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Paths and strategies for a resilient megacity based on the water-energy-food nexus

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ABSTRACT

Megacities are more vulnerable to disasters because of their large population and high external dependence on basic resources. To deal with short-term shocks and long-term pressures, there is an urgent need for megacities to enhance their resilience. As the basic resources for production and living, water, energy, and food show a relationship called "nexus," which affects the ability of megacities to address the impact of disasters. Hence, an evaluation index system of a resilient megacity based on water–energy–food nexus (WEFN) was established to assess the resilience level of megacities. The entropy weight-TOPSIS method and obstacle degree model were used, and Zhengzhou was selected as an example to study the paths and strategies for its resilience. It was found that infrastructure construction was key to Zhengzhou's resilience; problems caused by production, allocation, and consumption of water, energy, and food had great impacts on it. To improve its resilience, Zhengzhou should optimize its industrial structure, strengthen its social security, improve infrastructure investment, and strengthen the supply chain. The resilience framework of megacities accounting for WEFN can more comprehensively review the deficiencies in resilience construction and then provide decision-making tools for resilience construction planning of megacities.

1. Introduction

Megacities are the main places for economic activities and play an important role in social and economic development in various countries (You, 2016). As compared with ordinary cities, their huge population scale, complex social system, and fragile ecological environment endow them with more severe "urban diseases," such as resource shortage and environmental pollution (Cho, 2020). The economic and social characteristics of megacities introduce higher requirements for their ability to address disaster risks; that is, megacities should have strong resilience to be able to resist disasters, reduce disaster losses by their own ability, and reasonably allocate resources to recover quickly from disasters (Li et al., 2020). Especially in an environment of pandemic and climate change, enhancing resilience of megacities has become an urgent task (Ahmed et al., 2018; Hasselwander et al., 2021). For instance, Zhengzhou suffered from heavy rainstorm in July 2021 and COVID-19 in August 2021, causing casualties and economic losses and affecting industrial and agricultural production.

Resilience was first used in the field of engineering, and then the term was applied in natural ecology and gradually extended to human ecology and other fields such as city, economy, and society, showing a transformation paradigm of "engineering resilience - ecological resilience - evolutionary resilience." Klein et al., and Thomalla (2003), Walker et al., and Kinzig (2004), and other scholars defined the concept of resilience from different perspectives, but they all emphasized the integration of hardware (infrastructure) and software (social governance) after being hit by the system to absorb disturbances and reduce losses by learning and reorganization, make the system adapt to the new environment, resist external influences, and recover. Barker et al., and Rocco (2013) presented resilience as a function of interaction among reliability, vulnerability, survivability, and recoverability, with vulnerability and recoverability being the important drivers for resilience.

At the United Nations Global Summit on Sustainable Development in 2002, Local Governments for Sustainability (ICLEI) introduced the concept of a "resilient city." Resilient cities have become a research hotspot to provide practical schemes to improve the resistance,

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resilience, and adaptability of urban systems to uncertain factors. In 2010, the United Nations launched the Making Cities Resilient campaign to address issues on urban disaster risk (Velasquez, 2015). Campanella (2006) argued that resilience is the ability of a city to recover from damage. Similarly, Hamilton (2009) defined resilience as the ability of a city to recover and continue to provide its main functions of life, commerce, industry, government, and social aggregation in the face of disasters and other hazards. Spaans and Waterhout (2017) believed that resilience is the ability of individuals, communities, institutions, companies, and systems in cities to survive, adapt, and develop regardless of the type of chronic pressure and acute shock. Ribeiro and Pena (2019) proposed that urban resilience can be divided into five dimensions: natural, economic, social, physical, and institutional. It can be observed from the above that the scope and content of urban resilience are expanding, from urban resilience to resilience of individuals and organizations in cities, to the ability to resist natural disasters to various types of chronic pressures and acute shocks.

Many scholars and organizations established frameworks and designed tools for resilient city construction, for example, the resilience maturity model (Labaka et al., 2019), the European resilience management guideline (Marana et al., 2019), and the Resilience Performance Scorecard (Khazai et al., 2018). Wardekker et al. (2020) adopted the Resilience Diagnostic Tool to describe different paths taken for urban resilience construction and diagnose possible consequences of various choices and applied it to flood risk management in Rotterdam. Jabareen (2013), who accounted for the complexity and uncertainty of an urban system and the impacts of economic, social, spatial, and physical factors, proposed a resilient urban planning framework to deal with climate change and environmental risks. Irwin et al., and Nirupama (2016) proposed the decision support tool ResilSIM to assess resilience of urban systems to the consequences of natural disasters and applied it to Toronto and Ontario. Moghadas et al., and Kötter (2019) constructed a comprehensive urban resilience index, including six dimensions of social, economic, institutional, infrastructural, community capital, and environmental, developed a hybrid multicriteria decision-making method, and applied this tool to the resilience assessment of Tehran. Aiming at resilient city construction under extreme events and climate change, Chang et al. (2021) applied an interrelated social–ecological–technological systems (SETS) vulnerability framework by developing an urban flood vulnerability index for six U.S. cities. On the other hand, Lu et al., and Zhang (2022) proposed a mixed-methods approach to urban agglomeration resilience estimation combining particle swarm optimization algorithm, back propagation neural network, entropy weight method, and other methods. In addition, Sharifi (2020) reviewed the literature on urban resilience assessment and found that the focus shifts from risk reduction and vulnerability assessment to development of adaptive methods to adaptation to climate change and flood resistance; in addition, much attention has been paid to infrastructure, institution, and environment at the expense of economic and social aspects.

Existing work on resilient cities focuses more on concept definition, assessment, and tool development but lacks the roadmap analysis of disasters affecting urban safety and development, which makes evaluation indicators of a resilient city differ and practical countermeasures difficult to propose. In addition, ensuring the stable supply of basic resources such as water, energy, and food while sustainably managing them is one of the qualities of constructing a resilient city. Facing the increasingly intensified resource and environmental constraints, traditional research from a single or pairwise perspective can no longer meet the urgent needs of urban resources management due to close interdependence among energy consumption, food production, and water use (Foran, 2015; Muller, 2015). Hence, the concept of water–energy–food nexus (WEFN) is introduced to express their interrelationships, showing that changes in one resource will affect the other two. WEFN has been the focus of research in the fields of resource management, urban management, and sustainable development. Integrated urban water resources management under climate change risk (Özerol et al., 2020; Sahin et al., 2017), energy consumption and carbon emissions in the urban water cycle (Kim & Chen, 2018), and the relationship between land use mode and water consumption (Stoker & Rothfeder, 2014) are hotspots in the field of urban WEFN, which are related to urban resilience. Both WEFN and urban resilience are popular government policies for sustainable development, considering that WEFN in the framework of urban resilience can more comprehensively identify the advantages and disadvantages in urban resilience development. Hence, we present the roadmap of disasters affecting the safety and development of megacities based on the economic and social characteristics of megacities, propose an evaluation index system of a resilient megacity based on WEFN, and select Zhengzhou as a case to determine how to improve resilience.

2. Theoretical basis

2.1. Economic and social characteristics of megacities

The term megacity refers to a city with large population, high industrialization, complex social structure, and fragile ecological environment. The classification of megacities is based on the number of urban permanent residents. In China, a megacity means a city with an urban permanent resident population of >5 million and <10 million. Meanwhile, a huge population shows that megacities have a developed economy, several employment opportunities, a high level of public services, and perfect infrastructure construction, therefore attracting many people to live there. However, a huge population can also mean a decrease of per capita resources, an increase of demand for living resources, and an increase of domestic waste, such as the decrease of per capita ownership of water and land and increase of domestic wastewater and domestic garbage (Pan et al., 2019; Zhang et al., 2020).

Megacities are economically developed and highly industrialized. Adjustment of the industrial structure is a key feature in the industrialization process where a change of sector share is obvious (Tian et al., 2014). Industrialization in megacities is earlier, and megacities are generally at the post industrialization stage dominated by the service industry. From the data of the Seventh National Population Census in China, in 2020, China had 14 megacities, including Wuhan, Nanjing, and Zhengzhou. The proportion of industrial added value and service industry added value of the 14 megacities in China in 2020 is shown in Fig. 1.

From Fig. 1, although the service industry in megacities generally accounted for more than 50% of GDP, the industry is still an important pillar of economic and social development in Chinese megacities. The proportion of industrial added value generally exceeded 20%, and those in Dongguan and Foshan even exceeded 40%. Environmental pollution brought by industrialization is one of the factors affecting megacity resilience.

Megacities have a complex social structure and encounter many risk factors. Industrialization has led to complex social space conditions. The problem of social space inequality becomes increasingly prominent in megacities, which may have a negative effect on their development (Chen et al., 2020; Knight, 2013). For instance, in the early stage of industrialization, a mismatch between local population and immigrant population brought great difficulties to local governance. In deindustrialization and industrial upgrading, factors such as demolition, housing, and insufficient urban functional space cause social contradictions (He et al., 2018; Sheng et al., 2017). In the point of view of social resilience, strengthening social inclusion and capacity-building in the development and redevelopment in megacities is important (Berkes & Ross, 2013).

Megacities have a fragile ecological environment. On the one hand, environmental pollution brought by industrialization poses a great challenge to environmental resilience of megacities. Pollution caused by industrial and transportation activities; industrial and domestic

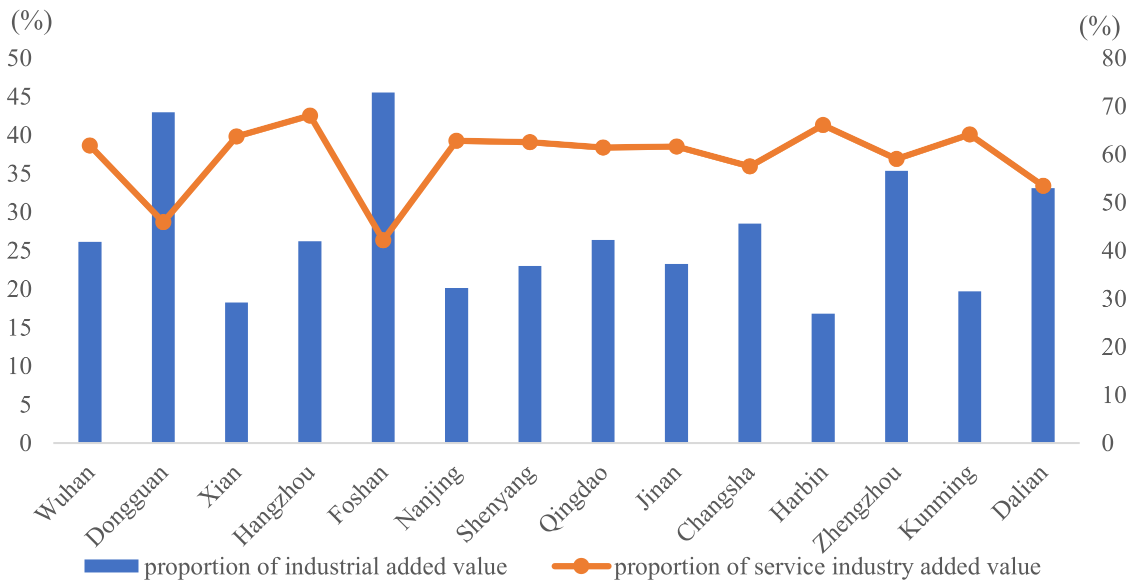

Fig. 1. Proportion of industrial added value and service industry added value of the 14 megacities in China in 2020.

wastewater; and industrial, medical, and domestic wastes puts pressure on the environment and reduces the living standards of residents in megacities (Taksibi et al., 2020). On the other hand, there is greater demand for commercial and residential lands due to the developed service industry and the huge population of megacities, thus crowding out ecological land and agricultural land, resulting in weakness in some spatial functions of megacities.

Megacities have perfect infrastructure. To attract enterprises and population, infrastructure in megacities should be improved continuously, including transportation, medical, and communication infrastructure. For instance, perfect transportation infrastructure can not only reduce production cost for enterprises but also improve commuting efficiency for residents. Infrastructure such as medical treatment, education, and communication can improve the residents' living standards and attract talents to support megacity development (Mueller et al., 2020; Tateishi et al., 2021). These hardware facilities are the basis for addressing the impact of disasters and an important part of urban resilience assessment (Meerow, 2017).

Megacities have a high governance level. A flat management model is not applicable for densely populated megacities. Megacities should

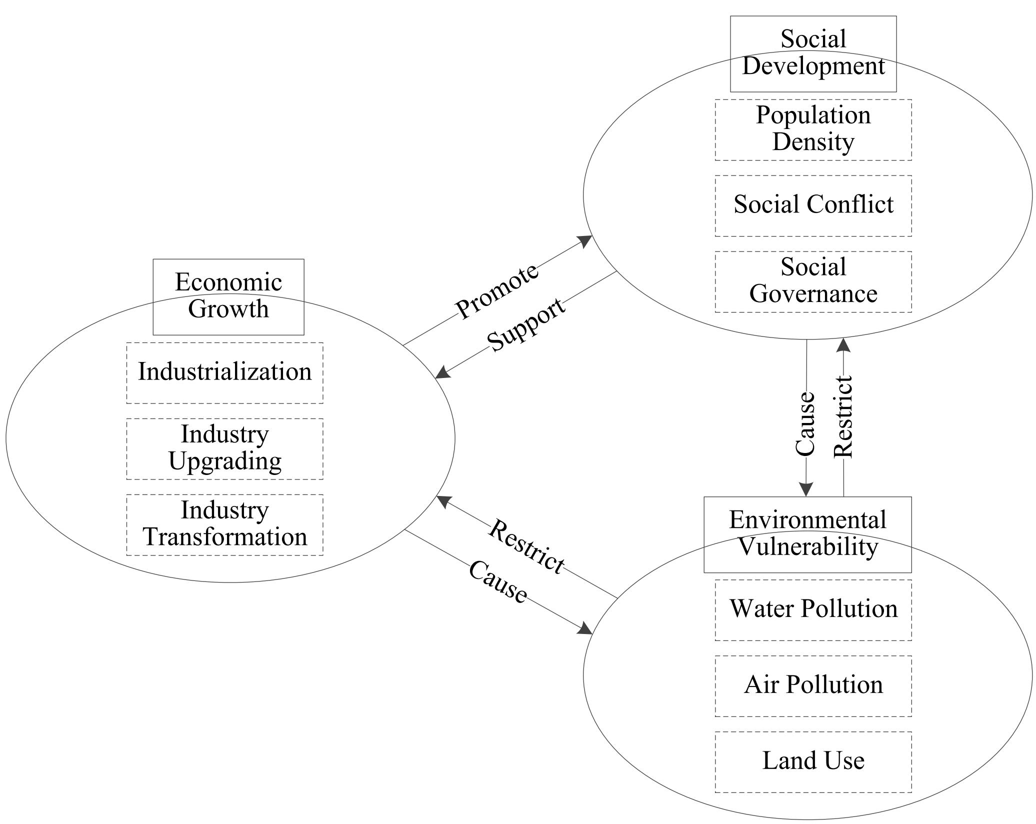

Fig. 2. Relationships between economy, society, and environment in a megacity.

adopt a diversified governance model dominated by government and participated by the public (Gao et al., 2020). Chronic pressures such as rising environmental costs, social exclusion and inequality within cities, and acute impacts such as intensified climate change and frequent emergencies all require megacities to innovate governance models and mechanisms to meet the requirements of their resilience construction.

Economy, society, and environment in megacities are interrelated and interactive (Fig. 2).

2.2. WEFN in megacities

Development in megacities is inseparable from water, energy, and food, which are the basic resources to support production and living in megacities. Due to its economic and social characteristics, such as developed service industry and dense population, megacities have less agricultural land, less grain production, high pressure on water supply, fierce competition for water among sectors, less energy production than consumption, and unreasonable energy consumption structure, showing the characteristics of separation between production and consumption of water, energy, and food (Damerau et al., 2016; Kaddoura & Khatib, 2017). Considering the availability of data on water, energy, and food in different cities and the differences in publication time, we chose 12 megacities in China, and Figs. 3–5 illustrate their water, energy, and food production and consumption data.

China's per capita water resources are significantly lower than the world average. Taking permanent residents in megacities as the object, per capita water resources in the 14 megacities in 2019 was 492.07 m^3 per capita, about 1/14 of the world average, showing serious shortage of water resources. Among the nine megacities that published data for water diversion and transfer in, the average proportion of water diversion and transfer in their total water supply was 25.2%, which indicates that megacities need water allocation to support their economic and social development and ecological protection. In the viewpoint of water consumption structure, an average proportion of agricultural, industrial, and domestic waters of about 30% and an average proportion of ecological water of about 10% were found. Agricultural water usually accounted for 60% of water resources consumption, while the proportion of industrial, domestic, and ecological waters increased in megacities due to their industrial development, urbanization, and fragile ecological environment.

From the available energy data, we chose 10 megacities in China to analyze their energy purchase and consumption. In Fig. 4, energy consumption in the 10 megacities in 2019 mainly depended on transfer in from outside the cities. The average purchase and consumption ratios of raw coal, gasoline, diesel oil, natural gas, heating, and electricity were 99.51%, 99.01%, 101.01%, 127.67%, 65.62%, and 83.60% respectively. The average proportion values for industrial production of raw coal, gasoline, diesel oil, natural gas, heating, and electricity were 99.92%, 57.19%, 88.30%, 99.42%, 99.59%, and 98.75% respectively. This reveals that megacities have the characteristics of high industrialization and separation between energy production and consumption.

The average per capita food production in the 14 megacities in 2019 was 241.19 kg per person, as shown in Fig. 5, among which per capita food production in 12 megacities was less than 400 kg per person, i.e., lower than the world food security standard. Food consumption in megacities mainly depended on transfer in from outside the cities. Based on the data for the production, consumption, and allocation of water, energy, and food in the 14 megacities, at least one resource depended on transfer in, and the production in megacities was difficult to meet the needs of their economic and social development. However, there is a complex dynamic relationship among water, energy, and food (Stucki & Sojamo, 2012).

This complex relationship is reflected in resource flow, resource demand, and supply. For resource flow, water is used for irrigation, hydropower generation, and other energy production behaviors; energy is essential in the process of water treatment, transportation, and distribution, as well as food production and storage; food could be used as biomass energy (Gold & Webber, 2015; Hamidov & Helming, 2020). From a more macro perspective, the increase in the global demand for food will lead to groundwater depletion (Lee et al., 2020), and as a consequence, the depletion of groundwater will cause increased energy use for groundwater exploitation (Fishman et al., 2016). To achieve sustainable development, water, energy, and food must be considered as a system (Karan et al., 2018).

Hoff suggested the concept of WEFN to show this relationship, and it has garnered much attention from both academe and the government as it provides ideas to the government to solve challenges on global resources while obtaining social, environmental, and economic benefits (Larkin et al., 2020; Urbinatti et al., 2020). Any change in one resource will lead to changes in the other two resources (Allan et al., 2015). As an evolutionary system, the complexity of WEFN lies in inevitable advantages and disadvantages of water, energy, and food in different dimensions, and these advantages and disadvantages can only be evaluated from different perspectives (Salmoral et al., 2019;

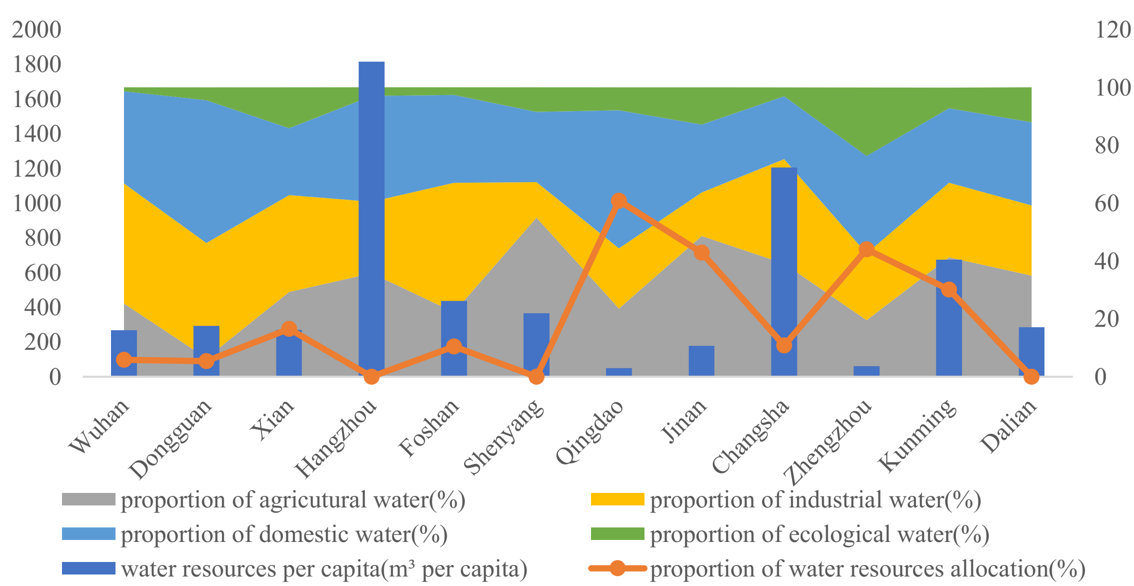

Fig. 3. Water production and consumption in 12 megacities in China.

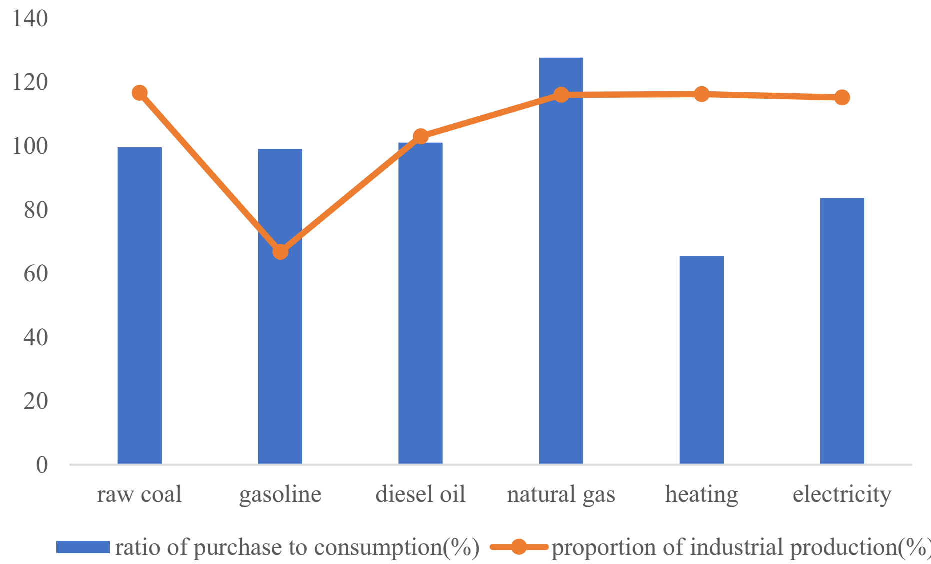

Fig. 4. Energy purchase and consumption in 10 megacities in China.

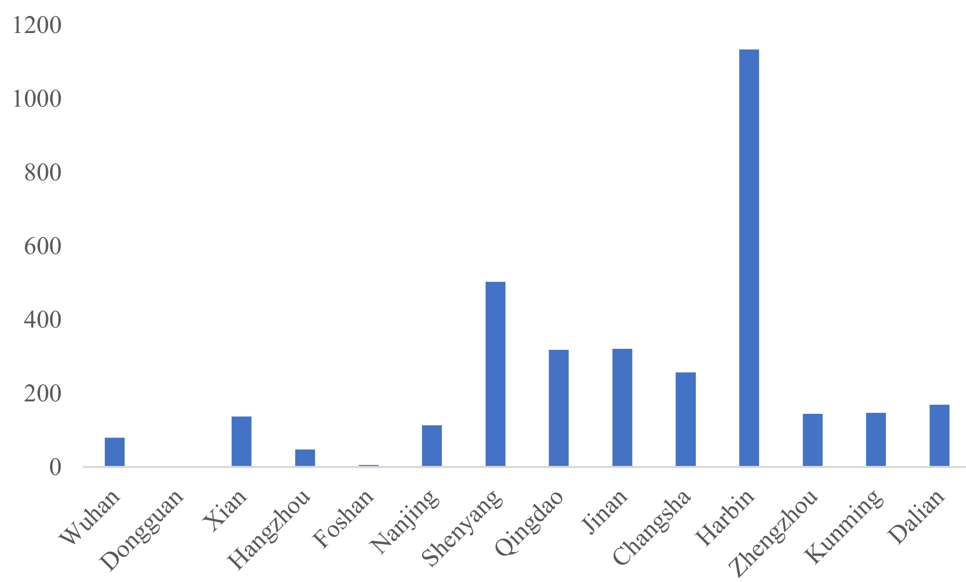

Fig. 5. Food production in the 14 megacities in China.

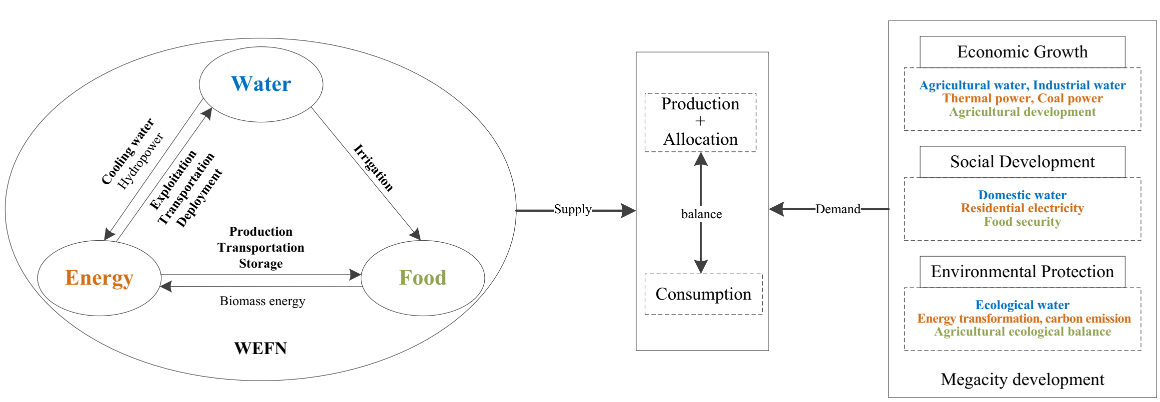

Fig. 6. Water–energy–food nexus in a megacity.

Serrano-Tovar et al., 2019). The lack of comprehensive modeling tools and methods makes it difficult to assess its complexity and to apply studies in policy-making and decision-making (Dargin et al., 2019). Moreover, WEFN is an open complex system with a dynamic boundary (Conway et al., 2015), and factors that influence WEFN, such as climate change and socioeconomic change, also change dynamically (Lele et al., 2013). Fig. 6 shows WEFN in a megacity.

2.3. Roadmap of disaster affecting resilience of a megacity

The frequency of natural disasters such as floods and droughts has recently accelerated and the degree of harm has deepened, which has caused great damage to economic and social development in megacities. Disasters cause serious damage to infrastructure and prevent provision of important urban services. Natural disasters are complex, uncertain, and dynamic, which brings many challenges to emergency management in megacities (Sun et al., 2016). Herein, the resilience of a megacity is divided into five dimensions: economic resilience, social resilience, environmental resilience, infrastructural resilience, and institutional resilience. The impact of disasters on resilience of megacities can be divided into short-term shocks and long-term pressures (Fig. 7).

Short-term shock of disasters on resilience of the megacity is reflected in destruction of infrastructure, difficulty in emergency management, short supply of daily necessities, and rising prices. Floods, earthquakes, and other disasters reduce infrastructural resilience of megacities by destroying communication, transportation, and medical infrastructure, resulting in poor communication during rescue work, untimely material transportation, and high pressure on supply of medical materials, making it more difficult for personnel rescue after disasters. During the heavy rainstorm disaster in Zhengzhou, roads, bridges, and base stations were damaged, there was communication block among the affected people, leading to a difficulty in obtaining evacuation information in a timely manner, and rescue workers could only rescue the affected people through rescue ships. Simultaneously, the occurrence of disasters puts forward higher requirements for institutional resilience of megacities. Deviation between the current emergency system and the perfect emergency system makes it difficult to reach the optimal state of emergency management. Moreover, short-term shutdown caused by disasters will reduce production and increase the imbalance between supply and demand in water, energy, and food, as well as other basic materials needed by residents. Transportation infrastructure destruction makes it more difficult to supply food and other daily necessities, resulting in a short supply of materials and rising grain prices, which is easy to cause social contradictions.

Long-term pressure of disasters on resilience of megacities is reflected in restoration of the supply chain and water–energy–food security. In WEFN security, water security includes consumption security, conflict, and cooperation and disaster risk reduction (Cook & Bakker, 2012). Energy security needs to consider both supply and demand challenges, including security, environmental sustainability, and reliability. Food security mainly aims to achieve equal access of everyone to food, that is, fair distribution, availability, and price (Masters & Shively, 2008).

Taking COVID-19 as an example, the pandemic impeded the flow of raw materials, labor, intermediate products, and other resources in megacity production activities. Tertiary industries such as catering and transportation were greatly affected. Secondary industries such as manufacturing and construction had short-term stagnation. Consumption, investments, imports, and exports were damaged. The complexity and conductivity of WEFN risk were more significant due to its dense population, rapid personnel flow, external dependency of resources, and intensified contradiction between urban development and resources.

Particularly, the pandemic posed a threat to food security in megacities, accelerated formation of risk factors, promoted new changes in food production and supply patterns, and intensified imbalance and instability of food supply and purchasing capacity. Megacities faced risks such as insufficient food supply, supply chain interruption, and soaring food prices, leading to social panic and social contradictions.

For energy security, the impact from COVID-19 on the energy industry was more direct. It brought about major changes and severe challenges to energy production, supply, and consumption, which was mainly reflected in the sharp shrinkage of energy consumption, instability of the energy industry chain, and serious obstruction of import and export. The pandemic caused many enterprises to shut down and greatly reduced industrial energy consumption while increasing the demand for domestic energy. In energy industry chain instability, ensuring the energy security of domestic consumption was the focus during this period. In the post-pandemic period, great changes took place in the global energy supply pattern, and ensuring the energy security of resumption of production is a long-term challenge for megacities.

3. Materials and methods

3.1. Evaluation index system of resilience of a megacity based on WEFN

Based on the analysis of the economic and social characteristics of megacities, WEFN in megacities, and the roadmap of disasters affecting resilience of megacities in Section 2, WEFN was considered in the framework of resilience of a megacity. Hence, an evaluation index system of a resilient megacity based on WEFN was established using the following five dimensions: economic, social, environmental, infrastructural, and institutional resilience (Table 1). The evaluation index

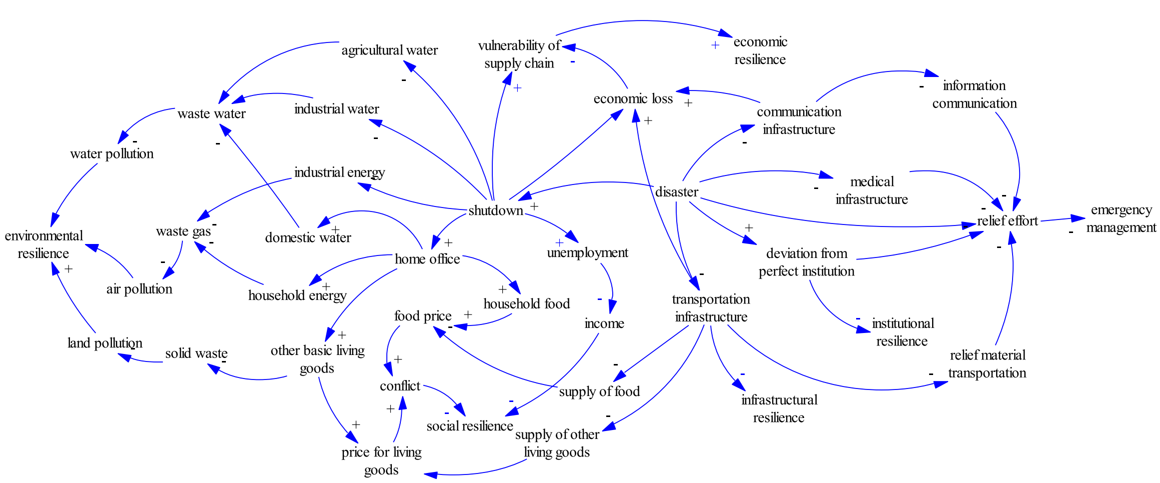

Fig. 7. Causal relationship of disasters affecting the resilience of a megacity.

Table 1
Evaluation system of resilient megacity based on WEFN.

Objective	Dimension	Criterion	Indicator	Description	Effect	Weight
Index system of resilience of megacity	economic	Economic structure	Industrial structure	Proportion of tertiary industry	Positive	0.0245
			Employment structure	Employment proportion of primary industry	Negative	0.0270
			Firm structure	Proportion of manufacturing enterprises	Negative	0.0250
			Water consumption	Proportion of industrial water	Negative	0.0194
			Energy consumption	Proportion of industrial energy consumption	Negative	0.0173
		Economic behavior	Public expenditure policy	Proportion of social security expenditure	Positive	0.0164
			Tax policy	Proportion of tax revenue	Positive	0.0131
		Economic capacity	Savings	Per capita disposable income	Positive	0.0199
			Consumption	Engel coefficient	Negative	0.0203
			Housing	Proportion of people with their own housing	Positive	0.0219
	social	Social structure	Age	Proportion of elderly over 65	Negative	0.0195
			Gender	The ratio of men to women	Positive	0.0112
			Immigration	The ratio of permanent population to registered residence population	Negative	0.0133
			Health	Mortality	Negative	0.0333
		Social capacity	Identity	Proportion of rent in housing expenditure	Negative	0.0287
			Equity	Urban-rural income ratio	Negative	0.0251
			Social network	Proportion of social organizations	Positive	0.0294
			Social capital	Proportion of household deposits	Positive	0.0281
		Social demand	Water demand	Proportion of domestic water	Positive	0.0174
			Energy demand	Proportion of household electricity	Positive	0.0191
			Food demand	Food consumption of urban residents	Positive	0.0241
	environmental	Resource endowment	Water endowment	Per capita water resources	Positive	0.0161
			Land endowment	Proportion of urban area	Negative	0.0244
		Pollution	Water pollution	Discharge of industrial wastewater and domestic wastewater	Negative	0.0208
			Air pollution	Industrial waste gas emission	Negative	0.0200
			Land pollution	Industrial waste emissions	Negative	0.0220
		Environmental protection	Land protection	Greening coverage	Positive	0.0337
			Ecological protection	Proportion of ecological water use	Positive	0.0267
			Pollution control	Environmental governance investment	Positive	0.0165
	infrastructural	Perfection	Communication perfection	Ratio of mobile phone users to permanent residents	Positive	0.0248
			Transportation perfection	Per capita road area	Positive	0.0248
			Medical perfection	Hospital beds per 10,000 people	Positive	0.0262
			Water conservancy perfection	Per capita drainage pipe density	Positive	0.0199
			Electricity perfection	Length of public distribution line per capita	Positive	0.0211
		Potential	Communication potential	Proportion of infrastructure investment in information transmission, software and information technology services	Positive	0.0194
			Transportation potential	Proportion of infrastructure investment in transportation, warehousing and postal industry	Positive	0.0198
			Medical facility potential	Proportion of pharmaceutical manufacturing investment	Positive	0.0230
			Electricity potential	Proportion of fixed asset investment in power and heat production and supply industry	Positive	0.0188
			Water conservancy potential	Proportion of infrastructure investment in water conservancy, environment and public facilities management industry	Positive	0.0209
	Institutional	Emergency management	Emergency material storage	Number of fast food per capita	Positive	0.0148
			Emergency material price	Price index of fast food	Positive	0.0245
			Emergency material availability	Number of employees in public administration and social organizations per 10,000 people	Positive	0.0345
		Supply chain	Water allocation	Ratio of transferred water to total water supply	Negative	0.0262
			Energy allocation	Ratio of purchase and consumption of raw coal and other energy	Negative	0.0215
			Food allocation	Ratio of food consumption to food production	Negative	0.0256

system was based on Moghadas et al. (2019) and Zhu et al., and Feng (2019) that included the five dimensions. The difference is that this work aimed at the overall resilience level of megacities and incorporating urban WEFN, with the index system accounting for the short-term impact such as disasters and the long-term impact such as urbanization, while the works by Moghadas et al. and Zhu et al. focused on the inherent characteristics and capacities of Tehran in the context of flash floods from surface water or from the overflow of rivers and the resilience of smart cities and the relationship between smartness and resilience.

3.1.1. *Economic resilience*

The economic structure of megacities determines the economic sustainability and the impact in the face of disasters, including industrial structure, employment structure, firm structure, water consumption, and energy consumption. Megacities dominated by manufacturing face great impacts and will be difficult to recover when facing disasters such as floods or COVID-19. Economic behavior refers to the measures the government tends to take in reconstruction, including public expenditure policy and tax policy. Economic capacity represents the economic capacity of residents to address disasters, including savings, consumption, housing.

3.1.2. Social resilience

The social structure of megacities represents disaster resistance and tolerance of megacity residents, including age, gender, immigration, and health. Social ability represents the residents' sense of belonging and their willingness to make efforts to fight disasters, including identity, equity, social network, and social capital. Social demand represents the basic resources needed by residents in megacities facing disasters, including water, energy, and food demands.

3.1.3. Environmental resilience

The ecological environment plays a supporting role in economic and social development in megacities. Ecological resilience is an important part, including environmental endowment, pollution, and environmental protection. It is expressed in water endowment, land endowment, water pollution, air pollution, land pollution, air protection, ecological protection, and pollution control.

3.1.4. Infrastructural resilience

Infrastructure is the key hardware facility for megacities to address disasters. Indicators are selected from two aspects: infrastructure perfection and infrastructure development potential, including communication, transportation, medical, water conservancy, and electricity perfection, as well as communication, transportation, medical, water conservancy, and electricity potential.

3.1.5. Institutional resilience

Institutional resilience is the software to deal with short-term shock and long-term pressure from disasters, including emergency management and supply chain. Emergency management is the basis for megacities to address the short-term shock, including emergency material storage, emergency material price, and emergency material availability, while the supply chain is fundamental to addressing long-term pressure, including water, energy, and food allocation. During the COVID-19 outbreak, a good supply network was the channel for the flow of key resources and elements.

3.2. Research methods

3.2.1. Entropy weight-TOPSIS

The evaluation index system of a resilient megacity based on WEFN was a multi-index and multidimension index system; it needed to select a multi-index comprehensive evaluation method to synthesize multiple indexes into a single index for analysis. The core of synthesizing multiple indexes into resilience of a megacity was to weight each index and then use the weighting function method to calculate the resilience level of the megacity. Weighting methods can be divided into subjective and objective weighting methods. After the literature review, the entropy weight-TOPSIS method was used for weighting. Details for the entropy weight-TOPSIS method were shown in the literature (Y. Chen, 2020).

Resilience scores of megacities are calculated as follows:

$$R_{ij} = \sum_{i=1}^{n} w_j p_{ij}. \tag{1}$$

where w_j. is the weight of each index and p_{ij}. is t probability matrix.

The separation between evaluation indexes and the positive ideal solution and negative ideal solution is calculated using the following equation:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(z_{ij} - Z_j^+\right)^2}. \tag{2}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(z_{ij} - Z_j^-\right)^2}. \tag{3}$$

where z_{ij}. is the weighted normative decision matrix, Z_j^-., Z_j^+. is the negative ideal solution and the positive ideal solution, respectively, and $i = 1, 2, 3, \ldots, m.$, $j = 1, 2, 3, \ldots, n.$.

Rive proximity is calculated using the following eation:

$$N_i = \frac{D_i^-}{\left(D_i^+ + D_i^-\right)},\ 0 \le N_i \le 1. \tag{4}$$

The larger the N_i., the closer is an index in this year is to the optimal value, indicating that the index has a better optimization dree f resilience of the megacity.

3.2.2. Obstacle degree model

The obstacle degree model is helpful to systematically analyze various indicators and identify the main obstacle factors of megacity resilience, so as to provide a basis for improving the resilience level of the megacity. The formula is as follows:

$$O_i = \frac{W_i P_i}{\sum_{i=1}^{n} W_i P_i},\ P_i = \left|X_i - D_n^+\right| \tag{5}$$

where O_i. represents the obstacle degree, meaning the obstacle degree of each indicator on resilience of the megacity; W_i. represents the weight of each indicator; X_i represents the standardized value of each indicator; and P_i. represents the absolute deviation between the indicator and the positive ideal value. According to $TO_i = \sum^{O_i}$, the obstacle degree of each subsystem egacity resilience could be calculated.

3.3. Case selection

Zhengzhou was selected as the object due to these following reasons.

(1) The urban permanent resident population of Zhengzhou from 2011 to 2019 was between 5 million and 10 million, meeting the population requirements of megacities. Problems brought by huge population, such as aging of population, reduction of cultivated land, and rising costs of living, challenged the ability of Zhengzhou to address disasters.
(2) Industries in Zhengzhou are mainly traditional industries such as coal, chemical, machinery manufacturing, electric power, and textile. It is facing the pressure and challenges of resource depletion and industrial transformation. Simultaneously, Zhengzhou has formed characteristic industries such as automobile, food, electronic information, bioengineering, pharmacy, and energy; it is slightly insufficient to become a strong city in the central part of the country. In addition, the upgrading process of the regional industry is still in its infancy.
(3) Zhengzhou faces great long-term pressure brought by a mismatch between resource supply and demand. Zhengzhou is in the Yellow River Basin, with uneven temporal and spatial distribution of water resources, and the per capita water resources is 61.05 m^3 per capita, showing serious shortage of water resources. Simultaneously, the acceleration of urbanization and industrialization in Zhengzhou brings about the increased demand for water, energy, and food for living and production, showing chronic pressure on Zhengzhou's resilience.
(4) The short-term shock of extreme events such as extreme climate and COVID-19 recurrence also poses great challenges to Zhengzhou's resilience. A heavy rainstorm in July 2021 caused casualties and economic losses, affecting industrial and agricultural production; COVID-19 relapsed in August and put forward higher requirements for the timely supply of water, energy, and food needed by the residents, as well as resource resumption after the end of the pandemic.
(5) Zhengzhou is the representative of inland cities with dense population hit by floods, which has the same characteristics with

Fig. 8. Location of Zhengzhou, China (No. GS(2019)1652).

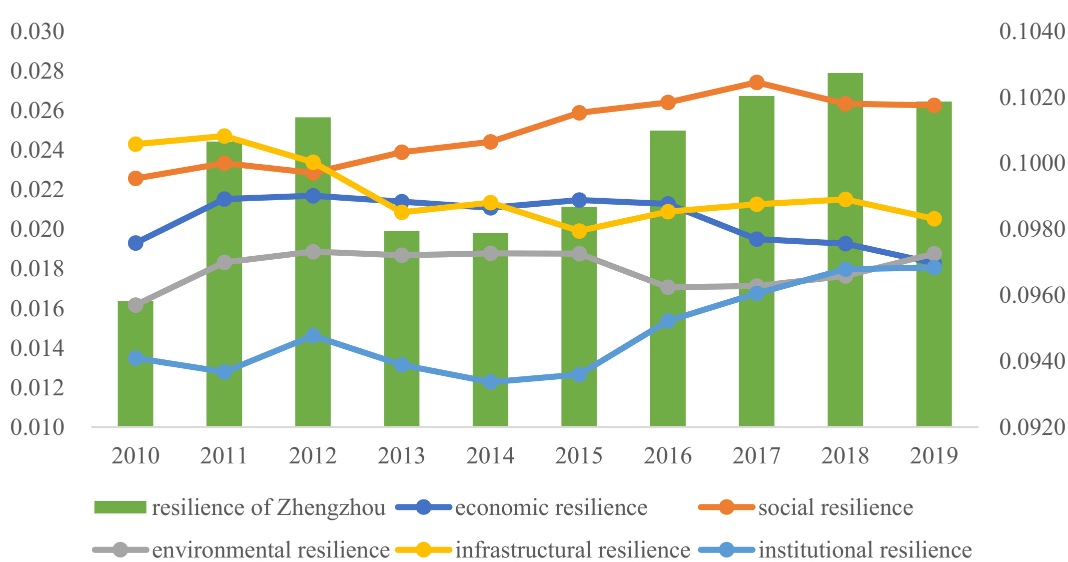

Fig. 9. Resilience level of Zhengzhou between 2010 and 2019.

Xi'an (China), Khon Kaen (Thailand), Prague (Czech Republic), Chicago (USA), Neuquén (Argentina), and Budapest (Hungary). They all face many pressures from climate change and population growth. Fig. 8 illustrates the location of Zhengzhou.

3.4. Data source

All data were gained from the statistical yearbook 2011–2020 of Zhengzhou, the bulletin of Zhengzhou water resources 2010–2019, and the statistical bulletin of Zhengzhou National Economic and social development 2010–2019.

4. Results and discussion

4.1. Resilience level of Zhengzhou

Table 1 shows the weight of each subsystem in Zhengzhou's resilience. The weights of economic, social, environmental, infrastructural, and institutional resilience of Zhengzhou were 0.2048, 0.2493, 0.1802, 0.2187, and 0.1471 respectively, indicating that social resilience, infrastructural resilience, and economic resilience were more important to Zhengzhou's resilience. Among the secondary indicators, the weights of infrastructure perfection (0.1168), economic structure (0.1114), social capacity (0.1132), infrastructure potential (0.1019), and social structure (0.0774) ranked the top five. Hence, infrastructure construction was the key to Zhengzhou's resilience. Fig. 9 exhibits its levels of resilience between 2010 and 2019.

In Fig. 9, there was an overall growth trend between 2010 and 2019 in Zhengzhou's resilience, increasing from 0.09582 in 2010 to 0.10187 in 2019. Between 2010 and 2012, Zhengzhou's resilience increased significantly, but it decreased significantly in 2013 and began to improve steadily in 2014. The decline in 2013 was due to the significant decline of infrastructural and institutional resilience, among which emergency management, infrastructure perfection, and infrastructure potential decreased the most.

Economic resilience showed an upward trend first and then a downward trend. There was a large increase in 2011, mainly due to the adjustment of economic structure, such as improvement of industrial energy efficiency. A sharp decline in 2017 was mainly due to the decline in economic capacity, such as a significant decline in proportion of people with their own housing. This showed that when Zhengzhou vigorously developed its urban economy and adjusted the industrial structure, urbanization increased the number of urban permanent residents, but the economic ability of residents did not improve with the urban development in a short term.

Social resilience showed an upward trend, but there was a downward trend in the past two years. 2018 showed a large decline that was mainly due to an increase in social demand, such as a significant increase in the proportion of domestic electricity and food consumption. This showed that an increased demand for energy, food, and other resources in Zhengzhou posed a great challenge to its resilience.

Environmental resilience showed an upward trend. A significant decrease in 2016 was observed, mainly due to the decrease in environmental protection, such as a decrease in completion of environmental governance investment. There was a significant increase in 2011 and 2019, mainly due to the increase of environmental protection, such as the increase of the proportion of ecological water, and due to reduction of environmental pollution, such as reduction of industrial waste gas emission, respectively. This showed that optimized utilization of water resources and adjustment of the energy structure in Zhengzhou could actively promote its resilience.

Infrastructural resilience showed a downward trend, which decreased significantly in 2012, 2013, 2015, and 2019. Decreases in 2012–2013 was mainly due to the decline in infrastructure perfection, such as the number of beds per 10,000 people and the proportion of mobile phone users. After 2013, the decrease was mainly due to the decline in infrastructure potential. For example, the proportion of electricity infrastructure investment and water conservancy infrastructure investment decreased. This showed that there was constant improvement in Zhengzhou's infrastructure, but the existing infrastructure could not address the short-term shock and long-term pressure. It is still necessary to further improve infrastructure construction such as water conservancy and electricity.

Institutional resilience showed an upward trend, with significant growth in 2012, 2016, 2017, and 2018. The increase in 2012 was mainly due to improvement of the supply chain, such as the decline in the ratio of energy purchase to consumption. The increase in 2016–2018 was mainly due to improvement of emergency management capacity, such as the increase in the number of employees in public management and social organizations per 10,000 people, per capita possession of fast food, etc. This showed that emergency management capacity and supply chain perfection in Zhengzhou were continuously improved, which promoted its resilience. On the premise that external dependence on water, energy, and food in Zhengzhou increases year by year, ensuring supply chain security is an important content of its resilience construction.

4.2. Optimization degree of subsystem on Zhengzhou's resilience

Relative proximity was introduced to analyze the optimization degree of each index on Zhengzhou's resilience, and Fig. 10 shows the results.

In Fig. 10, the optimization degree of subsystems on Zhengzhou's resilience showed a downward trend, from 0.5714 in 2010 to 0.4311 in 2019. The optimization degree of social, environmental, institutional, economic, and infrastructural resilience gradually decreased, and all showed a downward trend. It indicated that these subsystems were farther away from the optimal path, and they had poor optimization. The main reason lies on reduction of the optimization degree of secondary indicators such as economic structure, social structure, social demand, and supply chain. That is, Zhengzhou need to improve its resilience from these aspects.

4.3. Obstacle factors on Zhengzhou's resilience

The obstacle degree of each subsystem was calculated according to formula (5). Results are shown in Fig. 11.

Obstacles from environmental resilience and infrastructural resilience gradually increased, as shown in Fig. 11. Among them, social resilience and infrastructural resilience were the main reasons hindering Zhengzhou's resilience construction, with obstacle degrees of 0.2695 and 0.2101, respectively. Supporting from environmental resilience and institutional resilience was obvious. In the point of view of secondary indicators, in the past three years, economic structure, social structure, environmental protection, infrastructure perfection, and supply chain had the greatest obstacles to Zhengzhou's resilience, while obstacles from social structure, resource endowment, environmental pollution, infrastructure perfection, and supply chain increased.

4.4. Discussion

Compared with Zhu et al. (2019) work on resilient cities, it was agreed that the levels of institutional, infrastructural, and economic resilience of Zhengzhou were relatively low. According to the above analysis on Zhengzhou's resilience, it was limited by infrastructure construction, consistent with Moghadas et al. (2019) where infrastructure is one of the key factors of urban resilience. In addition, as many researchers argued (Nhamo et al., 2021; Páez-Curtidor et al., 2021; Sun et al., 2016), a series of problems caused by production, allocation, and consumption of water, energy, and food in industrial production and domestic living were also important reasons affecting Zhengzhou's resilience construction. The main reasons hindering the resilience

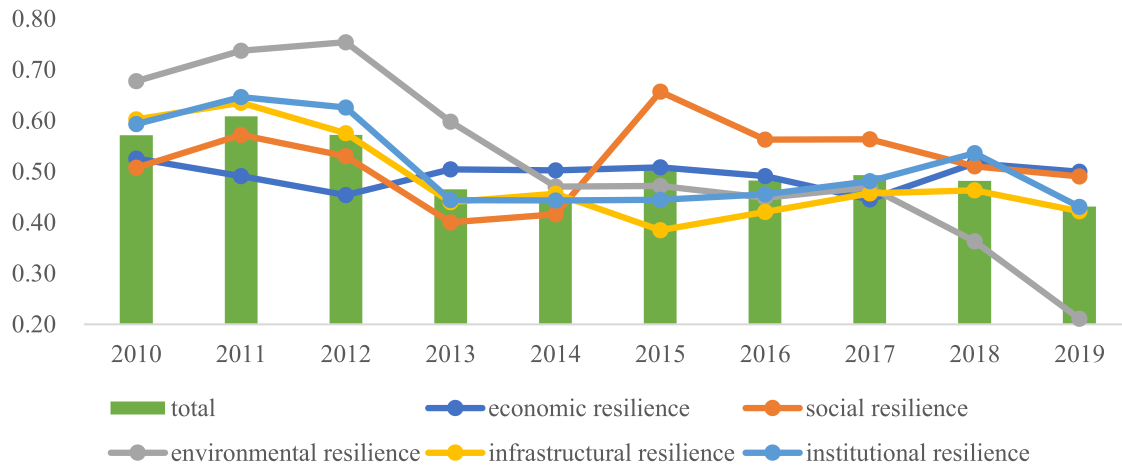

Fig. 10. Relative approximation of subsystems on Zhengzhou's resilience.

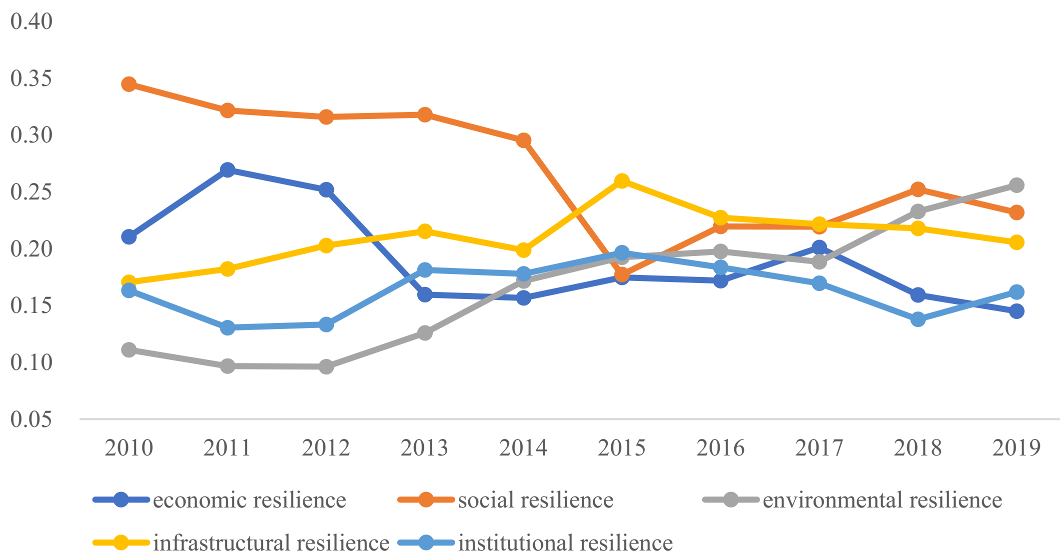

Fig. 11. Obstacle degree of subsystems on Zhengzhou's resilience.

construction were analyzed, and some suggestions for improving resilience and city design were put forward.

4.4.1. Main reasons hindering the resilience construction

The main reasons could be concluded from the two aspects of hardware and software for dealing with the impact: infrastructure and institution.

The existing infrastructure fails to adapt to the changing environment of the economy, society, and nature. On the one hand, with the growing economy, the deeper urbanization, and the changing weather, chronic long-term impacts caused by expanding demand poses great pressure on existing infrastructure. Especially, the increasing demand for water, energy, and food for living and production puts forward higher requirements for water conservancy and energy infrastructure. That is, it should not only meet the demands at this stage but also complete the improvement and upgrading of infrastructure before the demands change qualitatively. Intergovernmental Panel on Climate Change (IPCC) reported that droughts become more frequent in continental East Asia and arid Eastern Central Asia becomes wetter. The existing infrastructure in Zhengzhou was designed to adapt to arid weather but not suitable for a wetter weather. On the other hand, sudden disasters such as floods and COVID-19 challenge the ability of the existing infrastructure to respond to unconventional needs, that is, redundancy. Infrastructure in megacities should be designed to improve its function as much as possible considering cost and benefit. The medical infrastructure was designed for conventional treatment or minor emergencies, not taking into consideration major public health emergencies.

Imperfect systems and the practice of emergency management could not meet the requirements of dealing with short-term impacts. The emergency system and mechanism has not been tested in practice yet. Although nearly every megacity has its emergency management system and mechanism, whether it works or not needs to be verified in practice and it should make continuous improvement based on that. Dense population in the megacity enlarges the difficulty in emergency management, and lessons on how to help residents prevent disasters and avoid risks effectively and quickly should be drawn from practice. For example, during the "7.20″ torrential rain disaster in Zhengzhou, it showed the problem of weak emergency management system and capacity, as well as the imperfect linkage mechanism of early warning and response, causing heavy casualties and serious economic losses. On the other hand, there is a gap between theory and practice in emergency management. Even if a megacity has a perfect emergency management system and mechanism, there are still deviations in its practice, such as lack of risk awareness, lack of unified leadership, and insufficient knowledge of self-rescue. These factors were also the causes of great losses in the "7.20″ torrential rain disaster in Zhengzhou.

4.4.2. Paths to improve the resilience level

There are two paths to improve the resilience level. One is to minimize long-term pressure and short-term shocks as much as possible, including optimizing industrial structure and strengthening social security; the other is to improve the ability to deal with long-term pressure and short-term shocks, including improving infrastructure investment and strengthening supply chain resilience.

Optimizing industrial structure. Zhengzhou's economic structure had poor optimization and strong obstacle on its resilience, in which industrial structure was the key. Although Zhengzhou is dominated by the tertiary industry, the contribution rate of industry to GDP is still more than 1/3. When it comes to megacities, demand growth is inevitable and problems of water use, energy use, and pollution emission brought by industrial production posing challenges to its resilience could be reduced by adjusting the industrial structure and optimizing the basic resource demand structure. When facing short-term shock of disasters, production characteristics of industrial enterprises make them more vulnerable to economic losses and their resumption will be affected by energy and supply chain; therefore, it is difficult to recover quickly. Therefore, accelerating optimization of industrial structure and developing intelligent, green, service-oriented emerging industries can improve resilience by improving the economic, environmental, and organizational resilience levels.

Strengthening social security. Optimization of social structure was weakened while its obstacle was strengthened, in which population structure was the focus. Population aging in Zhengzhou is deepening, and resident population is far more than registered residence population. When it comes to megacities, a huge population increases water, energy, and food consumption, as well as the demand for housing and emission of domestic pollutants, which introduces higher requirements for municipal engineering, resource supply, housing land, and social services. When facing short-term shock of disasters, a large population increases the difficulty of emergency management and improves the standards of emergency material reserve and availability. Hence, strengthening social security, building affordable housing, improving municipal infrastructure, and increasing the number of employees in public management and social organizations can improve resilience.

Improving infrastructure investment. Infrastructure construction is the short board of Zhengzhou's resilience. There is still room for improvement in terms of infrastructure perfection and infrastructure development potential. From the heavy rainstorm in July to the tight power supply in September this year, it posed challenges to its infrastructure construction, including water conservancy infrastructure and electricity infrastructure. In the context of climate change, Zhengzhou, which was always a water shortage area, encountered the worst flood in a century. The existing water conservancy infrastructure cannot meet its flood fighting requirements. When it comes to megacities, improving and upgrading water conservancy infrastructure are the focus of dealing with floods and other disasters in the context of climate change. Also, under the goal of "carbon peak and neutrality," investing in construction of new energy facilities and improving production efficiency of existing power facilities can also improve resilience of megacities.

Strengthening supply chain resilience. Zhengzhou strongly depended on external resources for water, energy, and food supply, and its proportion of resource allocation increased year by year. When it comes to megacities, once the supply chain breaks, its own water resources, energy, food, and emergency materials cannot afford to meet the basic requirements for industrial production and domestic living. During COVID-19 or typhoons, food supply in supermarkets and energy supply from power companies are required to meet the needs of domestic living. The supply chain as a link links different subjects, and resilience of this link is the basis of urban resilience. Enhancing supply chain resilience improves the flexibility, redundancy, collaboration, velocity, and visibility of the supply chain and focuses on improving the corresponding ability in different stages of risk events (Ali et al., 2017).

4.4.3. Suggestions for resilient city design

Maintaining redundancy is one of the best ways to deal with short-term shocks. Redundancy means maintaining an idle response capability to access in case of disruption, such as redundant capacity and safety stock. Redundant emergency materials, supply chains with redundancy, emergency organizations with redundant personnel, and infrastructure with redundant capacity are necessary for designing a resilient city. For example, once a power plant interrupts the power supply due to flood, other power plants should have enough capacity to make up for the lack of power generation. Also, once a communication base station fails, redundant base stations are needed to maintain information communication during emergencies. In addition, water conservancy facilities should be designed in accord with precipitation change caused by climate change.

In the face of long-term pressures, improving efficiency is one of the key ways for resilient city design while preparedness is the basis. Preparedness means accurately predicting the probability and consequences of risks and actively preparing for them. Governments should predict the resource supply and demand under different conditions to adopt policies for early adaptation, such as climate change, population growth, consumption preference, and pollution control. Hence, appropriate tools and methods for prediction, such as monitoring equipment for precipitation, transportation, infectious diseases, pollution, housing price, and power consumption, as well as monitoring systems, are essential. The purpose of designing such a resilient city is to enhance its ability to deal with impacts, and improving efficiency enables it to recover from the impact quickly. Hence, intelligent infrastructure, such as smart roads, smart grids, smart healthcare, and big data bases, should be designed for resilient cities.

5. Conclusions

Due to the economic and social characteristics of megacities, they are vulnerable to the impacts of extreme events such as climate change, especially the characteristics of separation between production and consumption of water, energy, and food in megacities. The roadmap of disaster impacting on the resilience of megacities was analyzed to select indexes, an evaluation index system of a resilient megacity based on WEFN including the five dimensions was established, and the entropy weight-TOPSIS method and obstacle degree model were used to assess Zhengzhou's resilience. The following conclusions can be drawn:

(1) In terms of index weight, social resilience, infrastructural resilience, and economic resilience were more important for Zhengzhou's resilience. Among the secondary indicators, infrastructure perfection, economic structure, social capacity, infrastructure potential, and social structure ranked among the top five. Infrastructure construction was key to Zhengzhou's resilience.
(2) In terms of Zhengzhou's resilience level, it showed an upward trend between 2010 and 2019. Due to significant reduction of infrastructural resilience and institutional resilience, Zhengzhou's resilience level decreased significantly in 2013 and began to grow steadily in 2014. Problems of social demand, environmental protection, supply chain caused by production, allocation, and consumption of water, energy, and food had a great impact on Zhengzhou's resilience.
(3) In terms of optimization degree of subsystems on Zhengzhou's resilience, the optimization degree generally showed a downward trend between 2010 and 2019, and the optimization degree of social resilience, environmental resilience, institutional resilience, economic resilience, and infrastructural resilience decreased as a consequence and showed a downward trend. It was mainly due to the decrease of some secondary indicators such

as economic structure, social structure, social demand, and supply chain.

(4) In terms of obstacles factors on Zhengzhou's resilience, social resilience and infrastructural resilience were main reasons hindering its resilience construction. Economic structure, social structure, infrastructure perfection, and supply chain had great obstacles on Zhengzhou's resilience, while obstacles from environmental resilience and infrastructural resilience gradually increased.

(5) Zhengzhou should optimize industrial structure, strengthen social security, improve infrastructure investment, and strengthen the supply chain to improve its resilience, for example, improving industrial water use efficiency, improving industrial energy use efficiency, and promoting agricultural intellectualization; optimizing the population structure and establishing a safe and resilient supply network of water–energy–food; increasing infrastructure investment and construction of water conservancy projects, smart roads, and power networks; and dynamic monitoring on demand and consumption of water–energy–food and establishing an early warning mechanism on extreme weathers.

Urban resilience and urban WEFN are both popular governance schemes for cities to address climate change and various challenges, and they are interrelated to some extent. Taking WEFN into account in urban resilience, the evaluation index system based on WEFN proposed in this paper could more comprehensively assess resilience of megacities. The results help to reveal the Zhengzhou's resilience level, find its advantages and disadvantages, and propose paths and strategies on how to become resilient, as well as provide enlightenment for the resilience construction of other megacities. This evaluation system can provide tools for policy makers on how to formulate the development plan and implementation measures of resilient cities effectively.

The main contribution of this paper is that based on characteristics of separation between production and consumption of water, energy, and food in megacities, WEFN is taken into account in the index system of resilient megacities, which enriches the research on urban resilience. The limitation of this paper is that index selection is based on the availability of data, and some second-hand data cannot fully represent the actual situation. In the future, combination of first-hand data with second-hand data to assess resilience level of other megacities could be done. How to improve the resilience of the water–energy–food supply chain in megacities is the future research direction.

Data availability

The data supporting the results were incorporated in article.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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