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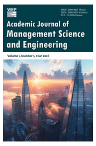

Assessment of Flood Resilience in the Zhengzhou Metropolitan Area in 2022 Based on Principal Component Analysis

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ABSTRACT

Floods are characterized by their suddenness, destructive power, and unpredictability, posing serious threats to human society and the natural environment. Building resilience provides a new approach for urban systems to cope with floods. This study constructs a flood resilience index system and uses principal component analysis to comprehensively evaluate the basic resistance, disaster prevention and early warning, emergency response, and adaptive recovery capabilities of the Zhengzhou metropolitan area, thereby determining the resilience level of each city within the Zhengzhou metropolitan area. Simultaneously, the natural discontinuity method is used to compare the spatial differences in flood resilience among different cities. The results show that in 2022, the ranking of the comprehensive flood resilience scores of cities in the Zhengzhou metropolitan area was as follows: Zhengzhou > Pingdingshan > Xuchang > Xinxiang > Luohe > Luoyang > Jiyuan > Kaifeng > Jiaozuo, with Zhengzhou achieving the highest comprehensive flood resilience score. The 2022 flood resilience levels in the Zhengzhou metropolitan area show that 5 cities were at a low resilience level, 3 cities at a medium resilience level, and Zhengzhou at a high resilience level, exhibiting strong spatial differences and generally showing a pattern of high resilience in the middle and low resilience from east to west. The research findings can provide a basis for formulating policies to enhance the resilience of the Zhengzhou metropolitan area to flood disasters.

KEYWORDS

Zhengzhou metropolitan area; Flood disaster; Resilience; Principal component analysis; Natural breakpoint method.

1. INTRODUCTION

In February 2022, the "Henan Province New Urbanization Plan (2021-2035)"was issued, proposing to optimize and reshape the spatial layout of the Zhengzhou metropolitan area and accelerate the integrated development of cities within the region. Implementing the national regional coordinated development strategy, major regional strategies, functional zoning strategy, and new urbanization strategy, the Plan comprehensively plans the spatial development and protection pattern of the Zhengzhou metropolitan area, creating a modern metropolitan area with international influence. This is particularly important for supporting the construction of a modern Henan with Chinese characteristics, achieving high-quality regional development, enhancing urban safety and resilience, and strengthening disaster emergency response capabilities. Urban disaster resilience and high-quality economic development are mutually reinforcing and interdependent. Floods are characterized by their suddenness, extreme destructiveness, and unpredictability, often causing severe casualties and property damage, and posing serious threats to human society and the natural environment. The harm caused by floods is comprehensive, requiring our high attention and proactive response. The term "resilience" originates from the concept of resilience in physics. Since its introduction in 1973 by ecologist Holling, who systematically explained the concept from the perspective of ecosystem attributes, it has gradually formed several academic schools of thought in fields such as engineering, ecology, and management. Faced with environmental and socio-economic uncertainties and risks, "resilience" has also become a core objective of urban planning, construction, and development [1]. The concept of urban flood disaster resilience stems from resilience research, and the concept of "resilience" has gradually shifted from a single perspective of engineering or ecological resilience to a comprehensive, multi-dimensional perspective encompassing socio-ecological system resilience and the resilience of human-land systems. Resilience, as a systemic approach that involves "flexible recovery" and "adaptation to change" in response to internal or external influences, offers new insights for urban systems to cope with flood disasters. Slobodan Simonovic [2], Chairman of the International Conference on Flood Management, believes that flood risk management is closely related to sustainable urban development, and therefore proposes a new development model: "reducing flood risk and enhancing resilience." Urban flood resilience refers to the ability of an urban system to maintain the normal operation of its main functions when it is subjected to floods, effectively resist the threat of floods, promptly restore normal functions after some subsystems are damaged, and continuously adapt and adjust the internal structure of the urban system in order to better cope with the next flood[3]. The focus of urban resilience research is on addressing disturbances caused by climate change and natural disasters, with extreme rainstorms and floods being a form of uncertainty disturbance[4]. Urban flood resilience is considered the ability of a city's socioeconomic system to effectively resist, absorb, recover from, and successfully adapt to and cope with flood disasters in both the long and short term[5]. Whether there are differences in the resilience levels to flood disasters across different regions warrants further investigation. Principal component analysis (PCA) is a multivariate statistical method for dimensionality reduction of multiple indicator components. This study uses PCA to comprehensively evaluate the basic resilience, disaster prevention and early warning, emergency response, and adaptive recovery capabilities of the Zhengzhou metropolitan area, aiming to determine the resilience levels of various cities within the Zhengzhou metropolitan area and provide a reference for improving the flood disaster resilience and enhancing the city's ability to cope with flood disasters.

Previous studies have referenced the three elements of "resilience": the system's defensive capability against external disturbances, its ability to respond rapidly after being impacted, and its adaptive recovery capability in the face of similar risks. Previous resilience studies have mostly evaluated the resilience level of a region based on a combination of subjective and objective evaluation methods, and the research areas are mostly concentrated in urban agglomerations, with relatively few studies on metropolitan areas. This paper, based on the response process of various cities in the Zhengzhou metropolitan area to disaster events, analyzes the impact of flood disasters on the system performance of each city from a comparative perspective, proposes an urban flood disaster resilience evaluation method based on principal component analysis, and constructs an urban flood disaster resilience evaluation index system. By calculating the comprehensive score, the flood disaster resilience level of each region in the Zhengzhou metropolitan area in 2022 is obtained. Then, the natural breakpoint method is used for classification to intuitively reflect the resilience level of each city, providing an immediate evaluation basis for effectively evaluating the "7.20" Zhengzhou torrential rain event.

2. OVERVIEW OF THE STUDY AREA AND DATA SOURCES

2.1. Overview of the Study Area

The Zhengzhou Metropolitan Area is located in the north-central part of Henan Province, with latitude and longitude ranging from 33°74'N to 35°30'N and 112°16' E to 115°15'E. The February 2022 "Plan" clearly defines the spatial distribution pattern of the Zhengzhou Metropolitan Area as "one core, one sub-center, one belt, and multiple points," encompassing the integrated development of nine cities:

Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Xinxiang, Jiaozuo, Luohe, Xuchang, and the Jiyuan Demonstration Zone. The "Zhengzhou Metropolitan Area Territorial Spatial Planning (2022-2035)" covers the period from 2022 to 2035, with a near-term target of 2027 and a long-term vision extending to 2050. The planning scope focuses on the spatial area defined in the "Zhengzhou Metropolitan Area Development Plan," and also incorporates other areas of Luoyang, Pingdingshan, Xinxiang, Jiaozuo, Luohe, and the Jiyuan Demonstration Zone into the unified plan. The Zhengzhou metropolitan area has a warm temperate continental monsoon climate, characterized by significant seasonal variations in temperature and precipitation, with rain and heat occurring simultaneously. The average annual temperature is around 15°C, with most rainfall concentrated in the summer. The region has numerous rivers, a terrain that slopes from west to east, and is surrounded by mountains on three sides. The large population concentration, rapid urbanization, and increased extreme weather events due to climate change have presented the city with numerous uncertainties and challenges. In particular, the devastating rainstorm in Henan Province that lasted for nearly a week starting on July 17, 2021, resulting in 398 deaths and missing persons and direct economic losses of 120.06 billion yuan[6], underscores the importance of enhancing urban resilience and safety in the pursuit of high-quality economic development.

2.2. Data Sources and Processing

This paper selects data from eight indicators in 2022 for nine cities (districts) in the Zhengzhou metropolitan area. Most of the data comes from the 2023 Henan Statistical Yearbook. Data on the number of meteorological observations at each city's meteorological station is from the Henan Provincial Meteorological Bureau Office document Yu Qi Ban Fa [2019] No. 2, "Announcement of the Henan Provincial Meteorological Bureau Office on the Scope of Meteorological Observation Environmental Protection Zones for Meteorological Observation Stations in Henan Province in 2019." Data on the capacity of emergency shelters in each city is from the "Yu Shi Ban" mini-program's statistics on emergency shelters in various cities of Henan Province in June 2024. Data statistics and analysis were performed using SPSS 26.0 for analysis of variance, significance analysis, and data standardization; ArcGIS 10.8 was used for natural breakpoint classification.

3. RESEARCH METHODS AND INDICATOR SYSTEM CONSTEUCTION

3.1. Research Methods

Principal Component Analysis (PCA) is a commonly used statistical and machine learning method that primarily utilizes data dimensionality reduction. Simply put, it can compress multiple related variables into a few unrelated composite variables, while minimizing information loss; these composite variables are called principal components. The top-ranked principal components represent most of the information from the causal variables. Further research uses scree plots and cumulative variance contribution rates to determine how many principal components to retain.

Let the original data matrix be X = (x1, x2, …, xp). The principal component transformation is expressed as: Fi= ai1x1+ ai2x2+…+aip xp, i = 1, 2, …, m.

In the formula, Fi is the i-th principal component, ai1, ai2,…,aip, are the loading coefficients of the i-th principal component on each of the original variables, p is the number of original variables, and m is the number of extracted principal components, where m≤p. The principal component loading coefficients must satisfy the normalization constraint $\sum_{j=1}^{p} a_{ij}^2 = 1$.

Since the indicators selected for evaluating each stage of flood disaster emergency response are different in unit, the zero mean and normalized standard deviation method of PCA are used to standardize the raw data of each indicator. The correlation coefficient and characteristic are calculated, and the components with characteristic values greater than 1 are identified as principal components. The coefficients in the principal components are subjected to weighted average normalization to convert each indicator into a standard normal distribution with a mean of 0 and a standard deviation of 1.

$$Z_{ij} = \frac{X_{ij} - \overline{X}_j}{S_j}$$

In the formula, Zij is the standardized score of the i-th sample on the j-th indicator, Xij is the original observation value, and Xj and Sj are the mean and standard deviation of the j-th indicator, respectively. The standardized data follows a standard normal distribution with a mean of 0 and a variance of 1, which meets the basic requirements of principal component analysis for data distribution.

The weights of each dimension's indicators are determined based on the principal component loading matrix rotation results. The maximum variance method is used to achieve orthogonal rotation of the factor space, and variables with an absolute value of loading coefficient greater than 0.5 are considered representative indicators of that principal component. A weighted summation model is used to calculate the overall score.

$$F = \sum_{i=1}^{m} \lambda_i F_i / \sum_{i=1}^{m} \lambda_i$$

In the formula, F is the overall evaluation score, Fi is the score of the i-th principal component, λi is the variance contribution rate of the corresponding principal component, and m is the number of principal components. The weights of each indicator in the principal components and the scores of each principal component are calculated. The variance contribution rate of each principal component is used as the weight to calculate the total principal component score[7].

The KMO statistic is used to measure the degree of partial correlation between variables. A larger KMO value indicates that the data is suitable for factor extraction. The Bartlett's test of sphericity requires a significance level ($P < 0.05$) to confirm that the correlation matrix is not an identity matrix.

3.2. Construction of the Indicator System

This study establishes an evaluation index system considering urban resistance, predictability, adaptability, and resilience to describe the resilience level of urban systems in the face of flood disasters. Combining the process of urban response to flood disasters into four stages: prevention and emergency preparedness, monitoring and early warning, emergency response and rescue, and recovery and reconstruction, the flood disaster resilience of the Zhengzhou metropolitan area is divided into four aspects: basic resistance, disaster prevention and early warning, emergency response, and adaptive recovery capacity.

Basic resilience refers to the ability of an urban system to withstand the impact of floods and reduce direct losses through infrastructure construction, including urban flood control projects, drainage facilities, and the construction of urban ecosystems. Disaster early warning refers to the ability to promptly report dangerous situations to relevant departments and the public before a flood occurs, based on existing intelligence and data, summarizing information such as the probability of a disaster, and notifying all units to prepare for disaster prevention and response, thereby minimizing flood losses to the greatest extent possible. Emergency response refers to the ability of units and social organizations at all levels to promptly and effectively organize, coordinate, and utilize various emergency resources and take a series of measures to protect the lives and property of the people and maintain social stability during a flood. Adaptive recovery refers to the ability of an urban system to quickly restore normal order after being impacted by floods, and on this basis, further enhance the city's resilience to floods[8].

In this indicator system, the target layer is urban flood disaster resilience, the criterion layer consists of four aspects: basic resistance, disaster prevention and early warning, emergency response and adaptive recovery, and the indicator layer includes a total of eight specific indicators, all of which are positive indicators.

Table 1. Index System for Flood Resilience

Target layer	Criterion layer	Indicator layer	Direction
Flood Resilience	Basic resilience	Drainage pipe density in built-up areas (unit: km/km²)	+
		Green coverage area of built-up area (unit: hectares)	+
	Disaster early warning	Number of meteorological stations in each city (unit: stations)	+
		Number of legal entities in the software and information technology services industry (Unit: (entities))	+
	Emergency response	Capacity of emergency shelters in each city (unit: people)	+
		Number of beds in medical and health institutions in each city (unit: beds)	+
	Adaptive recovery	Number of legal entities in the water conservancy, environment, and public facilities management industry (Unit: (units))	+
		Highway mileage in each city (unit: kilometers)	+

3.3. Research Framework

To study the flood resilience of the Zhengzhou metropolitan area, this research conducted a four-step study from a comparative perspective. First, the study explored the connotations of flood resilience in the Zhengzhou metropolitan area across four aspects: basic resistance, disaster prevention and early warning, emergency response, and adaptive recovery capabilities. Second, an evaluation index system for flood resilience in the Zhengzhou metropolitan area was constructed, and principal component analysis was used to measure the flood resilience of the Zhengzhou metropolitan area in 2022. Based on the comprehensive scores, the resilience levels of nine cities in the Zhengzhou metropolitan area were determined. Third, with the resilience scores of each city determined, the natural discontinuity method was used for preliminary classification, and the differences in flood resilience among different cities in the Zhengzhou metropolitan area were compared. Fourth, this study systematically evaluated the flood resilience of the Zhengzhou metropolitan area in 2022 and discussed how to more effectively build resilience in the Zhengzhou metropolitan area in the future.

4. EMPIRICAL RESULTS AND DISCUSSION

4.1. Principal Component Analysis Was Used to Derive The Overall Resilience of Flood Disasters in Various Cities and Prefectures.

Table 2 shows the descriptive statistics of eight indicators of flood resilience in the Zhengzhou metropolitan area, including the average value and standard deviation of the indicators.

This study uses principal component analysis for information condensation. First, it analyzes whether the flood disaster resilience data is suitable for principal component analysis. As shown in Table 3 above, the KMO is 0.488, which basically meets the prerequisite requirements for principal component analysis. In addition, the data passes the Bartlett's test for sphericity ($p<0.05$), indicating that the research data is suitable for principal component analysis.

Table 2. Descriptive statistics of eight indicators of flood resilience.

Descriptive statistics			
Indicator	Mean	Standard Deviation	Number of Cases Analyzed
Drainage pipe density in built-up areas	9.4167	2.42849	9
Green coverage area in built-up areas	8138.8889	8337.92335	9
Number of meteorological stations observed in each city	6.3333	3.08221	9
Number of legal entities in the information transmission, software and information technology services industry	6512.6667	11314.23308	9
Number of people accommodated in emergency shelters in each city	684977.8889	647045.08877	9
Number of hospital beds in each city	40787.2222	30929.16379	9
Number of legal entities in the water conservancy, environment and public facilities management industry	1342.2222	946.46867	9
Mileage of highways in each city	11104.5556	5267.19214	9

Table 3. KMO and Bartlett's Test

KMO and Bartlett test		
KMO sampling appropriateness measure		.488
Bartlett's sphericity test	Approximate chi-square	76.391
	Degrees of freedom	28
	Significance	.000

Analysis of the principal component extraction results and information content in Table 4 reveals that the principal component analysis extracted two principal components. These two principal components explained 68.832% and 15.318% of the variance, respectively, for a cumulative variance explanation of 84.150%. Furthermore, the weighted variance explanations (i.e., the weights) of the two principal components extracted are: 5.507/6.732 = 81.8% and 1.225/6.732 = 18.20%, respectively.

Table 4. Eigenvalues, variance contribution rates, and cumulative variance contribution rates of the two principal components.

Explanation of total variance						
Element	Initial eigenvalues			Extraction of sum of squared loads		
	Total	Percentage of variance	Accumulation %	Total	Percentage of variance	Accumulation %
1	5.507	68.832	68.832	5.507	68.832	68.832
2	1.225	15.318	84.150	1.225	15.318	84.150
3	.816	10.205	94.355			
4	.299	3.738	98.094			
5	.117	1.463	99.556			
6	.023	.284	99.840			
7	.012	.150	99.990			
8	.001	.010	100.000			

The number of principal components was determined using the scree plot (Figure 1). When the line suddenly becomes flat, the number of principal components corresponding to this transition is the reference number of principal components to be extracted. Based on the correspondence between principal components and urban rainstorm and flood disaster research items, the number of principal components was determined to be 2. The figure shows that when the horizontal axis is 2-3, the line suddenly becomes relatively flat.

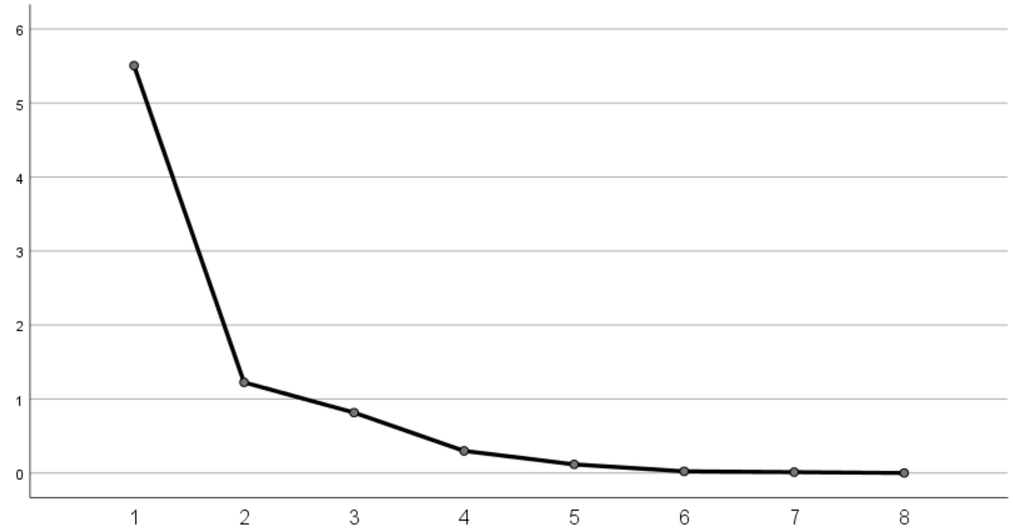

Figure 1. Gravel map

In Table 5, the "Initial" column indicates that when all components are included, no information is removed from the study, and all variation in the data can be explained, with each variable's variation explained by a factor of 1, meaning 100% is explained. The "Extract" column indicates that when only selected components are retained, only a portion of the components are preserved, and the explained variation of all variables decreases.

Table 5. Common factor variance of the 8 indicators

Common factor variance		
	Initial	Extract
Drainage pipe density in built-up areas	1.000	.426
Green coverage area in built-up areas	1.000	.914
Number of meteorological stations observed in each city	1.000	.846
Number of legal entities in the information transmission, software and information technology services industry	1.000	.979
Number of people accommodated in emergency shelters in each city	1.000	.808
Number of hospital beds in each city	1.000	.971
Number of legal entities in the water conservancy, environment and public facilities management industry	1.000	.891
Mileage of highways in each city	1.000	.897
Extraction method: Principal component analysis.		

Based on the component matrix and eigenvalues of each principal component, calculate the weight values of each component and derive the functional expressions for each principal component, as follows: $F1=-0.455X1/\sqrt{5.507}+0.923X2/\sqrt{5.507}+0.821X3/\sqrt{5.507}+0.896X4/\sqrt{5.507}+0.806X5/\sqrt{5.507}+0.98X6/\sqrt{5.507}+0.944X7/\sqrt{5.507}+0.685X8/\sqrt{5.507}$; $F2=0.468X1/\sqrt{1.225}+025X2/\sqrt{1.225}-0.415X3/\sqrt{1.225}+0.419X4/\sqrt{1.225}+0.397X5/\sqrt{1.225}+0.103X6/\sqrt{1.225}-0.028X7/\sqrt{1.225}-0.654X8/\sqrt{1.225}$.

Where X1, X2, X3……X8 represent different evaluation indicators. Using the variance contribution rates of the two principal components as their respective weights, a comprehensive evaluation model is constructed, yielding a comprehensive score F=5.507/（5.507+1.225）F1+1.225/（5.507+1.225）F2.

The model was used to calculate and rank the comprehensive scores of different regions in the Zhengzhou metropolitan area. The results (Table 6) show that the comprehensive scores of flood disaster resilience of each city in the Zhengzhou metropolitan area are ranked as follows: Zhengzhou > Pingdingshan > Xuchang > Xinxiang > Luohe > Luoyang > Jiyuan > Kaifeng > Jiaozuo. Zhengzhou has the highest comprehensive score of flood disaster resilience (F=821074.423).

Table 6. Principal Component Scores, Overall Scores, and Rankings of Flood Resilience in Various Cities within the Zhengzhou Metropolitan Area

city	F1	F2	Overall score F	rank
Zhengzhou	825181.042	802613.076	821074.423	1
Kaifeng	53990.615	33992.447	50351.614	7
Luoyang	100519.073	63911.059	93857.632	6
Pingdingshan	328114.667	396715.686	340597.770	2
Xinxiang	217154.930	197602.161	213596.976	4
Jiaozuo	2177.090	250156.810	47301.147	9
Xuchang	273600.516	264598.100	271962.376	3
Luohe	154564.340	149156.029	153580.208	5
Jiyuan	68226.959	66074.817	67835.341	8

4.2. Comparison of Spatial Differences in Flood Resilience Across Cities Using the Natural Discontinuity Method

Based on previous research[9], and using the natural discontinuity method to maximize the differences in resilience among different groups, this study appropriately adjusted the classification boundaries to better compare the differences in resilience in the Zhengzhou metropolitan area. The study divided the flood resilience of the Zhengzhou metropolitan area into three levels: low resilience (27145.044 < comprehensive resilience score ≤ 93857.632), medium resilience (93857.632 < comprehensive resilience score ≤ 340597.770), and high resilience (340597.770 < comprehensive resilience score ≤ 821074.430). In 2022, the flood resilience level in the Zhengzhou metropolitan area showed strong spatial differences, generally exhibiting a pattern of high resilience in the middle and low resilience from east to west. Zhengzhou City had the highest flood resilience level, belonging to the first level. Pingdingshan City, Xuchang City, and Xinxiang City had a medium resilience level, belonging to the second level. Luoyang, Kaifeng, Jiaozuo, Luohe, and Jiyuan are at a low resilience level, classified as Level 3.

5. CONCLUSION

Building resilience capabilities provides new insights for urban systems to cope with floods. The overall resilience score ranking of cities in the Zhengzhou metropolitan area is as follows: Zhengzhou > Pingdingshan > Xuchang > Xinxiang > Luohe > Luoyang > Jiyuan > Kaifeng > Jiaozuo.

1) Zhengzhou's overall resilience score is significantly higher than other cities, indicating an uneven development in resilience building within the Zhengzhou metropolitan area.

2) The overall resilience score shows strong spatial differences, generally exhibiting a pattern of high scores in the middle and low scores towards the east and west, with scores generally higher in the north-south direction than in the east-west direction.

6. POLICY RECOMMENDATIONS

1) Construct a robust protection system and improve infrastructure to enhance engineering resilience. The Zhengzhou metropolitan area needs to coordinate upstream and downstream areas to build an overall flood control and drainage pattern based on the terrain characteristics of "high in the northwest and low in the southeast." This includes advancing major flood control and drainage projects and improving the flood discharge capacity of urban rivers. It also involves continuously expanding sponge city construction, addressing urban drainage network blockages, and upgrading key infrastructure and flood-prone areas.

2) Enhance emergency management and technological resilience, and build a comprehensive emergency rescue network. This includes establishing an intelligent monitoring system for urban flood control and drainage, predicting urban flooding risks with the support of intelligent models. Simultaneously, a long-term pipeline inspection mechanism and a refined grid management system have been established to ensure the rapid collection and handling of waterlogging information.

3) Emphasize social and institutional resilience and stimulate public participation. To enhance flood resilience, the government should improve the legal and standard system, issue a series of planning, construction, and management measures for sponge cities, and is currently revising the flood control plan. At the same time, it is crucial to improve the public's ability to cope with floods by raising public awareness of risks and self-rescue and mutual aid capabilities through publicity and education, and encouraging public participation in supervision to jointly maintain urban drainage facilities.

7. RESEARCH LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

A thorough analysis of the resilience level of flood disasters in the Zhengzhou metropolitan area in 2022 is beneficial for targeted improvement of resilience levels in various regions. However, limitations include insufficient coverage of selected indicators and a lack of analysis at the primary indicator level. The study also lacks analysis of other dimensions of resilience. Despite these limitations in indicator selection and data processing, the conclusions of this study have high reliability and practical significance. Future research should further expand the scope of indicators and explore other variables that may affect resilience, aiming to gain a more comprehensive understanding of flood disaster resilience.

DATA AVAILABILITY

Data will be made available on request.

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