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Data-Driven Urban Resilience Evaluation Using Four Dimensions for Cities in Northern Anhui Province

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Abstract: Urban resilience is a crucial determinant of sustainable urban development. Northern Anhui, one of the rapidly growing cities in China, is making significant efforts toward sustainable urban development. However, there is a lack of a comprehensive method to assess its level of urban resilience. Hence, this study aimed to develop an urban resilience evaluation index for Anhui based on four dimensions: social, economic, infrastructure and ecological (SEIE). The study evaluated urban resilience and the major influencing factors that affected the urban resilience level. The entropy weight method was used to evaluate urban resilience, the coupling coordination degree model measures the SEIE coupling coordination degree of each city and the obstacle degree model identifies key obstacles. The results indicated that the overall spatial distribution of resilience levels in the study area was higher in the east and west and lower in the north and south. The SEIE showed a pattern of "high coupling, low coordination" in Northern Anhui, with the social dimension having the most significant impact on urban resilience. The factors most influencing urban resilience in different cities in Northern Anhui were pension insurance coverage, facilities, health institutions and green spaces. Therefore, some recommendations were made to promote regional coordinated development, increase investment in social development and formulate targeted policies to enhance investments. The findings provide theoretical support for improving urban resilience in Northern Anhui and offer a reference for local governments and planners. Furthermore, the SEIE index could also be applied to evaluate the level of urban resilience in other similar cities across China.

Keywords: Data-driven, Urban resilience evaluation index, Coupling coordination, Obstacle degree, Northern Anhui Province

INTRODUCTION

Many cities have experienced rapid urbanisation over the past few decades. The substantial growth in human populations and uneven distribution of natural resources have influenced the balance between humans and the environment, resulting in a complex global natural disaster. In particular, the challenges posed by extreme disaster events, public health and safety issues have intensified recently, posing a serious threat to human well-being and the sustainable development of cities (Zuccaro and Leone, 2021; Liu et al., 2023). Over the past decade, several severe natural disasters have occurred globally, resulting in significant loss of life and property. For example, a glacier collapse in the Chamoli district of North Akhand, India, triggered massive floods in the Alaknanda and Dhauliganga Rivers, leading to over 207 deaths and disappearances, as reported by the Ministry of Emergency

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Management of the People's Republic of China (2022) compilation of the top 10 global natural disasters of 2021. Similarly, this report revealed temperatures reached 47.5°C in Lytton during June and July in British Columbia, Canada, setting a new record for the highest temperature recorded in the country. In addition, in April 2022, heavy rainfall in south-eastern Indonesia and East Timor resulted in severe flooding disasters. As of 18th August 2024, these events had caused the deaths of 222 people, with dozens more missing and displaced tens of thousands in both countries. In addition, natural disasters have also impacted public health and safety issues. By the end of 2021, the World Health Organisation (WHO) reported that 15 million people worldwide had died from pneumonia, highlighting the impact of sudden-onset disasters on our cities and underscoring the urgent need to enhance their resilience.

Cities are complex mega-systems with a certain degree of resilience that allows them to maintain their functions and dynamic stability (Meerow, Newell and Stults, 2016). Urban resilience is defined as the ability to cope with long-term stresses and unforeseen shocks that may arise during urban development, to protect its internal structure and maintain healthy development (Büyüközkan, Ilıcak and Feyzioğlu, 2022) while continually adjusting and improving over time (Wang, Fu and Zhou, 2023). After a disaster, the speed of economic and social recovery depends on the resilience level (Wang, Li and Li, 2021). Regions with lower resilience are less adaptable, requiring more time and resources for recovery. In contrast, more resilient cities can quickly recover and potentially surpass their pre-disaster conditions when faced with known and unknown external disturbances (Wang, Li and Li, 2021). Recognising these dynamics underscores the critical need for deeper exploration into disaster management and urban resilience enhancement.

Many countries have proposed relevant policies to promote and implement urban resilience initiatives. In 2013, the Rockefeller Foundation presented the "100 Resilient Cities" programme to promote the process of urban construction and since then, urban resilience in Asia has entered a stage of rapid development (Wardekker et al., 2020). In 2013, Japan enacted the Basic Law for Land Resilience and, in 2014, issued the Basic Plan for Land Resilience to form its land resilience policy. In the same year, the New York City government formulated a master plan entitled "A Stronger, More Resilient New York". Two years later, it developed and enacted the master plan "One New York 2050: Building a Strong and Equitable City", which included a chapter on "Resilient Cities" (OneNYC, 2015). In October 2020, China introduced the concept of Resilient Cities for the first time, highlighting the importance of enhancing the quality and stability of ecosystems in the "Recommendations of the Central Committee of the Communist Party of China on Formulating the Fourteenth Five-Year Plan for National Economic and Social Development and the Long-Range Objectives for 2035" (National Development and Reform Commission, People's Republic of China, 2020). Subsequently, various provinces in China also began formulating relevant resilience policies. For example, Anhui Province proposed in its 2021 Government Work Report that urban renewal actions should be implemented over the next five years to build resilient cities and to improve the modernisation of urban governance. By assessing urban resilience, it is possible to judge the ability of existing cities to withstand crises, maintain and restore urban systems and identify parts of the urban system that are not sufficiently resilient to further improve resilience (Feng et al., 2020). In short, these policies provide crucial theoretical support for this research.

Past research primarily focused on developed cities, though developing regions face the most significant vulnerability in terms of both disaster resistance and recovery when encountering unforeseen disasters. Therefore, studying the disaster resilience of cities in developing regions has become an urgent and practical issue. Despite the rapid economic and social development in Anhui Province, the level of urban development remains relatively slow and its capacity for resistance and buffering is still insufficient. Before the implementation of national policies, the construction of disaster resilience in the region's cities had not received sufficient attention, resulting in poor outcomes. For example, before the COVID-19 pandemic, Anhui Province's economic output ranked 11th among the 31 provinces and cities in China, but it dropped to 21st after the outbreak. Northern Anhui, as one of the slower-developing regions in the province, faces even greater challenges. Therefore, researching urban disaster resilience in this region is crucial for its sustainable and stable development in the future.

This study aimed to answer the following questions: (1) How has the resilience level of cities in Northern Anhui changed in terms of spatial and temporal characteristics? and (2) What are the key factors influencing urban resilience in this region? Several strategies were proposed to improve urban disaster resilience, which was crucial for theoretical insights and practical applications in promoting the sustainable and healthy development of cities in Northern Anhui. This study introduced innovations in several aspects: (1) the development of a more targeted four-dimensional framework for evaluating urban disaster resilience by integrating social, economic, infrastructure and ecological indicators, (2) conducting coupling coordination and obstacle analysis for each dimension to pinpoint the major influencing factors in different cities and (3) focusing in developing regions, where the established framework can be implemented in other cities with similar conditions.

LITERATURE REVIEW

Concept of Urban Resilience

Resilience originates from the Latin word *resilio*. In the 1970s, Holling (1973) first introduced the concept of resilience into the field of ecology and described ecological resilience as the sustained coping of ecosystems in response to the influence of external factors. In the 21st century, the connotation of resilience has gradually been extended to the field of urban construction and scholars have proposed the concept of urban resilience from the perspectives of different disciplines. Alberti (2008) summarises urban resilience as the high absorptive capacity of a city during a series of changes and combinations. The Rockefeller Foundation in the United States considers urban resilience to be the ability of individuals, communities, institutions, industries and other components of a system to survive, adapt and thrive, regardless of whether they experience sudden or slow disruptions (Spaans and Waterhout, 2017). The United Nations defines urban resilience as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate and recover from disasters in a timely and effective manner, including through the preservation and restoration of its basic structures and functions". Although different fields and scholars have different interpretations of urban resilience, the core concept is largely the same, including the ability to resist and recover despite unknown disasters (van Hoek, 2020; Yao et al., 2022). This study, combined with the literature, explained urban resilience as the ability of urban mega-systems to adapt and recover rapidly when faced with internal instability and external contingency shocks.

Framework for Assessing Urban Resilience and Influencing Factors

Researchers continuously endeavour to develop urban resilience assessment systems from various disciplinary perspectives (Zhao et al., 2022; Liu et al., 2022). They have proposed evaluation methods suited to their respective fields (Mu, Fang and Yang, 2022; Qiao and Pei, 2022) that encompass qualitative approaches, such as indicator evaluation and model simulation and quantitative methods, including questionnaires (Carpenter, Westley and Turner, 2005; Cutter, Burton and Emrich, 2010; Boston et al., 2014). Many scholars focus on various dimensions such as society, economy, ecology, infrastructure, population and community (Cutter, Ash and Emrich, 2014; Zhao et al., 2022; Mu, Fang and Yang, 2022; Cao et al., 2023). Some researchers even explored the level of urban resilience in the study area from the perspectives of robustness, rapidity, redundancy and resourcefulness (Huang et al., 2021). In contrast, Zhang, Yang and Lu (2023) divided the north-eastern provinces of China into three spatial regions to assess the level of resilience.

Institutional safeguards, industrial transformation, economic development, health organisations and municipal infrastructure are the main obstacles to improving urban resilience (Zhao et al., 2022). Due to advancements in technology and knowledge, the key factors influencing urban resilience levels have shifted from economic status, industrial structure and educational levels to public infrastructure, technological advancements and educational development (Wang, Liu and Zhou, 2023). In contrast, Chen et al. (2021) found that the market is the most influential factor in urban resilience, followed by openness, technology, finance and government. Zhang et al. (2019) found that the percentage of actual utilisation of foreign investment in gross domestic product (GDP) and carbon emissions per CNY10,000 of GDP had a negative impact on urban resilience in 56 cities in China. However, factors like GDP per square kilometre, urban pension coverage rate, proportion of population with higher education levels and expenditure on urban maintenance and construction have positive impacts on urban resilience. Furthermore, some research indicates that the ecological variables driving the geographical heterogeneity of urban resilience, represented by per capita ecological land area, are progressively taking centre stage, with the combined effects of these factors having a greater influence than the sum of their individual effects (He, Zheng and Zhao, 2023).

Strategies for Strengthening Urban Resilience

Many scholars have offered suggestions for improving urban resilience measures. For example, Shi et al. (2022) suggest adopting moderate-scale planning and management could enhance urban resilience. Relatively backward cities should focus on economies and the provision of public services and facilities to enhance their overall resilience. Mu, Fang and Yang (2022) argue that enhancing the urban resilience of city clusters requires improving the resilience of cities resilience outside the core area. This includes strengthening the spillover effect, enhancing intercity linkages, identifying the direction of industrial development, actively adjusting the industrial structure, building and sharing public services and enhancing the risk-resistant capacity of infrastructure.

Urban resilience can also be improved by increasing investments in economic development and healthcare resources (Liu et al., 2023). Through the promotion of digital health services and the establishment of an intelligent health management system, the output value of health and social work in relatively underdeveloped areas can be upgraded. Upgrading their management systems and supervision mechanisms and increasing social participation can improve the operational efficiency and capacity of harmless treatments. In addition, the path to enhancing urban resilience is to improve its shortcomings and focus on cross-regional urban cooperation in public services, such as healthcare, human resources and social security (Shi et al., 2022; Zhao et al., 2022).

While extensive research has been conducted to explore urban resilience levels, three research gaps were identified. Firstly, in terms of indicator selection, many studies chose a relatively small number of indicators (Ma et al., 2020; Wu et al., 2023; Mitrović et al., 2023). In contrast, the current study selected 22 indicators based on key influencing factors identified from previous literature and taking into account data availability, aiming for a more comprehensive and scientifically robust approach. Second, while many studies focused on investigating influencing factors directly, research on the coupling coordination degree of each dimension is relatively limited. Third, the majority of research focuses on developed regions (Mu, Fang and Yang, 2022; He, Zheng and Zhao, 2023; Cao et al., 2023), while comparatively less attention was given to developing regions. This study analysed the coupling coordination degree of SEIE and the relative importance of each influencing factor to provide a more comprehensive framework to assess the urban resilience levels in China.

RESEARCH METHODOLOGY

The research methodology flow of this study is shown in Figure 1. Based on the actual situation of the research area and the collected data, a resilience assessment system for the region's cities was constructed. The entropy method was used to calculate resilience levels from 2017 to 2021, while ArcGIS was utilised for visual analysis of their spatiotemporal characteristics. Additionally, a coupling coordination model was employed to assess the coupling coordination relationships between various dimensions. Finally, the obstacle degree model was used to explore the main factors affecting urban resilience in the study area and recommendations are proposed based on the research findings.

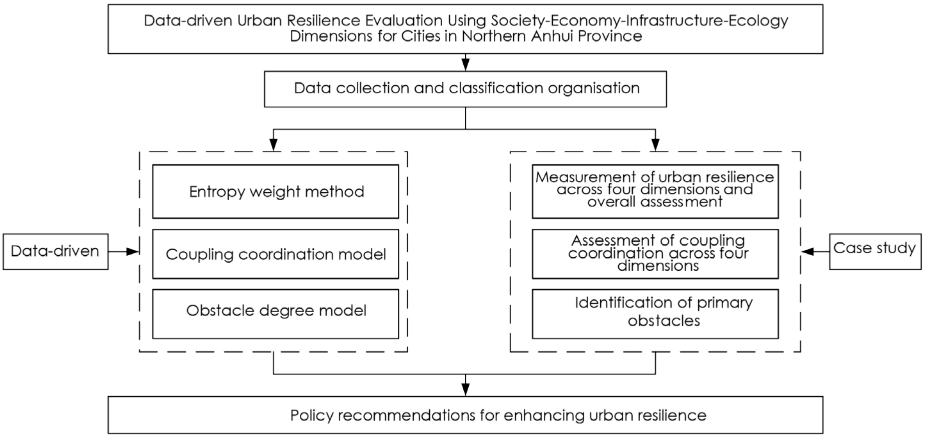


Figure 1. Research flowchart

Study Area

Northern Anhui is in the Yangtze River Delta region, with Jiangsu to the east, Southern Anhui to the south, Henan to the west and Shandong to the north (as shown in Figure 2). It contained six provincial municipalities: Suzhou, Huaibei, Bengbu, Fuyang, Huainan and Bozhou. The study area covers 39,200 km^2, accounting for approximately 27.98% of Anhui, which is 140,100 km^2 overall. By the end of 2022, the resident population of Northern Anhui totalled 26,723,000, with economic levels in the middle and back of the province.

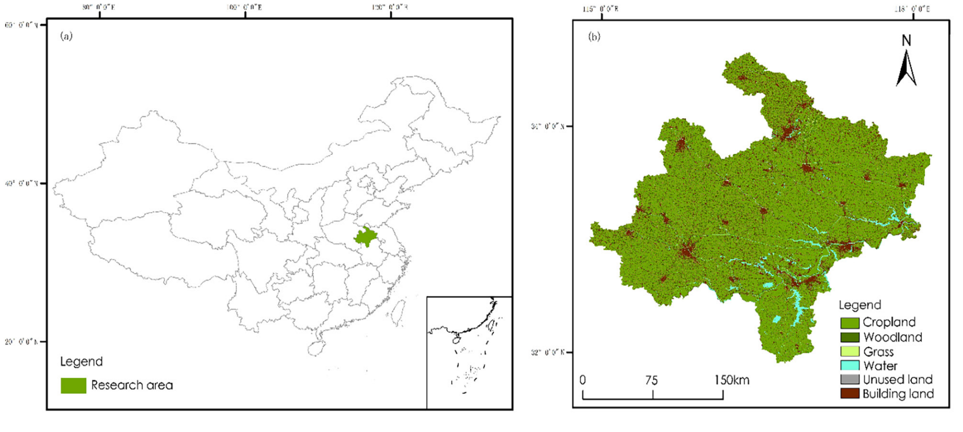


Figure 2. Case study area

System Indicators to Evaluate Urban Resilience

The social, economic, infrastructure and ecological dimensions have been consistently considered essential components within the urban system (Ma et al., 2020; Zhang et al., 2019; Chen, Su and Zhou, 2021; Zhao et al., 2022; Wang, Liu and Zhou, 2023; He, Zheng and Zhao, 2023). Based on the principles of objectivity, scientific rigour and comparability, along with considerations of data accessibility and practicality and in reference to state-issued guidelines on safety resilience city evaluation, a total of 22 evaluation indices (C1 to C22) in four dimensions, namely "Social" (B1), "Economic" (B2), "Infrastructure" (B3) and "Ecological" (B4), were selected to construct the urban resilience evaluation system. Figure 3 shows a schematic diagram of the four dimensions and their corresponding resilience components.

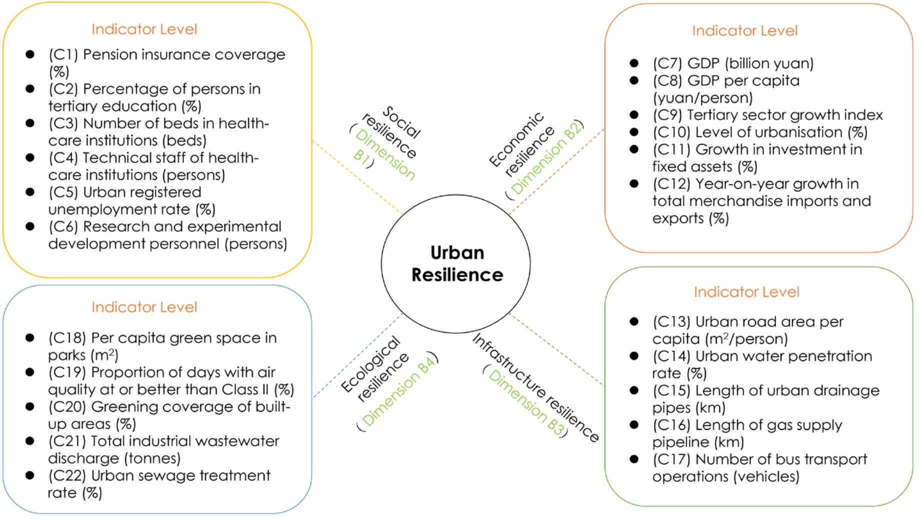


Figure 3. Resilience evaluation index system for Northern Anhui cities

This study employed indicators C13 to C17 to represent public infrastructure, technological development and educational advancement factors, as proposed by Wang, Liu and Zhou (2023). In accordance with Zhang et al. (2019), this study used indicators C1 to C2 and C6 to C8 to represent GDP per square kilometre, urban pension insurance coverage rate, the proportion of the population with higher education and urban maintenance and construction expenditure in their study on urban resilience. Based on Chen et al. (2021), market, openness and technology factors require special attention, so indicators C10 to C12 were also included in the framework. Zhao et al. (2022) indicate that industrial transformation, health organisations and municipal infrastructure are major obstacles to improving urban disaster resilience. Over time, the impact of environmental and social indicators has gradually increased (He, Zheng and Zhao, 2023), hence this study included indicators C3 to C5, C9 and C18 to C22.

Entropy Weight Method

The entropy weight method determines the weights of indicators by calculating the entropy value of the indicator data to assess the degree of dispersion of the indicators. Specifically, a higher entropy value indicates a greater degree of dispersion for the indicator, thus implying a higher impact on the comprehensive evaluation and consequently, a higher weight allocation (Wang et al., 2022b). Compared to other methods, the entropy weight method is more objective and can effectively avoid the influence of subjective factors (Wang, Zhou and Shen, 2023). The specific steps of this calculation method were as follows:

1. An initial evaluation matrix was constructed with *m* as research objects and *n* as indicators where X_{ij} denoted the value of the *j*th indicator for the *i*th research subject.

   $$X = [\chi_{ij}]_{mn} \quad \text{Eq. 1}$$

2. The inconsistency in the indicator outline causes the data of different indicators to be large or small, thereby affecting the calculation results. To eliminate the influence of the quantitative outline, raw data should be standardised before analysis. Positive indicators were subjected to normalisation (as shown in Equation 2) and reverse indicators were reversed (as shown in Equation 3) where maxX_{ij} denoted the maximum value and *min*X_{ij} denotes the minimum value.

   $$\chi'_{ij} = \chi_{ij} - \min \chi_{ij} / \max \chi_{ij} - \min \chi_{ij} \quad \text{Eq. 2}$$

   $$\chi'_{ij} = \max \chi_{ij} - \chi_{ij} / \max \chi_{ij} - \min \chi_{ij} \quad \text{Eq. 3}$$

3. The information entropy value of indicator e_j was calculated as in Equation 4 where P_{ij} was the weight of the indicator in which the *j*th indicator was located in year I and e_j was the information entropy of the *j*th indicator.

   $$e_j = -k\left[\sum_{i=1}^{n} P_{ij} \ln (P_{ij})\right] \quad \text{Eq. 4}$$

4. The information utility value *dj* was calculated as in Equation 5.

   $$d_j = 1 - e_i \quad \text{Eq. 5}$$

   This indicated that the larger the value of information entropy, the smaller the role of its influence on the comprehensive evaluation and the smaller the weight it occupied; and vice versa, the smaller the value of information entropy, the larger the role of its influence on the comprehensive evaluation and the larger the weight it occupied.

5. The weights of the evaluation indicators were determined in Equation 6 where $0 \leq w_j \leq 1$. The greater the weight of the indicator, the greater the impact on the target.

$$w_j = (1 - e_j) / \sum_{j-1}^{m} (1 - e_j) \qquad \text{Eq. 6}$$

Data for 22 evaluation indicators for the four dimensions of urban resilience were obtained from the Anhui Statistical Yearbook, statistical yearbooks for the cities in Northern Anhui and annual reports of municipal governments providing information disclosure. The data were collated and substituted into Equations 1 to 6 to calculate the urban resilience levels for the six cities in Northern Anhui from 2017 to 2021.

Coupling Coordination Degree Model

The coupling degree of coordination was used to evaluate the level of coupling and coordinated development of the four dimensions of resilience within the city, "social-economic-infrastructure-ecological" and the calculation formula was as follows:

$$C = \frac{4' \, (U_1{}' U_2{}' U_3{}' U_4)^{1/4}}{U_1 + U_2 + U_3 + U_4} \qquad \text{Eq. 7}$$

where C was the coupling degree and the value range was [0,1]. The larger the value of C, the better the coupling relationship within the city's various systems which facilitates orderly operation; U_1, U_2, U_3 and U_4 respectively, represented the fourth subsystem of the composite index.

$$T = aU_1 + bU_2 + cU_3 + dU_4 \qquad \text{Eq. 8}$$

where T was a comprehensive evaluation index that reflects the overall level of urban resilience. The larger the value of T, the higher the level of urban resilience. a, b, c and d represented weights and the four systems were equally important for urban resilience, $a = b = c = d = 1/4$.

$$D = (C'T)^{1/2} \qquad \text{Eq. 9}$$

where D was the degree of coupling coordination and the value range was [0,1]. A larger D indicated a more coordinated level of development between the subsystems and vice versa indicating a low degree of synergy. Based on related studies (Luo et al., 2022; Xiong et al., 2022), the coupling coordination degree was divided into eight levels, as listed in Table 1.

Table 1. Criteria for evaluating the degree of coupling coordination

Degree of Coupling (D) Coordination	Level of Coordination
0.8 < D ≤ 1.0	Senior coordination
0.7 < D ≤ 0.8	Intermediate coordination
0.6 < D ≤ 0.7	Primary coordination
0.5 < D ≤ 0.6	Reluctant coordination
0.4 < D ≤ 0.5	Impending disorder
0.3 < D ≤ 0.4	Mild disorder
0.2 < D ≤ 0.3	Moderate disorder
0.0 < D ≤ 0.2	Serious disorder

Barrier Degree Model

To determine the optimal direction for enhancing urban resilience in the study area, the obstacle degree model was used to assess the negative impact of each indicator on the overall system. This helped identify how each indicator impeded and limited urban resilience levels. The formula was as follows:

$$O_{ij} = \frac{w \times P \times (\frac{X - X_{min}}{X_{max} - X_{min}})}{\sum_{j=1}^{m} w \times P \times \left(\frac{X - X_{min}}{X_{max} - X_{min}}\right)} \qquad \text{Eq. 10}$$

where O_{ij} was the degree of obstacles of indicator layer *j* under criterion layer *i* to the improvement in the urban resilience level, *w* was the weight of the criterion layer and *P* was the weight of the indicator layer. The larger the value of $O_{ij,}$ the greater the degree of obstacles to urban resilience.

$$O_i = \sum O_{ij} \qquad \text{Eq. 11}$$

where O_i was the degree of the obstacle of criterion layer *i* to the increase in the urban resilience level, which was the sum of O_{ij} values. The larger the value, the greater the degree of the obstacle to urban resilience.

RESULTS AND DISCUSSION

Spatio-Temporal Changes of Urban Resilience

The mean value of the urban resilience level in Northern Anhui was obtained by calculating the average value for each year (as shown in Table 2 and Figure 4). The results showed a gradual increasing trend in urban resilience levels from 2017 to 2021 across the six cities in Northern Anhui. Interestingly, there was a substantial increase in urban resilience level of approximately 20.67% from 2020 to 2021, which was due to the increased investment in social resources following the new crown epidemic.

Table 2. Resilience level of Northern Anhui cities in different years

City	Years				
	2017	2018	2019	2020	2021
Huaibei	0.3744	0.3972	0.4500	0.5178	0.5855
Bozhou	0.2402	0.3207	0.3852	0.4447	0.5139
Suzhou	0.2334	0.2737	0.2981	0.3204	0.4465
Bengbu	0.4880	0.5041	0.5664	0.5973	0.6930
Fuyang	0.2943	0.4295	0.4425	0.4515	0.5436
Huainan	0.3380	0.3325	0.3526	0.3883	0.4997

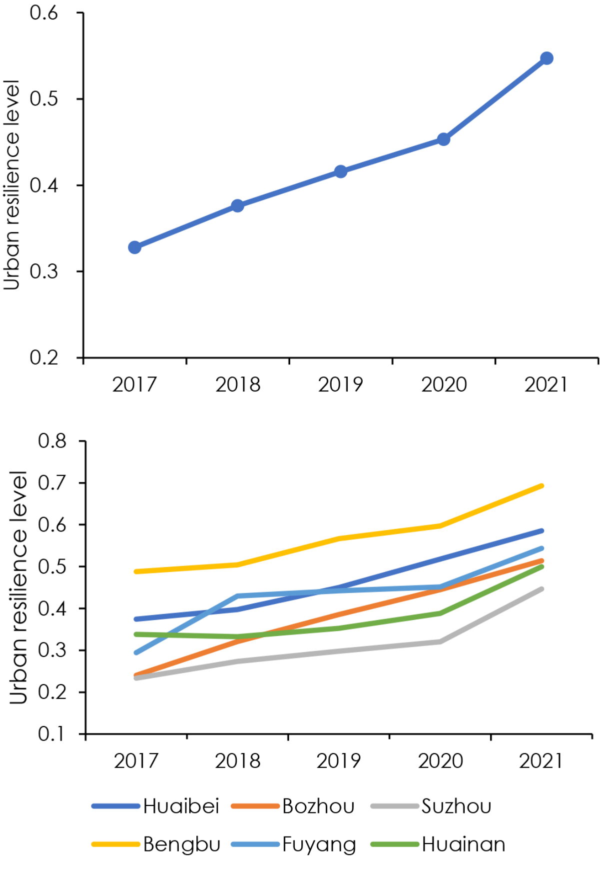


Figure 4. Changes in resilience levels overall and for cities in Northern Anhui cities from 2017 to 2021

To have a clearer understanding of the spatial changes, the data were visualised using ArcGIS software (as shown in Figure 5). The resilience level of the cities in Northern Anhui fluctuated considerably over the study period. The eastern and western areas showed slightly higher resilience to risks, whereas the northern and southern areas consistently showed lower resilience capabilities. Except for Bengbu, the resilience level of the regional cities was generally low in 2017. In 2021, the resilience levels of cities in the east, west and centre of the region increased, with the east and west regions showing the highest resilience levels. However, the central region exhibited the greatest increase in resilience.

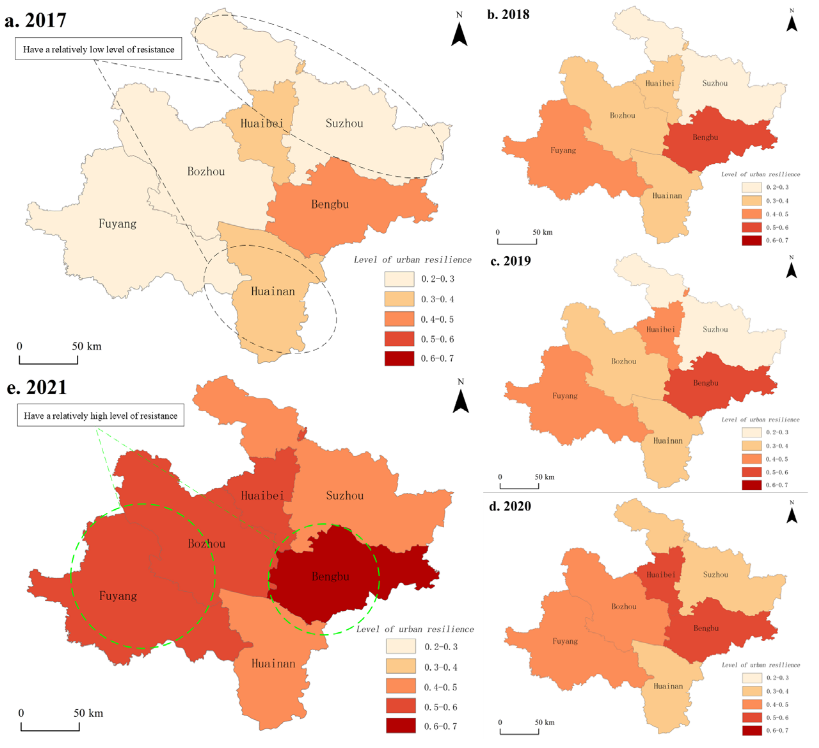


Figure 5. Spatial and temporal distribution of urban resilience in Northern Anhui cities from 2017 to 2021

Resilience levels in the four dimensions

The results for the four dimensions in relation to the toughness levels for cities in Northern Anhui from 2017 to 2021 are plotted in Figure 6. In terms of the level of social resilience, the six cities in Northern Anhui showed similar development trends over the study period, with all peaked in 2021 (as shown in Figure 6a). Due to the promotion of national policies, cities in Northern Anhui were actively responding, leading to further enhancement of resilience through economic advancement, ecological protection, construction of transportation infrastructure and improvement in educational quality. This is consistent with the findings of Huang et al. (2021) that policies are important factors influencing urban resilience. Bengbu was always ranked highest in terms of social resilience, while Bozhou was always ranked lowest. The low rank of Bozhou was associated with its comparatively small number of highly educated experts in the city. According to Yang, Jiao and Zhang (2022), insufficient innovation capability is one of the key factors hindering the improvement of urban resilience levels, which also explains the decline in their urban resilience.

Huaibei, Huainan and Bengbu generally demonstrated slightly higher economic resilience levels than the other three cities during the study period, with the highest economic resilience levels in 2021, in terms of economic resilience levels (as shown in Figure 6b). Bengbu showed a consistent decline trend during economic toughness after 2018, reaching its lowest point in 2020, primarily due to a significant decrease in the growth rate of fixed asset investment. A similar trend was observed in Fuyang, Suzhou and Bozhou, attributed to the impact of the COVID-19 pandemic. For example, there was reduced fixed asset investment as well as reduced import and export trade of goods.

Regarding the level of infrastructure resilience, except for Fuyang and Bengbu, the other cities showed a gradually increasing trend from 2017 to 2021 (as shown in Figure 6c). Huainan showed a relatively gradual increasing trend in resilience level, while Bozhou exhibited the fastest rate of increase. One possible explanation was that Bozhou received strong support from the provincial party committee and government. In 2017, the goal of "building Bozhou into a well-known capital of traditional Chinese medicine at home and abroad" was proposed, leading to active infrastructure development such as high-speed railway connectivity in 2019.

Figure 6d depicts the ecological resilience levels, with Huaibei, Bengbu and Bozhou showing a steady, gradual increase, while Fuyang, Suzhou and Huainan exhibited fluctuating patterns. Since 2019, Suzhou experienced continuous improvement due to initiatives focused on revitalising old neighbourhoods and enhancing the community living environment, culminating in its recognition as a "National Civilised City" in 2020. In contrast, Huainan, as a major industrial city, faces challenges such as low green coverage in urban areas, poor air quality and a low rate of urban sewage treatment, which contributed to its consistently low ecological resilience.

In short, resilience levels across various dimensions exhibited fluctuations in different years for cities. However, some cities experienced prolonged challenges in recovering or improving after a decline, indicating a slower resilience capability.

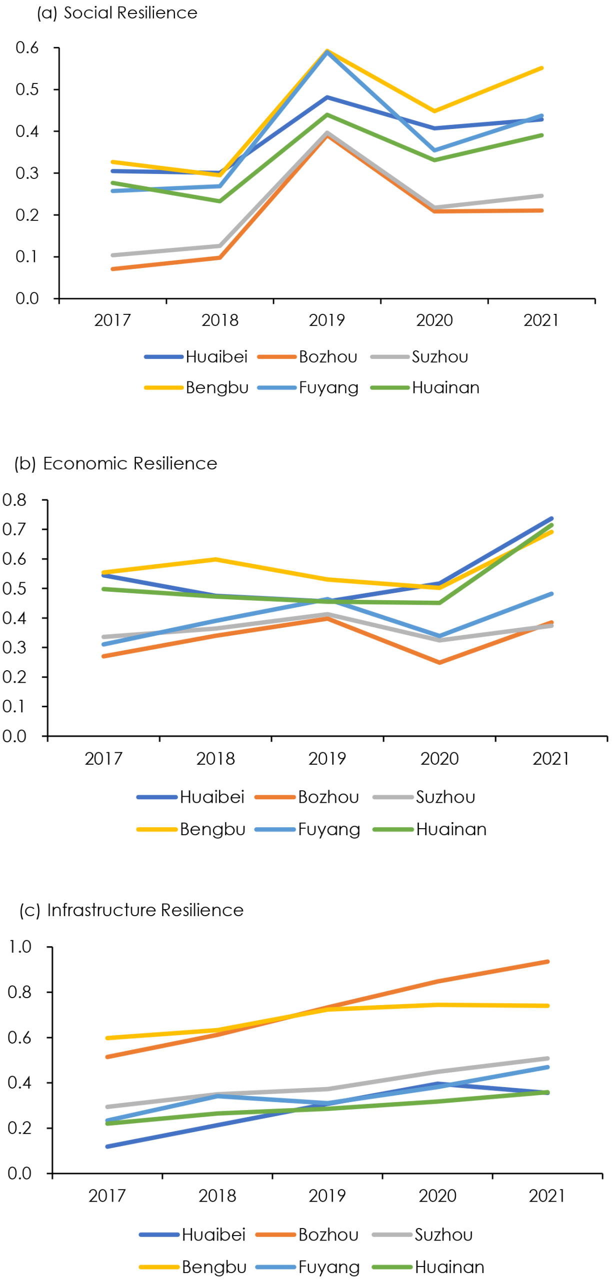


Figure 6. Variations in resilience levels across four dimensions in Northern Anhui cities from 2017 to 2021 (*Continued on next page*)

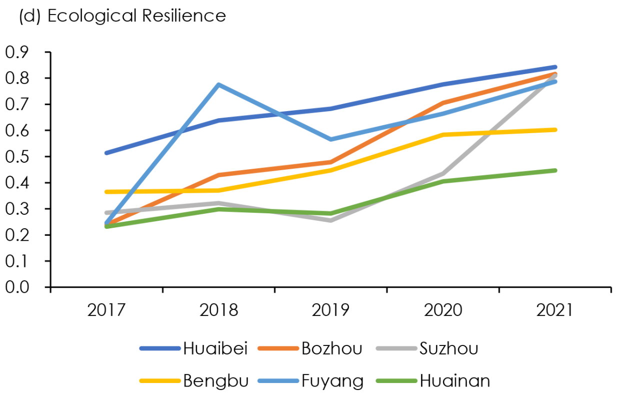


Figure 6. *Continued*

Coupling Coordination Degree

The resilience data from cities in Northern Anhui Province were used in Equations 7 to 9 to calculate the coupling coordination degree to obtain the results of the coupling degree, comprehensive evaluation index and coupling coordination degree between the four dimensions of each city from 2017 to 2021 (as shown in Figures 7 and 8).

Based on the coupling coordination degree between the four dimensions, a coupling coordination degree classification was generated (as shown in Figure 8). The coupling and coordination degree of the four dimensions "B1–B2–B3–B4" toughness, which promoted the development of the Northern Anhui region, showed that it was developing in a good direction. This indicates that the interactions and correlations among the four SEIE dimensions are increasing and becoming more orderly; however, the values of coupling coordination degree were lower than those of the degree of coupling (as shown in Figure 7). During the study period, the degree of coupling coordination for Suzhou was significantly lower than for several other cities, indicating that the development of its cities was more unbalanced among the dimensions.

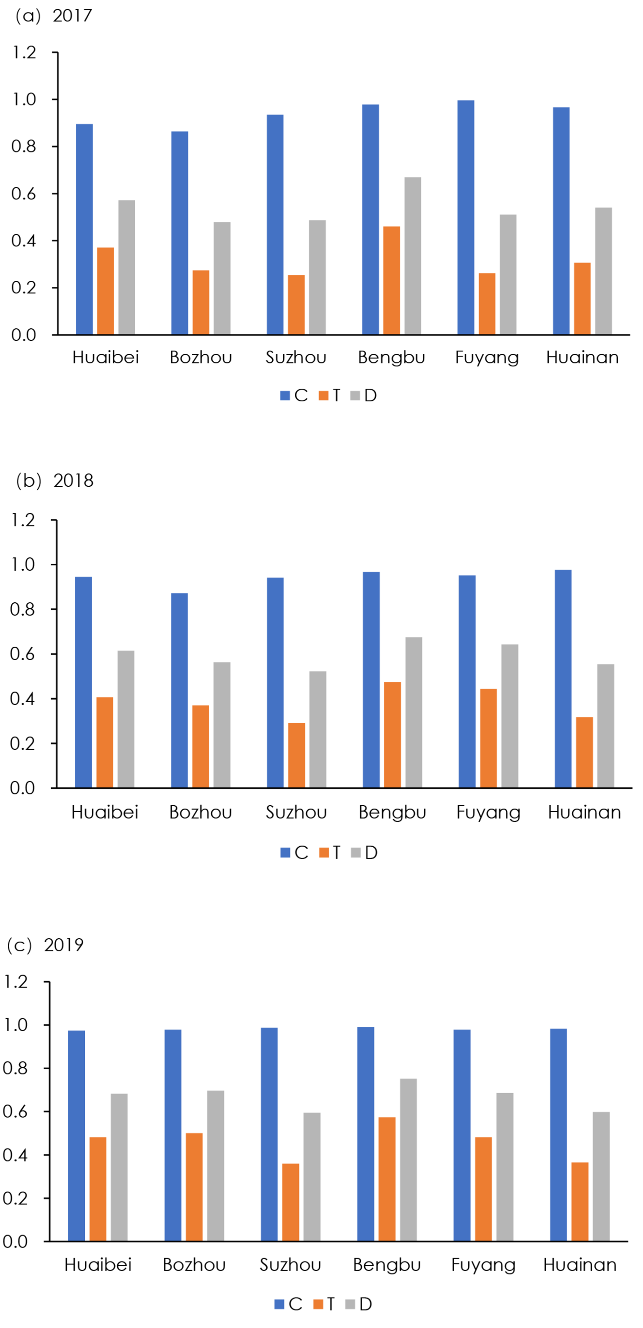


Figure 7. Coupling degree (*C*), comprehensive evaluation index (*T*) and coupling coordination degree (*D*) values for the four dimensions of urban resilience in Northern Anhui cities (*Continued on next page*)

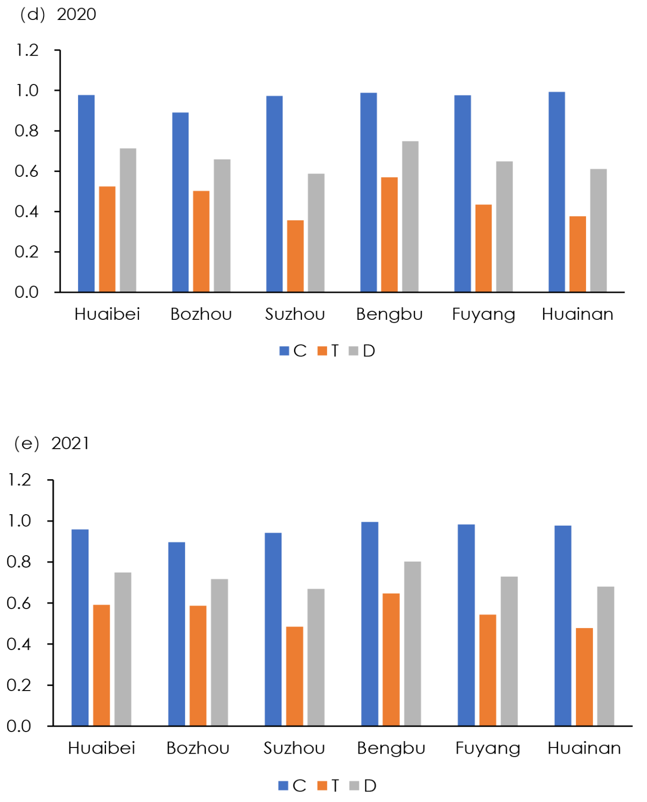


Figure 7. *Continued*

The degree of coupling coordination between "B1–B2", "B1–B3" and "B1–B4" was in the state of primary and intermediate coordination during the study period. This indicated that "Social" is the weaker driver compared to the other three dimensions; thus, an area that should be improved in the future. While economic development leads to infrastructure and ecological environment improvements, advancements in social security have not yet been kept comparatively. In 2021, the toughness of some of the cities in Northern Anhui Province, "B1–B4", "B2–B4" and "B3–B4" were in a state of primary and intermediate coordination. For "B3–B4", the level of coordinated development was in an advanced coordination state relatively more, which indicated a better driving role between the two.

Figure 8 shows that only Bengbu (0.8256) was expected to reach an advanced level of coordination by 2021. Huaibei, Bozhou and Fuyang showed intermediate levels of coordination across the four dimensions. In Bozhou, the coordination between the "B1–B2" dimensions showed relatively low levels and was barely coordinated. Suzhou and Huainan exhibited primary coordination across all four dimensions, with Suzhou's "B1–B2" dimensions also being barely coordinated.

In general, the relationship between the dimensions of urban resilience in Northern Anhui Province exhibited high coupling and low coordination. Although a strong correlation between the dimensions was observed, there was still a deficiency in social aspects such as life and job security, indicating room for improvement in both coupling and coordination. In short, there is a critical need to prioritise the coordinated development of society alongside the other three dimensions while also promoting regional development, as urban construction continues to advance.

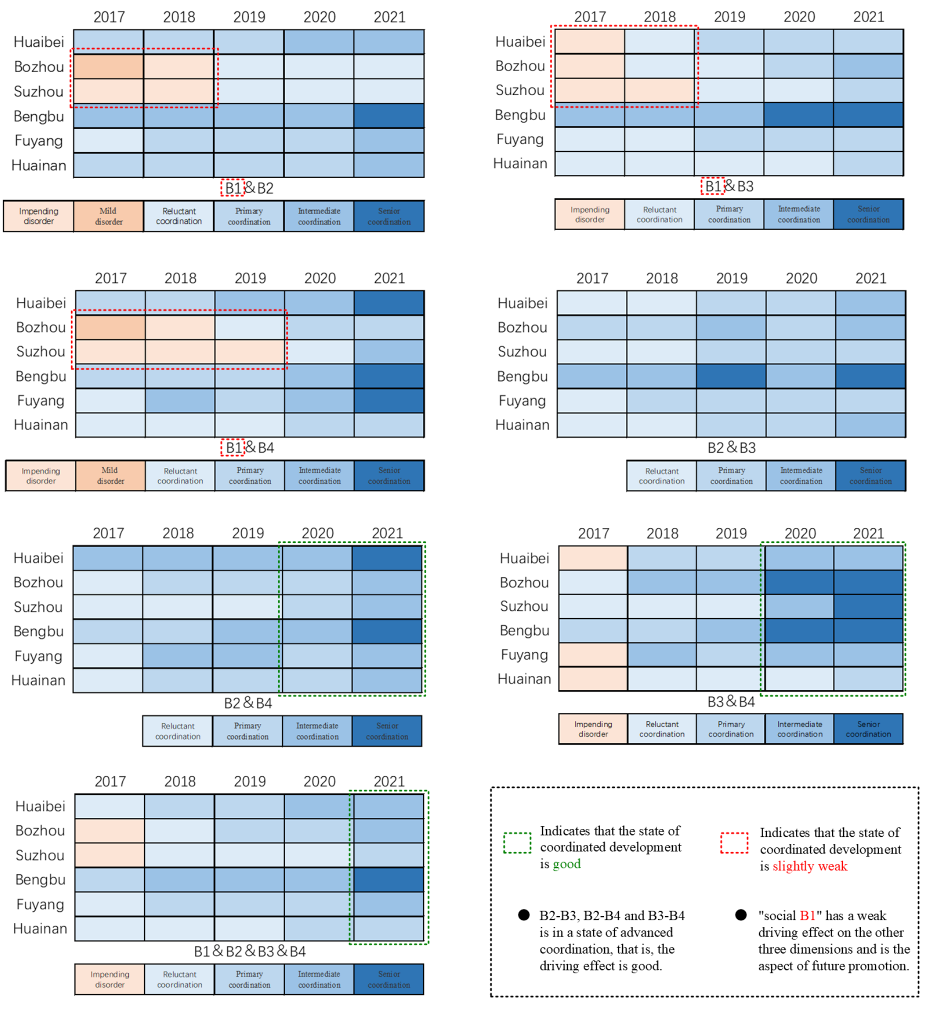


Figure 8. Coordination of the four dimensions of resilience in Northern Anhui cities (2017–2021)

Analysis of Obstacle Degree

The obstacles in the guideline layer (B1–B4) are shown in Figure 9. For all cities in Northern Anhui, the social resilience dimension (B1) had the greatest impact. The indicator tier (C1–C22) had a large influence on the degree of obstruction, with the top one influencing factor selected based on their degree as listed in Table 3.

Table 3. Key factors influencing urban resilience in Northern Anhui cities

Year	City					
	Huaibei	**Bozhou**	**Suzhou**	**Bengbu**	**Fuyang**	**Huainan**
2017	C3	C1	C1	C18	C1	C13
2018	C3	C1	C1	C18	C1	C18
2019	C3	C1	C1	C18	C1	C18
2020	C3	C1	C1	C9	C1	C13
2021	C3	C1	C1	C18	C1	C13

Pension insurance coverage emerged as the most influential factor affecting the urban resilience levels in Bozhou, Suzhou and Fuyang, which is consistent with the findings of Zhang et al. (2019). The study revealed that for every 1% increase in the coverage rate of urban pension insurance, the level of urban resilience increased by 0.356%. In Huaibei, the number of beds in healthcare institutions is the major obstacle factor to improving urban resilience. Wang et al. (2022a) propose that the construction of medical facilities plays an important role in enhancing resilience when responding to large-scale public health emergencies. Therefore, it is essential for Huaibei to prioritise improving its health facilities.

In addition, the per capita green space in parks (C18) stood out as the most influential factor contributing to the enhancement of urban resilience in Bengbu. This factor could improve human health and well-being, promote social interaction and enhance the resilience and safety of biological systems (Mukherjee and Takara, 2018; He, Zheng and Zhao, 2023). The urban toad area per capita (C13) was the most significant factor influencing the improvement of urban resilience in Huainan. The development of transportation infrastructure ensures a city's strong recovery and reconstruction capabilities, making it an important pathway to building resilient cities (Wang et al., 2023). Therefore, in the future, Huainan's policies and finances should be directed towards regional transportation construction.

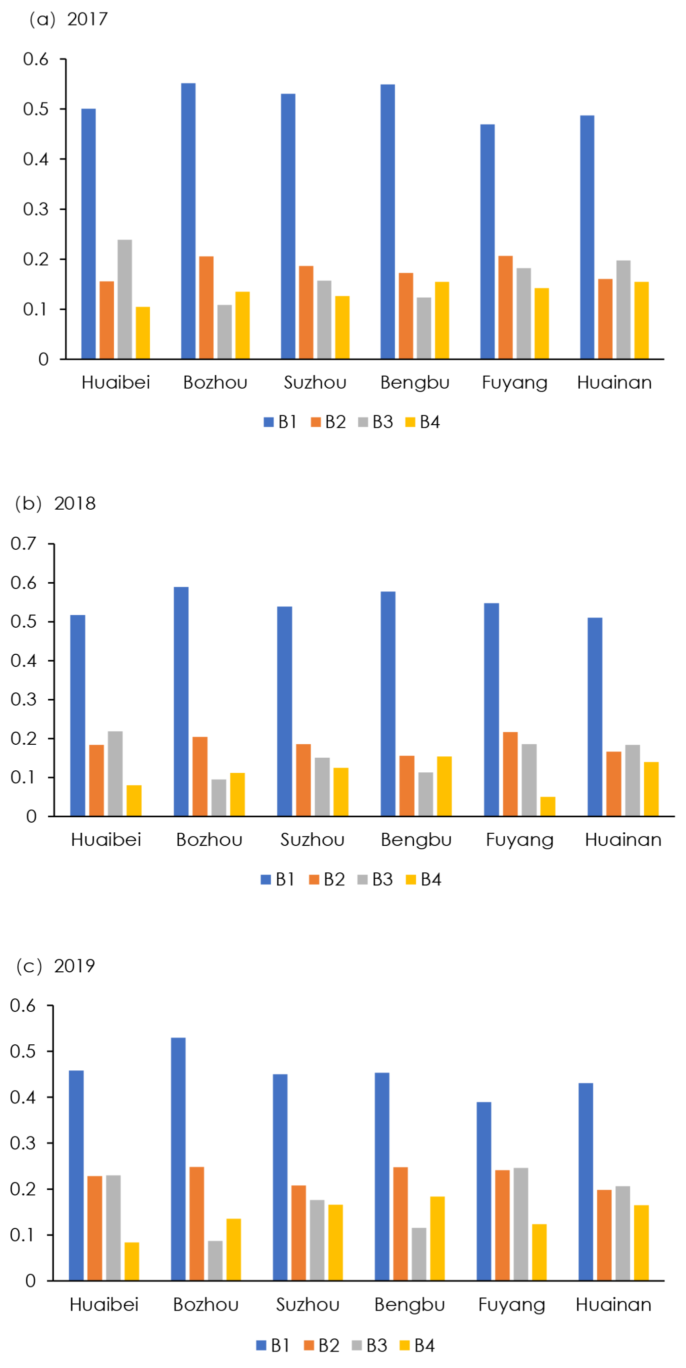
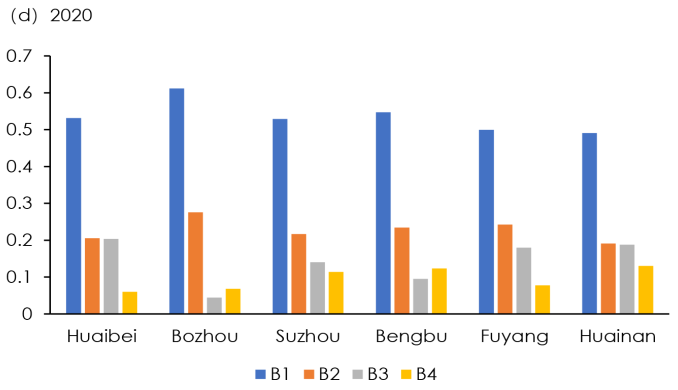


Figure 9. Barriers at the guideline level from 2017 to 2021 (*Continued on next page*)



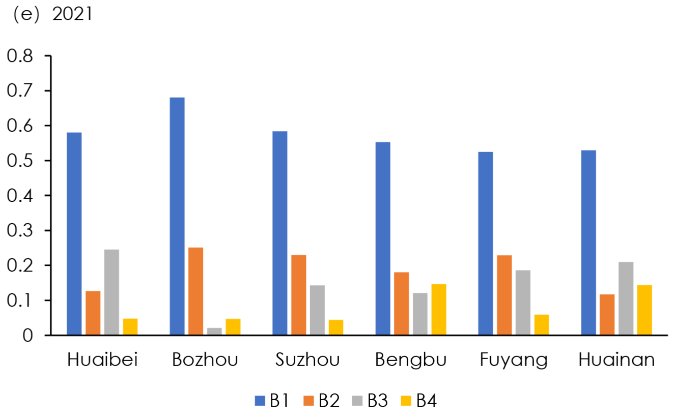


Figure 9. *Continued*

Recommendations

Owing to the variability in the respective situations of the cities, the key influencing factors were slightly different. Accordingly, this study laid out three recommendations.

Firstly, regional co-development and regional urban resilience should be promoted and balanced. The spatial distribution of urban resilience in the Northern Anhui region was characterised as 'high in the east and west and low in the north and south'. This indicates the need to further promote regional collaborative development. The radiation-driving roles of cities neighbouring Suzhou and Huainan should be strengthened and near- and long-term plans should be developed for the construction of resilient cities in Suzhou and Huainan to continuously improve urban resilience and achieve balanced regional development.

Secondly, inputs related to social development should be increased by enhancing social resilience. All types of facilities in healthcare institutions should be upgraded, staff at all levels should be increased, pension insurance coverage should be improved and the number of people in higher education should be increased to actively absorb and attract higher education talent from within and outside the region (Liao, Du and Huang, 2022). This will provide more jobs, increase the employment rate and promote an overall improvement in the level of social resilience and its coordinated and orderly development in the three dimensions of economy, infrastructure and ecology.

Finally, there is a need to increase relevant inputs and develop targeted policies and measures based on the influencing factors. This is because the factors contributing to the degree of barriers varied across the cities in Northern Anhui. For example, Huainan should also pay attention to the maintenance of the ecological environment and improve the per capita green area of parks. Bengbu should increase the land area of roads and effectively promote the smooth development of traffic and Huaibei should focus on improving the per capita urban road area in addition to improving the GDP. Therefore, according to the different degrees of influence of the obstacle degree factor, cities in Northern Anhui Province should develop targeted policies and measures to improve their urban resilience.

CONCLUSIONS

The resilience levels of cities in Northern Anhui had a fluctuating upward trend from 2017 to 2021, with a spatial distribution characterised by higher resilience in the east and west and lower in the north and south. The resilience across social, economic, infrastructure and ecological (SEIE) dimensions showed an upward trend but with larger general fluctuations. In comparison, the resilience of the social dimension alone was weak. The coupling and coordination of the SEIE dimensions in the cities in Northern Anhui showed characteristic 'high coupling and low coordination', indicating that special attention should be paid to the coordinated development of society and the other three dimensions. The obstacle analysis showed that the biggest obstacles to the development of resilience in the cities were social dimension and pension insurance coverage, facilities and staffing of medical and health institutions and per capita green space in park developments, which were the most important factors affecting social resilience.

In comparison to prior studies (Liu et al., 2022; Zhao et al., 2022), this study significantly contributes to the development of a new urban resilience index that encompasses SEIE dimensions. Additionally, a data-driven approach was employed to collect multi-source, authentic and accurate data for the resilience evaluation index for the study area, allowing more objective assessment and identification. This helps promote the sustainable development of cities in underdeveloped regions. Additionally, this study can effectively and specifically serve local governments and planners by serving as a reference for urban resilience research in various geographical contexts.

This study provides a scientific basis for analysing urban resilience in the research region and other similar regions, but there are still certain limitations. Due to the exclusion of data that are difficult to quantify (such as policy indicators), the construction of the urban resilience evaluation index system in this article is not comprehensive enough, which may lead to some inaccuracies in the assessment of urban resilience. The duration of the study was also not long enough. Future studies should explore more quantitative data, such as policy and cultural dimensions, to conduct a more detailed and comprehensive, long-term urban resilience assessment, thereby more effectively enhancing the research area's capacity to withstand risks.

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