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Research on the Evaluation of Water Resources Carrying Capacity in the Central Plains Urban Agglomeration Based on the PS-DR-DP Model

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ABSTRACT: Adequate Water Resource Carrying Capacity (WRCC) is of great significance for the sustainable development of urban agglomerations. Accurately evaluating WRCC is of great significance for the coordinated development of urban agglomerations. Based on the PS-DR-DP framework, an evaluation index system for water resources carrying capacity was established, and the main obstacle factors affecting CPUA WRCC were analyzed using an obstacle degree model. The WRCC index of the Central Plains Urban Agglomeration (CPUA) was calculated using the Improved TOPSIS model, and the evolution and spatial distribution characteristics of WRCC were analyzed.The results indicate that the water resources carrying capacity of the Central Plains urban agglomeration has been coordinated and sustainable in recent years.

KEYWORDS: Central Plains Urban Agglomeration; Water resource carrying capacity; Improved TOPSIS model.

1. 0 INTRODUCTION

Water is an irreplaceable and precious resource that humans rely on for survival. Water resource carrying capacity refers to the ability to support a certain number of people and other living and production facilities within a certain time and space without damaging the ecological environment. Liang, L., Wang, Z., & Li, J. (2019). The effect of urbanization on environmental pollution in rapidly development urban agglomerations. Journal *of cleaner production*, 237, 117649.The carrying capacity of water resources is directly related to human survival and development. With the rapid development of the economy and society, the contradiction of water resource shortage in China has become increasingly prominent and has become one of the main limiting factors for sustainable economic and social developmentSun, J., Li, Y. P., Gao, P. P., & Xia, B. C. (2018). A Mamdani fuzzy inference approach for assessing ecological security in the Pearl River Delta urban agglomeration, China. Ecological *Indicators*, 94, 386-396..At the same time, the carrying capacity of water resources is also an important basic condition for the implementation of regional sustainable development strategiesChen, Q., Zhu, M., Zhang, C., & Zhou, Q. (2023). The driving effect of spatial-temporal difference of water resources carrying capacity in the Yellow River Basin. Journal *of Cleaner Production*, 388, 135709.. In the case where the carrying capacity of water resources remains unchanged, the larger the regional population and economic development scale, the lower the carrying capacity of water resources; On the contrary, the higher the carrying capacity of water resourcesWang, T., Jian, S., Wang, J., & Yan, D. (2022). Research on water resources carrying capacity evaluation based on innovative RCC method. Ecological *Indicators*, 139, 108876..

Based on the limitations of previous research, this study will attempt to answer the following research questions:

(1) From a sustainable perspective, what is the current status of water resources in the Central Plains urban agglomeration during the planning period?

(2) What is the WRCC index of CPUA?

(3) What are the spatiotemporal characteristics of CPUA WRCC?

(4) What are the key factors affecting CPUA WRCC?

The evaluation method proposed in this article can be summarized as follows: firstly, establish an initial indicator database with a wide range of selected indicators, screen the indicators, and construct an evaluation indicator system; Using game theory to determine the weights of indicators based on AHP and entropy weight method, identifying the main obstacle factors using obstacle degree model, and finally proposing suggestions to improve the water resources carrying capacity of the Central Plains urban agglomeration.

The structure and organization of this article are as follows. The first part constructs an evaluation index system, the second part mainly introduces the research methods and data sources, the third part mainly explains the spatiotemporal evolution characteristics of CPUA WRCC and the factors that affect WRCC, and the fourth part is the conclusion and recommendations.

2.0 RESEARCH AREA

The Central Plains Urban Agglomeration (CPUA) is located in the hinterland of the Central Plains, with a total area of 287000 square kilometers. The urban agglomeration has a superior geographical location, with developed coastal cities to the east and resource rich western regions to the west, connecting the east and opening up the west. It plays a significant role in driving the economic rise of central China. The urban agglomeration includes Zhengzhou, Kaifeng, Luoyang, Nanyang, Anyang, Shangqiu, Xinxiang, Pingdingshan, Xuchang, Jiaozuo, Zhoukou, Xinyang, Zhumadian, Hebi, Puyang, Luohe, Sanmenxia, and Jiyuan in Henan Province, Changzhi, Jincheng, and Yuncheng in Shanxi Province, Xingtai and Handan in Hebei Province, Liaocheng and Heze in Shandong Province, Huaibei, Bengbu, and Suzhou in Anhui Province. Composed of 30 prefecture level cities in 5 provinces including Fuyang and Bozhou (as shown in Figure 2), due to dense population, their coordinated development is severely constrained by water scarcity. Based on the above reasons, Based on the PS-DR-DP theoretical framework, a CPUA WRCC evaluation index system was constructed.

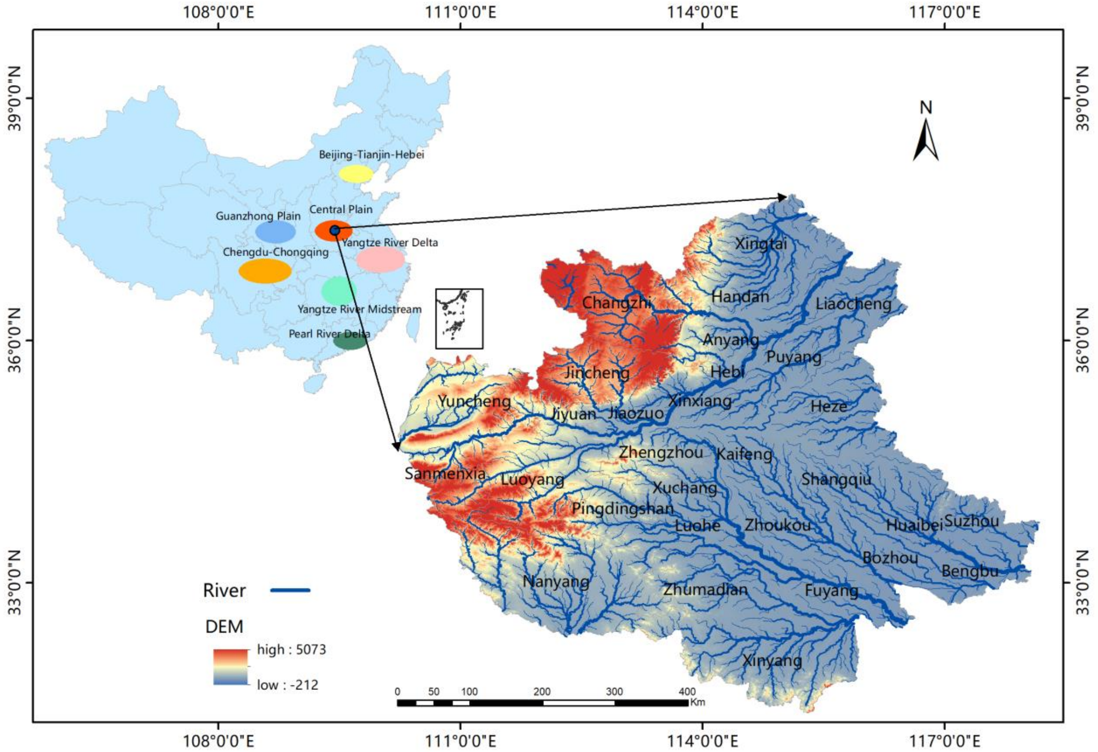

Figure 2.1: Study Area Map

3. 0 DATA SOURCES AND METHODS

The data sources used in this study mainly come from the China Statistical Yearbook (2003-2021), Henan Statistical Yearbook, Shandong Statistical Yearbook, Anhui Statistical Yearbook, Hebei Statistical Yearbook, and Shanxi Statistical Yearbook. The data on domestic water use rate, per capita water resources, unit area precipitation, and unit area groundwater resources are sourced from the Henan Water Resources Bulletin, Shandong Water Resources Bulletin, Anhui Water Resources Bulletin, Hebei Water Resources Bulletin, and Shanxi Water Resources Bulletin. The TREND function interpolation method is used for missing year values.

3.1 DETERMINE THE WEIGHT OF WRCC

Based on the actual situation of the research area, in order to avoid the subjective arbitrariness of subjective weights and the lack of objective decision-making considering the intentions of decision-makers, this study adopts a combination weighting method for each indicator. The specific calculation process is as follows:

3.1.1 IMPROVED TOPSIS MODEL

This study adopts a game theory combination weight model to confirm the combination weight based on the subjective weight of AHP and the objective weight of entropy weight method, that is, to seek the maximum common interest point between indicatorsBao, C., Wang, H., & Sun, S. (2022). Comprehensive simulation of resources and environment carrying capacity for urban agglomeration: A system dynamics approach. Ecological *Indicators*, 138, 108874.

1. Wang, X., Zhang, S., Tang, X., & Gao, C. (2023). Spatiotemporal heterogeneity and driving mechanisms of water resources carrying capacity for sustainable development of Guangdong Province in China. Journal *of Cleaner Production*, 412, 137398.

Lu, Y., Xu, H., Wang, Y., & Yang, Y. (2017). Evaluation of water environmental carrying capacity of city in Huaihe River Basin based on the AHP method: A case in Huai'an City. Water *Resources and Industry*, 18, 71-77.. This method can scientifically provide the optimal combination of subjective and objective weights, improving the rationality of indicator weights. The steps are as follows:

Firstly, based on the weights of various water resources carrying capacity indicators calculated by AHP and EVM, a basic weight vector set is constructed, represented as$W_k=\{w_{k1},w_{k2},...,w_{kn}\}$,(K=1,2,...,K), where n is the number of indicators, K is the number of weighting methods, and K is 2. If the weight coefficient of the linear combination is set to $\alpha=\{\alpha_1,\alpha_2,...,\alpha_k\}$, then the random linear combination of these vectors is represented as:

$$W=\sum_{k=1}^{n}\alpha_k w_k^T \qquad (3.1)$$

In formula (3.1), w is a linear combination of weights; α_k is a weight coefficient; w_k^T is the transpose matrix k of the set of basic weight vectors w.

Secondly, the optimal combination of different weights is carried out, minimizing dispersion w and w_k using k combination coefficients with linear weights. Optimize α_k in formula (1) to obtain the optimal weight in units of W. The resulting objective function is as follows:

$$\min\left\|\sum_{k=1}^{n}a_k w_k^T-w_k\right\|_2 \qquad (3.2)$$

In formula (3.2), α_k is the weight coefficient; w_k^T is the transpose matrix of the set of basic weight vectors w; w_k is a set of basic weight vectors.

3.1.2 IMPROVED TOPSIS MODEL

The TOPSIS model is an analytical method suitable for comparing and selecting multiple indicators and options, as it can rank a limited number of evaluation options based on their proximity to optimization objectives.

1. Use vector normalization to obtain the standardized decision matrix, which is the normalization matrix Y in the entropy method.

2. Construct a dimensionless evaluation matrix by combining the weights obtained from the entropy weight method:

$$C_{ij}=W_j*Y_{ij} \qquad i=1,2,...m;j=1,2,...n$$

Determine and organize positive and negative ideal solutions.

$$\begin{cases}C_j^+=\max\{C_{1j},C_{2j},\dots,C_{mj}\}\\ C_j^-=\min\{C_{1j},C_{2j},\dots,C_{mj}\}\end{cases}$$

3. Calculate the distance between each solution and the positive and negative ideal solutions.

Positive ideal solutions $D_i^+=\sqrt{\sum_{j=1}^{n}(C_{ij}-C_j^+)}$

Negative ideal solutions $D_i^-=\sqrt{\sum_{j=1}^{n}(C_{ij}-C_j^-)}$

4. Calculate the closeness (i.e. comprehensive evaluation value).

$$T_i=D_j^-/(D_j^-+D_j^+)$$

3.1.3 IDENTIFY THE MAIN OBSTACLES OF WRCC

Clarifying the main influencing factors of WRCC is a prerequisite for proposing targeted control measures and improving the carrying capacity of water resources. Further calculate the impact of the indicator layer on the criterion layer using the obstacle degree model, in order to identify the main obstacle factors affecting WRCC. The specific calculation formula is as follows:

$$O_{ij}=\frac{Co_{ij}*De_{ij}}{\sum_{j=1}^{n}\sum_{i=1}^{m}Co_{ij}*De_{ij}}=\frac{w_{ij}*\mu_j*[1-U_j(e_{ij})]}{\sum_{j=1}^{n}\sum_{i=1}^{m}w_{ij}*\mu_j*[1-U_j(e_{ij})]} \qquad (3.3)$$

In formula (3.3), O_{ij} is the obstacle level of the i-th indicator in the jth subsystem,the larger the value, the deeper the degree of obstruction produced, Co_{ij} is the factor contribution degree, which refers to the weight of a single indicator on the overall goal,De_{ij} is the deviation degree of the indicator, expressed as the degree of difference between the values of each individual indicator and the optimal value,$U_j(e_{ij})$ is the standard value of the evaluation object obtained from the above formula; w_{ij} represents the weight values of each indicator obtained from formula (3.1) in this study.

3.1.4 STANDARD DEVIATION ELLIPSE MODEL

Standard deviation ellipse is a spatial statistical technique used to measure the distribution characteristics of geographic featuresZhang, J., & Dong, Z. (2022). Assessment of coupling coordination degree and water resources carrying capacity of Hebei Province (China) based on WRESP2D2P framework and GTWR approach. Sustainable *Cities and Society*, 82, 103862.. The spatial distribution characteristics of WRCC in the Central Plains urban agglomeration were studied using standard deviation ellipse. The analysis of standard deviation ellipse usually includes the weighted average center, major axis, minor axis, and directional direction of the ellipse. The specific calculation steps are as follows:

$$\overline{X_I}=\frac{\sum_{i=1}^{n} WiXi}{\sum_{i=1}^{n} Wi},\overline{Y_I}=\frac{\sum_{i=1}^{n} Wiyi}{\sum_{i=1}^{n} Wi} \quad (3.4)$$

In the above equation, $\overline{X_I}$ and $\overline{Y_I}$ are weighted average centers, and w_i is the weight assigned to the WRCC of each city in CPUA.

$$\delta_x=\sqrt{\frac{\sum_{i=1}^{n}(WiXi\cos\theta-WiYi\sin\theta)^2}{\sum_{i=1}^{n} Wi^2}} \quad (3.5)$$

$$\delta_y=\sqrt{\frac{\sum_{i=1}^{n}(WiXi\sin\theta-WiYi\cos\theta^2}{\sum_{i=1}^{n} Wi^2}} \quad (3.6)$$

In the equation, δ_x and δ_y represent the lengths of the minor and major axes, respectively. θ is the direction of the ellipse, which represents the angle formed by the clockwise rotation in the north direction and the major axis of the standard deviation ellipse, measuring the directionality of the spatial distribution of CPUA WRCCPeng, T., & Deng, H. (2020). Comprehensive evaluation on water resource carrying capacity based on DPESBR framework: A case study in Guiyang, southwest China. Journal *of Cleaner Production*, 268, 122235..

4.0 RESULTS AND DISCUSSION

4.1 ESTABLISHMENT OF EVALUATION INDICATORS

Based on the specific water environment of the Central Plains urban agglomeration, combined with the regional status quo and previous research results, and considering the integrity of the water ecosystem, the selected indicator factors should not only reflect the regional resource endowment and ecological environment status, but also reflect the mutual feedback between human disturbance and natural environmental processes and the quantity and capacity of water resources and water environment. Based on the PS-DR-DP theoretical framework and referencing existing literature, an indicator system was constructed from six perspectives: pressure, support, destructiveness, elasticity, degradation, and promotion. Pressure($C_1 - C_3$) refers to the consumption of water resources by production activities and residents, as well as the potential pressure on water resources due to population size and growth rate. Support ($C_4 - C_6$) mainly refers to all potential resources available under current technology. Destructive ($C_7 - C_8$) refers to habitat destruction caused by human activities, including environmental pollution, epidemics, and major natural disasters. Resilience ($C_9 - C_{10}$) refers to the ability of humans to reduce environmental pollution, as well as the ability to predict, resist, and repair major natural disasters. Degradation ($C_{11} - C_{12}$) refers to the state of degradation of resources and ecology. Promoting ($C_{13} - C_{14}$) refers to utilizing advanced technology to enhance the ability to utilize resources

Table 4.1 Index System of Water Environment Carrying Capacity in the Central Plains Urban Agglomeration

TARGET LAYER（A）	CRITERION LAYER (B)	INDEX LAYER（C）
	Pressure（B_1）-	Natural growth rate of population (C_1) Per capita GDP (C_2) Domestic water consumption ratio (C_3)
	Support（B_2）+	Water resources per capita (C_4) Precipitation per unit area (C_5) Groundwater resources per unit area (C_6)

CARRYING CAPACITY OF WATER ENVIRONMENT IN THE CENTRAL PLAINS URBAN AGGLOMERATION （A_1）	Destructiveness（B_3）-	Smoke and dust emission from Industry (C_7) Sulphur Dioxide Emission from Industry (C_8)
	Resilience（B_4）+	Treatment Rate of Sewage (C_9) Innocent Disposal Rate of Living Garbage (C_{10})
	Degradation（B_5）-	Artificial afforestation (C_{11}) Incidence Rate of Forest Diseases and Pests (C_{12})
	Promotion（B_6）+	Per Capita Public Green Area (C_{13}) Coverage Rate of Green Areas in Developed (C_{14})

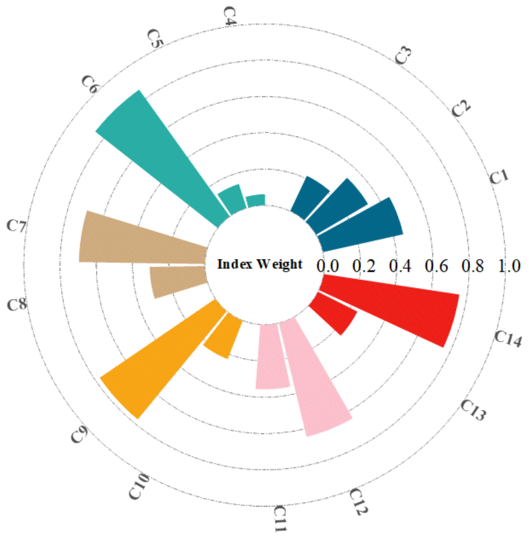

Figure 4. 2 Weight of each indicator

The specific weight calculation results are shown in Figure 3. The weight difference calculated using game theory methods is quite significant, with a range of weight values between 0.06 and 0.86. The top five indicators with higher weights calculated based on game theory are groundwater resources per unit area, urban sewage treatment rate, industrial smoke and dust emissions, green coverage rate in built-up areas, and incidence of forest pests and diseases. In the evaluation process, these 5 indicators have a greater impact on the carrying capacity of water resources.

Based on the evaluation index system and comprehensive weights of water resources carrying capacity in the Central Plains urban agglomeration, the Improved TOPSIS model was used for analysis. This study selected 2003, 2012, and 2021 as representative years to reveal the changing characteristics of CPUA WRCC from 2003 to 2021.

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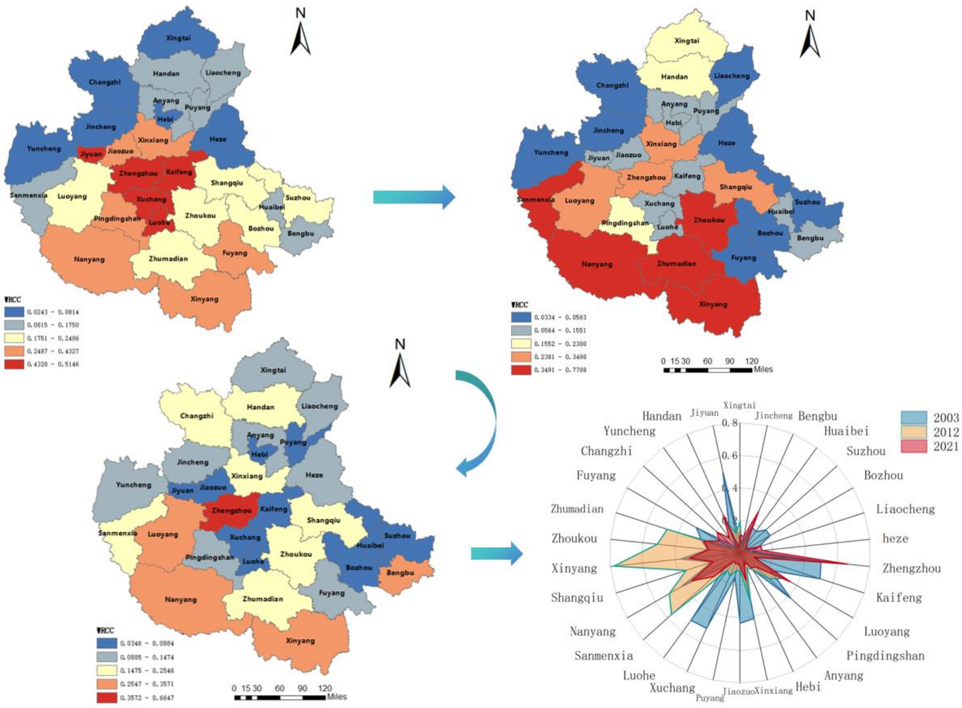

Figure 4.3 Evolution of CPUA WRCC from 2003 to 2021

4.2 WRCC FACTORS AFFECTING CPUA

4.2.1 OBSTACLE DEGREE MODEL RESULTS

According to the distribution of influencing factors (Figure 4.4), from the perspective of the carrying entities, Innocent Disposal Rate of Living Garbageis the main influencing factor of WRCC in the Central Plains urban agglomeration, with the largest impact in the year, followed by Sulphur Dioxide Emission from Industry In recent years, Groundwater resources per unit area has gradually become an important influencing factor.

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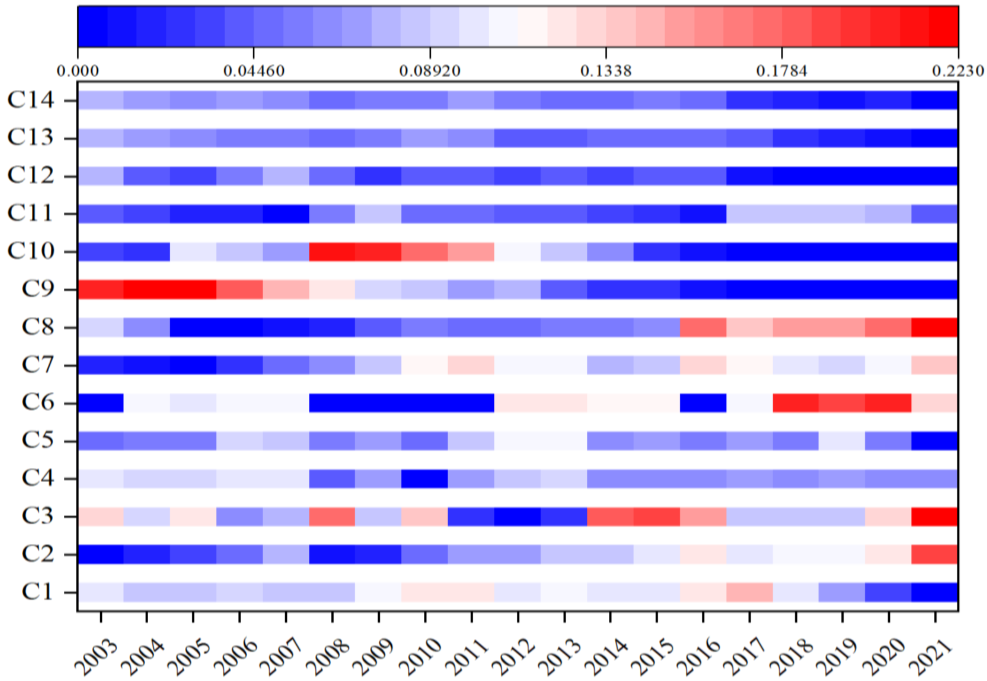

Figure 4.4 Main obstacle factors in different years

4.2.2 ANALYSIS RESULTS OF STANDARD ELLIPSE DEVIATION MODEL

In order to visualize the distribution of water resources in the Central Plains urban agglomeration more intuitively, the standard deviation ellipse was used to study the location characteristics of CPUA WRCC. Figure 7 shows the transmission path of the center of gravity and the specific values of the standard deviation ellipse related parameters from 2003 to 2021.

The spatial distribution pattern of WRCC in CPUA gradually shifts from northeast southwest to north, and research has found that water pressure in central cities such as Kaifeng and Zhengzhou exhibits obvious spatial characteristics. Unlike previous studies, this study quantitatively analyzed the concentration direction of WRCC in CPUA using the azimuth angle of the standard deviation ellipse.

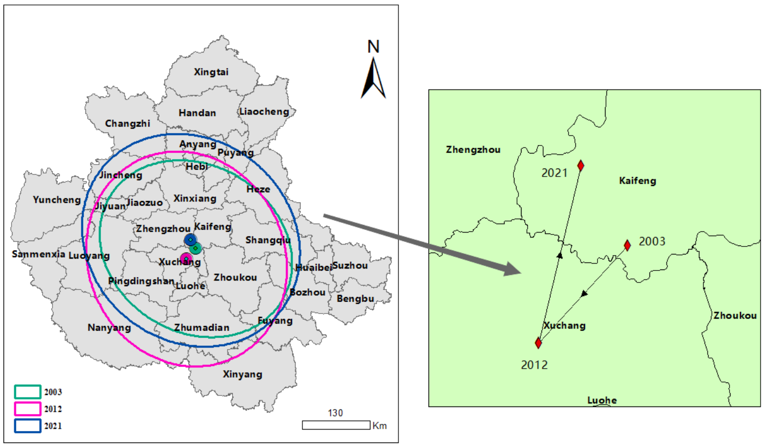

Figure 4. 5 Spatial Migration Characteristics of WRCC from 2003 to 2021

The spatial distribution pattern of WRCC in CPUA gradually changes from southwest direction to north-south direction. Research has found that the water pressure in central cities such as Kaifeng and Zhengzhou exhibits obvious spatial characteristics. Unlike previous studies, this study quantitatively analyzed the concentration direction of WRCC in CPUA using the azimuth angle of the standard deviation ellipse.As shown in Figure 6, the azimuth angle decreased from 124.1771 ° in 2003 to 119.9325 ° in 2021, with an average annual change of 0.2234 °, and the annual azimuth angle change showed a significant clockwise shift. The above results indicate that the spatial pattern in the north-south direction continues to weaken and gradually tends towards the southwest direction, which means that the north-south differences in WRCC between cities are gradually narrowing. This is attributed to the implementation of the coordinated development strategy of the Central Plains urban agglomeration, which has promoted the transfer of water resources between cities and thus narrowed the differences in water resources between regions.

The center of gravity of WRCC has always been located at the intersection of Kaifeng City and Zhengzhou City, with little deviation. From 2003 to 2012, the distance of center of gravity migration was 3.6425 km, and the migration speed was 0.4047 km/year; The center of gravity migration distance from 2012 to 2021 was 7.2569 km, with a migration speed of 0.8063 km/year. The lengths of the major and minor axes gradually became similar, indicating that the standard deviation ellipse was close to a perfect circle, and the distribution of WRCC tended to cluster. This may be attributed to the progress of water-saving technology in Zhengzhou and Kaifeng, which has improved the carrying capacity of water resources.

5. 0 CONCLUSION AND EVALUATION

This study investigated CPUA WRCC and comprehensively evaluated the influencing factors of WRCC. Reasonably and truthfully evaluating CPUA WRCC is an important task for clarifying and utilizing water resources, ensuring regional economic development, and meeting human living needs. Based on panel data from 30 cities in the Central Plains Urban Agglomeration from 2003 to 2021, a comprehensive evaluation system for WRCC integrating ecological civilization concepts was constructedGuo, L., Zhu, W., Wei, J., & Wang, L. (2022). Water demand forecasting and countermeasures across the Yellow River basin: Analysis from the perspective of water resources carrying capacity. Journal *of Hydrology: Regional Studies*, 42, 101148.. The Improved TOPSIS model and standard deviation ellipse model were used to analyze the spatiotemporal evolution characteristics and spatial migration of WRCC, and the obstacle degree model was used to scientifically identify the obstacles to the development of WRCC.

Water resource protection is achieved on the basis of scientific and effective management. The impact of water resource status, environmental conditions, and climate change on water resource systems in different regions has its regional characteristicsLi, Q., Liu, Z., Yang, Y., Han, Y., & Wang, X. (2023). Evaluation of water resources carrying capacity in Tarim River Basin under game theory combination weights. Ecological *Indicators*, 154, 110609.. As an important area in the Central Plains region, the Central Plains Urban Agglomeration should provide scientific adaptive management suggestions based on familiarity with the regional environment, climate change, technological level, and defense system measures to increase WRCC. The main suggestions are as follows:

(1) From the preliminary data of various indicators, it can be seen that in recent years, with the increase of population density and the acceleration of urbanization, urban water consumption has significantly increased. Therefore, the government should control the population size of urban agglomerations and reduce the pressure of population growth on regional water resource systems. At the same time, it is necessary to strengthen the comprehensive quality education of citizens, enhance public awareness of water conservation, and establish a water-saving societyWang, Z., & Fu, X. (2023). Scheme simulation and predictive analysis of water environment carrying capacity in Shanxi Province based on system dynamics and DPSIR model. Ecological *Indicators*, 154, 110862..

(2) Pay attention to ecological environment protection and restoration. Regional vegetation coverage should be increased and surface water should be prevented from directly flowing into the ground. The groundwater and surface water in the Central Plains region are closely connected, and the groundwater is easily polluted by surface pollutants. The underground pipelines in the region are crisscrossed, and the polluted water bodies are difficult to treat. The government should strictly control the treatment and discharge of industrial and agricultural wastewater. In addition, natural disasters that are prone to occur in the region should also be prevented and managed. Regional economic development should be coordinated with regional water and ecological environment protection to avoid exacerbating regional resource and

environmental problems, while also benefiting the improvement of CPUA WRCC.

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