



# Spatial-temporal evaluation of urban resilience in the Yangtze River Delta from the perspective of the coupling coordination degree

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Received: 16 June 2022 / Accepted: 23 February 2023  
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## Abstract

Scientific evaluation of urban resilience will help to improve the ability of self-prevention and self-recovery when facing internal and external pressure. However, existing studies are on basis of the overall perspective of the urban resilience evaluation index system to measure urban resilience, often ignoring the coupling and coordination degree among indicators. Therefore, an empirical analysis is developed, which is used to measure the urban resilience of eight cities in the Yangtze River Delta urban agglomeration from 2010 to 2019 from the perspective of coupling coordination degree based on the urban resilience evaluation index system. The empirical results show that (1) In time, the eight cities' resilience fluctuated dynamically and varied to different degrees. It presents the spatial distribution characteristics of “high in the center and low in the periphery” in space. (2) In time, the coupling coordination degree in the eight cities fluctuated slightly. The spatial distribution pattern of “high in the center and low in the periphery” was formed in terms of space. (3) There is a long-term stable relationship between urban resilience and the coupling coordination degree among all indicators. In a certain sense, the higher the coupling coordination degree is, the higher the urban resilience is. These results can improve urban resilience to some extent and make cities more resilient in the future collaborative development process, and provide a way to evaluate urban resilience at different spatial-temporal scales.

**Keywords** Urban resilience · Coupling coordination degree · Spatial-temporal evaluation · Yangtze River Delta urban agglomerations · Econometric panel model

## 1 Introduction

With the development of urbanization and globalization, cities are increasingly becoming places for people to live in. More than half of the population has already lived in cities. Human beings are ushering in a veritable “urban era”. According to the report “World

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Urbanization Trend in 2018” released by the United Nations Department of Economic and Social Affairs (UNDESA), 55% of the population in the world today lives in cities. Global urbanization is expected to reach 68% by 2050.

The increase in the number of cities and the continuous expansion of the scale of cities make cities gradually become the breeding, gathering, and occurrence place of various risks, and also the main target of natural disasters such as extreme weather, typhoon, rainstorm, and flood (Tu et al., 2022). Since 1980, over \$3.7 trillion and more than 2.4 million people have been lost to disasters caused by natural hazards globally. Meanwhile, total damages increased by more than 800%, from \$18 billion a year in the 1980s to \$167 billion a year in the last decade (World Bank, 2021).

Since the twenty-first century, with the accelerating pace of urban development in China, urban activities are highly concentrated, and problems of spatial imbalance emerge one after another. From 1978 to 2021, China’s urbanization rate increased from 17.92% to 64.72%, and the urban population increased from 1.7 billion to 9.1 billion. The urbanization level of China is expected to reach 70% by 2030, and the total urban population will exceed 1 billion people. To this extent, the demand for urban land space, housing, employment, infrastructure, education, medical, sports, and cultural facilities in China will increase dramatically. Coupled with natural disasters (floods, earthquakes) and man-made disasters (disease transmission), Chinese cities are facing severe tests. For example, the COVID-19 epidemic, the tornadoes in Suzhou and Wuhan, the heavy rain in Shanxi, and the flood disaster in Zhengzhou has seriously affected the development process of the city and people’s life.

In this realistic context, it is undoubtedly of great academic and social value to establish a resilient city research system, explore ways to strengthen urban resilience, and improve the evaluation criteria of resilient cities. However, the urban system is huge and complex, and the research on urban resilience spans multiple disciplines. Its related technologies and practical advancement are restricted by the urban management system, economic capacity, and social development level. How to mitigate the impact of similar public emergencies on urban development has aroused the reflection of all sectors of society on urban risk prevention and control, and it is increasingly important and urgent to build a “resilient city” to improve urban “resilience”. The resilient city refers to the ability of a city and its internal system to resolve and resist external uncertain disturbances through reasonable planning and preparation of different functional systems and constituent areas to maintain the safe operation of public order and ensure the efficient operation of economic construction when it is subjected to unknown disturbances (Ahem, 2011). Urban resilience evaluation can give the foundation for constructing urban resilience and promoting effective communication between practice and theory (Shamout et al., 2021; Ghouchani et al., 2021). Based on the concept of urban resilience, the related assessment methods focus on ecological resilience assessment (Zhang et al., 2020; Huang et al., 2022), natural resilience assessment (Wang et al., 2022; Utami et al., 2021; Haque et al., 2022), economic resilience assessment (Oliva et al., 2018), and social resilience assessment (Jacinto et al., 2020; Ciobanu et al., 2021).

## 1.1 Research problem statement and contributions

Most of the existing evaluation assessment methods used the urban resilience evaluation index system to measure urban resilience from the overall perspective, often ignoring the coupling and coordination degree among indicators. The empirical analysis of the relationship between coupling coordination degree (CCD) and urban resilience is

lacking. Meanwhile, existing evaluation assessment methods can be mainly divided into two categories, including quantitative assessment methods and qualitative assessment methods. Resilient city construction is a complex and systematic project concerning many fields, including economy, society, and nature. The construction and development between different fields are not independent, and a city with high resilience can achieve coordination and coupling in multiple fields. Thus, the urban resilience evaluation should consider the integrity of multiple fields and the CCD between them.

The Yangtze River Delta urban agglomeration is the Yangtze River economic belt and an important intersection of “Belt and Road”. It plays a decisive strategic role in the overall situation about national modernization of China and opening up. It is an important platform for China to take part in international competition, a vital engine for social and economic development, and one of the regions with the best urbanization foundation in China. The integrated development of the triangle region has become a national strategy. At the same time, integration and high quality have become the two key points for the coordinated development of the Yangtze River Delta, and urban resilience has increasingly become an important standard to test whether the integration and high quality are coordinated.

Based on the above background information, Yangtze River Delta city is selected as the research object, from the impact toughness degree of coupling among the indicators of coordination degree perspective, explore the time and space differences of Yangtze River Delta city of toughness degree and the city, the relationship between the degree of toughness and CCD of the toughness evaluation method to improve the city and urban construction is of great significance to improve toughness.

There are two main contributions of this paper. (1) Theoretically: The dynamic evaluation model of urban resilience is developed to assess cities’ toughness from the perspective of time and space. To investigate the intrinsic coordination mechanism among evaluation indexes of resilient cities, the dynamic CCD model is proposed according to the concept of coupling. An econometric panel model is introduced to discuss the relationship between cities’ toughness and CCD. (2) Empirically: Considering the economic status and functional radiation capacity related to urban agglomeration in the Yangtze River Delta, this paper selects it as the research region of empirical research and explores the temporal-spatial evolution law of urban agglomeration resilience. Meanwhile, some policy implications are provided based on evaluated results.

This study aims to learn from the existing urban resilience evaluation index system constructed by the some scholars, collect the panel data of eight sample cities in the Yangtze River Delta urban agglomeration from 2010 to 2019, construct the urban toughness dynamic evaluation model and urban dynamic coupling coordination model, respectively, and analyze the temporal and spatial differences of the toughness of the above cities and the CCD among the indexes with the help of kernel density estimation. The panel regression model is constructed using the econometric panel model to quantitatively analyze the urban toughness and the CCD among the indicators to offer a reference for the construction of resilient cities.

This paper is organized as follows. In Sect. 2, we mainly reviews the existing literature about urban resilience assessment. In Sect. 3, the study methodology is introduced, which including research area, data collection, a dynamic evaluation model of urban resilience, a dynamic CCD model, and an econometric panel model. Section 4 investigates the empirical results in detail. In Sect. 5, we conclude the main conclusions and some policy implications of this paper.

## 2 Literature review

At present, urban resilience is becoming a key scientific issue that influences and restricts the sustainable development of modern cities. Meanwhile, the construction of a “resilient city” has become a common concern and development direction of the whole society. A series of exploratory studies on resilient cities have been carried out in recent years, including defining the concept of resilient cities and constructing evaluation index systems and evaluation methods. The definition of a resilient city varies according to the complexity of city itself and the interdependence between systems. Holling (1973) gave the urban resilience concept from the perspective of ecological resilience, which is the capacity of a system to absorb disturbance and reorganize while changing to still retain essentially the same function, structure, identity, and feedback. Alberti et al. (2003) defined urban resilience as the ability and degree for absorbing and resolving changes before the reorganization of a series of structural and process changes in a city. The results of the study provided by Admiraal and Cornaro (2020) show that the subsurface and use of underground spaces can impact urban resilience. Wilbanks and Sathaye (2007) argued that urban resilience is the ability of a city or urban system to digest while retaining its main key functions, structures, and features. Godschalk (2003) believes that urban resilience should be the combination of the sustainable physical system and human community, and the planning of physical systems should be considered when building human communities. Due to the overall complexity of cities, resilient cities cover a wide range of areas. As a result, most research on urban resilience focuses on multiple dimensions, including technical, organizational, social, and economic (Wu and Chen, 2018). Ireni-saban (2013) studied the disaster resilience of urban communities at the micro-community level based on urban communities. The pandemic has exposed the vulnerability and resilience of urban systems, but it has also driven changes in global resilient urban and regional planning (Banai, 2020).

With the rapid development of urban construction, the research on urban resilience has gradually developed into a trend of diversified perspectives, multi-level scales, and rich research methods (Bai et al., 2019). The research perspective has gradually shifted from single-discipline research such as ecology and disaster management to interdisciplinary and integrated research. The research scope is extended to different levels of the whole country, province and city, region, and urban agglomeration. Sun et al. (2017) evaluated the degree of urban resilience from the urban social ecosystem by using geographic information system (GIS) spatial analysis and superposition function method and determined the standard measurement value. Fu et al. (2021) proposed a scenario-based planning support system with a robust indicator set to assess urban resilience from the perspective of green infrastructure. Mou et al. (2021) evaluated dynamic sustainability and resilience of Chengdu from environment, resource, economy, science technology, and population. Chong et al. (2021) proposed a “cost-capacity-energy efficiency” evaluation model for urban resilience, comprehensively using the entropy method, principal component analysis method, slacks-based measure (SBM) model, exploratory spatial data analysis (ESDA), K-means clustering method, and geographically weighted regression (GWR) to assess the resilience of 126 cities in the Yangtze River economic zone. Based on the natural disaster background of waterlogging, Li et al. (2022) constructed an index system to assess the level of urban resilience and built an assessment model of resilience based on the index system. There are two main aspects urban infrastructure and urban economic resilience, they are used to measure urban resilience. Peng et al. (2021) studied the temporal and spatial differences between industrial structure and urban economic resilience, and Liu et al. (2021) explored

the influence of smart city pilot policies on urban development quality based on resilience development. Sharif et al. (2017) provided an example of how co-design methods can be employed for conceptualizing resilience. Tepes and Neumann (2020) investigated the resilience mechanisms by eliciting subjective views based on fuzzy cognitive mapping (FCM), and verified the methodology based on a case study about the wastewater sector. Some existing methods were developed based on assessment information about different qualitative aspects of resilience provided by experts. (Hosseini et al., 2016; Wu et al., 2022a, b).

Using multi-source data and landscape-based analysis, Liu et al. (2019) measured the urban resilience from diversity, connectivity, decentralization, and self-sufficiency, and the perspective of the urban landscape. According to UN-Habitat city prosperity index, Schlör et al. (2018) developed food, energy, and water (i.e., the FEW nexus) systems for measuring urban resilience. Sun et al. (2021) proposed an assessment index system about urban resilience and designed a theoretical framework considering the contradiction between supply and demand. To assess the resilience of urban road networks, Liu et al. (2022) developed a resilience assessment method, which includes three indexes, i.e., the recovery index, the robustness index, and the resilience performance index. Shi et al. (2021) studied the resilience of cities by proposing a framework of complex urban systems from the perspective of complex systems theory. To evaluate natural hazards, Feofilovs and Romagnoli (2021) presented a dynamic urban resilience by considering the urban systems' multi-dimensionality characteristics and time reference with short and long term. Based on pre-disaster, disaster, and post-disaster, Zhang et al. (2021) proposed a new multi-stage resilience assessment model to investigate the resilience of 31 cities. Lin et al. (2022) made a spatiotemporal assessment of urban resilience efficiency in the Yangtze River economic belt by decision-making method and an SBM model. Based on the connotation of urban resilience, Sun and Zhen (2021) built a framework of urban activity resilience from the theoretical level by considering main contradictions of China's urbanization. Aydin et al. (2018) developed a method to assess the resilience of transportation network topology when exposed to environmental hazards. For an overview of research work on resilient cities, please see (Tong et al., 2021; Büyüközkan et al., 2022).

According to the above literature review, the current research on urban toughness evaluation has achieved rich results, but there are still some contents that need further research:

- (I) In terms of research focus, it mainly measures the urban toughness level according to the constructed urban toughness evaluation index system and pays less attention to the coupling and coordination among the indexes;
- (II) In terms of research methods, it mainly focuses on the design and construction of evaluation methods, but rarely analyzes the relationship between CCD and urban toughness from a quantitative perspective.

### 3 Research methodology

The framework of this paper is shown in Fig. 1. First, the index system for evaluating urban resilience is developed. Then, two data standardization methods are introduced. Meanwhile, the dynamic evaluation model of urban resilience is constructed using the urban resilience evaluation indexes. Furthermore, the dynamic CCD model is proposed according to the coupling concept for discussing the intrinsic coordination mechanism among evaluation indexes

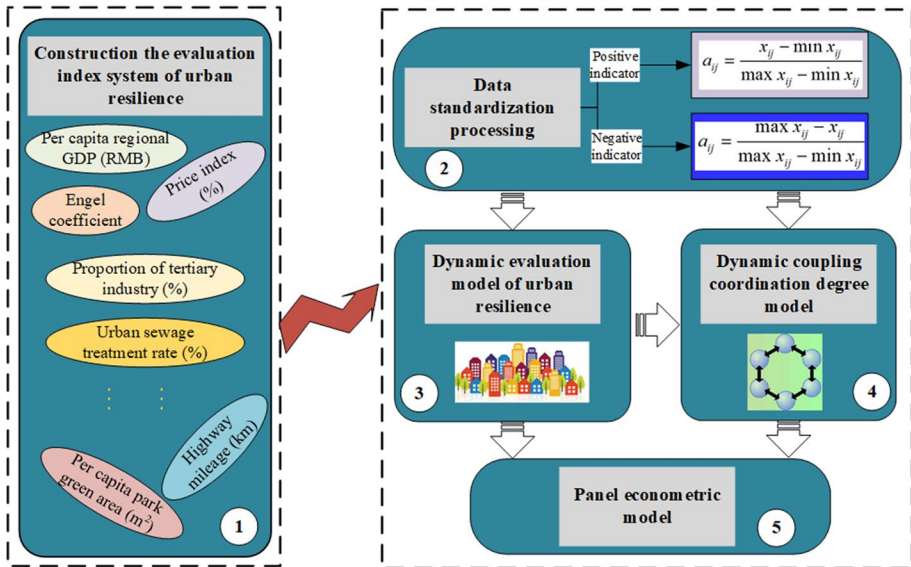


Fig. 1 The framework of this study

of resilient cities. Finally, an econometric panel model is introduced to discuss the relationship between cities' toughness and CCD among assessment indexes.

### 3.1 Construction of the evaluation index system of urban resilience

We establishes an urban resilience index system based on the existing literature to more comprehensively, objectively, and accurately evaluate the urban resilience of sample cities. It follows the principles of scientificity and integrity from four dimensions, including the society, economy, infrastructure, and ecology. It mainly includes urban social resilience, urban economic resilience, urban infrastructure resilience, and urban ecological resilience. Meanwhile, on this basis, 18 indicators such as per capita regional gross domestic product (GDP), price index, urban sewage treatment rate, and power consumption of the whole society are selected, as shown in Fig. 2.

### 3.2 Research methodologies

#### 3.2.1 Data standardization processing

To prevent the influence of unit difference on the data, we first employ the range transformation method to deal with the original index data dimensionless. The details are as follows:

For positive indicator, the standardized formula is:

$$a_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{1}$$

For negative indicator, the standardized formula is:

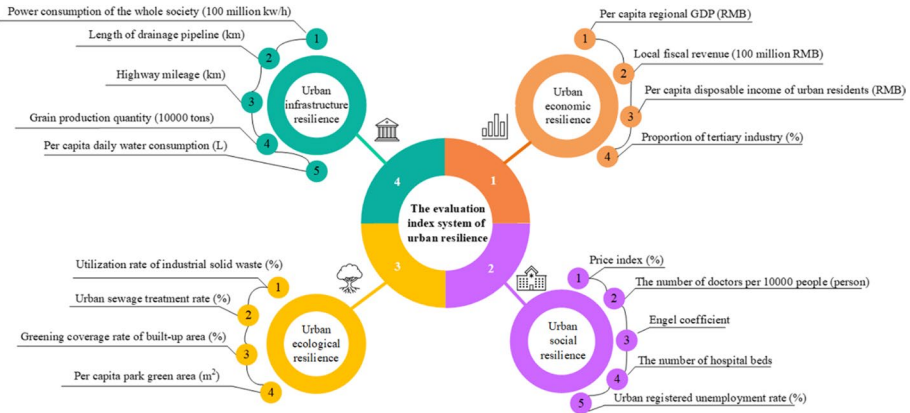


Fig. 2 The evaluation index system of urban resilience

$$a_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{2}$$

### 3.2.2 Dynamic evaluation model of urban resilience

Based on the evaluation index system of urban resilience, the dynamic evaluation model of urban resilience is constructed to compute urban resilience index (CRI) as follows:

$$CRI_k(t) = \varphi(ER_k(t), SR_k(t), ECR_k(t), IFR_k(t)) \tag{3}$$

where

$CRI_k(t)$ —The resilience of city  $k$  in  $t$  year. It is defined by the economic resilience, social resilience, ecological resilience and infrastructure resilience. It comprehensively reflects urban resilience.

$ER_k(t)$ —Economic resilience of city  $k$  in  $t$  year. It is measured by per capita regional GDP, local fiscal revenue, per capita disposable income of urban residents, and the proportion of tertiary industry. It reflects the economic vitality of the city.

$SR_k(t)$ —Social resilience of city  $k$  in  $t$  year. It is computed by using price index, number of doctors per 10,000 people, Engel coefficient, urban registered unemployment rate, and number of hospital beds. It indicates the living standards of urban people.

$ECR_k(t)$ —Ecological resilience of city  $k$  in  $t$  year. It is calculated by urban sewage treatment rate, the utilization rate of industrial solid waste, greening coverage rate of built-up areas, and per capita park greening area, which shows the urban ecological environment quality.

$IFR_k(t)$ —Infrastructure resilience of city  $k$  in  $t$  year. It is measured by the power consumption of the whole society, per capita daily water consumption, grain production quantity, highway mileage, and drainage pipeline length. It represents the urban infrastructure development level.

$\varphi(\cdot)$ —Linear weighting function and the weight is given according to the method in (Zhang et al., 2019).

To better reflect the resilience level of each city, this paper makes a basic classification, and the grading standards are given in Table 1, which is improved by (Zhang & Feng, 2018).

### 3.2.3 Dynamic coupling coordination degree model

As a physical concept, the coupling is used to reflect the close cooperation and interaction of two or more systems. With the help of a coupling degree, we can reveal the interaction and internal coordination mechanism among economic development, social development, ecological construction, and infrastructure construction in the construction of resilient cities. A coupling degree is defined as:

$$C_k(t) = \left( \frac{\prod_{i=1}^m f_i^k(t)}{\left( \prod_{i=1, i < p}^m \frac{f_i^k(t) + f_p^k(t)}{2} \right)^{2/m}} \right)^{1/m} \tag{4}$$

in which

$f_i^k(t) = \sum_{j=1}^n w_{ij}^k(t) \bar{y}_{ij}^k(t)$  represents the value of city  $k$  in  $i$ -th dimension in  $t$  year, in which  $i$  includes economic resilience, social resilience, ecological resilience, and infrastructure resilience,  $\bar{y}_{ij}^k(t)$  denotes the standardized data of the  $j$ -th index under the  $i$ -th dimension at  $t$  year of city  $k$ , and  $w_{ij}^k(t)$  denotes the weight of the  $j$ -th index under the  $i$ -th dimension in  $t$  year of city  $k$ .

$C_k(t)$  is the coupling degree between  $m$  dimensions of city  $k$  in  $t$  year. It reflects the strength of interdependence and interaction among subsystems.

The greater the coupling degree ( $C_k(t) \in [0, 1]$ ) is, the higher the coupling degree is. It indicates that the systems are orderly coordinated and closely related.

Coupling degree can only describe the degree of collaborative development between systems, but it is not sure whether the system promotes each other at a higher level or is closely related at a lower level (Zhu & Li, 2015). Therefore, the dynamic CCD is further defined as follows:

$$CCD_k(t) = \sqrt{C_k(t) \times \sum_{i=1}^m \lambda_i f_i^k(t)}. \tag{5}$$

where

**Table 1** Evaluation standard of resilience grade

Resilience	Resilience grade	Resilience type
$0.8 < CRI \leq 1$	First level	High resilience
$0.5 < CRI \leq 0.8$	Second level	Moderate resilience
$0.3 < CRI \leq 0.5$	Third level	General resilience
$0 < CRI \leq 0.3$	Fourth level	Low resilience



$CCD_k(t)$  is the CCD among the society, urban economy, infrastructure, and ecology of city  $k$  in  $t$  year.  
 $\lambda_i$  represents the weight of the dimension  $i$  in the evaluation index system.

The CCD can not only reflect the coordination degree between urban society, urban economy, urban infrastructure, and urban ecology but also reflect the stage of coordinated development level. When the CCD is greater, it shows that urban economy, urban society, urban ecology, and urban infrastructure are coordinated at a high level. The classification standard of CCD is presented in Table 2, which is improved by (Zhang & Feng, 2019).

### 3.2.4 Econometric panel model

To further explore the relationship between the CCD and CRI among the indicators, this paper constructs the following panel regression equation:

$$CRI_k(t) = \alpha_k + \beta_k CCD_k(t) + u_k(t) \tag{6}$$

in which  $k$  is the city  $k$ , including Shanghai, Nanjing, Suzhou, Hangzhou, Hefei, Nantong, Ningbo and Wuxi,  $t$  is the  $t$  year, from 2010 to 2019,  $\alpha_k$  represents individual fixed effect,  $u_k(t)$  represents random error term,  $CRI_k(t)$  represents urban resilience and  $CCD_k(t)$  is the CCD among the indicators of urban resilience.

## 4 Case Study

### 4.1 Research area and data collection

This study takes the Yangtze River Delta urban agglomeration as the research object. To use the caliber of big cities, this paper selects eight cities with a population of more than 1 million and a GDP of more than a trillion as sample cities from 26 cities in the Yangtze River Delta urban agglomeration. It mainly involves Shanghai, Nanjing, Suzhou, Hangzhou, Hefei, Nantong, Ningbo, and Wuxi and comprehensively calculates their urban toughness and CCD. On this basis, the temporal and spatial differences in urban resilience and CCD of each city are analyzed, and the relationship between them is explored. On this basis, the differences between urban resilience and CCD of each city are analyzed from spatial and temporal, and the relationship between them is explored. The datasets are mainly from the China Statistical Yearbook from 2010 to 2019, the statistical yearbook of provinces and cities, and the statistical bulletin of national economic and social

**Table 2** Evaluation standard of CCD

CCD	Coordination level
$0.8 < CCD \leq 1$	Senior coordination
$0.6 < CCD \leq 0.8$	Intermediate coordination
$0.4 < CCD \leq 0.6$	Primary coordination
$0.3 < CCD \leq 0.4$	Reluctant coordination
$0.2 < CCD \leq 0.3$	Mild disorder
$0 < CCD \leq 0.2$	Serious disorder

development. Furthermore, the missing data are filled by using the trend changes in recent years, adjacent years' data, and the mean interpolation method. (See Fig. 3).

## 5 Results and discussion

### 5.1 Spatial-temporal difference analysis of urban resilience

According to Eq. (3), the urban resilience of eight sample cities from 2010 to 2019 is obtained, and the relevant results are given in Table 3.

### 6 (1) Time evolution characteristics of urban resilience

Kernel density estimation, as a nonparametric estimation method, is used to analyze the hierarchical situation of urban resilience of sample cities. The corresponding estimation results of urban resilience are shown in Fig. 4. From the morphology, it finds that the resilience of the sample cities generally presents the evolution characteristics of “multimodal distribution” to “unimodal distribution”. At the beginning of the study, the resilience of the sample cities varies greatly and shows a grading trend. However, with the continuous improvement in the resilient cities construction, the difference in resilience of sample cities gradually decreases, the grading trend gradually weakens, and the peak value continues to increase.

According to Table 3, the overall urban resilience of the sample cities shows dynamic fluctuations with varying degrees of change from 2010 to 2019. The specific analysis is given in the following.

From 2010 to 2013, the urban resilience of sample cities generally shows a downward trend. The main reason for this phenomenon is that after the 2008 global financial crisis, the country introduced policies to stimulate economic recovery, and the economic vitality of the sample cities has basically improved, but the living standards of urban people, the quality of the urban ecological environment and the development level of urban infrastructure have declined to varying degrees. It should be noted that the urban social resilience index of Shanghai decreased by 63.86%, the industrial solid waste utilization rate of Wuxi decreased by 21.85%, and the per capita daily water consumption of Nantong decreased by 25.78%. This shows that the resilience construction of each dimension of the sample city is unbalanced, and it is necessary to further coordinate the coordinated development of each dimension.

From 2014 to 2017, most sample cities' resilience showed an upward trend. Especially, the urban resilience about Shanghai and Nanjing increased rapidly, reaching 8.20% and 8.25%, respectively. This reflects that the sample cities are actively responding to the call of the 18th National Congress of the Communist Party of China to accelerate the transformation and upgrading of economic structure and promote the construction of social and ecological civilization, thus strengthening the construction of all aspects about the urban system and accelerating the improvement rate of urban resilience.

From 2018 to 2019, the urban resilience of Wuxi, Shanghai, and Nantong tends to decline, while other sample cities' urban resilience, including Nanjing, Suzhou, Hangzhou, Hefei, and Ningbo, tends to rise. The decline of the former shows that the development of urban functional systems has been unbalanced in recent years. For example, the

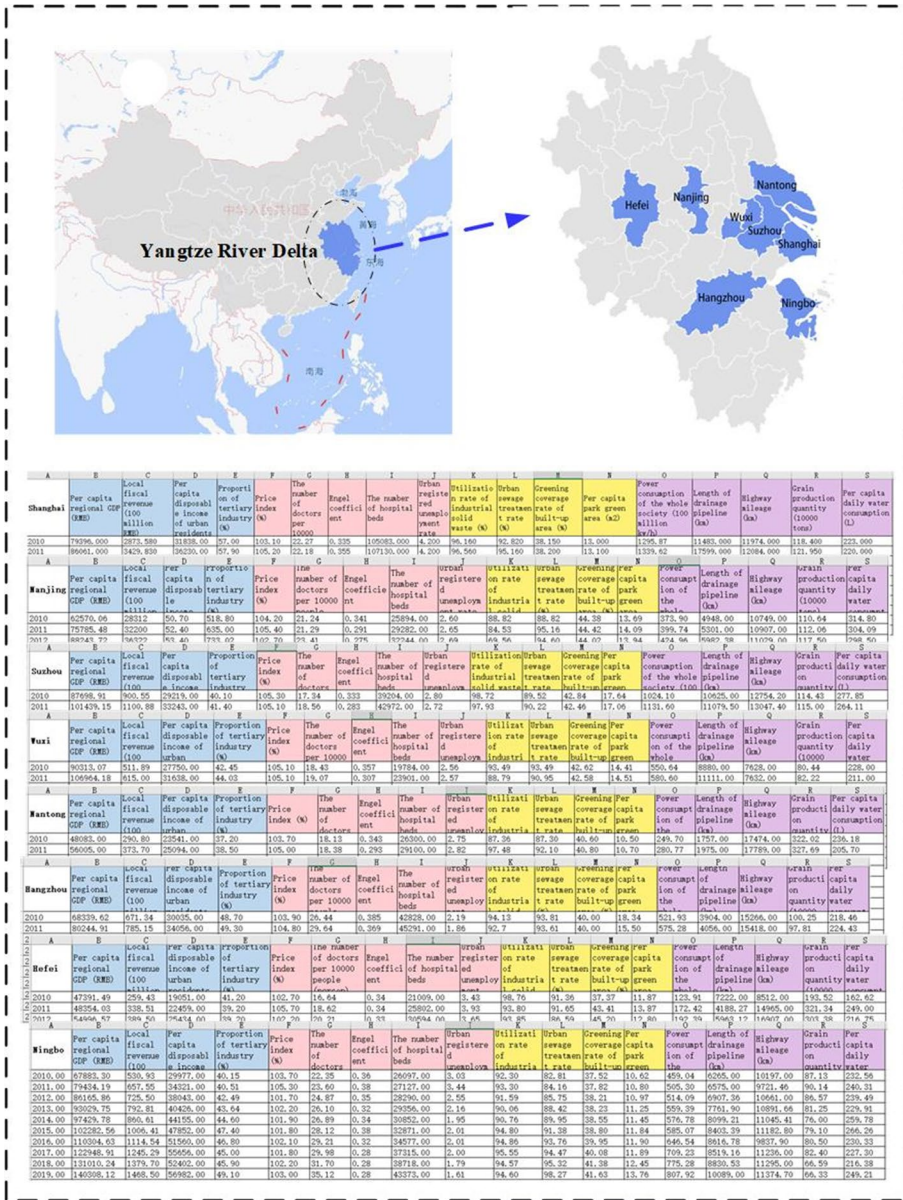
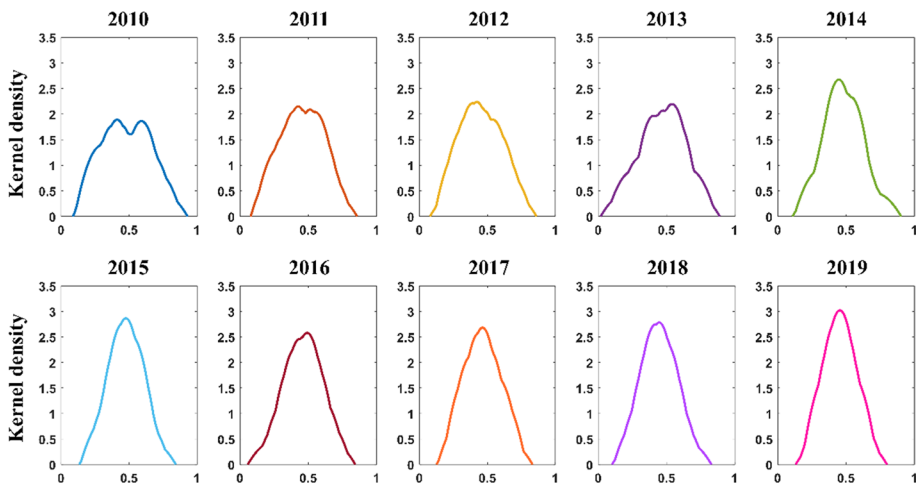


Fig. 3 Research area and data collection

social resilience index of Shanghai increased by 9.3%, while the ecological resilience index decreased by 76%. Due to the unbalanced development, the resilience of the city to cope with the changes in the internal and external environment was reduced. Thus, it is necessary to further strengthen the planning and resilient cities construction to enhance adaptability, emergency response and enhance the overall resilience of cities. The rise of the latter indicates that the resilience construction of the city has been continuously strengthened

**Table 3** The urban resilience from 2010 to 2019

City	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Shanghai	0.7292	0.6567	0.6604	0.6398	0.5489	0.5631	0.6434	0.6309	0.6273	0.5989
Nanjing	0.4883	0.5025	0.4863	0.4900	0.5211	0.5134	0.5242	0.5641	0.4964	0.5033
Suzhou	0.6549	0.5919	0.6031	0.6889	0.7028	0.6426	0.5863	0.5648	0.5352	0.5433
Wuxi	0.5105	0.4535	0.4119	0.4986	0.4669	0.4775	0.4614	0.4836	0.4445	0.4029
Nantong	0.2982	0.3382	0.3222	0.4209	0.4650	0.4927	0.4002	0.3976	0.3917	0.3324
Hangzhou	0.5715	0.5345	0.5291	0.5011	0.4920	0.4388	0.4599	0.4019	0.4481	0.4955
Hefei	0.2867	0.2795	0.2780	0.2181	0.3085	0.3339	0.2581	0.3266	0.3019	0.3946
Ningbo	0.3167	0.2792	0.3242	0.2976	0.3317	0.3490	0.3660	0.3403	0.3239	0.3690
Mean	0.4820	0.4545	0.4519	0.4694	0.4796	0.4763	0.4624	0.4637	0.4461	0.4550

**Fig. 4** The kernel density of urban resilience

to improve the ability to resist risks, and the completeness and adaptability of the urban system are also continuously enhanced in recent years. For example, the economic resilience index of Nanjing increased by 1.97%, and the ecological resilience index increased by 2.24%, while the ecological resilience index decreased by only 0.66%.

## 7 (2) Spatial distribution pattern of urban resilience

From Fig. 5, we find that the resilience level of the sample cities studied has significant regional differences, i.e., the overall spatial distribution characteristics are “high in the center and low in the periphery”. The resilience gradually decreases from Shanghai to the periphery. The resilience of Shanghai and Suzhou is significantly higher than other cities and is basically maintained at the level of medium resilience close to high resilience. This shows that Shanghai and Suzhou have been relatively perfect and reasonable in the urban functional systems construction. In the process of development, they attach importance to the coordinated and balanced development of various systems. Thus, in the face of the

impact of man-made and natural disasters, adaptability is better and adjustment and recovery are faster. The urban resilience of Nanjing, Wuxi, Nantong, and Hangzhou has always been at the general level, which indicates that the four cities are relatively balanced and stable in the development of urban the society, urban economy, infrastructure, and ecology. However, there is still a gap in resilience compared with Shanghai and Suzhou. Therefore, the construction of urban functional systems needs to be further strengthened and optimized. In addition, the urban resilience of Ningbo and Hefei is relatively low. Meanwhile, the urban resilience level of the two cities has increased from low resilience to general resilience. It indicates that the two cities gradually pay attention to the coordinated and balanced development of various systems in the process of resilient cities construction.

Generally speaking, the resilience of sample cities is usually low, and the regional differences are significant. Therefore, in the Yangtze River Delta urban agglomeration,

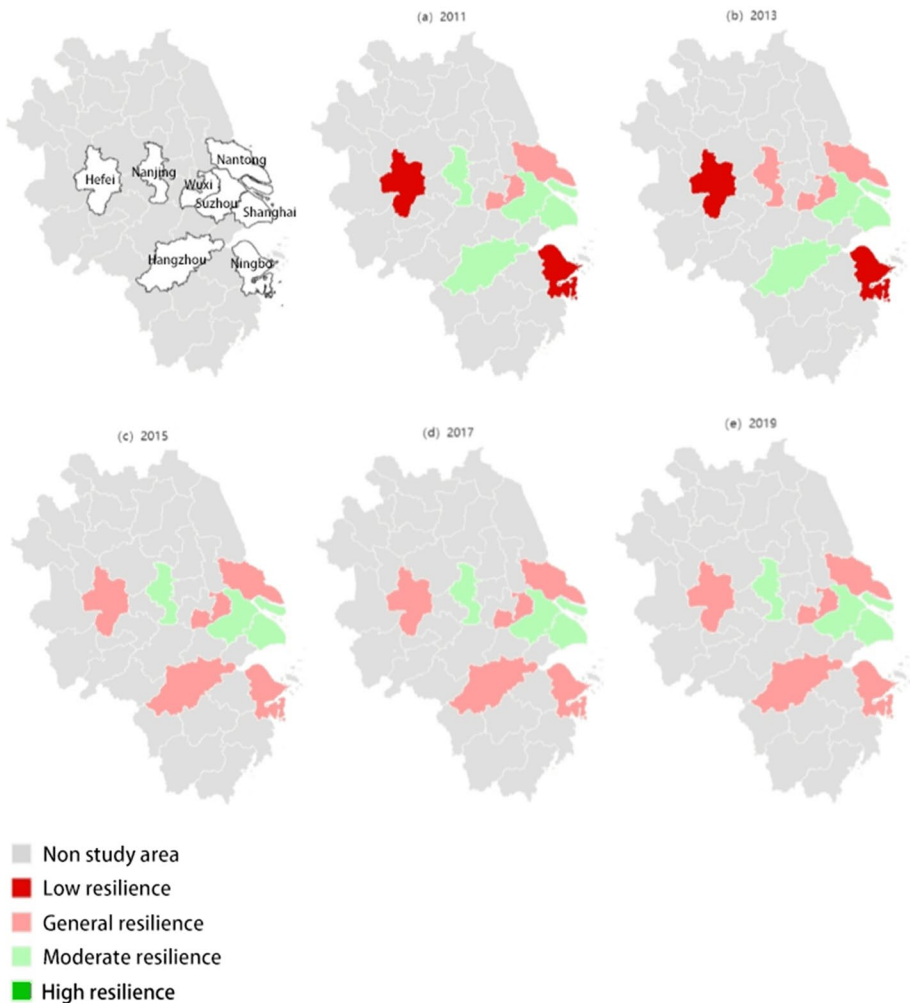


Fig. 5 Spatial distribution of resilience of sample cities in some years

constructing a resilient city is still the focus of future development planning, and optimizing the urban spatial layout, and system construction still need a long-term process.

## 7.1 Spatial-temporal difference analysis of urban coupling coordination degree

Using Equations 4 and 5 define in the dynamic CCD model, CCD among indicators of sample cities from 2010 to 2019 is calculated. The corresponding results are given in Table 4.

## 8 (1) Time evolution characteristics of urban coupling coordination degree

Kernel density estimation, as a nonparametric estimation method, is used to analyze the hierarchical situation of CCD of sample cities. The corresponding estimation results of the CCD among the indicators of sample cities are shown in Fig. 6. From the morphology, it can be seen that the CCD of the indicators of sample cities generally presents the evolutionary characteristics of “unimodal distribution” to “multimodal distribution” and then to “unimodal distribution”. Specifically, from 2010 to 2011, the CCD among the indicators of sample cities basically did not show a grading trend, and the peak value increased. From 2012 to 2016, the CCD among the indicators of sample cities showed an obvious grading trend, and the peak value increased. From 2017 to 2019, there was no grading trend in the CCD among the indicators of sample cities.

According to Table 4, from 2010 to 2019, the CCD of the sample cities studied generally fluctuated slightly, and most of the cities were in a relatively stable state. The specific analysis is as follows:

From 2010 to 2013, the CCD among the indicators of sample cities showed a downward trend. This is because, after the financial crisis, cities focused on restoring economic vitality, resulting in the uneven development of indicators and a decline in coupling coordination. As a result, there is a serious unbalance in the CCD among the indicators in Hefei.

From 2014 to 2017, the CCD between the indicators of most sample cities showed an upward trend. This indicates that the sample cities were actively responding to the call of the 18th National Congress of the Communist Party of China to accelerate the transformation and upgrading of economic structure and promote the construction of social and

**Table 4** CCD among indicators of sample cities from 2010 to 2019

City	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Shanghai	0.7520	0.6932	0.6812	0.6854	0.6042	0.6100	0.6730	0.6669	0.6573	0.5768
Nanjing	0.5915	0.5928	0.5834	0.5849	0.6073	0.6025	0.6084	0.6333	0.5890	0.5941
Suzhou	0.7039	0.6632	0.6725	0.7265	0.7354	0.7007	0.6612	0.6482	0.6263	0.6328
Wuxi	0.5922	0.5347	0.5136	0.5699	0.5484	0.5628	0.5488	0.5613	0.5382	0.5006
Nantong	0.4128	0.4432	0.4337	0.5056	0.5453	0.5626	0.5011	0.4990	0.4920	0.4396
Hangzhou	0.6449	0.6047	0.6071	0.5898	0.5739	0.5242	0.5467	0.5000	0.5275	0.5766
Hefei	0.3828	0.3103	0.0000	0.0000	0.0000	0.0000	0.2331	0.3476	0.4018	0.5047
Ningbo	0.4329	0.4034	0.4483	0.3789	0.4518	0.4769	0.4869	0.4696	0.4528	0.4925
Mean	0.5641	0.5307	0.4925	0.5051	0.5083	0.5050	0.5324	0.5407	0.5356	0.5397

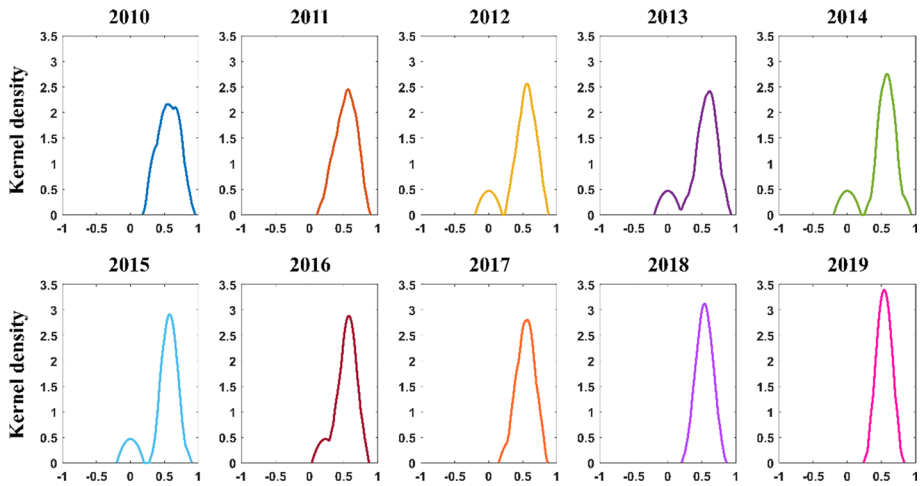


Fig. 6 The kernel density estimation of CCD among indicators in sample cities

ecological civilization, and strengthen the coordinated development of various urban systems. The CCD among the indicators in Shanghai increased by 10.38%. The CCD among the indicators in Hefei has increased from serious disorder to reluctant coordination by industrial structure adjustment, transformation and upgrading, and continuous innovation.

From 2018 to 2019, the CCD among indicators in most cities tended to be stable. Nanjing, Wuxi, Nantong, Hangzhou, Hefei, and Ningbo are in the primary coordination stage. Suzhou has the intermediate coordination stage. This shows that the urban resilience construction has entered a relatively stable stage, and the society, urban economy, infrastructure, and ecology have developed together.

## 9 (2) Spatial distribution pattern of urban coupling coordination degree

As shown in Fig. 7, the spatial differentiation effect of urban CCD is obvious, and the overall spatial distribution pattern of “high in the center and low in the periphery” is formed. The “high in the center” agglomeration effect is mainly reflected in the CCD among indicators in Shanghai and Suzhou is significantly higher than that in other cities, which are in the intermediate coordination state. This represents that the urban resilience indicators development in Shanghai and Suzhou is more balanced than that in other cities, and the coordinated and balanced development of urban system construction is emphasized. The agglomeration of “low in the peripheral” is mainly reflected in the CCD between the indexes of Wuxi, Hangzhou, Nanjing, and Hefei, which are basically in the primary coordination state, which is lower than that of Shanghai and Suzhou. This because is the uneven development between systems. For example, the urban infrastructure level of Wuxi is lower than in other areas, resulting in a low degree of coupling and coordination among the indicators. The CCD among the indicators in Hefei has experienced three stages from serious disorder to reluctant coordination and then to primary coordination, which shows that Hefei has gradually

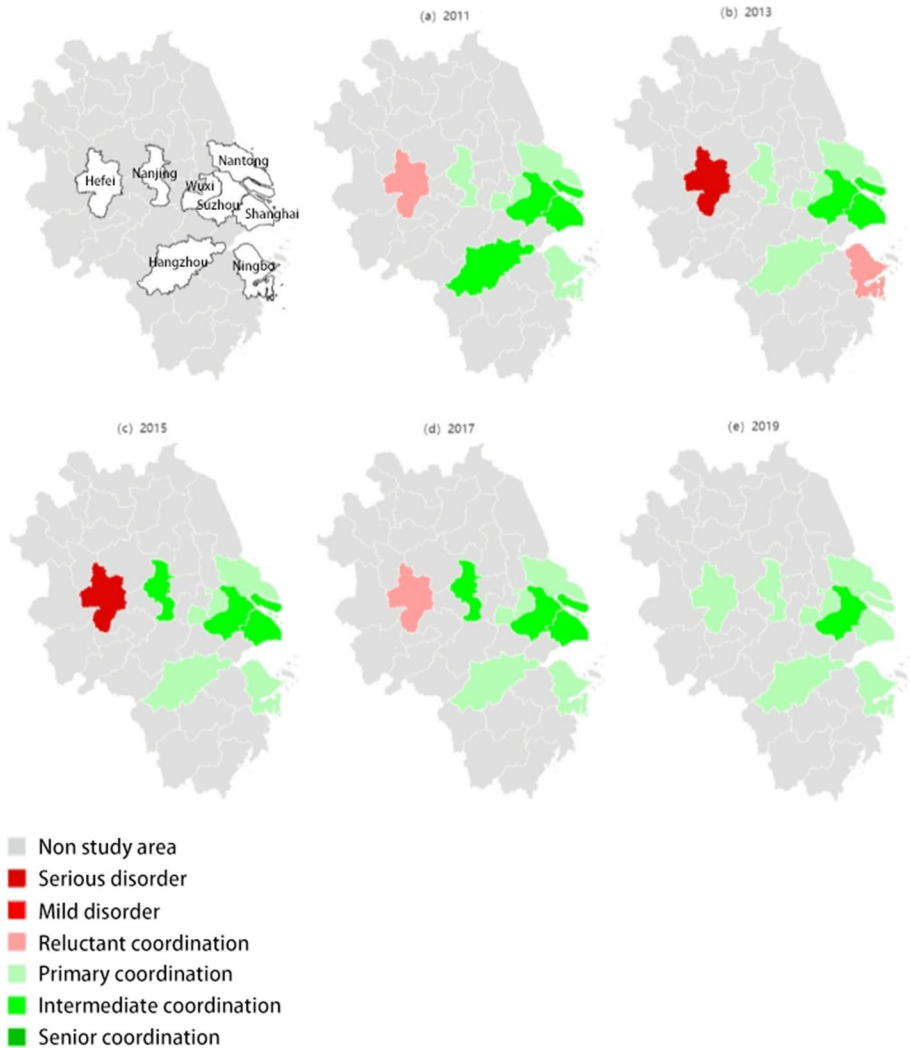


Fig. 7 Spatial distribution of CCD of sample cities

realized the coordinated development of the society, urban economy, infrastructure, and ecology through adjusting industrial structure and optimizing industrial layout in the process of building a resilient city.

Overall, the CCD of each index in sample cities is generally low, and most of them are in the transition stage from primary coordination to intermediate coordination. Meanwhile, with the continuous development of urban construction, the relevance and synergy between the various systems have become increasingly important. Strengthening the resilience construction of the four dimensions of society, urban economy, infrastructure, and ecology is the core to improving the coordination degree of urban coupling and the focus of future planning and development.



**Table 5** Unit root test results

Variable	LLC		Fisher – ADF	
	Statistic	<i>P</i> value	Statistic	<i>P</i> value
CRI	– 3.8278	0.0001	21.8797	0.1471
CCD	– 2.7525	0.0030	19.0379	0.2667
$\Delta$ CRI	– 7.0088	0.0000	46.1924	0.0001
$\Delta$ CCC	– 5.6236	0.0000	36.3712	0.0026

**Table 6** Pedroni cointegration test results

Methods	Statistic	<i>P</i> -value
Panel <i>v</i> -Statistic	– 0.6741	0.7499
Panel rho-Statistic	– 1.6498	0.0495
Panel PP-Statistic	– 6.6309	0.0000
Panel ADF-Statistic	– 7.5980	0.0000

## 9.1 Urban resilience and coupling coordination degree

### 10 (1) Stationarity test

To verify the relationship between the CRI and the CCD among the indicators, this paper makes a regression analysis on the CCD between the indicators and urban resilience. Moreover, the stationarity test is carried out to guarantee the effectiveness of the regression results. The number of cross sections of the panel data in this paper is 8, and the number of times is 10, so the panel data are long panel data. Therefore, the Fisher Augmented Dickey–Fuller (Fisher-ADF) test and Levin-Lin-Chu (LLC) test are used to make the unit root test for panel data. Table 5 gives the unit root test results of the original sequences of the two sequences of CRI and CCD. It is found that both original sequences have unit roots. This indicates that the two sequences are non-stationary sequences. Meanwhile, there is no unit root in the first-order difference of the original sequence, indicating that the sequence is a first-order unitary sequence.

To further test whether there is a long-term equilibrium relationship between the two sequences, the Pedroni cointegration test is conducted, and related results are listed in Table 6. Based on the Pedroni test results, there is a cointegration relationship between the two variables. Therefore, there is a long-term equilibrium and stable relationship between CRI and CCD, and the regression residual of the equation is stable.

### 11 (2) Selection of panel measurement model

According to Tables 5 and 6, it can be seen that the CCD among the indicators and the CRI are first-order unitary sequences. There is a long-term equilibrium and stability relationship between them, and the residual of the regression equation between them is stable. Thus, on this basis, the regression model between urban resilience and the CCD

**Table 7** Results of F test and Hausman test

Test method	Test result	Explain
F test	$F = 24.5614 > F(8, 69)$	Reject hybrid model
Hausman test	$\chi^2(1) = 7.5589, P = 0.0060$	Rejection random effect model

**Table 8** Regression results of panel data regression equation

Variable	CRI		
	Coefficient	Standard error	P-value
CCD	0.3286	0.0579	0.0000
Constant term	0.2915	0.0307	0.0000

among the indicators can be directly carried out. Firstly, the following panel regression equation is constructed as follows:

$$CRI_{i,t} = \alpha_i + \beta_i CCD_{i,t} + u_{i,t}$$

Which  $i$  is the city  $i$ , including Shanghai, Nanjing, Suzhou, Hangzhou, Hefei, Nantong, Ningbo, and Wuxi,  $t$  is the  $t$  year, from 2010 to 2019,  $\alpha_i$  represents individual fixed effect,  $u_{i,t}$  represents random error term,  $CRI_{i,t}$  represents urban resilience,  $CCD_{i,t}$  is the CCD among the indicators of urban resilience.

To determine the final panel regression model, the F test and Hausman test were performed, as presented in Table 7. It can be seen that the panel regression equation should select the individual fixed effect model:

$$CRI_{i,t} = \alpha_i + \beta CCD_{i,t} + u_{i,t}.$$

Table 8 gives the correlation regression results. We can find that at the significance level of 1%, the coefficient of the CCD among the indicators of urban resilience passes the significance test. It indicates that the CCD among the indicators has a significant impact on CRI.

The coefficient of the CCD among the indicators is significantly positive, which indicates that the CCD among the indicators has a positive role in promoting urban resilience. Specifically, when the CCD among the indicators of urban resilience increases by one point, the urban resilience CRI will increase by 0.3286. This also theoretically illustrates that building a resilient city is a systematic project. It needs to comprehensively consider the coordinated development of the society, urban economy, infrastructure, and ecology. The improvement in the CCD among the indicators of urban resilience will improve urban resilience. If cities only pay attention to one aspect and ignore the development of other aspects, it will hinder the resilient cities construction and the improvement in urban resilience. The results of the panel measurement model indicate that urban resilience can be improved by improving the coupling and coordination degree between the indicators. To improve the CCD of each index, cities should adhere to green development for improving the quality of urban economic development, strengthen urban infrastructure construction, improve the urban social environment and the urban ecological environment.

## 12 Conclusion and Policy Implications

This study selects eight cities from Yangtze River Delta urban agglomeration as the research area, including Hangzhou, Shanghai, Hefei, Nanjing, Nantong, Suzhou, Ningbo, and Wuxi. Firstly, we construct the urban resilience evaluation index system from urban social resilience, urban economic resilience, urban infrastructure resilience, and urban ecological resilience. Then, according to the index system, the dynamic evaluation model is constructed to compute the urban resilience of sample cities from 2010 to 2019, and the temporal and spatial differences in the calculation results are analyzed with the help of kernel density estimation. Furthermore, the dynamic CCD model is constructed to calculate the CCD among the indicators of sample cities from 2010 to 2019, and the temporal and spatial differences in the calculation results are analyzed with the help of kernel density estimation. Finally, based on the econometric panel model, an individual fixed effect model is constructed to study and analyze the relationship between urban resilience and the CCD among the indicators.

### 12.1 Implications of theory

Some implications of theory are obtained as follows:

- (1) In terms of the time dimension, the urban resilience of sample cities showed dynamic fluctuations and changes in varying degrees during the study period. In the spatial dimension, the urban resilience of sample cities during the study period generally presents the spatial distribution characteristics of “high in the center and low in the periphery”. Suzhou and Shanghai are the core of the Yangtze River Delta urban agglomeration, and their urban resilience is relatively high, while other cities are relatively low.
- (2) In terms of the time dimension, the coupling and coordination degree among the indicators of sample cities showed a slight fluctuation trend during the study period and most of which were in a relatively stable state. In the spatial dimension, the CCD among the indicators of sample cities generally presents the spatial distribution characteristics of “high in the center and low in the periphery”. The CCD of Shanghai and Suzhou is at the forefront, while the CCD of other cities is relatively low.
- (3) The econometric panel regression model shows that there is a long-term stable relationship between urban resilience and the CCD among the indicators. The individual fixed effect model shows that, in a certain sense, the higher the urban CCD, the higher the urban resilience.

### 12.2 Implications of policy

Some implications of policy are obtained as follows:

- (1) In the context of regional integration development in the Yangtze River Delta and on the premise of maintaining the stable growth of urban resilience in Shanghai and Suzhou, the state should give full play to the leading core role of the construction of resilient cities in Shanghai and Suzhou, actively promote the integrated development

- of the Yangtze River Delta urban agglomeration, optimize the construction planning of resilient cities, and lead the cities in the Yangtze River Delta to construct resilient cities together.
- (2) Cities should actively promote the overall and coordinated development of the society, urban economy, infrastructure, and ecology and form a balanced development pattern of the society, economy, infrastructure, and ecology. Meanwhile, they should correctly handle the key issues of the society, economy, infrastructure, and ecology, adhere to scientific planning and rational layout, and actively promote the construction of resilient cities.
  - (3) The city should develop the concept of resilient city construction planning and scientifically integrate the concept of resilient city construction into urban construction. Moreover, the city should actively implement urban public safety planning, strengthen collaborative management and decision-making among urban departments. City also should bring into full play to their advantages according to local conditions, form an urban emergency system for early warning, treatment, repair, and reconstruction, strengthen the response and handling capacity for major risk accidents. Based on these, it hopes to form a multi-level emergency collaborative and efficient decision-making mechanism across regions, cities, and departments.

A resilient supply chain has become an important measure to handle the complex situation of current social and economic development and enhance national security and competitiveness. In the future, our proposed methods would be used to assess supply chain resilience. In addition, the evaluation of resilient cities is essentially a multi-attribute decision-making problem that evaluates cities with different attributes. Therefore, some multi-attribute decision-making methods, including Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) (Hwang & Yoon, 1981), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) (Opricovic & Tzeng, 2004), and TOMada de Deciso Iterativa Multicritr (TODIM) (Wu et al. 2022b), will be utilized to assess the cities' resilience in our future research.

**Funding** The authors of this study received financial support from the Anhui Provincial Philosophy and Social Science Program (AHSKQ2020D10).

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