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Evolution and analysis of urban resilience and its influencing factors: a case study of Jiangsu Province, China

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Abstract

This research uses panel data of cities in Jiangsu from 2009 to 2018 to construct a resilience framework that measures the level of urban resilience. A combination of the entropy method, Theil index, Moran′sI, and the Spatial Durbin Model (SDM) is used to explore regional resilience development differences, the spatial correlation characteristics of urban resilience, and its influencing factors. The study finds that: (1) The spatial heterogeneity of regional resilience development is significant, as the overall level of resilience presents a spatial distribution pattern of descending from southern Jiangsu to central Jiangsu and to northern Jiangsu. (2) The total Theil index shows a wave-like downward trend during the study period. The differences between southern Jiangsu, central Jiangsu, and northern Jiangsu make up the main reason for the overall difference of urban resilience in Jiangsu Province. Among the three regions, the gap in resilience development level within southern Jiangsu is the largest. (3) There is a clear positive spatial correlation between urban resilience in the province and an obvious agglomeration trend of urban resilience levels. Among all subsystems, urban ecological resilience is the weakest and needs to be further improved. (4) Lastly, among the five factors affecting urban resilience, general public fiscal expenditure/GDP, which characterizes government factors, has the largest positive impact on urban resilience, while foreign trade has a negative impact. In the following studies, the theme of urban resilience should be constantly deepened, and more extensive data monitoring should be carried out for the urban system to improve the diversity of data sources, so as to assess urban resilience more accurately.

Keywords Jiangsu province · Spatial distribution · Spatial Durbin model · Urban resilience

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1 Introduction

Urbanization is an objective trend in the development of human society and an important symbol of national modernization. As the urbanization rate of China's population reached 63.9% by 2020,[1] cities have become the main carriers of population and economic activities, and with this acceleration, China's urban development has shifted from large-scale expansion to high-quality development. However, due to the impact of COVID-19, the international environment is becoming increasingly complex. According to an analysis by the International Monetary Fund, the impact of the epidemic on the world economy is the worst since the Great Depression in the 1930s, leading to the first simultaneous recession in developed, emerging, and developing economies.[2] The world is entering a period of turbulence, and instability and uncertainty have increased significantly, hindering the safe advancement of urbanization and impacting the sustainable development of cities.

Resilience is perceived as a requirement for global and urban system sustainability, and there is a clear correlation between resilience and sustainability (Adger 1998; Ahern 2011; Cavallaro et al. 2014). The construction of resilient cities is an important manifestation of the high-quality development of cities, and it promotes their sustainable development. As the 14th Five-Year Plan proposal of China puts forward for the first time to "build resilient cities" to improve the level of urban governance and to strengthen risk prevention and control in the governance of megacities,[3] previous urban development concepts such as "urban sustainable development," "ecological green city," "healthy city," and "sponge city" have been gradually accepted and placed in the agenda of the nation's urban development. The construction of a resilient city places higher requirements on the basis of previous urban development. Resilient cities are required to continuously enhance their ability to resist risks, and the urban system must also have the ability to absorb external interference and maintain the stability of the main functional structure. The discussion of resilient cities can explain why some cities recover quickly after a crisis and seize opportunities for further development, while others fail.

Jiangsu, as a large economic province, has more than 11 million market entities, with an economy of nearly 10 trillion CNY, accounting for one tenth of China's GDP. Its industries are agglomerates and population are dense. Jiangsu took the lead in restarting work and production during the epidemic period, and took the lead in realizing positive economic growth nationwide, making outstanding contributions to China's first resumption of positive growth in the world's major economies. Under this realistic background, establishing a research framework for urban resilience, exploring methods to enhance urban resilience, and improving the evaluation criteria of resilient cities can undoubtedly reflect the current situation and future development trends of a city in a more scientific and objective manner. It is found that the shortcomings of the urban resilience development in Jiangsu and action plans to improve the level of resilience were formulated, so as to set an example for the

[1] China's National Bureau of Statistics, 2020. https://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0305&sj=2020. Accessed 23 December 2021.

[2] International Monetary Fund. https://www.imf.org/en/Publications/WEO/Issues/2021/03/23/world-economic-outlook-april-2021. Accessed 26 December 2021.

[3] China's National Development and Reform Commission. The Fourteenth Five-Year Plan for the National Economic and Social Development of the People's Republic of China and the Outline of the Long-range Goals to 2035, http://gbdy.ndrc.gov.cn/gbdyzcjd/202103/t20210323_1270126.html. Accessed 30 December 2021.

national construction of resilient cities and provide theoretical support for the planning of improving the level of urban resilience.

This research selects 25 evaluation indicators covering five perspectives: ecology, economy, society, infrastructure and community. Due to the lack of statistics and difficulty of index selection, most previous studies do not consider community indicator in construction of the urban index system for resilience evaluation. This paper takes into account community resilience and includes it into the index system to comprehensively evaluate urban resilience. By constructing this evaluation system of urban resilience, the study uses the entropy method to calculate the urban resilience of Jiangsu Province from 2009 to 2018 and analyzes its spatial and temporal characteristics by ArcGIS. Finally, this study explores the influencing factors of urban resilience using the spatial Durbin model.

The rest of the paper is organized as follows. Section 2 is a literature review. Section 3 is the research area and data resource. Section 4 is a methodology introduction. Section 5 is the result of empirical analysis and discusses the urban resilience of Jiangsu Province during COVID-19 pandemic. Section 6 is the discussion of the current research and an outlook for future research. Section 7 summarizes the paper.

2 Literature review

2.1 Theoretical study on the concept of resilience

Resilience was originally transformed from the Latin word "resilio" and came from applied science, meaning to recover the original state (Klein et al. 2003). The concept of "resilience" was introduced into the field of ecology for the first time (Holling 1973), and after comparing the differences between durability and stability, resilience was distinguished into engineering resilience and ecological resilience (Holling 1996) in 1996. Engineering resilience has one and only one steady state, which emphasizes how much an interference system needs to break away from the original stable state, and how fast it can recover to the initial state after being shaken out of the stable state by external shock(s) and interference(s) (Bruijn 2004; Davoudi et al. 2012; Folke 2006). Maintaining the function and the existing state is the key factor for engineering resilience.

After more than 40 years' development, the concept of resilience has been applied from the field of natural ecology to the field of human ecology and has gradually evolved from engineering resilience and ecological resilience to social-ecological resilience (Holling 1973). This means that the system does not necessarily exist in one or more equilibrium states. Regardless of the presence or absence of outside intervention, its essence is continuously adapting and changing over time (Davoudi et al. 2012). In other words, evolution resilience includes adaptability and convertible—namely, the ability to build a new system (Folke et al. 2010; Walker et al. 2004).

2.2 The deduction of the resilience theory and international experience

Scholars mainly explain the concept of a resilient city and its evolution history (Alliance 2007; Béné, Newsham, Davies, Ulrichs and Godfrey-Wood 2014; Meerow and Newell 2015; Santos, Yip, Thekdi and Pagsuyoin 2018). The resilience alliance literature argues that resilience cities are those that retain their original primary features, structures, and key functions after absorbing external interferences (Alliance 2007). It is more focused

on the resilience of the system, such as Wilbanks, defining urban resilience as the ability of urban systems to prepare for, respond to, and recover from multiple threats (Wilbanks and Sathaye 2007). Bruneau comprehensively considers the concept and connotation of resilience and believes that resilient cities refer to their resilience in the face of external uncertain risks, and they can adjust such resilience during the long-term adaptation process (Bruneau et al. 2012). The above definition of a resilient city contains the following three elements. First, it has the ability to absorb external shocks and disturbances and can maintain the stability of the system structure to a certain extent. Second, it has the ability to quickly return to a normal state after damage. Third, it focusses on the ability of the system to adapt to or reach a new state through learning and reorganization after suffering from external shocks.

2.3 Evaluation and application of urban resilience

The research of most scholars has focused on the threat of natural disasters and committed to applying the concept of urban resilience to urban planning, geography, and disaster science (Bruneau et al. 2012; Dhar and Khirfan 2017; Rgodschalk and Chan 2015; Shi et al. 2021; Wilbanks 2007). infrastructure planning (Meerow and Newell 2017), infrastructure planning (Meerow and Newell 2017), community participation (Rgodschalk and Chan 2015; Timothy and Peter 2013), technological innovation (Seeliger and Turok 2013), social organization collaboration (Folke 2010), and other ways to enhance the level of urban resilience. They have extended the concept of resilience to the urban micro-level and improved the ability of risk response. However, many scholars suggest that the study of resilience needs to be systematically combined with urban planning to explain the evolution of resilience from the perspective of urban construction (Kaerrholm 2014; Masnavi et al. 2018; Yamagata and Sharifi 2018).

In terms of research scales, assessment dimensions, and measurement methods, the research on urban resilience is different. From the perspective of research region and scale, the urban resilience assessment includes China's developed areas including disaster-prone areas along the Yangtze River and coastal areas and economically developed urban agglomerations (Liu, Xiu and Song 2019; Zhang et al. 2016). Scholars evaluate and measure urban resilience by constructing an index system (Cutter et al. 2014; Feng et al. 2020; Lyu et al. 2018; Ma et al. 2020; M. Zhang et al. 2019). There are two methods to measure city resilience, a multidimensional index and unidimensional index, and most research is still conducted from the four-dimensional perspective. Specifically, Ma et al. (2020) and Zhang et al. (2019) both conducted studies on urban resilience from the perspectives of infrastructure, economy, ecology, and society. Different from the multi-dimensional research perspective, Lyu et al. (2018) comparatively analyzed the impact of floods on Guangzhou metropolitan operation by using the analytic hierarchy process and interval analytic hierarchy process. From the perspective of landscape pattern (scale-density-form), Feng et al. (2020) constructed a resilience, comprehensively measuring and evaluating the resilience of Shenyang (in Liaoning Province). Statistical data and remote sensing images help form resilience spatial evolution characteristics of visualization (Ključanin et al. 2021).

2.4 Summarization

From the existing literature, there are scant provincial-level analyses in the scale selection of resilience evaluation, and the screening of evaluation factors lacks localization and

innovation. Under the COVID-19 epidemic outbreak in 2020, community has become the basic unit of management and is now an important stronghold of epidemic prevention and control. Community living patterns for outbreak prevention and control have played a positive role in enhancing a city's ability to respond to sudden public events and for its resilience. In addition, there is less in-depth analysis of interregional and dimensional resilience differences in existing studies.

In view of the above, the main innovations and contributions of this paper are as follows. (1) An influential and representative research area is selected. Taking Jiangsu Province as the research object, which continues to lead in resuming work and production, it is beneficial to serve as a demonstration in promoting the construction of resilient and sustainable cities throughout the country. (2) On the basis of the existing four dimensions of urban ecological environment, economic level, social environment, and infrastructure resilience, the resilience dimension of urban grassroots communities is added. The urban resilience evaluation index system is constructed from five aspects to measure urban resilience. (3) Jiangsu Province is divided into three regions, southern Jiangsu, central Jiangsu, and northern Jiangsu, and the Theil index is used to analyze the overall and partial differences of resilience development in Jiangsu Province. (4) The spatial Durbin model is introduced to analyze the influencing factors of urban resilience. It provides important understanding basis and theoretical guidance for urban resilience construction, urban sustainable and healthy development in the future.

3 Research area and data resource

3.1 Overview of the area of study

Jiangsu is at the intersection of the Belt and Road Initiative (BRI) and has the superposition of multiple national strategies such as the development of the Yangtze River Economic Belt and the integrated development of the Yangtze River Delta. It is one of the regions with the strongest degree of openness, development vitality, and best level of urbanization in China. Jiangsu includes Suzhou, Wuxi, Changzhou, Nanjing, Zhenjiang, Nantong, Taizhou, Yangzhou, Xuzhou, Suqian, Huai'an, Yancheng, and Lianyungang, or a total of 13 prefecture-level cities, with all exhibiting economic prosperity, developed education, and cultural prosperity. In 2020, per capita GDP reached 121,231 CNY, and the province's development and life index (DLI) ranked first in China. The Yangtze River Delta urban agglomeration, which is composed of Shanghai, Jiangsu, Zhejiang, and Anhui, has become one of six world-class urban agglomerations. Taking 13 prefecture-level cities in Jiangsu Province as the research object, this paper comprehensively calculates their resilience, focusing on the analysis of the influencing factors of urban resilience in order to clarify their internal spatial differences, action direction, and degree of execution.

3.2 Data resource

The statistical data used in this paper cover 13 prefecture-level cities in Jiangsu Province from 2009 to 2018. The basic indicators are mainly from China Urban Statistical Yearbook, China Urban Construction Statistical Yearbook, Statistical Yearbook of Jiangsu and 13 prefectural-level cities, Statistical Bulletin of National Economic and Social Development, Bulletin on the State of the Environment, and the forward-looking Database. It should be noted that any city

in this study takes on the caliber of a whole city. Due to a lack of data, some indicators are approximately replaced by the caliber of municipal districts, and missing data in individual years are filled by interpolation.

4 Methodology

4.1 Entropy method

In order to avoid interference and calculation error of subjective factors, this study adopts the entropy method on the dimensions and indicators of empowerment to ensure objectivity and accuracy. In order to further improve the entropy method (Shirowzhan et al. 2018), a time variable is introduced into the model to make the results more reasonable. The improved evaluation model runs as follows.

The index matrix is constructed with N years, M cities, and Z indices. The J index value of city I in year h is expressed as x_{hij}. In this study, n, m, and z are 1, 13, and 25, respectively. In order to eliminate dimensional differences, the level difference method is adopted to standardize the original data, and the obtained value is X_{hij}.

1. If x_{hij} is a positive indicator, then the standardization equation is given as follows:

$$X_{\mathrm{hij}} = \frac{x_{\mathrm{hij}} - x_{j\min}}{x_{j\max} - x_{j\min}}. \tag{1}$$

2. If x_{hij} is a negative index, then the standardization equation is given as follows:

$$X_{\mathrm{hij}} = \frac{x_{j\max} - x_{\mathrm{hij}}}{x_{j\max} - x_{j\min}}. \tag{2}$$

Normalization of indicators is given as follows:

$$Y_{\mathrm{hij}} = X_{\mathrm{hij}} \Big/ \sum_{h=1}^{n} \sum_{i=1}^{m} X_{\mathrm{hij}} \tag{3}$$

The entropy value of index j is given as follows:

$$E_j = -\kappa \sum_{h=1}^{n} \sum_{i=1}^{m} Y_{\mathrm{hij}} \ln Y_{\mathrm{hij}}, \text{ and } k = 1/\ln(n \times m). \tag{4}$$

The utility information of the first j indicator is given as follows:

$$G_j = 1 - E_j. \tag{5}$$

We evaluate the weight of each index as follows:

$$W_j = G_j \Big/ \sum_{j=1}^{Z} G_j. \tag{6}$$

The weight of each dimension in the criterion layer is given as follows:

$$W_j^{;} = \sum_{j=1}^{s} W_j, \tag{7}$$

where s is the number of indicators in each resilience dimension.

We calculate the comprehensive score of the urban resilience level as follows:

$$\mathrm{RES}_{\mathrm{hi}} = \sum_{j=1}^{z} W_j X_{\mathrm{hij}}. \tag{8}$$

4.2 Urban resilience evaluation index system

We screen and modify the evaluation indicators according to the connotation of urban resilience and in line with the development level of urbanization, on the basis of combining the existing evaluation indicators of predecessors with the principles of science, representativeness, and data availability. From the 5 subsystems of ecological, economic, social, infrastructure, and community, 25 indices can accurately reflect the resilience indicators of various prefectures and cities in Jiangsu Province. As shown in Table 1, they constitute a comprehensive evaluation index system of urban resilience.

4.3 Theil index

The Theil index mainly measures the level of regional resilience difference. Compared with other indices, this index has the advantage of decomposing regional differences and measuring the contribution of intra-group gap and inter-group gap to total gap. The specific calculation formula is given as follows:

$$T = \frac{1}{m} \sum_{i=1}^{m} \frac{y_i}{\overline{y}} \log\left(\frac{y_i}{\overline{y}}\right) = T_b + T_w, \tag{9}$$

$$T_w = \sum_{r=1}^{R} \left(\frac{m_r}{m} \frac{\overline{y_r}}{\overline{y}}\right) T_r, \tag{10}$$

$$T_b = \sum_{r=1}^{R} \left(\frac{m_r}{m} \frac{\overline{y_r}}{\overline{y}}\right) \log\left(\frac{\overline{y_r}}{\overline{y}}\right). \tag{11}$$

In the formula, T is the Theil index of urban resilience, T_b and T_w are the inter-group gap and intra-group gap, respectively, and $y_i$and$\overline{y}$ represent the comprehensive value of resilience level of city I and the average resilience level of all cities. If M cities are divided into R groups, then each group is $g_r (r = 1, 2 \ldots R)$. If the number of individuals in Group R g_r is m_r, then $\sum_{r=1}^{R} m_r = m$, and y_r represents the total resilience of group R. In this study, R is 3: Southern Jiangsu, Central Jiangsu, and Northern Jiangsu.

Table 1 Weight and assessment indicator of urban resilience in Jiangsu Province from 2009 to 2018

Level 1 Indicator	Weight	Level 2 Indicator	Weight	Unit	Reference
Urban ecological resilience	0.0894	Green coverage rate in urban constructed areas	0.0214	%	Ma et al. (2020), Zhang et al. (2019), Chen et al. (2021), Chen and Quan (2021)
		Public green area per capita	0.0296	m^2	
		Volume of industrial wastewater discharged	0.0128	10,000 tons	
		Percentage of sewage disposed	0.0150	%	
		Harmless disposal rate of household garbage	0.0106	%	
Urban economic resilience	0.2169	GDP per capita	0.0361	CNY	Bozza et al. (2015), Chen et al. (2021), Fang (2015), Ma et al. (2020), Tan et al. (2020), Zhang et al. (2019)
		Proportion of tertiary industry in GDP	0.0288	%	
		Actual utilization of foreign capital	0.0420	US$100 million	
		Urban disposable income per capita	0.0306	CNY	
		Revenue in the general public budgets	0.0794	100 million CNY	
Urban social resilience	0.1750	Number of college students on campus	0.0876	Persons	Chen et al. (2021), Ma et al. (2020), Zhang et al. (2019), Bozza et al. (2015), Fang et al. (2015)
		Number of beds in health facilities	0.0324	Pieces	
		Percentage of non-farm employment	0.0289	%	
		Registered urban unemployment rate	0.0099	%	
		Gross floor area per capita	0.0162	m^2	
Urban infrastructure resilience	0.2405	Urban road area per capita	0.0286	m^2	He et al. (2018), Ma et al. (2020), Zhang et al. (2019), Bozza et al. (2015), Fang et al. (2015), Yoon et al. (2016)
		Urban drainage pipe density	0.0380	km/km^2	
		Annual electricity consumption	0.0810	100 million kw·h	
		Freight traffic of highways	0.0310	10,000 tons	
		Internet broadband access users	0.0619	10,000 households	

Table 1 (continued)

Level 1 Indicator	Weight	Level 2 Indicator	Weight	Unit	Reference
Urban community resilience	0.2782	Number of residents' committees	0.0475	Pieces	Cutter et al. (2014), Tian et al. (2019), Xu et al. (2020), Yoon et al. (2016), Lak et al. (2021)
		Number of people covered by unemployment insurance	0.0705	10,000 persons	
		Minimum subsistence allowance for urban residents	0.0579	Persons	
		Expenditure on urban and rural community affairs	0.0822	100 million CNY	
		Average number of urban residents per employed population	0.0201	Persons	

4.4 Exploratory spatial data analysis (ESDA)

Spatial correlation reveals the interdependence, mutual influence, and interaction of things in different regions in a geographical space. There are mainly two kinds of global and local indicators to measure regional correlation.

4.4.1 Global autocorrelation

Using Moran′s Index to analyze the overall degree of spatial correlation of Jiangsu's urban resilience, the formula is given as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i-\bar{x}\right)\left(x_j-\bar{x}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i-\bar{x}\right)^2}. \tag{12}$$

here n is the number of cities, x_i and x_j are the variable values of cities i and the j, and w_{ij} is the spatial weight matrix.

This paper analyzes the spatial correlation characteristics of Jiangsu's urban resilience by using the geographic distance matrix (Liu 2013) and the economic geographic distance matrix (Yongze and Dayong 2013). The spatial weight matrix is given as follows:

$$W_{ij}^{d} = \begin{cases} \frac{1}{d^2}, i \neq j \\ 0, i = j \end{cases}, W_{ij}^{d'} = \frac{W_{ij}^{d}}{\sum_j W_{ij}^{d}}, i \neq j. \tag{13}$$

$$W_{ij}^{e} = W_{ij}^{d} diag\left(\frac{\overline{Y_1}}{\overline{Y}}, \frac{\overline{Y_2}}{\overline{Y}}, \ldots, \frac{\overline{Y_n}}{\overline{Y}}\right), W_{ij}^{e'} = \frac{W_{ij}^{e}}{\sum_j W_{ij}^{e}}, i \neq j. \tag{14}$$

We note that W_{ij}^{d} is the geographical distance matrix, and d refers to the distance between city i and city j in the spatial scope, which is usually expressed by the straight-line distance between the centers of the two places or the seats of their governments. Moreover, W_{ij}^{e} is the economic distance matrix, $\overline{Y_i} = 1/\left(t_1 - t_0 + 1\right)\sum_{t_0}^{t_1} Y_{ij}$ is the GDP mean value of area i in the observation period, and $\bar{Y} = 1/n\left(t_1 - t_0 + 1\right)\sum_{i=1}^{n}\sum_{t_0}^{t_1} Y_{ij}$ is the average GDP value in the total observation period. This study standardizes the spatial weight matrix to facilitate calculation and interpretation of the results in practical application.

4.4.2 Local spatial autocorrelation

Global autocorrelation reflects the resilience of all cities in the geographical space from the macro-level, but does not reflect the relationship between urban units at the micro-level. The Moran scatter graph can be used for local autocorrelation analysis. The four quadrants of the scatter map correspond to four types of local spatial correlation forms: the first quadrant to the fourth quadrant is high-high (HH), low–high (LH), low-low (LL), and high-low (HL). The Moran scatter plot is used to analyze the correlation characteristics of urban resilience in Jiangsu Province.

4.5 Spatial regression model

The resilience of a city is composed of various subsystems—that is, to a certain extent, the resilience of ecology, economy, society, infrastructure, and community represents the resilience of the city. However, the value of each index in the subsystem is often determined by other factors that influence the index layer, which can be attributed to those that jointly determine the value of urban resilience. This study selects 10 factors from five aspects: government investment, degree of innovation, market vitality, foreign trade, and financial efficiency, which include general public financial expenditure/GDP (SG), patent application authorization (NP), total post and telecommunications business (PT), population density (PD), Engel coefficient (EC) of urban residents, degree of foreign trade dependence (FT), urbanization rate (UR), average wage (AW) of on-duty workers, total deposit and loan amount/GDP (BS) of financial institutions, and deposit balance/loan balance (BE) of financial institutions. The mechanism and spatial externality of urban resilience in Jiangsu Province are analyzed by the spatial Durbin model (SDM).

To avoid the heteroscedasticity caused by any sharp fluctuation of the absolute value data and by considering that logarithmic processing will not change the characteristics of the absolute value data, this paper deals with the logarithm of the amount of patent application, the total amount of post and telecommunications business, the population density, and the average salary of on-duty workers.

$$\begin{aligned} RES_{it} =& \alpha_0 + \rho W_{ij} RES_t + \alpha_1 EG_{it} + \alpha_2 lnNP_{it} + \alpha_3 lnAW_{it} + \alpha_4 lnPT_{it} + \alpha_5 lnPD_{it} \\ &+ \alpha_6 FT_{it} + \alpha_7 UR_{it} + \alpha_8 BS_{it} + \alpha_9 BE_{it} + \alpha_{10} EC_{it} + \alpha_{11} WEG_{it} + \beta_2 WlnNP_{it} \\ &+ \beta_3 WlnAW_{it} + \beta_4 WlnPT_{it} + \beta_5 WlnPD_{it} + \beta_6 WFT_{it} + \beta_7 WUR_{it} \\ &+ \beta_8 WBS_{it} + \beta_9 WBE_{it} + \beta_{10} WEC_{it} + \varepsilon_{it} \end{aligned}$$

5 Results and analysis

5.1 Overall analysis of resilience levels

Through a comprehensive calculation of the data by the entropy method, we obtain an evaluation of the resilience values of 13 prefecture-level cities in Jiangsu from 2009 to 2018 (Table 2).

According to the level of urban resilience (Table 2), on the whole there are obvious differences in such a level in Jiangsu Province. Nanjing has the highest average level of comprehensive resilience (0.5828), while Suqian has the lowest (0.1335), which also shows the internal imbalance of urban resilience value in this province.

From the viewpoint of the law of spatial evolution, we note the following main characteristics. (1) The general level of regional resilience shows a spatial distribution pattern decreasing successively from south to central Jiangsu and then to northern Jiangsu, in which the average resilience of Nanjing is the highest (0.5828), and that of central Jiangsu's Nantong (0.2685) is the highest. In northern Jiangsu, the highest average resilience of Xuzhou is 0.2523, which is in line with the overall economic level of each city in the region, and the higher the total economic output is, the greater is urban resilience.

Table 2 The comprehensive evaluation of urban resilience of 13 prefecture-level cities in Jiangsu province from 2009 to 2018

City	Year										
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Average
Suzhou	0.3952	0.4345	0.4749	0.5123	0.5447	0.5790	0.6092	0.6360	0.6695	0.6997	0.5555
Nanjing	0.4416	0.4719	0.5326	0.5591	0.5730	0.5896	0.6115	0.6462	0.6866	0.7162	0.5828
Wuxi	0.2826	0.3115	0.3388	0.3585	0.3718	0.3845	0.4234	0.4482	0.4802	0.5044	0.3904
Changzhou	0.1858	0.2123	0.2390	0.2599	0.2758	0.3140	0.2979	0.3178	0.3292	0.3338	0.2766
Zhenjiang	0.1400	0.1587	0.1807	0.2001	0.2178	0.2264	0.2325	0.2442	0.2481	0.2531	0.2101
Nantong	0.1689	0.1873	0.2165	0.2363	0.2571	0.2818	0.3042	0.3269	0.3382	0.3675	0.2685
Taizhou	0.0951	0.1161	0.1238	0.1405	0.1606	0.1774	0.1887	0.2100	0.2376	0.2503	0.1700
Yangzhou	0.1476	0.1608	0.1755	0.1845	0.1906	0.2142	0.2197	0.2378	0.2517	0.2605	0.2043
Xuzhou	0.1301	0.1609	0.2018	0.2276	0.2525	0.2820	0.2883	0.3123	0.3231	0.3447	0.2523
Suqian	0.0732	0.0856	0.0930	0.1025	0.1265	0.1500	0.1605	0.1773	0.1786	0.1875	0.1335
Huai'an	0.0812	0.0996	0.1222	0.1411	0.1490	0.1899	0.1872	0.1979	0.2032	0.2152	0.1586
Lianyungang	0.0795	0.0958	0.1332	0.1430	0.1695	0.1808	0.1803	0.1839	0.2049	0.2003	0.1571
Yancheng	0.0866	0.1115	0.1375	0.1453	0.1678	0.1964	0.2081	0.2149	0.2214	0.2414	0.1731
Average	0.1775	0.2005	0.2284	0.2470	0.2659	0.2897	0.3009	0.3195	0.3363	0.3519	0.2718

Table 3 Theil index and decomposition

Year	Theil Index	Intra-group	Inter-group	Southern Jiangsu	Central Jiangsu	Northern Jiangsu
2009	0.0820	0.0552/67.30%	0.0268/32.70%	0.0363	0.0116	0.0103
2010	0.0710	0.0471/66.28%	0.0239/33.72%	0.0329	0.0080	0.0115
2011	0.0644	0.0401/62.32%	0.0243/37.68%	0.0322	0.0108	0.0140
2012	0.0607	0.0378/62.20%	0.0229/37.80%	0.0301	0.0096	0.0150
2013	0.0530	0.0322/60.93%	0.0208/39.07%	0.0282	0.0084	0.0124
2014	0.0451	0.0263/58.41%	0.0187/41.59%	0.0264	0.0079	0.0100
2015	0.0467	0.0265/56.84%	0.0201/43.16%	0.0288	0.0090	0.0096
2016	0.0453	0.0255/56.32%	0.0198/43.68%	0.0283	0.0079	0.0103
2017	0.0460	0.0258/56.04%	0.0202/43.96%	0.0301	0.0055	0.0100
2018	0.0463	0.0247/53.38%	0.0216/46.62%	0.0316	0.0069	0.0113

(2) Although the overall resilience levels of southern Jiangsu and central Jiangsu are higher than that of northern Jiangsu, there are some differences between individual cities. For example, the comprehensive score of Xuzhou in northern Jiangsu is higher than that in Zhenjiang in southern Jiangsu as well as in Taizhou and Yangzhou of central Jiangsu. This is because Xuzhou, as the central city of the Huaihai Economic Zone, is located on the main road of traffic in China. The construction of transportation infrastructure is at the forefront of the country, and the total number of higher education institutions ranks second in the province. In recent years, with the transformation of old coal mining areas, industry, city, and ecological transformation, the ecological environment has greatly improved, the urban social ecosystem is healthier, and it has the ability to resist external shocks and interference.

From the perspective of the time development trend, the evolution law of urban resilience has the following characteristics. (1) In Jiangsu Province, except for Changzhou, Huai'an, and Lianyungang, the comprehensive value of urban resilience decreased slightly from 2014 to 2015, but the resilience of all other prefecture-level cities shows a linear upward trend during the ten years from 2009 to 2018. The main reason is that the number of ordinary college students and the expenditure on urban and rural community affairs in these three cities have decreased from 2014 to 2015. This led to the weakening of social and grass-roots resilience in the three cities, which in turn reduced the overall resilience level of the cities. From a comparison between the final year and the initial year, we can see that the level of resilience of all prefecture-level cities has increased somewhat, with a total increase of more than 62% in ten years. Yancheng has the fastest growth rate among the 13 cities at an average of 17.87%. The slowest growth is only 6.22% in Nanjing. It is worth mentioning that the resilience of Xuzhou in the initial year is less than that of Zhenjiang and Yangzhou, but it has been surpassed since 2010 and has maintained this trend. (2) The annual average of overall resilience in the province increased from 0.1775 in 2009 to 0.3519 in 2018, with an average annual growth rate of 9.83%, which shows that the overall level of urban resilience development in the province is good. This closely relates to the overall level of economic development in Jiangsu.

The establishment of a number of modern and high-level comprehensive passenger transport hub stations has effectively promoted the spatial expansion of cities along the railway and the optimal layout of industries, promoted the transformation and upgrading

Table 4 Global Moran′sI of urban resilience in Jiangsu Province under different weight matrices

Year	Geographic distance matrix				Economic distance matrix			
	Moran's I	E(I)	SD	P(I)	Moran's I	E(I)	SD	P(I)
2009	0.220	− 0.083	0.141	0.031	0.458	− 0.083	0.70	0.001
2010	0.223	− 0.083	0.141	0.030	0.462	− 0.083	0.170	0.001
2011	0.193	− 0.083	0.140	0.048	0.413	− 0.083	0.169	0.003
2012	0.193	− 0.083	0.140	0.049	0.412	− 0.083	0.169	0.003
2013	0.189	− 0.083	0.140	0.052	0.402	− 0.083	0.169	0.004
2014	0.180	− 0.083	0.140	0.060	0.376	− 0.083	0.169	0.007
2015	0.207	− 0.083	0.141	0.039	0.415	− 0.083	0.170	0.003
2016	0.208	− 0.083	0.141	0.039	0.415	− 0.083	0.171	0.003
2017	0.211	− 0.083	0.141	0.037	0.427	− 0.083	0.171	0.003
2018	0.212	− 0.083	0.142	0.037	0.418	− 0.083	0.171	0.003

of industrial structure, and optimized the ratio of employment to industrial personnel. The end result is greater economic growth and, to a certain extent, providing a fundamental guarantee for the improvement of urban resilience.

5.2 Analysis of differentiation characteristics of urban areas

To further analyze the spatial difference of urban resilience development in Jiangsu Province, the Theil index of the whole province is calculated and decomposed (Table 3). Thirteen prefecture-level cities in Jiangsu Province are divided into three regions: southern (Suzhou, Nanjing, Wuxi, Changzhou, Zhenjiang), central (Nantong, Taizhou, Yangzhou), and northern (Xuzhou, Suqian, Huai'an, Lianyungang, Yancheng). We then calculate the contribution rate of inter-group and intra-group for global imbalance. According to the calculation in Table 3, during the study period the overall resilience imbalance of cities in the province shows a wavy downward trend of first decreasing, then slightly increasing in 2015, and then experiencing a slow expansion after a brief decline. The total index decreased from 0.0820 in 2009 to 0.0463 in 2018, or a drop of 43.54%.

Urban resilience of Jiangsu Province has the characteristics of high spatial structure in the south and low spatial structure in the north, but the overall difference is gradually narrowing. From the differentiation results of the Theil index, we can see that the variation characteristics of inter-regional differences are basically similar to those of overall differences. Among them, the Theil index between groups decreased by 55.25% from 0.0552 in 2009 to 0.0247 in 2018, and the average contribution to the total Theil index reached 60.005%. It shows that the inter-regional imbalance is the main reason for the difference of urban resilience within Jiangsu Province, but the difference at the resilience level among the three regions is gradually narrowing. Affected by the central city status of Nanjing and the development gap between Suzhou and Zhenjiang, there is a large gap in the level of resilience within the southern Jiangsu plate, and it is necessary to release the spatial spillover effect of the development of Nanjing and Suzhou to narrow the gap of urban resilience within the plate.

5.3 Spatial interaction analysis

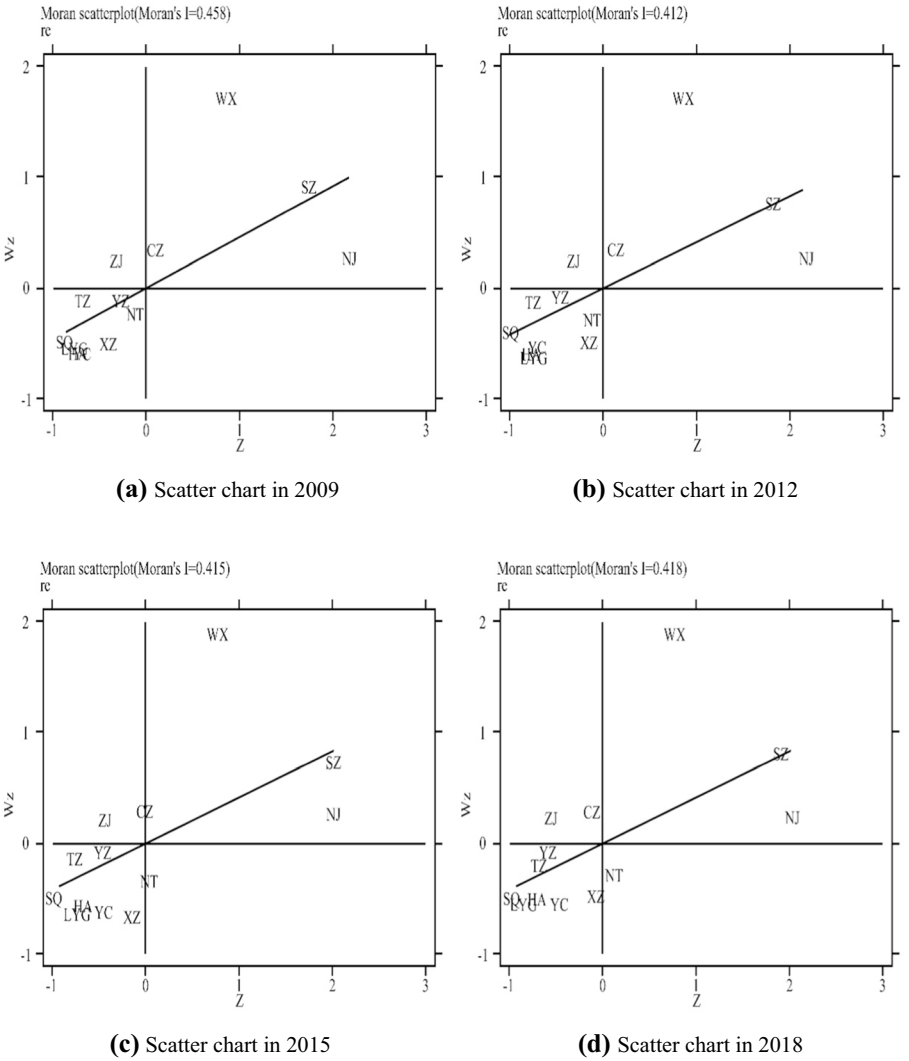
5.3.1 Global autocorrelation test

Based on the global autocorrelation formula, we use Stata 15 software to calculate the global spatial correlation coefficient for Moran′sI of urban resilience in Jiangsu Province from 2009 to 2018. The global value of Moran′sI passes the significance test of $P < 0.05$ in terms of geographical distance and economic geography matrix (Table 4), and urban resilience has positive spatial correlation. It shows that the resilience of cities in Jiangsu Province has strong spatial correlation and an observably extension characteristic—that is, an increase in resilience level in one region obviously drives an increase in resilience level in other regions. However, this positive promotion effect gradually has weakened from the initial peak during the observation period and continued to weaken after a brief recovery in 2015. The overall positive spatial correlation shows a weakening trend.

5.3.2 Spatial local correlation test

It is known that the global Moran′sI weighted by geographical distance and economic distance matrix is greater than zero at the 5% significant level, but the level of urban resilience is often inseparable with the level of regional economic development, and the calculation connotation of economic distance matrix is richer and more representative. Based on the global Moran′sI of weighting calculation of the economic distance matrix, we analyze the local spatial agglomeration of four representative years (2009, 2012, 2015, and 2018) and obtain the Moran′sI scatter chart by using Stata 15 software. The horizontal axis Z represents the observed values of all urban variables. The vertical axis WZ is the spatial average value of the observed values of a certain city and its neighboring cities.

Figure 1 shows that most cities in the province are located in the first and third quadrants with little change from year to year. Based on the four images of (a), (b), (c), and (d), we find that the cities of Suzhou, Wuxi, and Changzhou near Shanghai and the provincial capital city Nanjing belong to the high-high agglomeration type, while Zhenjiang is in the low–high agglomeration type, indicating that the urban relationship within the Shanghai metropolitan area is close to a state of high-level spatial agglomeration, and the diffusion and spillover effects of the central city Shanghai are significant, basically forming the pattern of center-periphery coordinated development. Limited by economic and geographical conditions, Nantong, Taizhou, Yangzhou, Xuzhou, Suqian, Huai'an, Yancheng, and Lianyungang, which are far away from each other and relatively weak in economic foundation, are located in low agglomeration areas, showing a pattern of continuous distribution from south to north. The results show that urban resilience in the Nanjing metropolitan area is lower than that in the Shanghai metropolitan area. The spatial distribution of urban resilience in Jiangsu is not random, but there is an interaction relationship between areas with an equivalent economic level and similar geographical distance.



(a) Scatter chart in 2009 **(b)** Scatter chart in 2012

(c) Scatter chart in 2015 **(d)** Scatter chart in 2018

Fig. 1 Scatter chart of urban resilience in Jiangsu Province. *Source* based on the data in Electronic Supplementary Material

5.4 Visual analysis of horizontal spatial difference of urban resilience

5.4.1 Subsystem analysis of spatial difference of urban resilience level

The average value of ecological resilience of 13 prefecture-level cities in 2018 was 0.0564, in which the score of Yancheng was the lowest (0.0379), and the maximum value was 0.1509 for Nanjing. As shown in Fig. 2, the ecological level of most cities in the province is in the middle level and high level, but there is also obvious spatial heterogeneity. Taking southern Jiangsu as an example, only Nanjing, the provincial capital, has a high resilience

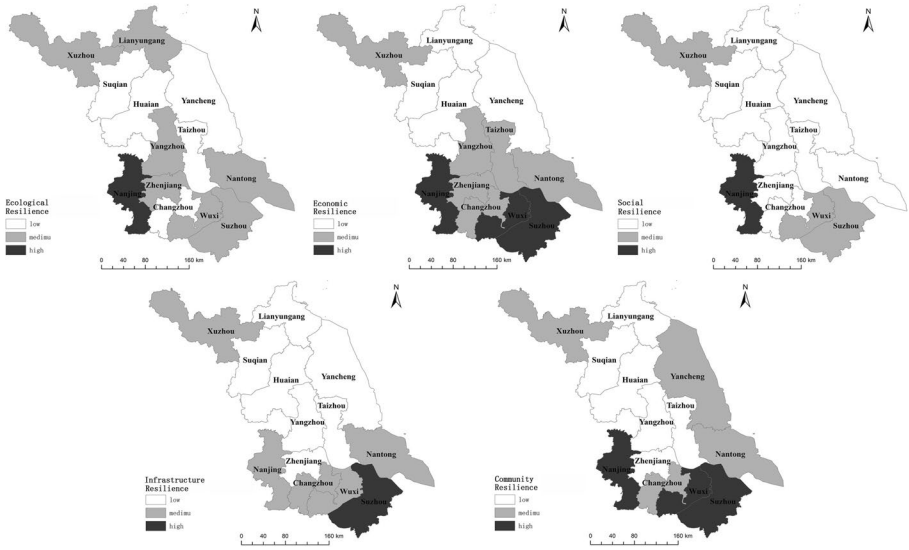


Fig. 2 Resilience values of various dimensions of Jiangsu cities in 2018. *Source* our own compilation based on the data in Appendix Table 9

value within the region, which is mainly due to advocacy of the local government's concept of green ecological civilization construction, the transformation and upgrading of enterprises, the positive response of urban residents, and effective cooperation. Changzhou in southern Jiangsu, the three cities of Suqian, Huai'an, and Yancheng in northern Jiangsu, and Taizhou in central Jiangsu have low resilience values, mainly because the greening effect is not paid enough attention by both government and industry in urban construction. Compared with medium and high resilience cities, the redundancy of low-value cities is also poor, and the buffer space is insufficient. The worsening environmental problems greatly weaken the function of traditional green infrastructure, and the urban ecosystem may break through the threshold and collapse in a short time.

The overall average value of urban infrastructure resilience is 0.0696. Only Suzhou in southern Jiangsu Province had a high level of infrastructure resilience with a score of infrastructure resilience at 0.1646. Figure 2 shows that Wuxi, Changzhou, and Nanjing in southern Jiangsu, Nantong in central Jiangsu, and Xuzhou in northern Jiangsu have values of infrastructure resilience at only in the middle level. The distribution of low resilience is relatively compact in the region, extending from Zhenjiang to Yangzhou and Taizhou and then northward to Suqian and Lianyungang, which coordinates with the level of local economic development. For areas with rapid economic development and good foundation, the government's public revenue is relatively high, and so there is more investment in infrastructure construction.

The overall average value of urban social resilience is 0.0713. As shown in Fig. 2, high values of urban social resilience in Jiangsu are scant. Only the provincial capital city Nanjing exhibits high resilience at 0.1807. The other cities have medium–low resilience, and the development is not coordinated in the region. Taking southern Jiangsu as an example, the coexistence of high, medium, and low resiliencies indicates that there is significant heterogeneity in the development of the region. The uneven development of the regions is prominent, which is mainly determined by location advantages and social benefits. Places

with regional advantages often have an obvious siphon effect and strong gathering power of resource, which can guarantee the normal operation of the urban system when subjected to external shocks. The average value of community resilience is 0.0744, with the highest score in Suzhou at 0.2044 and the lowest for Suqian at 0.0384. In each dimension, the difference between the highest and lowest values of community resilience is the largest at up to 0.166. There are different numbers of low resilience cities in the south, central, and north of Jiangsu, indicating that investment in community affairs such as public security and public health capital in some cities needs to be increased. The redundancy of basic services to ensure the daily livelihood of residents is still lacking.

The overall average value of economic resilience is 0.0802, which is the highest among the average values of each subsystem. Suzhou topped the list with a score of 0.1625, while Suqian, which has a weak economic foundation, gets the lowest score of 0.0310. Although cities with medium and high resiliencies occupy the dominant position in the economic dimension, there is spatial heterogeneity in the region. The southern region clearly leads over northern Jiangsu, which is reflected in the low economic resilience of all the cities in the northern part of Jiangsu except Xuzhou, while southern Jiangsu and central Jiangsu have medium and high economic resiliencies. The main reason is that Nanjing and Xuzhou are the central cities of the metropolitan areas, have the advantages of geographical location and rich resources, and are coupled with the support of national policies. Their economic status has become more and more prominent, and they have gradually become the growth poles of north and south Jiangsu.

5.4.2 Analysis on the evolution of spatial difference of urban resilience level

The 13 prefecture-level cities in Jiangsu can be divided into three regions: southern, central, and northern. According to the classification of the resilience grades of each city in the main years in Table 5 and the corresponding visualization chart, the characteristics of spatial differences can be analyzed.

As can be seen from the above Table 5 and Fig. 3, the spatial differentiation of urban resilience in Jiangsu is obvious, with a decreasing trend of southern Jiangsu-central Jiangsu-northern Jiangsu and the multi-layer compound core–edge characteristics. In 2009 and 2012, the comprehensive values of resilience of all prefecture-level cities in northern and central Jiangsu were at a low level, and the number of cities without high resilience increased to two cities, Nanjing and Suzhou. The comprehensive value of urban resilience in Jiangsu was on the low side as a whole, and development was slow. This situation improved after 2015. Xuzhou, Nantong, and Changzhou increased from low resilience to moderate resilience. In addition, Wuxi rose to a high resilience city in 2018, and the total number of low resilience cities decreased from 10 in 2009 to 7 in 2018. The number of high resilience cities increased from 0 at the beginning to 3 later.

As far as the metropolitan area is concerned, the level of comprehensive resilience of central cities is often higher than that of their surrounding cities. The reason is that the central cities of the Xuzhou Metropolitan area, Nanjing Metropolitan area, and Suzhou-Wuxi-Changzhou Metropolitan area have comparative advantages such as their level of economic development, transportation facilities, relatively perfect comprehensive facilities, good resource aggregation, and other comparative advantages to support the construction of urban resilience. In terms of the current stage of development, although the overall level of urban resilience in Jiangsu is also increasing with time, the number of low resilience cities still accounts for more than half, and there is still huge room for improvement in

Table 5 Resilience evolution of cities in Jiangsu Province

Resilience	Year			
	2009	2012	2015	2018
Low resilience (0–0.2718)	Changzhou, Zhenjiang, Nantong, Taizhou, Yangzhou, Xuzhou, Suqian, Huai'an, Lianyungang, Yancheng	Xuzhou, Suqian, Huai'an, Yancheng, Lianyungang, Nantong, Taizhou, Yangzhou, Zhenjiang, Changzhou	Suqian, Huai'an, Yancheng, Lianyungang, Taizhou, Yangzhou, Zhenjiang	Suqian, Huai'an, Yancheng, Lianyungang, Taizhou, Yangzhou, Zhenjiang
Medium resilience (0.2718–0.5)	Suzhou, Wuxi, Nanjing	Wuxi	Xuzhou, Nantong, Changzhou, Wuxi	Xuzhou, Nantong, Changzhou
High resilience (more than 0.5)	None	Nanjing, Suzhou	Nanjing, Suzhou	Nanjing, Wuxi, Suzhou

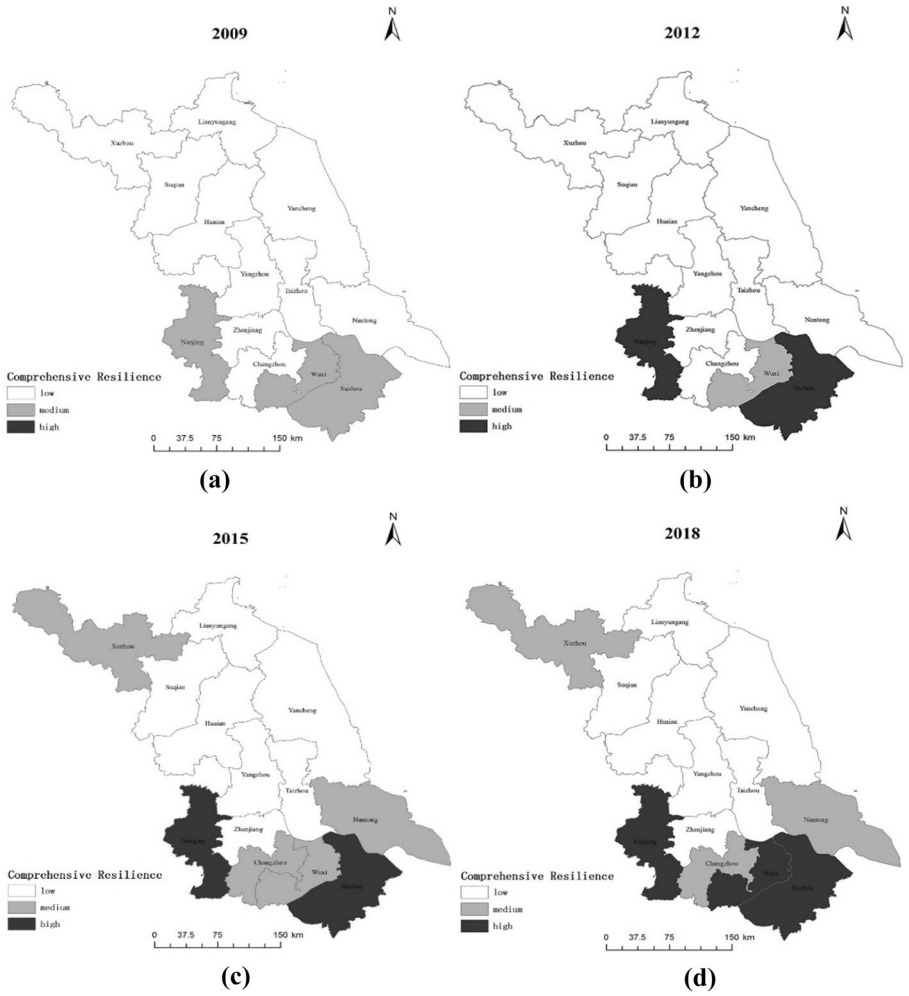


Fig. 3 Comprehensive resilience of Jiangsu Province (a 2009; b 2012; c 2015; d 2018). *Source* our own compilation based on the data in Table 2

urban resilience construction. In order to form a balanced ecological balance and sustainable endogenous development, it is necessary for the government, the market, and the community to cooperate with each other to promote urban co-governance.

5.5 Analysis on the influencing factors of urban resilience

From Moran′sI in Table 4 above, we see a spatial correlation in urban resilience and now choose the Spatial Durbin model (SDM), which can take into account the spatial correlation of resilience among cities in the province. The comprehensive resilience value of the city is set as the explained variable, and the Ward test and likelihood ratio (LR) test are

Table 6 Estimation results of spatial autocorrelation model

Variable	Coefficient	*P* value
EG	0.492232	0.000
LNNP	−0.0173953	0.002
FT	−0.0006995	0.001
UR	−0.0080762	0.000
LNAW	0.011455	0.803
BS	−0.184332	0.007
BE	−0.0232387	0.151
LNPT	0.0210661	0.066
LNPD	−0.0176354	0.519
EC	0.002402	0.057
ρ	−0.2502335	0.000
Wald test	/	0.0033
LR test	/	0.0159
R-sq	0.7417	/
Model selection	Fixed effect	/

Table 7 Direct effect, indirect effect, and total effect

Variable	Direct effect	Indirect effect	Total effect
EG	0.4473268 (0.001)	0.6197206 (0.004)	1.067047 (0.000)
LNNP	− 0.0179437 (0.001)	0.0062764 (0.538)	− 0.0116673 (0.280)
FT	− 0.0006511 (0.001)	− 0.0003754 (0.114)	− 0.0010266 (0.001)
UR	− 0.0087644 (0.000)	0.0088743 (0.013)	0.0001098 (0.966)
LNAW	0.0223713 (0.616)	− 0.1386893 (0.168)	− 0.116318 (0.239)
BS	− 0.0174779 (0.012)	− 0.0114683 (0.637)	− 0.0289461 (0.231)
BE	− 0.0311953 (0.072)	0.1053105 (0.014)	0.0741152 (0.098)
LNPT	0.0193086 (0.094)	0.0188098 (0.478)	0.0381184 (0.167)
LNPD	− 0.021865 (0.417)	0.0816659 (0.213)	0.0598009 (0.398)
EC	0.0023784 (0.072)	0.0004802 (0.858)	0.0028585 (0.282)

used to examine the imitative effect of the model. The regression results reject the original hypothesis at the 5% significance level, which means that SDM cannot degenerate into the spatial lag model (SLM) and the spatial error model (SEM). Furthermore, the individual fixed effect is selected in the spatial panel econometric model by the Hausmann test, and the related results are shown in Table 6. The direct effect, indirect effect, and total effect are further given in Table 7.

Table 6 shows for Jiangsu Province that the general public budget expenditure/GDP, the total amount of post and telecommunications business, and the Engel coefficient of urban residents play a positive role in promoting urban resilience and pass the 10% significance test. On the other hand, the number of authorized patent applications, the degree of dependence on foreign trade, the urbanization rate, and the total deposits and loans of financial institutions/GDP have significantly negative effects. Among them, the greatest impact is the proportion of general public budget expenditure to GDP, which is because the expenditure of general public finance of local governments is mainly used

for ensuring employment for residents, supporting the development of education, raising the level of social security, strengthening public health construction, supporting ecological environmental protection, and enlarging infrastructure construction. A larger proportion of general public budget expenditure in GDP shows that the government has not only created more vitality and resilience in promoting urban construction, but also plays a growing role in controlling air pollution and high-quality urban development. This has gradually become a stabilizer and so-called ballast stone to maintain a city's smooth operation.

After further decomposition of the results in Table 7, the estimated results show that the effects of the local and surrounding areas where the general public budget expenditure accounts for the proportion of GDP are positive, thus increasing the scale of government expenditure, which can enhance the resilience of the region and its surrounding areas. Compared with other impact indicators, the foreign trade capacity described by the degree of dependence on foreign trade has little impact on urban resilience. Its direct effect is significantly negative at the 1% level, the indirect effect is also negative, and the total effect is negative. This indicates that cities with higher foreign trade dependence are more likely to be affected by external environmental changes, and urban vulnerability subsequently greatly increases (Gong et al. 2020).

The direct effect of the deposit balance/loan balance of financial institutions is significantly negative at the 10% level, whereas the indirect effect is positive. It shows that the lower the loan-to-deposit ratio of financial institutions is, the less conducive this is to the improvement of resilience in the local region. On the contrary, it will improve the level of resilience in other regions. This is because a low loan-to-deposit ratio indicates that financial institutions have more deposits and less loans, and the profitability of financial institutions is poor; while it is difficult for enterprises in the market to obtain loans to carry out production and operation activities, which affects regional economic and social development. At the same time, profit-driven capital spurs the resource elements in the market to invest in the industries and regions with high returns, while the low rate of return of financial institutions in this region will make financial resources spill over into the surrounding regions and other cities, thus increasing the urban factor endowment of adjacent cities to enhance their resilience.

5.6 Actual urban resilience performance of Jiangsu province during the COVID-19 pandemic

This research is based on a case study of urban resilience in Jiangsu Province. The importance of Jiangsu Province in the Yangtze River Delta urban agglomeration and the whole country has been mentioned in a previous regional overview. In previous studies, regional resilience work usually analyzes regional economic resilience and recovery over several years (Davies 2011) or decades (Martin and Sunley 2020). However, here, we use GDP growth indicators in the first quarter and the first half of 2020, because urban resilience and economic development are highly interactive, and the level of resilience can be characterized by economic growth to a large extent. At the same time, the corresponding key indicators are selected from the aspects of work resumption and industry so as to measure the urban resilience performance of 13 prefecture-level cities during COVID-19. We are certainly aware that it would take a longer time to tell the full story of regional resilience in Jiangsu and China due to the COVID-19 pandemic crisis, but based on the data available

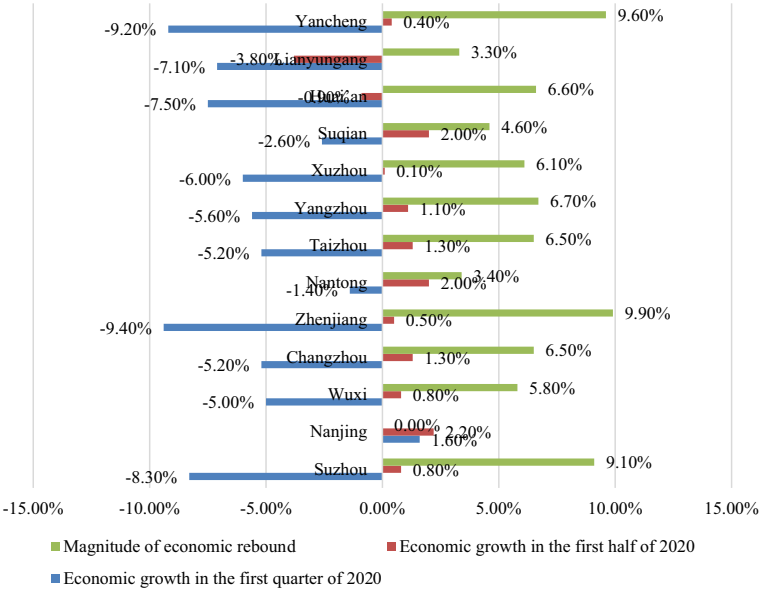


Fig. 4 Economic performance of Jiangsu Province in the first quarter and first half of 2020. *Source* Own compilation based on data from the statistics bureau of 13 prefecture-level cities

Table 8 Time and rate of work resumption in 13 prefecture-level cities of Jiangsu Province in 2020

City	Period				
	2020.01	2020.02	2020.03	2020.04	2020.05
Suzhou		> 95%			
Nanjing		> 95%	100% (March 18)		
Wuxi		100%			
Changzhou		> 95%			
Zhenjiang		> 95%			
Nantong		> 95%	97%	99.90%	
Taizhou		> 95%	99.6% (March 3)		
Yangzhou		70%		100% (April 13)	
Xuzhou		> 95%			
Suqian		100%			
Huai'an			82.2% (March 14)		
Lianyungang		> 90%	100%		
Yancheng		66%	94.1% (March 3)		

so far, we give at least some preliminary conclusions and also verify the resilience performances of 13 prefecture-level cities in Sect. 5.4.2.

According to data released by Jiangsu Provincial Bureau of Statistics, on the basis of a 5% year-on-year decline in GDP in the first quarter, GDP in the first half of the year increased by 0.9% year-on-year, achieving extremely difficult positive growth. Southern

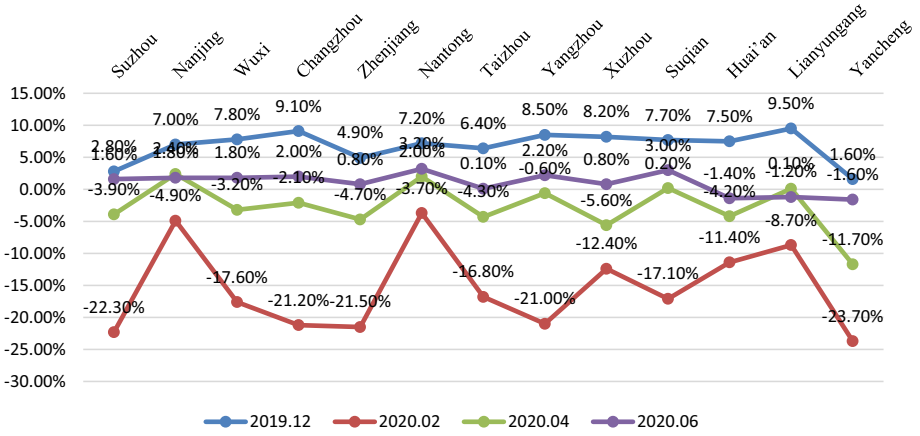


Fig. 5 Cumulative growth rate of above-scale industries in 13 prefecture-level cities from December 2019 to June 2020. *Source* Own compilation based on data from the statistics bureau of 13 prefecture-level cities

Jiangsu, the most dynamic economic development pioneer area in Jiangsu Province, suffered greatly from the epidemic, and the GDP of Zhenjiang in the first quarter fell at a rate of over 9% (Fig. 4). At the same time, Suzhou, as an export-oriented city with a developed economy, is deeply embedded in globalization, attracting more migrant workers, and many enterprises and projects were shut down due to the sudden epidemic, pushing the GDP to decline at a rate in the first quarter of 8.3%. However, during the epidemic, Suzhou attracted foreign investment on the basis of its strong industry and economy. The total amount and increase in the actual utilized foreign capital both reached a historical high since the reform and opening up. Industrial investment, in particular, has increased by 26.3%. Thus, its economy rebounded strongly in the first half of the 2020, achieving a positive growth of 0.8%. It is noteworthy that Fig. 4 shows that only Nanjing achieved positive economic growth (1.6%) in the first quarter, and it is also the only city among major cities in China that has achieved positive economic growth. This is not only beneficial from Nanjing's early introduction of the inclusive policy for small-and medium-sized enterprises (SMEs) as early as February 7, but also to the early resumption of production, which already reached 100% on March 8 (Table 8). At the same time, key projects have been continuously constructed, and the output value of advantageous industries or emerging industries such as high-tech manufacturing and electronic information has increased rapidly, thus promoting the steady increase in economic aggregate in the first quarter.

Compared with southern Jiangsu, central Jiangsu was less affected by the epidemic, and Nantong's GDP decreased by 1.4% in the first quarter, which was the lowest among the 13 prefecture-level cities except Nanjing's positive GDP growth. At that time, Nantong was an important birthplace of private enterprises, which played an important role in its economic development. During the epidemic, Nantong Municipal Government introduced a series of relevant policies to protect private enterprises, which retained the endogenous driving force of economic development and achieved 2% GDP growth in the first half of 2020. Compared with southern Jiangsu and central Jiangsu, northern Jiangsu was greatly affected by the epidemic, and the GDP growth rates of Huai'an and Lianyungang in the first quarter and the first half of the year were negative. Xuzhou, as the core city of Huaihai Economic

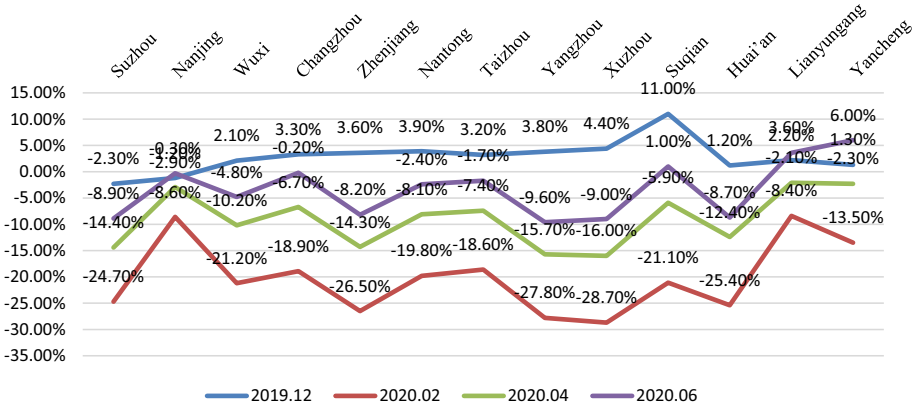


Fig. 6 Cumulative industrial electricity consumption of 13 prefecture-level cities in Jiangsu Province from December 2019 to June 2020. *Source* Own compilation based on data from the statistics bureau of 13 prefecture-level cities

Circle, experienced a 6% economic decline in the first quarter and a 0.1% growth in the first half of the year.

The running situation and development of industrial economy greatly affect the development of the whole national economy. From the industrial viewpoint, we select two indicators, the cumulative added value of industries above a designated size and the cumulative electricity consumption of industries, to analyze the industrial epidemic situation in 13 prefecture-level cities in Jiangsu Province from December 2019 to June 2020. It can be seen from Figs. 5 and 6 in December 2019 that the cumulative added value and electricity consumption of industries above a designated size in 13 prefecture-level cities in Jiangsu Province were in a state of growth, but by February 2020, the cumulative added value of industries above a designated size in 13 prefecture-level cities saw negative growth, among which Suzhou, Changzhou, Zhenjiang, Yangzhou, and Yancheng dropped by more than 20%. Compared with other cities, Nanjing and Nantong decreased by 4.9% and 3.7%, respectively. Combined with the time of resumption of work and production in Table 8, it is not difficult to find that the late resumption of work and production in Yangzhou, Huai'an, Yancheng, and other cities led to a series of chain reactions, so that the economic growth in the first half of the year lagged behind other cities.

By June 2020, the cumulative added value of industries above a designated size in most cities had been increasing positively, among which Nantong, Changzhou, and Yangzhou had increased by more than 2%, while Huai'an, Lianyungang, and Yancheng were still in a negative growth state. In terms of industrial cumulative electricity consumption, although the decline of cumulative electricity consumption in all prefecture-level cities had been narrowing continuously, most cities still had negative growth by June 2020, with only Suqian, Lianyungang, and Yancheng increasing positively, while Yangzhou and Xuzhou still having large declines at − 9.6% and − 9%, respectively.

The resilience level of cities in this epidemic overall is almost the same as that of low, medium, and high cities in Table 5 in 2018. Nanjing has bucked the trend in the epidemic and is the only city among the major cities in China to maintain positive GDP growth in the first quarter. Nantong promotes the development of large industries by promoting the landing of large projects. In terms of regional space, integrating into southern Jiangsu in an all-round

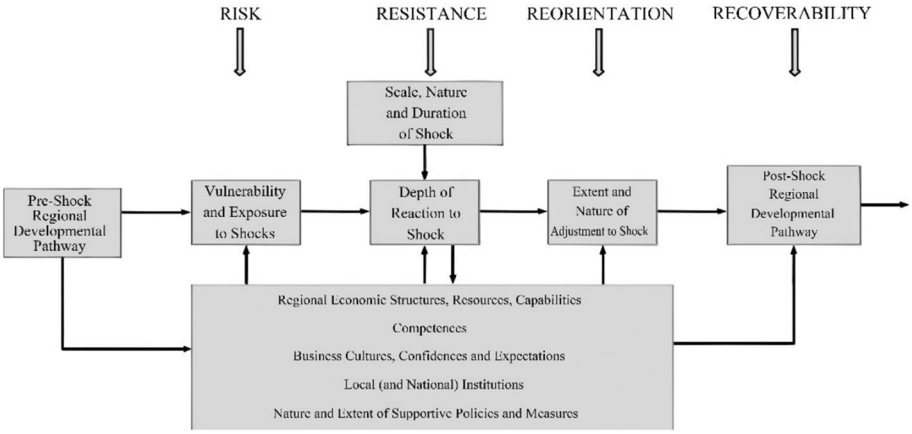


Fig. 7 Regional resilience to recessions. *Source* Martin et al. (2016)

way, connecting Shanghai in an all-round way, and promoting high-quality development in an all-round way, the city's economic scale successfully broke through the one trillion yuan mark in 2020. It is worth noting that Suqian, which is classified as a low-resilience city in Table 5, performed well during the epidemic. Both the GDP growth rate in the first half of the year and the resumption of work have been at the forefront of Jiangsu Province, and its GDP growth rate and Nantong rank second in the whole province, all of which benefit from Suqian's active layout of emerging industries and promotion of a strong industrial city.

The epidemic has accelerated the formation of a new pattern of world economic development. For this reason, the China government put forward its "Dual Circulation" strategy, emphasizing that the country's economy should churn faster to meet domestic demand as the starting point and be the foothold of development. How to explore the resilience of China's cities under the "Dual Circulation" strategy will be a major trend in the future. At the same time, during and after the COVID-19 outbreak, there have been few studies on regional resilience. Due to the scale of the current global crisis and recession during COVID -19, the definition of resilience will definitely change in the near future (Glaeser 2022). This will no doubt feed back into the conceptual debate about regional resilience (Martin and Sunley 2020). According to Martin et al. (2016), China is now in the recovery stage (Fig. 7). However, other countries and regions are at different stages in Fig. 7. The response policies of different countries to the COVID-19 outbreak and the role played by the governments are vital for analyzing and explaining the differences in crisis response and regional resilience (Djalante et al. 2020; Eakin et al. 2017; Hale 2020). Ultimately, enhancing regional resilience and sustainable development is a complicated political process. In the future, more people will pay attention to comparative studies of resilience between different countries or regions.

6 Discussion

Urban resilience involves many factors, from which this study selects economic, social, ecological, infrastructure, and community, while ignoring some internal non-quantifiable soft power indicators, such as sound social organizations, policy systems, and urban

culture. We consider covering more indicators of urban resilience in the following research and comprehensively evaluates such factors as policy systems and cultural systems by in-depth interviews and other methods. However, the selected research period is 2009–2018, a relatively short span, in the spatial–temporal analysis of urban resilience, placing certain constraints on exploring the law of urban development. As for studying spatial differentiation, as few objects of study as 13 cities in Jiangsu cannot fully reflect the law of spatial distribution differences. The research of urban resilience needs to be conducted in a longer time span and centered on more objects. In the subsequent research, the subjects will contain counties and townships of each city. The GIS technology will be applied to explore the mechanism of urban resilience evolution from a more microscopic perspective (Ključanin et al. 2021). Also, uncertain risk factors should be taken into account in the future study of urban resilience, and assessment methods of urban resilience should be constantly updated. The risk assessment method based on scenario simulation (Kimand Newman 2020) is more accurate and rarely used in the assessment of urban resilience, so it can be used to improve the assessment system of urban resilience. In the end, as cities are interrelated and interconnected, the occurrence and influence of major public emergencies, whether caused by human or natural factors, often go beyond a certain administrative region, involving multiple administrative bodies and showing cross-administrative characteristics. At present, there is little research on the degree of resilience correlation between cities from the perspective of spatial network. Subsequent research can be based on various factors, such as transport and population mobility (Chen et al. 2021; Chu et al. 2021; Gong et al. 2020) to analyze the resilience of urban spatial network structure.

7 Conclusions and recommendations

7.1 Conclusions

With the frequent occurrence of diversified and unpredictable major public security events, research is urgently needed on urban resilience for effective prevention before a disaster, maintenance of social order and stability during a disaster, and rapid recovery and reconstruction after a disaster. The global spread of the COVID-19 epidemic highlights the urgency and necessity of building resilient cities. Based on data from 2009 to 2018, this research measures the resilience of various cities in Jiangsu Province, visualizes the results by ArcGIS, and analyzes the overall and interval differences of resilience through the Theil index. Furthermore, Moran′sI and Moran scatter plot are used to describe the spatial correlation characteristics of urban resilience, and a spatial Durbin model is set to analyze the mechanism of urban resilience. The results are as follows:

1. From the perspective of urban comprehensive resilience value, the spatial pattern of the overall resilience of southern Jiangsu, central Jiangsu, and northern Jiangsu presents a decreasing trend. In terms of time frame, compared with the beginning of 2009, the resilience of various cities in Jiangsu was on the rise at the end of 2018.
2. For regional differentiation, the total Theil index shows a wave-like downward trend during the study period. Compared with the beginning of the period, the differences in resilience between cities are narrowing. According to the decomposition results of the Theil index, the imbalance among southern, central, and northern Jiangsu is the main reason for the differences of urban resilience in Jiangsu Province. However, the differ-

ence of resilience level among the three regions is also gradually narrowing. Among them, the internal difference of the south region is larger than that of the other two regions.

3. From spatial correlation analysis, we can see an obvious positive correlation between the whole and partial urban resilience in Jiangsu Province. This suggests that the spatial distribution of urban resilience in Jiangsu is not random, but there is an interaction relationship between the areas with equivalent economic level and similar geographical distance.
4. By measuring the resilience of urban subsystems, it can be seen in 2018 that the mean value of economic resilience in Jiangsu was the highest, while the mean value of ecological resilience was the lowest, which needs to be further improved. The spatiotemporal evolution map of urban resilience shows that the comprehensive value of urban resilience in Jiangsu is on the rise, the number of cities with high resilience is increasing year by year, and the number of cities with low resilience is decreasing.
5. In terms of factors affecting urban resilience, the comprehensive value of resilience level in other areas has a significantly negative effect on resilience in the local region. General public budget expenditure/GDP has a positive role in promoting the resilience of this region and other cities. The degree of dependence on foreign trade and the deposit balance of financial institutions/loans have a significantly negative impact on local resilience, but the former has a negative spatial effect on the resilience of other regions, while the latter has a positive impact on the resilience of cities in other spatial and geographical areas.

7.2 Recommendations

In view of the above empirical results, we offer measures to improve the overall level of urban resilience in Jiangsu Province and to narrow the gap between cities. (1) First, the authority should focus on the central and northern areas of Jiangsu, improve the level of public services in backward cities and areas around central cities, narrow the service gap between urban and rural areas, and improve the level of equalization of regional services. (2) The government should intensify the construction of urban greening, speed up the construction of an ecological spatial pattern of resilient cities, promote the co-construction of woodland and green space, build an interconnected ecological network, and improve the quality and stability of the ecosystem. (3) Cities should focus on the diversity of their own economic development and promote the internal production, distribution, circulation, and consumption of resource elements, rather than relying too much on foreign trade. In addition, during the process of planning and building resilient cities, the financial intermediary and financial market system should be improved, and the deposit/loan ratio of regional financial institutions should be appropriately raised to stimulate the endogenous power of the urban economy.

Appendix

See Tables 9 and 10

Table 9 Resilience values of various dimensions of Jiangsu cities in 2018

Year	City	Ecological resilience	Economic resilience	Social resilience	Infrastructure resilience	Community resilience
2018	Suzhou	0.0582	0.1625	0.1101	0.1646	0.2044
	Nanjing	0.1509	0.1441	0.1807	0.0997	0.1407
	Wuxi	0.0584	0.1226	0.0797	0.1080	0.1357
	Changzhou	0.0430	0.0967	0.0643	0.0731	0.0566
	Zhenjiang	0.0521	0.0674	0.0535	0.0425	0.0376
	Nantong	0.0534	0.0853	0.0680	0.0865	0.0743
	Taizhou	0.0389	0.0657	0.0563	0.0427	0.0467
	Yangzhou	0.0511	0.0651	0.0519	0.0475	0.0449
	Xuzhou	0.0509	0.0635	0.0805	0.0800	0.0698
	Suqian	0.0426	0.0310	0.0397	0.0357	0.0384
	Huai'an	0.0403	0.0500	0.0490	0.0399	0.0359
	Lianyungang	0.0557	0.0389	0.0397	0.0381	0.0280
	Yancheng	0.0379	0.0500	0.0534	0.0462	0.0539

Table 10 All abbreviations and nomenclatures used in this study are summarized as follows

SDM	Spatial Durbin Model
CNY	Chinese yuan
GDP	Gross domestic product
DLI	Development and Life Index
ESDA	Exploratory spatial data analysis
SG	General public financial expenditure/GDP
NP	Patent application authorization
PT	Total post and telecommunication business
PD	Population density
EC	Engel coefficient
FT	Degree of foreign trade dependence
UR	Urbanization rate
AW	Average wage
BS	total deposit and loan amount/GDP
BE	deposit balance/loan balance
SEMs	small- and medium-sized enterprises
SZ	Suzhou
NJ	Nanjing
WX	Wuxi
CZ	Changzhou
ZJ	Zhenjiang
NT	Nantong
TZ	Taizhou
YZ	Yangzhou
XZ	Xuzhou
SQ	Suqian
HA	Huai'an
LYG	Lianyungang
YC	Yancheng

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Declarations

Conflict of interest The authors declare no conflict of interest.

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