH, SZ, NT, TZ, YZ, NJ
	South Yanjiang High Speed Railway	SH, SZ, WX, ZJ, CZ, NJ
	Shanghai-Suzhou-Huzhou High-speed Railway	SH, SZ, HZ
	Shanghai-Zhapu-Hangzhou railway	SH, HZ, JX
	Hefei-Xinyi High Speed Railway	HF, CZ
	Zhenjiang-Xuancheng High-speed Railway	ZJ, NJ, CZ, XC
	Nanjing-Xuancheng-Huangshan High-speed Railway	NJ, XC
	Nanjing-Yangzhou High Speed Railway	NJ, YZ
	Nanjing-Maanshan High Speed Railway	NJ, MAS
Highway development	Nanjing-Maanshan Highway	NJ, MAS
	Nanjing-Hefei Highway	HF, CZ*, NJ
	Beijing-Shanghai Highway	SH, SZ, WX, YZ, TZ
	Changzhou-Taizhou Highway	CZ, TZ
	Nanjing-Yizhen Highway	NJ, YZ
	Suzhou-Nantong Highway	SZ, NT
	Chongming-Qidong Highway	SH, NT
	Shanghai-Zhoushan-Ningbo Highway	SH, ZS, NB

3.2.3. Sub-Metropolitan Area Synergy Enhancement

In recent years, some large cities in the city cluster have gradually expanded their capacity, and the trend of co-location has become increasingly evident. This has led to closer links and more frequent resource interactions between cities in the metropolitan area formed by the large cities and some of the surrounding cities. The development of these sub-metropolitan areas has significant positive implications for the city cluster resilience [52]. As of 2024, in the YRD city cluster, there are six sub-metropolitan areas

with higher regional synergistic development as shown in Table 2, namely the Shanghai metropolitan area, the Nanjing metropolitan area, the Hangzhou metropolitan area, the Hefei metropolitan area, the Suzhou-Wuxi-Changzhou metropolitan area, and the Ningbo metropolitan area.

Table 2. Six sub-metropolitan areas of the YRD city cluster.

Abbreviation	Metropolitan Areas	Cities Included	Number of Cities
SHMCA	Shanghai metropolitan area	SH, NT, YC, ZJ, TZ, HZ, NB, JX, ZS	9
NJMCA	Nanjing metropolitan area	NJ, YZ, TL, CZ*, MAS	7.5 *
HAMCA	Hangzhou metropolitan area	HZ*, SX, CZ**, XC	4
HFMCA	Hefei metropolitan area	HF, AQ, WH	5.5 *
SWCMCA	Suzhou-Wuxi-Changzhou metropolitan area	CZ, WX, SZ	3
NBMCA	Ningbo metropolitan area.	WZ, TZ*, JH	3

* Cities in the YRD city cluster that contain only part of a county or district are counted as 0.5.

3.3. Collection of Data on Economy, Transportation, Population, and Medical Resources

In this study, we collected basic data (as shown in Table 3) on the economy, transportation, population, and medical resources of the YRD city cluster. The economic data derived from the GDP of the cities and the data of urban built-up areas of the cities are published in the National Statistical Yearbook 2020. The population data are derived from the 7th Population Census of China. Despite these ages, we mainly focus on the methods to characterize the temporally stable structure of communities using this data, which still allows us to validate the effectiveness of our methods.

Table 3. Basic date sources.

Dimension	Indicator	Resource
Economic	g_i—GDP of city i	China Statistical Yearbook 2020 (www.stats.gov.cn)
Traffic	d_{ij}—Access distance from city i to city j	AMAP (ditu.amap.com)
Population	p_i—Resident population of city i	The seventh census of the National Bureau of Statistics of China (www.stats.gov.cn)
Urban built-up area	d_{ii}^2—Urban built-up area of city i	China Statistical Yearbook 2020 (www.stats.gov.cn)
Medical resources (s_i)	$s_i(1)$—Number of beds of hospitals	China Urban Statistical Yearbook 2020
	$s_i(2)$—Number of licensed (assistant) doctors	China Urban Statistical Yearbook 2020

The medical resources data are projected from the number of beds and the number of professional doctors in the 2022 China Urban Statistical Yearbook. As shown in Equation (1), Based on the study of KOU et al. [47], the measurement of medical resource of a city i consists of both the number of hospital beds ($s_i(1)$) and the number of licensed (assistant) doctors ($s_i(2)$), with the linearly estimating.

$$s_i = 2 * s_i(1) + s_i(2) \quad (1)$$

Lastly, the access distance between cities was obtained from AMAP. By inputting the latitude and longitude coordinates of two cities (city i and city j) and calling the accessibility calculation module of AMAP, the actual accessibility distance between the two cities under real-world conditions can be quickly evaluated. In this study, we sequentially measured the actual accessibility distance between pairs of vehicles across 27 cities in the YRD city cluster, ultimately constructing a 27 × 27 matrix of actual access distances.

4. Simulation Analysis for Resilience Enhancement

The application of complex network theory has important implications for the planning, construction, and management of city cluster resilience [53]. Desouza et al. [54] proposed key elements, processes, and interactions of complex city network systems that need to be further understood and managed to enhance resilience. Among them, the theory of regional synergy is widely recognized as a management approach to help enhance city cluster resilience [55]. Regional synergy is a key element in the development of emergency response to external shocks such as disasters [56,57], linking cities within a region through mutual support in terms of resources, information, etc. [58].

On the basis of the prequel study [14], We improve the analytical framework for the coupled impacts of disaster risk propagation and collaborative recovery in the YRD city cluster. Furthermore, we propose the three resilience enhancement paths based on city network synergistic response. Finally, we design a simulation scheme to quantitatively analyze the resilience enhancement status of the YRD city cluster under different resilience enhancement paths.

All parameters in this section are defined as shown in Table 4.

Table 4. Parameter definition used in the simulation analysis.

Parameter	Definition	Parameters Setting
$G(V,E)$	The coupled network model of risk propagation and synergy recovery	$G^{\alpha}(V,E^{\alpha})+G^{\beta}\left(V,E^{\beta}\right)$
$G^{\alpha}(V,E^{\alpha})$	The risk propagation network model	27 city nodes, 53 edges
$G^{\beta}\left(V,E^{\beta}\right)$	The synergy recovery network model	27 city nodes, 702 edges
v_i	The city node i of the network	Total 27 city nodes
e_{ij}^{α}	The risk propagation edge between node v_i and node v_j	Total 53 edges
e_{ij}^{β}	The synergy recovery edge between node v_i and node v_j	Total 702 edges
P_i^d	Damage probability from normal (vulnerable) to damage	$P_i^d(t)=\gamma ln\left(U_i^d\right)$
P_i^r	Recovery probability form damage to normal (immune)	$P_i^r(t)=\vartheta ln\left(U_i^r\right)$
U_i^d	The potential impact of risk propagation on node v_i	$U_i^d=\sum_{i=1}^{n}\frac{p_ip_j}{{d_{ij}}^2}q_j(t)$
U_i^r	The potential impact of synergy recovery on node v_i	$U_i^r=\sum_{j=1,j\neq i}^{n}\frac{s_jg_j{p_i}^{-1}}{{d_{ij}}^2}$
$U_i^r(self)$	The potential impact of recovery by city itself	$U_i^r(self)=\frac{s_ig_i{p_i}^{-1}}{{d_{ii}}^2}$
$U_i^r(others)$	The potential impact of recovery by other cities	$U_i^r(others)=\sum_{j=1,j\neq i}^{n}\frac{s_jg_j{p_i}^{-1}}{{d_{ij}}^2}$
$U_i^r(a)$	The potential impact of synergy recovery under the resilience path of adjustment of resource allocation	$U_i^r(a)=\sigma U_i^r(self)+\tau U_i^r(others)$ $(\sigma+\tau=1)$
$U_i^r(b)$	The potential impact of synergy recovery under the resilience path of development of transportation system	$U_i^r(b)=(1+\varphi)U_i^r$
$U_i^r(c)$	The potential impact of synergy recovery under the resilience path of integration of sub-metropolitan areas	$U_i^r(c)=(1+\omega)U_i^r$
γ	Risk propagation coefficient	0.02
ϑ	Synergy recovery coefficient	0.02
σ	Percentage of resources devoted to self-recovery	0~1, intervals of 0.1 steps
τ	Percentage of resources devoted to other-recovery	0~1, at intervals of 0.1 steps
φ	Growth coefficients under development of transportation system	0.5
ω	Growth coefficients under integration of sub-metropolitan areas	0.5
R	Resilience of the whole city cluster	$R=\int_0^T(1-Q(t))dt$
r_i	Resilience of the city i in the city cluster	$r_i=\int_0^T(1-q_i(t))dt$
$q_i(t)$	Quality state of city i at time t	$q_i(t)=1$ or $q_i(t)=0$
$Q(t)$	Quality state of the whole city cluster at time t	$Q(t)=\frac{\sum_{i=1}^{n}q_i(t)}{n}$
T	The strike simulation cycle	50

4.1. City Cluster Network Model Construction

As a product of highly integrated and synergistic regional development, the YRD city cluster can be viewed as a complex network system where cities interact with each other, adapt to each other, and evolve under the guidance of policies [55]. The connectivity of city cluster networks further facilitates the flow of resources from one subsystem to another, but it also enables risks to spread and amplify [22]. This means that disasters are more likely to have a greater impact on the normal functioning of the region and human activities [59]. However, the connectivity of city networks also provides new opportunities for disaster response, such as synergy recovery [60,61]. In the face of disaster strikes, the entire city cluster can carry out synergistic emergency responses by leveraging the city cluster network and integrating resources from various cities to rescue damaged areas. Therefore, the trade-off between risk propagation and synergy recovery makes the resilience of the YRD city cluster more complex. It is necessary to analyze the resilience capacity of the YRD city cluster system deeply from the perspective of the trade-off between risk propagation and synergy recovery.

As shown in Figure 2, the YRD city cluster system can be regarded as a coupled network model $G(V, E)$ with two layers of risk propagation and synergy recovery, which includes risk propagation network $G^{\alpha}(V, E^{\alpha})^{2}$ and synergy recovery network $G^{\beta}(V, E^{\beta})^{3}$. The city monoliths in the network are considered as nodes v_i, while the inter-city links (risk propagation or synergy recovery) are considered as connecting edges (e_{ij}^{α} or e_{ij}^{β}). With the interaction between each city, the regional resilience of the whole city cluster.

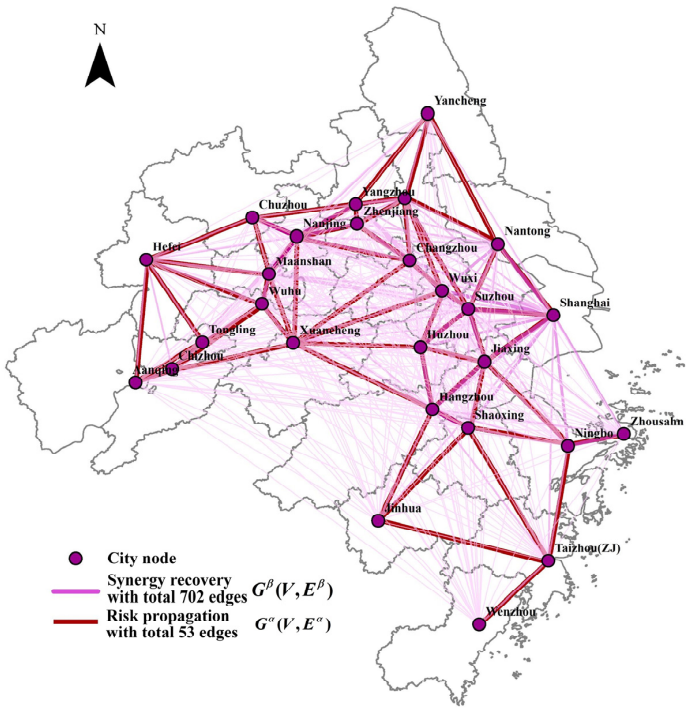


Figure 2. The risk propagation and synergy recovery coupled network of the YRD city cluster.

4.2. Dynamics Evolution of City Cluster Network Resilience After a Disaster Strike

In this section, we further improve the resilience dynamic evolution mechanism (as shown in Figure 3) based on the SIR[4]. model of risk propagation and synergy recovery coupling effects proposed in the prequel study [14], which is used to quantitatively analyze the complex dynamics of the resilience of the city cluster network system under the disaster impact.

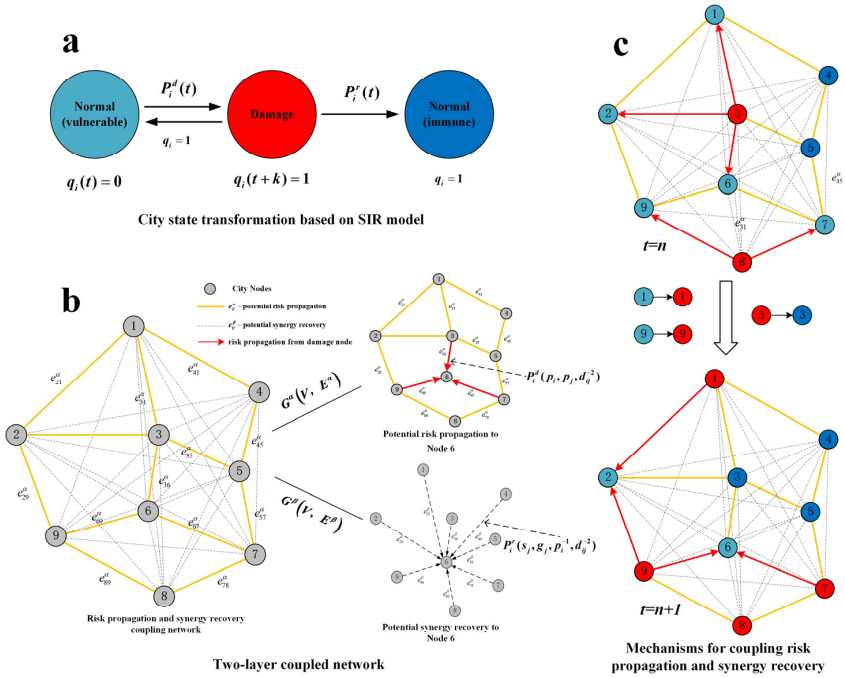


Figure 3. The coupled mechanism of disaster risk propagation and synergy recovery based on the SIR model ((**a**) shows the city-state transformation based on the SIR model, (**b**) illustrates the tow-layer coupled city network. (**c**) shows an example of the process of changing the state of the city cluster network).

As shown in Figure 3a, under the disaster impact, there exist three states of Normal (vulnerable), Damage, and Normal (immune) for each city node (This is analogous to the Susceptible, Infectious, and Recovered states in the SIR model.), which portray the resilience state performance of each city node. The likelihood of a transition from normal (vulnerable) to damage during risk propagation is defined as the risk propagation probability P_i^d, while the transition from Damage to Normal (immune) is defined as the synergistic recovery probability P_i^r. As shown in Equations (2) and (3), the probability of these two kinds of transitions has some correlation with the population, economic, transportation and other factors. For the risk propagation probability P_i^d, the population size of two cities is usually considered to be positively correlated with it. While for the synergistic recovery probability P_i^r, the availability of medical resources and the economic level of the relief city are usually considered positive factors, the population in the damaged city affects the speed of synergy recovery.

$$P_i^d(t) = \gamma ln\left(U_i^d\right) = \gamma ln\left(\sum_{i=1}^{n} \frac{p_i p_j}{{d_{ij}}^2} q_j(t)\right) \tag{2}$$

$$P_i^r(t) = \vartheta ln(U_i^r) = \vartheta ln\left(\sum_{j=1, j\neq i}^{n} \frac{s_j g_j {p_i}^{-1}}{{d_{ij}}^2}\right) \tag{3}$$

Figure 3b illustrates the tow-layer coupled city network with the potential risk propagation between neighborhood cities and the potential synergy recovery among all cities. $V = \{v_1, v_2, v_3, \ldots v_n\}$ is the set of nodes in the network representing the cities in the region. E^α and E^β are the sets of connected edges in the two-layer coupled network, where edge $e_{ij}^\alpha \in E^\alpha$ denotes the risk propagation action between nodes v_i and node v_j, and edge $e_{ij}^\beta \in E^\beta$, which denotes the cooperative recovery action between nodes v_i and nodes v_j.

Furthermore, Figure 3c shows an example of the process of changing the state of the city cluster network at the moment n under the disaster impact. In this example, city node 3&8 was in a state of damage, which denoted the risk propagation action through the edges $(e^{\alpha}_{32}, e^{\alpha}_{36}, e^{\alpha}_{31}, e^{\alpha}_{89}, e^{\alpha}_{87})$ and got the synergy recovery action through the edges (all the edges of e^{β}_{3j}&e^{β}_{8j}). As a result at the moment of $n + 1$, the city node 1&9 changed into the damage state, while city node 3 achieved recovery.

4.3. Measurement of City Cluster Dynamic Resilience

To build and manage resilience in city cluster systems more adequately, it is fundamental to achieve an appropriate and accurate quantification of this compound system attribute [62]. Unlike traditional regional security studies that focus on reducing interference, the resilience perspective puts more emphasis on the ability of a region to absorb blows and complete recovery under the impact of risks [63]. Performance change-based metrics are a widely used set of tools to quantify resilience by analyzing the time-series performance change in the functional level of a system, which can effectively describe the status of system resilience over time under disaster impact.

As shown in Figure 4, this study carries out a dynamic analysis of resilience based on the resilience curve formed by the fluctuation of the performance state of the city cluster system and extracts the corresponding indexes to describe the resilience capacity of the whole city cluster system and each city under disaster impact.

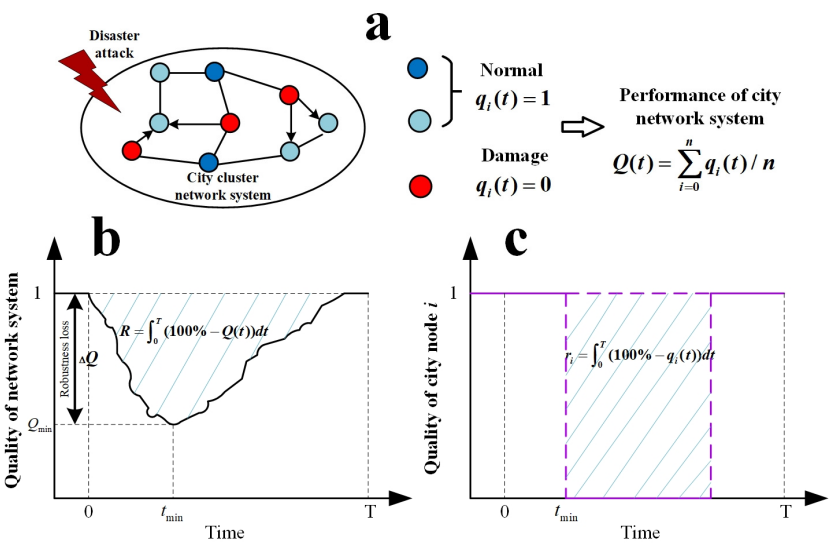


Figure 4. Measurement of regional resilience (**a**) shows the performance of the city network system under the transformation of the state, and (**b**,**c**) illustrate the performance curves of the whole city agglomeration system and of the individual cities themselves in the event of the disaster strike).

- Performance of city network system

The city cluster network performance indicator $Q(t)$ is quantitatively measured by the normal node ratio and has been widely used to measure the performance level of the network under risk propagation [64]. The calculation of network performance $Q(t)$ at period t is shown in Equation (4), where n represents the total number of nodes in the city network and $q_i(t)$ characterizes the state of the city node i at the moment t. If the city i is in normal state, $q_i(t) = 1$; while in a damaged state, $q_i(t) = 0$.

$$Q(t) = \frac{\sum_{i=1}^{n} q_i(t)}{n} \tag{4}$$

- Resilience of the whole city cluster

After a disaster strike, the spreading of the disaster risk will mean that the performance of the system will gradually decline. While, the city cluster system can also gradually realize the performance recovery under the effect of synergy recovery. Thus, the whole process from disaster occurrence to recovery can be described by the change of the performance curve. the city cluster system resilience capacity R is shown in Equation (5).

$$R = \int_0^T (1 - Q(t))dt \tag{5}$$

The resilience indicator R refers to the "resilience-triangle metric" proposed by Bruneau et al. [65]. It depicts the total loss of system resilience based on the real difference between 100% functionality and the actual time-dependent performance, which effectively combines the robustness and recovery time and takes the speed of network recovery into account [66,67].

- Resilience of each city node

As for each city within the cluster itself, its own resilience capacity is expressed as the total time it is in a state of damage during the T time period of the entire system strike-recovery. Equation (6) shows the resilience capacity r_i of each city within the city cluster under the disaster impact.

$$r_i = \int_0^T (1 - q_i(t))dt \tag{6}$$

4.4. Resilience Enhancement Paths

The development of the YRD city cluster has been accompanied by more frequent regional synergies among cities. The theory of regional synergy is widely recognized as a management approach to help enhance city cluster resilience [54,55]. As shown in Figure 5, this paper sequentially proposes the adjustment of nodes—to promote the resource allocation capacity of cities, the enhancement of edges—to strengthen the development of inter-city transportation system, and the enhancement of sub-networks—to improve the integration of sub-metropolitan areas as the three major resilience enhancement paths for YRD city cluster to enhance the regional resilience from the perspective of city networks synergistic response.

As shown in Table 5, under the three regional resilience enhancement paths based on city network synergistic response, The potential impact of synergy recovery ($U_i^r(a)$, $U_i^r(b)$, $U_i^r(c)$) would then be increased as follows:

- Under the adjustment of resource allocation for each city, the potential impact of synergy recovery U_i^r of each city node in Equation (2) can will be defined as the part for self-recovery and the part from other cities for others-recovery, where σ and τ represent the proportion of the city's limited recovery resources used for self-recovery and other-recovery. For individual city nodes, a better allocation of resources will mean more resilience.
- Under the condition of transportation development, the access distance between internal cities will be shortened, which means the potential impact of synergy recovery U_i^r will improve as $(1 + \varphi)U_i^r$.
- Under the development of the sub-metropolitan areas, the internal cities will have better synergistic relationships and the potential impact of synergy recovery U_i^r will improve as $(1 + \omega)U_i^r$.

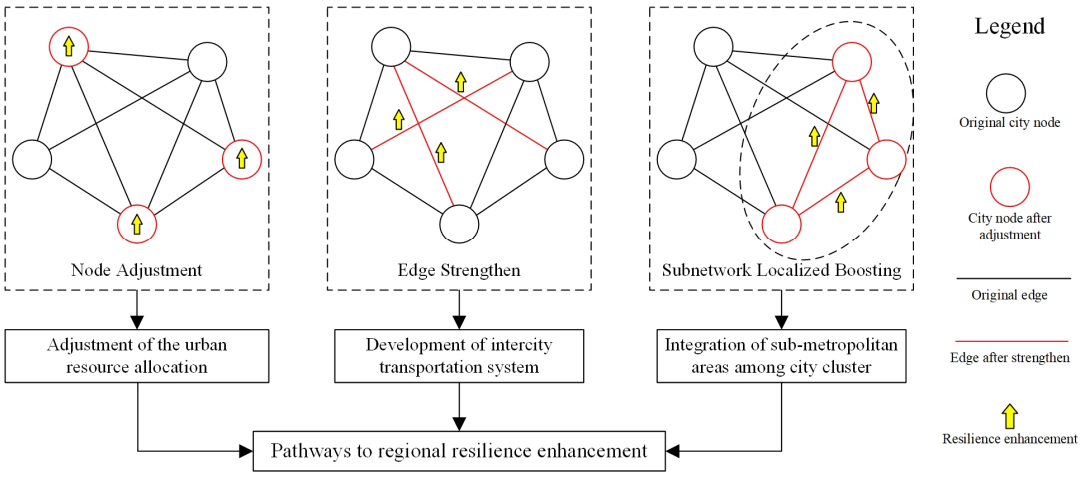


Figure 5. Paths to regional resilience enhancement.

Table 5. The potential impact of synergy recovery under the three regional resilience enhancement paths.

Regional Resilience Enhancement Paths	Network Perspectives	Synergistic Enhancement of the Formula
The adjustment of resource allocation	Node adjustment	$U_i^r(a) = \sigma U_i^r(self) + \tau U_i^r(others)$ $(\sigma + \tau = 1)$ $U_i^r(self) = \frac{s_i g_i {p_i}^{-1}}{{d_{ii}}^2}$ $U_i^r(others) = \sum_{j=1, j\neq i}^{n} \frac{s_j g_j {p_i}^{-1}}{{d_{ij}}^2}$
The development of transportation system	Edge strengthen	$U_i^r(b) = (1+\varphi)U_i^r$ (if city i is in a railroad or highway plan)
The integration of sub-metropolitan areas	Subnetwork localized boosting	$U_i^r(c) = (1+\omega)U_i^r$ (If city i is in a sub-metropolitan areas)

4.5. Simulation Flow of Regional Resilience Analysis

The simulation of the regional resilience enhancement (as shown in Figure 6) based on city cluster network synergistic response under disaster impact needs to compare the resilience under different resilience enhancement paths with the initial resilience profile.

- Step 1: Construct the coupled network $G(V, E)$ model. Determine the structure of risk propagation $G^{\alpha}(V, E^{\alpha})$ and synergy recovery network $G^{\beta}(V, E^{\beta})$ in turn.
- Step 2: Define the relevant parameters. The YRD city cluster has a subtropical monsoon climate with an annual rainfall of 1000–1400 mm [68], and about 70% of the rainfall is concentrated in the spring and summer months [69], which makes flooding more likely during these seasons. In 2020, severe floods occurred in the YRD region, which resulted in a total of 11.88 million people being affected, with a direct economic loss amounting to 27.19 billion yuan [70]. Therefore, for the disaster impact simulation, considering that flood disasters represent the most frequent and economically devastating hazard type confronting the YRD city cluster, the disaster impact simulation was specifically configured for flood disaster scenarios. In accordance with the National Standard of the People's Republic of China "Standard for Flood Control" (GB50201-2014) [71], major cities, which the cities in the YRD city cluster generally fall under, are required to maintain flood control standards corresponding to a minimum 50-year recurrence interval. Based on this regulatory framework, the risk propagation coefficient γ and synergy recovery coefficient ϑ in our disaster impact simulation model were parametrized as 0.02, respectively.
- Step 3: Simulate the disaster impact on the network. Simulate 1000 disaster strikes for each city sequentially. During the simulation, a city i is selected as the disaster outbreak

origin, which is struck by a disaster at the initial moment ($t = 0$) and enters a damaged state. The disaster then propagates outward according to the risk propagation mechanism within the city cluster network (with a probability of $P_i^d(t)$). After $t = 5$, the city cluster initiates synergy recovery to address the disaster. Cities gradually begin to coordinate their resources, achieving disaster recovery with a probability of $P_i^r(t)$ at each time step. Based on Section 4.2 (Dynamics evolution of city cluster network resilience after a disaster strike), the dynamic change process over T = 50 cycles after the disaster is simulated, encompassing the entire process from the initial disaster strike to the completion of overall recovery. Finally, a total of 27,000 experimental data were collected, which was used to average out the random effects.

- Step 4: Carve out the moment-by-moment performance of the city cluster network and plot the network resilience curve. Take the average of the network performance to plot the corresponding resilience curve to average out the random effects.
- Step 5: Resilience measurement. Extract the corresponding indexes to describe the resilience capacity of the whole city cluster system and each city under disaster impact.
- Step 6: Simulate resilience enhancement paths based on city cluster network synergistic response. Define the corresponding coefficients ($\varphi = 0.5, \omega = 0.5$)[5].
- Step 7: Repeat step 3–5 to complete the corresponding resilience measures. Compared with the initial resilience profile, analysis of the resilience enhancement status under different city networks synergistic response paths.

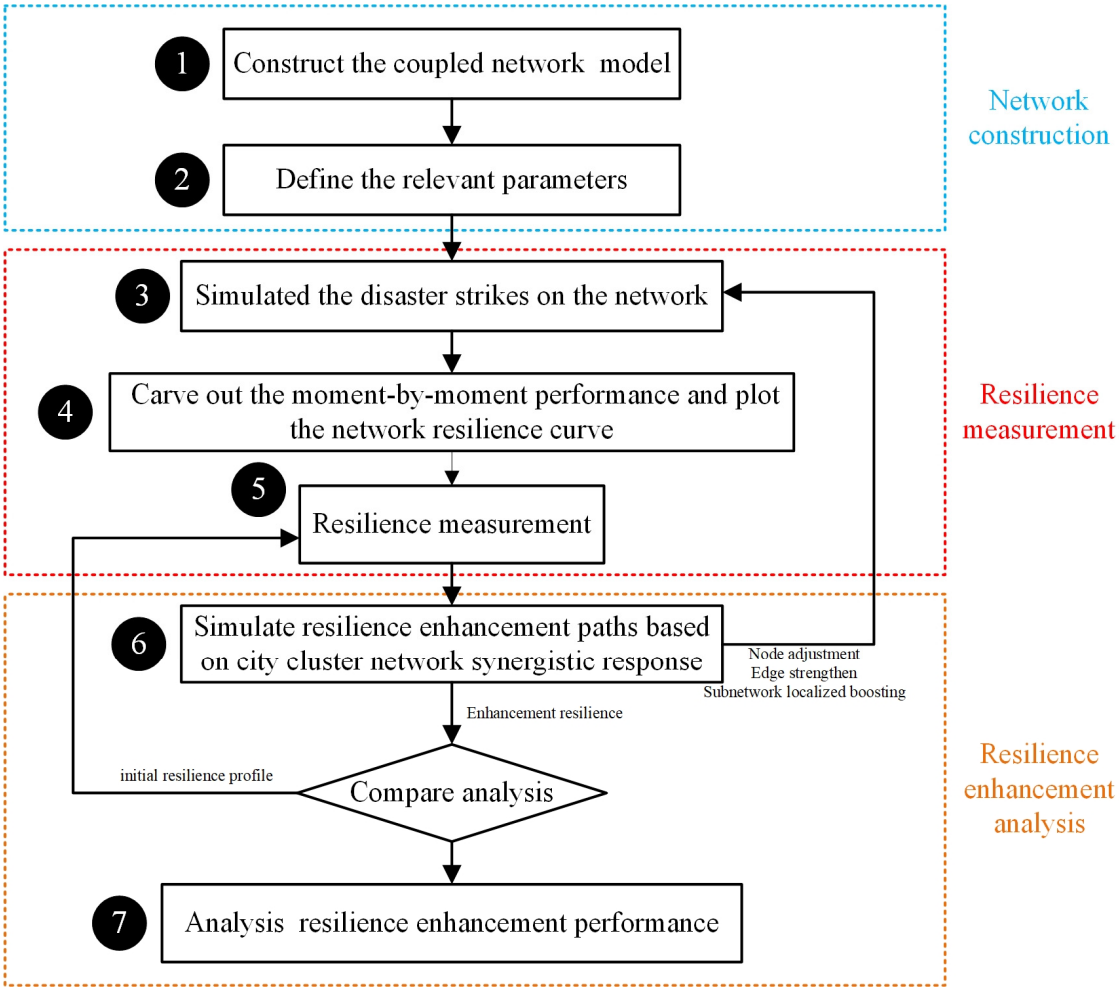


Figure 6. The algorithm flow chart.

5. Results

5.1. Initial Resilience Profile of YRD City Cluster

The initial resilience profile of the YRD city cluster system and each city under different varying disaster impact scenarios were visualized by ArcGIS 10.8, as shown in Figure 7, showing the performance loss of the whole city cluster and each individual city after different cities suffering disaster strikes, which means their resilience capacities. The results show that, for the whole city cluster system, cities in the middle of the inner YRD city cluster will have a more significant resilience impact on the whole city cluster system, especially for Xuancheng having the largest resilience impact. While cities on the outer edges produce a relatively weaker resilience impact. Meanwhile, the resilience of each individual city shows differences in space. In general, cities in Jiangsu Province and all the capital cities will experience a relatively higher performance loss, while cities in Anhui, located at the edge of the YRD city cluster, will experience a relatively smaller performance loss. Figure 7c,d further show the comparison between the resilience loss cause and the resilience suffering by each city under the disasters. Shanghai, Nanjing, Hangzhou, Hefei—higher-ranked municipalities and capital cities—are all in the category of suffering performance loss under disasters, while cities in the geometric center of the YRD cluster, such as Zhenjiang, Ma'anshan, Huzhou, and Wuxi, are notable in terms of causing performance loss.

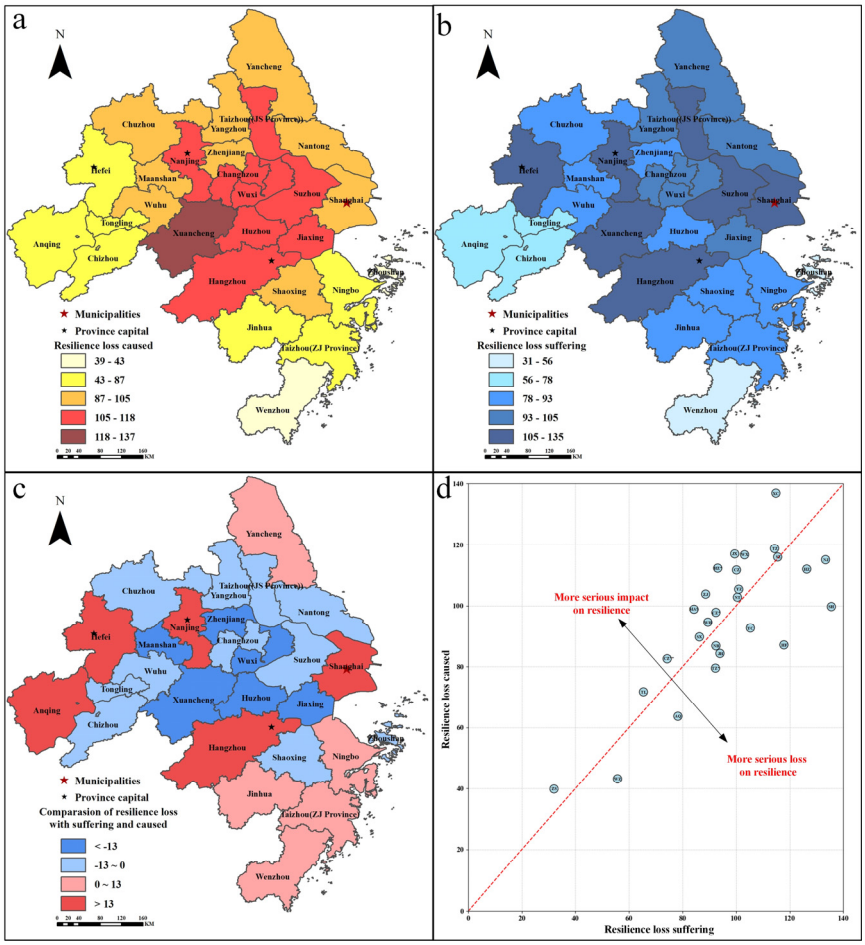


Figure 7. Initial regional resilience profile under varying disaster impact scenarios. ((**a**) shows the performance loss of the whole city cluster, (**b**) shows the performance loss of each individual city and, (**c**,**d**) further show the comparison between the resilience loss cause and the resilience suffering).

5.2. Resilience Enhancement of YRD City Cluster Based on Three Synergistic Response Paths

5.2.1. Adjustment of the Urban Resource Allocation

Figure 8 illustrates the different results of the resilience capacity of the city cluster system with respect to the resilience capacity of individual cities as a result of 11 different resource allocation ratios (as shown in Table 6).

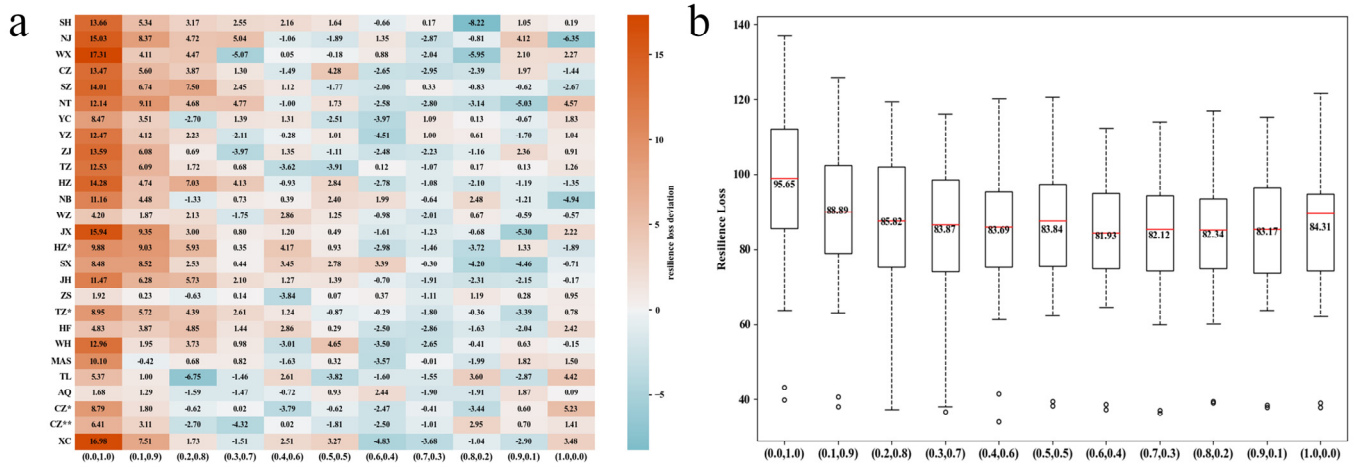


Figure 8. Resilience enhancement of different resource allocation models. ((**a**) shows the comparison of resilience of other-recovery-dominated resource allocation mode with the self-recovery. (**b**) shows the distribution of resilience under 11 different resource allocation ratios).

Table 6. Different share models of resource synergies.

Different Share Models (σ,τ)	Kind of Cities in Share Models
$(0.0, 1.0)$, $(0.1, 0.9)$, $(0.2, 0.8)$, $(0.3, 0.7)$	Other-recovery cities
$(0.4, 0.6)$, $(0.5, 0.5)$, $(0.6, 0.5)$	Integrated recovery cities
$(0.7, 0.3)$, $(0.8, 0.2)$, $(0.9, 0.1)$, $(1.0, 0.0)$	Self-recovery cities

In Figure 8a, compared to self-recovery, each city in the other-recovery-dominated resource allocation mode exhibits low resilience. In constant, the vast majority of cities will incur high resilience under the (0.6 self-recovery, 0.4 other-recovery) & (0.7 self-recovery, 0.4 other-recovery) models. Through the box plots, Figure 8b shows more intuitively the resilience of the whole YRD city cluster system under 11 different resource allocation ratios. Allocating 60% of resources to self-recovery and 40% to other-recovery is the optimal configuration for enhancing the overall system resilience of the YRD city cluster.

Furthermore, the spatial distribution of the optimal resource allocation patterns of the YRD cities (as shown in Figure 9) reveals that most of the cities in Zhejiang and southern Jiangsu province are self-recovery cities, while those in northern Jiangsu and Anhui province are integrated-recovery cities. This spatial difference in distribution is consistent with the actual level of economic development in the YRD city cluster, which is higher in southern Jiangsu and Zhejiang provinces and relatively lower in northern Jiangsu and Anhui provinces. Meanwhile, very few cities, such as Zhenjiang, Zhoushan, Tongling, and Chizhou, which all have the lowest population in each city with less than 20 billion, are other-recovery cities.

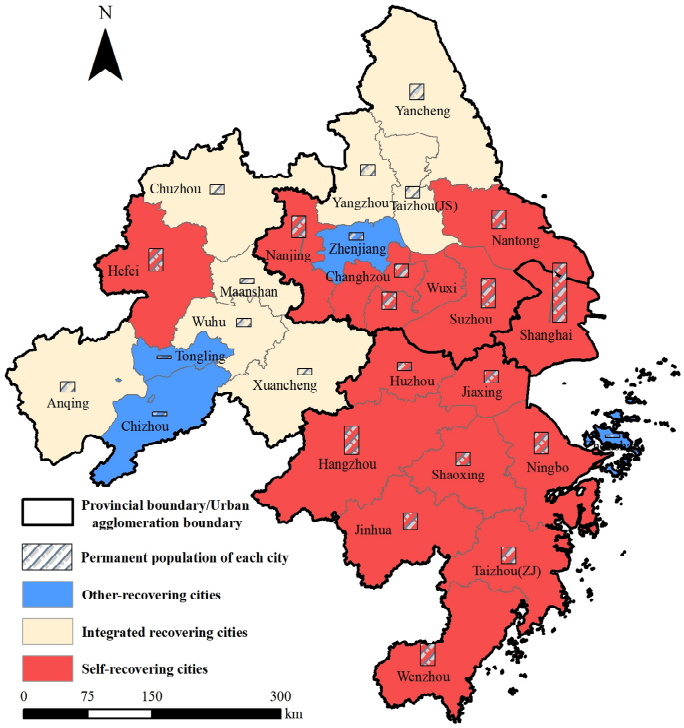


Figure 9. Spatial distribution of the optimal resource allocation patterns of the YRD cities.

5.2.2. Development of Inter-City Transportation System

The results of the regional resilience enhancement under the path of development of the inter-city transportation system are shown in Figure 10. Under the development of nine railways, the resilience of each city in the YRD city cluster increases more significantly, with an average increase of 8.46%. Shanghai and Suzhou have the most significant resilience improvement, which has 4 planned railways. Wenzhou and Shaoxing, which have no railways in the pipeline and are more remote, show less resilience improvement. In the case of highway development, although the whole city cluster improvement is only 6.59%, the resilience improvement of each city shows a better balance, and the variance is relatively small.

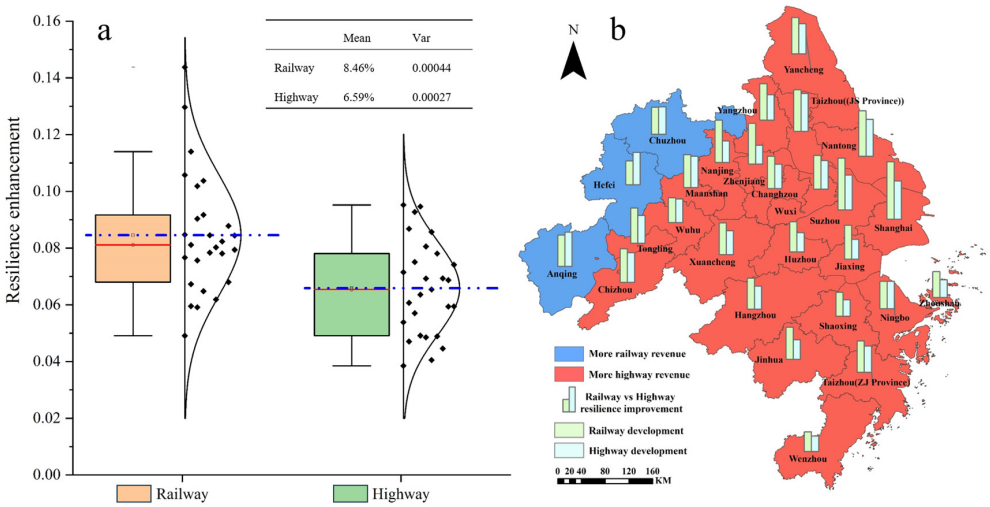


Figure 10. Resilience enhancement under railway and highway. ((**a**) shows the comparison of resilience enhancement between railway development and highway development. (**b**) shows the spatial distribution of resilience enhancement comparisons under railway development and highway development).

In terms of spatial distribution, a correspondingly small number of cities in the west, such as Chuzhou, Hefei, etc., which belong to Anhui province, rely more on highway development to enhance resilience. In contrast, more parts of cities in the east will enjoy the benefits of railway development more.

5.2.3. Integration of Sub-Metropolitan Areas Among City Cluster

As shown in Figure 11, among the six sub-metropolitan areas, the development of the Shanghai metropolitan area has the most significant impact on the resilience of the entire city cluster system, with the overall performance loss significantly reduced. Nanjing, Hefei, and Hangzhou are in the second tier of influence, while the Suzhou-Wuxi-Changzhou and Ningbo metropolitan areas have less impact on the resilience of the city cluster, which is consistent with the level and scale of each metropolitan area.

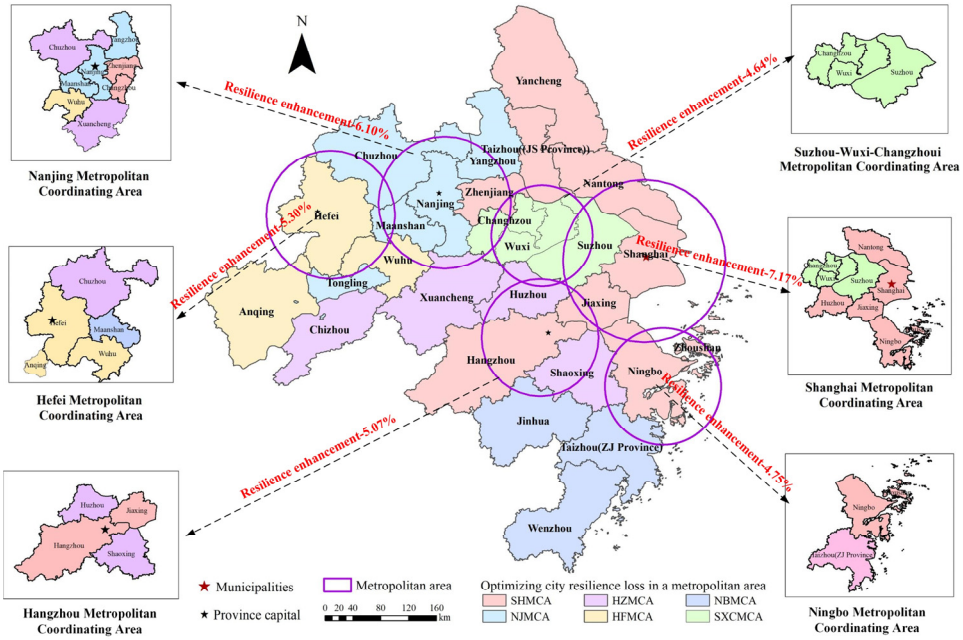


Figure 11. Resilience enhancement under different metropolitan coordinating areas.

Furthermore, for each city itself, in the spatial distribution of the optimal sub-metropolitan area, most coastal cities in the YRD city cluster exhibit better resilience under the development of the Shanghai metropolitan area. Further leveraging the core position of Shanghai in the YRD city cluster can maximize the benefits for more cities in the region. The Nanjing, Hefei, and Hangzhou metropolitan areas better serve the non-coastal cities in the YRD city cluster and promote development in the direction of a multi-core structure.

6. Discussion and Recommendations

According to the results of the comparison of regional resilience enhancement status under different city networks' synergistic response paths with the initial resilience profile, we summarize several important implications about regional resilience enhancement under three in these city clusters, which are of significant guidance for maintaining sustainable development.

1. Reasonable resource allocation is significant for regional resilience enhancement. and there are some differences in the resource allocation modes applied to different cities.

The optimal resource allocation mode for the YRD cluster is (0.4, 0.6), which means that each city allocates 60% of its resources for self-recovery, and puts 40% of resources into other-recovery. Under this resource allocation mode, the resilience of the YRD city

cluster increases by 14.3%. Meanwhile, there are differences in the allocation of appropriate resources to each city. To ensure the optimal resilience enhancement of the YRD city cluster, the capital cities, such as Nanjing and Hefei, as well as the more developed cities of Southern Jiangsu and the whole of Zhejiang, are more self-recovery dependent.

2. Transportation planning is an important driving force for regional resilience, with railway development showing a significant impact on the YRD city cluster. Spatially, railway development has a significant impact on the resilience of coastal cities, while highway development is more favorable to inland cities.

Comparing the impacts of railway and highway planning on the resilience of the regional urban agglomerations in the policy document "Outline of the Plan for the Integrated Development of the Yangtze River Delta", it is found that railway development involves more cities, and its resilience enhancement is more significant for the region as a whole. However, each city's resilience enhancement also further exacerbates the differentiation; the variance of each city's resilience enhancement ratio is larger, and the equity difference between cities is further widened. Highway development, on the other hand, is more balanced in terms of urban resilience and is also more significant in terms of resilience for inland cities.

3. The construction of sub-metropolitan areas is an important engine for city cluster resilience enhancement. While, different metropolitan areas show differences in the scale of resilience influence.

The integration and development of cities within the six existing sub-metropolitan areas of the YRD is the key to regional resilience enhancement. As the core of the YRD, Shanghai metropolitan area has the widest influence and radiation for regional resilience. Furthermore, most of the metropolitan areas have the most obvious influence on the integration and development of their local and neighboring regions. Therefore, Yancheng, Yangzhou and Taizhou on the northern border of the YRD, as well as Wenzhou and Taizhou on the southern border, with an economic development level of 500 billion and more than 5 million populations, it is necessary to further plan and develop sub-metropolitan areas in these two regions to promote regional integration and development, and to make up for the lack of the radiation of the existing metropolitan areas.

7. Conclusions

In this study, we designed an analysis framework for YRD city cluster resilience enhancement paths based on network response, which consists of the perspective of optimization in the node, edge, and sub-network. With the dynamic change mechanism of resilience under the coupling of network risk propagation and synergy recovery of the city cluster under disaster impact, we explore the dynamic change of city cluster resilience capacity under the three different resilience enhancement paths. The results reveal that the optimal resource allocation for the YRD city cluster needs to allocate 60% of resources for self-recovery and put 40% of resources into other-recovery. As relatively more cities still rely more on their own resources for self-recovery, while for smaller cities will rely more on the overall synergy. In the comparison of the resilience enhancement based on railways or highways in transportation development, it is found that railway development is more obvious for resilience enhancement in YRD city cluster, especially for coastal cities, while highways help more to a small number of cities in the western part. Last but not least, the development of sub-metropolitan areas is also an important engine for resilience enhancement, with the Shanghai metropolitan area, as the core of YRD city cluster, being the most extensive in terms of its influence and radiation.

However, this study has some limitations compared to the existing research base. Due to the availability of data, this study mainly discusses the status of resilience enhancement under the synergistic response of regional medical resources. The city cluster resilience under disaster impact is also affected by a combination of other resources, such as emergency food resources and firefighting resources, which will be the direction of this study to continue to expand and deepen. In addition, the discussion of city cluster resilience enhancement for each city in this study is mostly regarded as a homogeneous effect, whether it is the proportion of resource deployment, the impact of the development of sub-metropolitan areas, or the improvement of transportation facilities, there are more detailed differences in the enhancement of cities within the coverage area, and it is necessary to carry out a more detailed discussion in the subsequent study. In addition, this study only gives a quantitative assessment of the enhancement of the resilience of the YRD city cluster under different modes, and it will be a direction to continue to explore in depth how to further improve the resilience through optimization as well as to propose a universal strategy to enhance the resilience of the city cluster in a synergy manner in the future.

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Conflicts of Interest: Author Ye Yang was employed by the company China Aerospace Science and Industry Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Notes

1 Notes on city abbreviations: CZ is short for Changzhou in Jiangsu province. CZ* is the short for Chuzhou in Anhui province. CZ** is the short for Chizhou in Anhui province. TZ is the short for Taizhou in Jiangsu province. TZ* is the short for Taizhou in Zhejiang province. Hereinafter the same in the full paper.

2 Cities damaged by disasters are more probably to transmit risk to neighboring cities along their spatial boundaries. Thus, the risk propagation network $G^{\alpha}(V, E^{\alpha})$ is constructed based on the spatial relationships of cities.

3 City's recovery process from disaster damage can be assisted by all other cities. Thus, the cooperative recovery network $G^{\beta}\left(V, E^{\beta}\right)$ is fully connected.

4 SIR is the short for the "Susceptible-Infected-Recovered" model. The SIR model aims to predict the number of individuals who are susceptible to infection, are actively infected, or have recovered from infection at any given time. In this paper, we use the SIR model to simulate the propagation of disasters in city networks and the recovery process under urban synergy by analogizing cities affected by a disaster to populations affected by infectious diseases. Finally, this paper utilizes the number of cities in a state of damage to measure the performance and resilience of the YRD city cluster system.

5 Against the backdrop of transportation development and the integrated development of sub-metropolitan areas, the travel distance between cities will be significantly improved, which is of great significance for enhancing synergy recovery probability. For example, the operating speed of traditional regular railways is only 120–160 km/h, while the speed of high-speed trains such as EMUs and high-speed rails can reach 250–350 km/h. The speed limit on the original national highways between cities was

60–80 km/h, while the average speed on expressways can reach 100–120 km/h. This indicates that transportation development will increase the actual travel efficiency of the region by more than 50%. Therefore, we define the "Growth coefficients under development of transportation system" as $\varphi = 0.5$. The demarcation of a metropolitan area means that the original travel circle of about 2 h between cities will be reduced to a 1-hour commuting circle, meaning the actual travel efficiency will increase by more than 50%. Therefore, we define the "Growth coefficients under integration of sub-metropolitan areas" as $\omega = 0.5$.

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