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Article

Comprehensive assessment of sustainable development of water resources in the Longdong Loess Plateau

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Abstract: Assessment of water resources carrying capacity (WRCC) is of great significance for understanding the status of regional water resources, promoting the coordinated development of water resources with environmental, social and economic development, and promoting sustainable development. This study focuses on the Longdong Loess Plateau region and utilized panel data spanning from 2010 to 2020, established a three-dimensional evaluation index system encompassing water resources, economic, and ecological dimensions, uses the entropy-weighted TOPSIS model coupled with global spatial autocorrelation analysis (Global Moran's I) and the hot spot analysis (Getis-Ord Gi* index) method to comprehensively evaluate the spatial distribution of the WRCC in the study region. It can provide scientific basis and theoretical support for decision-making on sustainable development strategies in the Longdong Loess Plateau region and other regions of the world. From 2010 to 2020, the overall WRCC of the Longdong Loess Plateau area show some fluctuations but maintained overall growth. The WRCC in each county and district predominantly fell within level III (normal) and level IV (good). The spatial distribution of the WRCC in each county and district is featured by clustering pattern, with neighboring counties displaying similar values, resulting in a spatial distribution pattern characterized by high carrying capacity in the south and low carrying capacity in the north. Based on these findings, our study puts forth several recommendations for enhancing the WRCC in the Longdong Loess Plateau area.

Keywords: entropy-weighted TOPSIS model; temporal evolution; Longdong Loess Plateau; water resource carrying capacity

1. Introduction

Water is a vital resource for sustaining economic and social development, as well as ensuring human survival. Water resources are widely used not only in agriculture, industry, and daily life but also in power generation, water transportation, aquaculture, and environmental management (Xu et al., 2021). However, as society progresses and develops, water scarcity has emerged as a bottleneck that hinders social progress, economic development, and the improvement of regional living standards (Xiu et al., 2020). The World Economic Forum Global Risks Report specifically identifies the water crisis as one of the top five global threats, followed by climate change, extreme weather, food crisis, and social instability (Liu et al., 2018). Striking a balance between water resources development and utilization, socio-economic development, and ecological protection is crucial for achieving sustainable development strategies (Liang et al., 2019). The United Nations Sustainable Development Goals (SDGs) clearly propose holistically addressing development issues in the social, economic, and environmental dimensions from 2015 to 2030, with water resources being a significant constraint to sustainable development. Recently, the Chinese government and the Gansu provincial government have implemented measures to improve the utilization efficiency of water resource and promote regional sustainable development. Water resource carrying capacity (WRCC) is defined as the appropriate amount of regional water resources required for sound and sustainable socioeconomic development under a specific level of social, economic, scientific, and technological advancement (Duan et al., 2010). It serves as a crucial indicator of the synergy between regional sustainable development and water resources (Yu et al., 2020). Conducting a comprehensive evaluation of regional WRCC is of immense importance in achieving the synergistic enhancement of water resources, the economy, and the environment, thereby promoting a comprehensive regional sustainable development.

2. Literature review

Most foreign studies on the WRCC focus on the macro perspective of sustainable development, aiming to explore approaches to achieve sustainable water resource utilization. These approaches include water resource management, water quality monitoring, water resource protection, and demand forecasting. For example, Jeffrey et al. utilized GIS technology to investigate water treatment characteristics at the municipal scale in Oklahoma (United States) by incorporating the concept of WRCC (Jeffrey et al., 2017). Similarly, Jalal et al. (2016) forecasted Iran's future water demand to ensure water resource sustainability. Behrooz et al. (2015) examined water resource security in Central Asia and emphasized the need for transnational water resource management and protection. Su et al. (2019) conducted a situational simulation study on water resource security in Japan, employing a comprehensive index evaluation method combined with system dynamics. Naimi et al. (2016) determined the maximum population that Algiers' water resources could support by accounting for both water demand and supply. Yang et al. (2019) evaluated the WRCC in Xi'an. Sriyana et al. (2019) proposed a hierarchical evaluation index system based on watershed carrying capacity and determined the priority of watershed management. By considering water resource capacity as an integral component of the environment, Marganingrum (2018) combined the concept of water resource supply and demand with system dynamics to study the WRCC in the Bandung Basin. Kuspili et al. (2018) defined WRCC as the maximum population that the study area can sustain under sustainable utilization conditions and designed two scenarios to calculate and explore the WRCC of Crane Island. These studies have analyzed the methods and approaches for the sustainable use of water resources, greatly enriched the connotation of sustainable development, and provided a theoretical basis and scientific support for strengthening ecological environmental protection and resource recycling. However, there have been few studies on the carrying capacity of water resources based on the three-dimensional system of socio-economic, ecological environment and the current status of water resources.

Research on the WRCC in China began relatively late but has experienced rapid development due to the growing imbalance between water resource supply and demand and the high level of attention from the government and society. Several methods across a variety of research fields that adhere to government policies have been adopted to assess China's WRCC. For instance, Xu (2021) evaluated the WRCC of 14 cities (states) in Gansu Province using a four-dimensional (water resources, society, the economy, and the environment) evaluation index system and the entropy weight TOPSIS method. The authors also analyzed the main obstacles restricting WRCC in different regions of Gansu Province. Tang (2021) conducted a comprehensive analysis of WRCC in the Yellow River Basin from 2004 to 2018, encompassing nine provinces and autonomous regions. The evaluation was based on a four-element system coupling model (water resources, society, economy, and ecological environment) and employed a combined weighting approach that incorporated the entropy weight method and the analytic hierarchy process method. The analysis identified the main factors constraining the improvement the WRCC in the Yellow River Basin. Zhao et al. (2021) performed a dynamic evolution analysis of WRCC in 13 major grain-producing provinces in China using partial connection number and set pair analysis. Li et al. (2021) and Lu et al. (2021) evaluated the spatiotemporal characteristics of the WRCC in China and the Yangtze River economic belt using the ecological footprint model. Fan et al. (2019) analyzed the WRCC in the Pearl River Delta using the grey correlational entropy model. Yang et al. (2021) developed an index system for evaluating the WRCC in Hunan Province by accounting for key aspects such as water resources, economy, society, and the environment. The evaluation was conducted at the province scale using Hunan Province as an example. Ran et al. (2022) performed a multi-system comprehensive evaluation of WRCC by accounting for several key aspects including water resources, society, the economy, environmental quality, and coordinated management. The authors utilized the state-space method and GIS technology to analyze the spatial and temporal distribution of the WRCC in Chongqing. Wang et al. (2020) evaluated the WRCC of Zhangye County in the Heihe River Basin and suggested countermeasures and strategies for improving the WRCC in Zhangye City. These studies have analyzed the status of China's water resources carrying capacity using a variety of methods, enriching the scope of water resources carrying capacity research and technical theory. However, few studies have been conducted on small-scale areas such as counties and districts.

This study focuses on the Longdong Loess Plateau region and establishes a three-dimensional (water resources, the economy, and ecology) WRCC evaluation index from 2010 to 2020. The entropy-weighted TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) model is employed to evaluate WRCC, whereas global spatial autocorrelation analysis (Global Moran's I) and hot spot analysis (Getis-Ord Gi* index) are used to characterize spatial distribution. This study holds significant theoretical and practical importance. This research is based on the theory of ecological environmental protection, sustainable economic development and resource recycling methods, focusing on the problem of coordinated economic-social-ecological-resource development in small-scale regions. it enhances and complements the existing regional WRCC research system both from theoretical and empirical perspectives, thus contributing to the theoretical basis needed to promote sustainable regional development. Additionally, it provides a scientific basis for implementing strategies related to sustainable development of water resources, the environment, and the economy in the Longdong Loess Plateau region, Gansu Province, and even the entire Loess Plateau region. Furthermore, it offers theoretical support and decision-making guidance for protecting aquatic environments, water pollution prevention and control, improving water quality, and mitigating challenges associated with the regional water resource supply and demand, all of which are issues that must be prioritized.

3. Materials and methods

3.1. Description of the study area

The Longdong Loess Plateau (106°21′-108°45′ E, 34°54′-37°10′ N) is situated in the north-central region of China's Loess Plateau. It is bordered by the Jing River and Luo River at the middle and lower reaches, the Yellow River to the east, the Long Mountain (Liupan Mountain) to the west, the Guanzhong Plain irrigation area to the south, and the Ganquan-Huachi-Huanxian line to the north. The Longdong Loess Plateau has a total area of approximately 3.34×10^4 km^2, encompassing the entire city of Qingyang and parts of Pingliang City. The key counties within the area include Kongtong District, Jingchuan County, Chongxin County, Lingtai County, Xifeng District, Zhengning County, Huan County, Huachi County, Heshui County, Qingcheng County, Ning County, and Zhenyuan County (**Figure 1**). Lingtai County marks the southernmost point of the Loess Plateau in Longdong (Ling et al., 2019). The average elevation ranges from 838 to 2207 m, with a temperate continental climate featuring low total rainfall, high interannual variability, uneven temporal distribution of precipitation, and concentrated rainstorms that exhibit a northwest to southeast spatial distribution trend. The landforms are dominated by hills and gullies, high plateau gullies, earth and rocky mountains, with extensive areas of loess hills and gullies, sparse vegetation, and significant soil erosion issues (Lu et al., 2019). The major rivers in the region include the Jing, Malian, Pu, Silang, and Hulu rivers. The Hulu River is part of the Beiluo River Basin, whereas the others belong to the Jing River Basin. The Malian River covers a basin area of 1.7×10^4 km^2 in Qingyang, experiencing severe soil erosion with an annual sand transport of 1.34×10^8 t, accounting for 21% of the annual sediment volume entering the Yellow River in Gansu Province. The entire river exhibits high mineralization and poor water quality. In contrast, the Hulu River, a tributary of the Jing River, boasts good water quality that meets the drinking water source standards. The Hulu River belongs to the Beiluo River system and exhibits significant variations in annual runoff, with lower flow rates in winter and spring experience, followed by higher volumes in summer and autumn. Due to the uneven precipitation distribution in this region, the river experiences flooding with sediment during the summer and autumn seasons. Approximately 60% of the annual runoff is concentrated from July to September (Tian et al., 2023).

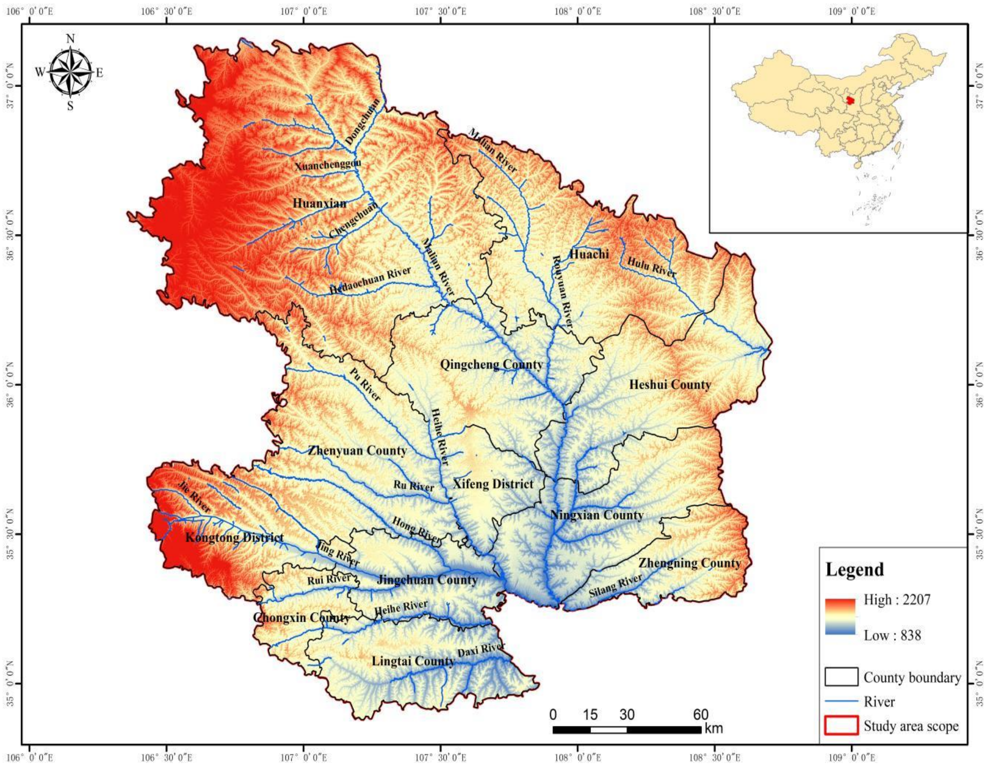

Figure 1. Overview of the Longdong Loess Plateau.

3.2. Evaluation index and data sources

Creating an indicator system is a crucial foundation and an essential component for analyzing and researching regional WRCC. The selection of indicators significantly influences the scientific and rational outcomes of an evaluation. Therefore, this study draws upon relevant research findings from both domestic and international studies (Chan et al., 2021; Dong et al., 2023; He et al., 2019; Liang et al., 2015; Lei et al., 2018; Shao et al., 2021; Wang et al., 2005; Wei et al., 2019; Wang et al., 2021; Wei et al., 2022; Yang et al., 2019; Zhang et al., 2021; Zhang et al., 2023). Efforts were made to ensure that the proposed indicator system adhered to the principles of validity, systematicness, comprehensiveness, representativeness, and independence, as established in the United Nations Sustainable Development Goals (SDGs). Additionally, our study considers the specific characteristics of the region to identify representative indicators that meet our research requirements. Thus, a comprehensive WRCC evaluation index system for the Longdong Loess Plateau area was established by focusing on three aspects: the water resources system, the socio-economic system, and the environment system (**Table 1**).

The necessary data was primarily derived from government-issued yearbooks, including the "Statistical Yearbook of Qingyang City" and the "Yearbook on the Development of Pingliang City" for the 2010-2020 period. Other sources include the "Water Resources Bulletin of Gansu Province," the "Rural Yearbook of Gansu Province," and the "Yearbook on the Development of Gansu Province," in addition to the national economic and social development statistical bulletin and government work reports issued by the authorities of Qingyang City and Pingliang City, which cover their respective counties and districts.

Table 1. Index system for comprehensive evaluation.

Target layer	System layer	Index layer	Units	Attribute	Significance
Water resource carrying capacity evaluation	Water resources systems	Percentage of surface water resources	%	+	Clarify the status of water resources and the extent of their development and utilization
		Water supply modulus	10,000 m^3/km^2	-	
		Per capita water holding	m^3/person	+	
		Water resources development utilization	%	-	
		Water production modulus	10,000 m^3/km^2	+	
		Per capita water supply	m^3/person	+	
		Per capita water consumption	m^3/person	-	
	Social economic system	Population density	10,000 person/km^2	-	Clarification of the socio-economic situation and level of development of the region
		Urbanization rate	%	+	
		Water consumption for urban population	10,000 m^3/person	-	
		Per capita GDP output value	10,000 Yuan/person	+	
		Tertiary industry share	%	+	
		Water consumption per ten thousand yuan of GDP	m^3/10,000 Yuan	-	
		Natural population growth rate	‰	-	
		Fertilizer (pesticide) use intensity	t/km^2	-	
		Cultivated land irrigation rate	%	-	
		Irrigation water consumption per unit area	10,000 m^3/km^2	-	
		Wastewater treatment rate	%	+	
		Water consumption for ten thousand yuan of industrial added value	10,000 m^3/10,000 Yuan	-	
	Ecological environment system	Annual precipitation	mm	+	Clarify regional ecological conditions and pollution control measures
		Water consumption rate of ecological environment	%	+	
		Forest coverage	%	+	
		Water loss and soil erosion control area	Thousand hectares	+	
		Water quality compliance rate	%	+	

4. Research methods

This study takes Longdong Loess Plateau region as the research object, establishes a three-dimensional water resources carrying capacity evaluation index system of “water resources-economy-ecology” based on the panel data from 2010 to 2020, determines the index weights by using entropy weighting method, and measures the level of water resources carrying capacity of Longdong Loess Plateau region by using the TOPSIS model, and reveals the overall spatial distribution of water resources carrying capacity by using the global spatial autocorrelation analysis (Global Moran’s I). The global spatial autocorrelation analysis was used to reveal the overall spatial distribution of water resources carrying capacity in Longdong Loess Plateau region, and the hotspot analysis (Getis-Ord Gi* index) was used to reveal its local spatial distribution characteristics (**Figure 2**).

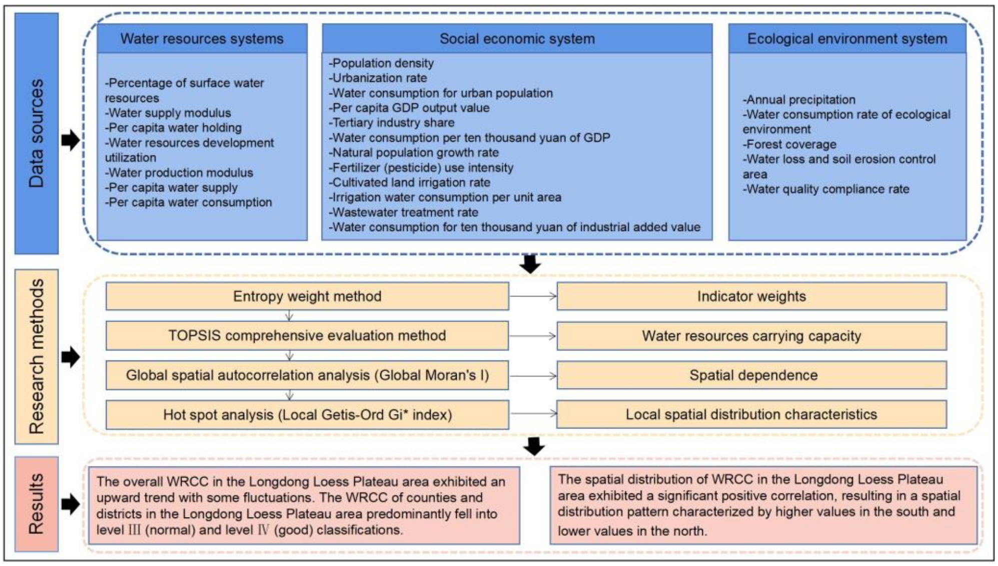

Figure 2. Flow chart of the research process used for this research.

4.1. Entropy weight method

The entropy weight method is employed to perform positive and standardized treatment based on the variations among the values of each index to obtain a standardized matrix. This serves as the basis for calculating the weight of each index using the entropy weight. The entropy weight method mitigates the inherent subjectivity of other weight methods, thus enabling a more scientifically sound representation of the importance of each index (Dai et al., 2020; Tian et al., 2020; Yang et al., 2019). The data processing and calculation procedures for the entropy weight method are outlined below:

Treatment of positive index:

$$X_{ij}' = \frac{X_{ij} - minX_{ij}}{maxX_{ij} - minX_{ij}} \tag{1}$$

Treatment of negative index:

$$X_{ij}' = \frac{maxX_{ij} - X_{ij}}{maxX_{ij} - minX_{ij}} \tag{2}$$

Proportion of characteristics:

$$f_{ij} = \frac{X_{ij}'}{\sum_1^m X_{ij}'} \tag{3}$$

Index entropy:

$$H_j = -\frac{1}{\ln m}\sum_{i=1}^m (f_{ij} \ln f_{ij}) \tag{4}$$

Index entropy weight:

$$\gamma_j = \frac{1 - H_j}{\sum_{j=1}^n (1 - H_j)} \tag{5}$$

Index weight:

$$w_j = \frac{\gamma_j}{\sum_{j=1}^n \gamma_j} \tag{6}$$

where X_{ij}' represents the standard value of the *j* index in the *i* research unit, $i = 1, 2, \cdots,$

m, *j* = 1, 2, ⋯, n; X_{ij} is the original data of the *j* index in the *i* research unit, $maxX_{ij}$ and $minX_{ij}$ are the maximum and minimum values of the original data of the *j* index in the *i* research unit. f_{ij} is the characteristics proportion of the *j* index in unit *i*. H_j is the entropy of the *j* index; γ_j is the entropy weight of the *j* index; w_j is the weight of the j index.

4.2. TOPSIS comprehensive evaluation method

The TOPSIS comprehensive evaluation method is commonly employed to address multi-objective decision-making problems within a limited number of solutions. This comprehensive approach utilizes a distance-based evaluation criterion to conduct system analysis. The proximity is determined by calculating the weighted Euclidean distance between the evaluation index data and the optimal solution, as well as the worst solution. In this study, the degree of proximity was utilized to characterize the WRCC, where a degree of proximity closer to 1 indicates a higher level of WRCC (Aiadi et al., 2020; Chen et al., 2020; Chen et al., 2023; Li et al., 2021). The specific calculation process is outlined below:

Non-dimensional treatment:

$$Z_{ij} = \frac{X'_{ij}}{\sqrt{\sum_{i=1}^{m} X'_{ij}}} \tag{7}$$

where Z_{ij} is the value after non-dimensional treatment of the *j* index in the *i* research unit; *i* = 1, 2, ⋯, m; *j*=1, 2, ⋯, n; X'_{ij} is the standard value of the *j* index in *i* research unit.

Determine the optimal and worst solutions:

$$\begin{cases} Z_j^+ = max\{Z_{1j},\ Z_{2j},\ \cdots,\ Z_{mj}\} \\ Z_j^- = min\{Z_{1j},\ Z_{2j},\ \cdots,\ Z_{mj}\} \end{cases} \tag{8}$$

where Z_j^+ is the optimal solution, which is the maximum value of *j* index in the *i* research unit; Z_j^- is the worst solution, which is the minimum value of the *j* index in the *i* research unit.

Determine the weighted Euclidean distance:

$$\begin{cases} D_i^+ = \sqrt{\sum_{j=1}^{n} [w_j(Z_{ij} - Z_j^+)]^2} \\ D_i^- = \sqrt{\sum_{j=1}^{n} [w_j(Z_{ij} - Z_j^-)]^2} \end{cases} \tag{9}$$

where D_i^+ is the weighted Euclidean distance of the j index in the *i* research unit relative to the optimal solution, and D_i^- is the weighted Euclidean distance of the *j* index in the *i* research unit relative to the worst solution.

Determine the degree of proximity:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, 0 \le C_i \le 1 \tag{10}$$

where C_i represents the degree of proximity between the research unit and the optimal solution. Higher C_i values are indicative of a better WRCC.

Classification of WRCC:

Based on the results of previous studies (Cao. 2016; Kang et al., 2020; Qi. 2021; Zhou et al., 2022; Lv et al., 2023), the authors ranked C_i according to its value, with higher values corresponding to better evaluation results. The WRCC is classified into five levels ranging from excellent to weak, as outlined in **Table 2**.

Table 2. Level of WRCC.

Level	**Weak (I)**	**Poor (II)**	**Normal (III)**	**Good (IV)**	**Excellent (V)**
C_i	(0, 0.2)	[0.2, 0.3)	[0.3, 0.4)	[0.4, 0.6)	[0.6, 1)

4.3. Global spatial autocorrelation analysis (Global Moran's I)

Global spatial autocorrelation analysis assesses whether there is spatial dependence in the water environmental carrying capacity of the Longdong Loess Plateau region. This approach can provide insights into the spatial correlation pattern and clustering of the environmental WRCC across an entire region. Typically, this is accomplished by estimating Moran's I spatial autocorrelation statistic to analyze the overall spatial correlation and variation within the region as a whole (Gao et al., 2019; Yuan et al., 2019; Zhang et al., 2019). The global Moran's I is calculated as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j\neq 1}^{n} W_{ij}(Y_i - \bar{Y})(Y_j - \bar{Y})}{\sum_{i=1}^{n}\sum_{j\neq 1}^{n} W_{ij}\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \tag{11}$$

where I is the global Moran's I value, n is the total number of counties, $\bar{Y}$ is the average of the sample values for all counties, Y_i is the sample value of the i th county, Y_j denotes the sample value of the j th county, and W_{ij} is the spatial weight matrix.

A significance test for I is required to further assess the existence of spatial autocorrelation. The test formula is outlined below:

$$Z = \frac{I - E(I)}{\sqrt{Var(I)}} \tag{12}$$

where Z is the global Moran's I test value, $E(I)$ is the expected value of I, and $Var(I)$is the variance of I.

The Moran's I index ranges from −1 to 1. When Moran's I exceeds 0, it indicates a spatial clustering in the WRCC of the Longdong Loess Plateau area. When Moran's I is below 0, it suggests a spatial dispersion. When Moran's I equals 0, it means that the WRCC in the Longdong Loess Plateau area is random distribution of values in space.

4.4. Hot spot analysis (Local Getis-Ord Gi* index)

Global spatial autocorrelation analysis only provides insights into the overall spatial distribution pattern, but it averages out the differences between different regions and is not able to reflect the distribution of high and low values and the degree of spatial differences in each region. Therefore, the hot spot analysis method (Local Getis-Ord Gi* index) was used to comprehensively reflect the distribution of high and low values of WRCC in the Longdong Loess Plateau region in each county and their spatial differences, thereby revealing the local spatial distribution characteristics (Feng, 2017; Qi et al., 2013; Shen et al., 2019).The hot spot analysis (Local Getis-Ord Gi* index) is calculated as follows:

$$G_i^* = \frac{\sum_{i=1}^{n} W_{ij} x_i}{\sum_{i=1}^{n} x_i} \quad (13)$$

where x_i is the observed value of region i; n is the total number of counties and regions, W_{ij} is the spatial weight matrix, and spatial adjacency is assigned a value of 1, whereas non-adjacency is assigned a value of 0. A significantly positive Gi* value indicates the presence of a hot spot, indicating a relatively high value around a given region. Conversely, a negative Gi* value indicates a cold spot, suggesting a relatively low value around the region.

5. Results and discussion

5.1. Evaluation and analysis of the WRCC in the Loess Plateau region of Longdong

Based on the previous water resources carrying capacity measurement method, the entropy weight method and TOPSIS model were used to calculate the overall water resources carrying capacity of the Longdong Loess Plateau region from 2010 to 2020, analyze the carrying capacity of the socio-economic system, the water resources system and the ecological environment sub-systems, and analyze the change of water resources carrying capacity of the counties and districts of the Longdong Loess Plateau region in a specific way.

5.1.1. Evaluation of the WRCC in Longdong Loess Plateau area

Based on TOPSIS calculations Eqs. (7) to (10), using the SPSS Pro software, we calculated the negative and positive ideal distances between the evaluation index of WRCC and the actual results of WRCC in the Longdong Loess Plateau area from 2010 to 2020. The calculated values are presented in **Table 3**. Additionally, we conducted an analysis of the WRCC and the carrying capacity of the socio-economic system, water resources system, and sub-systems of the ecological environment, as illustrated in **Figure 3**.

Table 3. Evaluation of the WRCC in the Longdong Loess Plateau region.

Year	Ideal positive solution distance (D +)	Ideal negative solution distance (D -)	Carrying capacity (C)	Rank	Level of carrying capacity
2010	0.826	0.412	0.333	11	III
2011	0.804	0.409	0.337	10	III
2012	0.707	0.476	0.402	8	IV
2013	0.695	0.461	0.397	9	III
2014	0.674	0.495	0.424	7	IV
2015	0.657	0.504	0.434	6	IV
2016	0.585	0.540	0.480	4	IV
2017	0.600	0.542	0.474	5	IV
2018	0.485	0.765	0.612	3	V
2019	0.393	0.815	0.675	1	V
2020	0.476	0.773	0.619	2	V

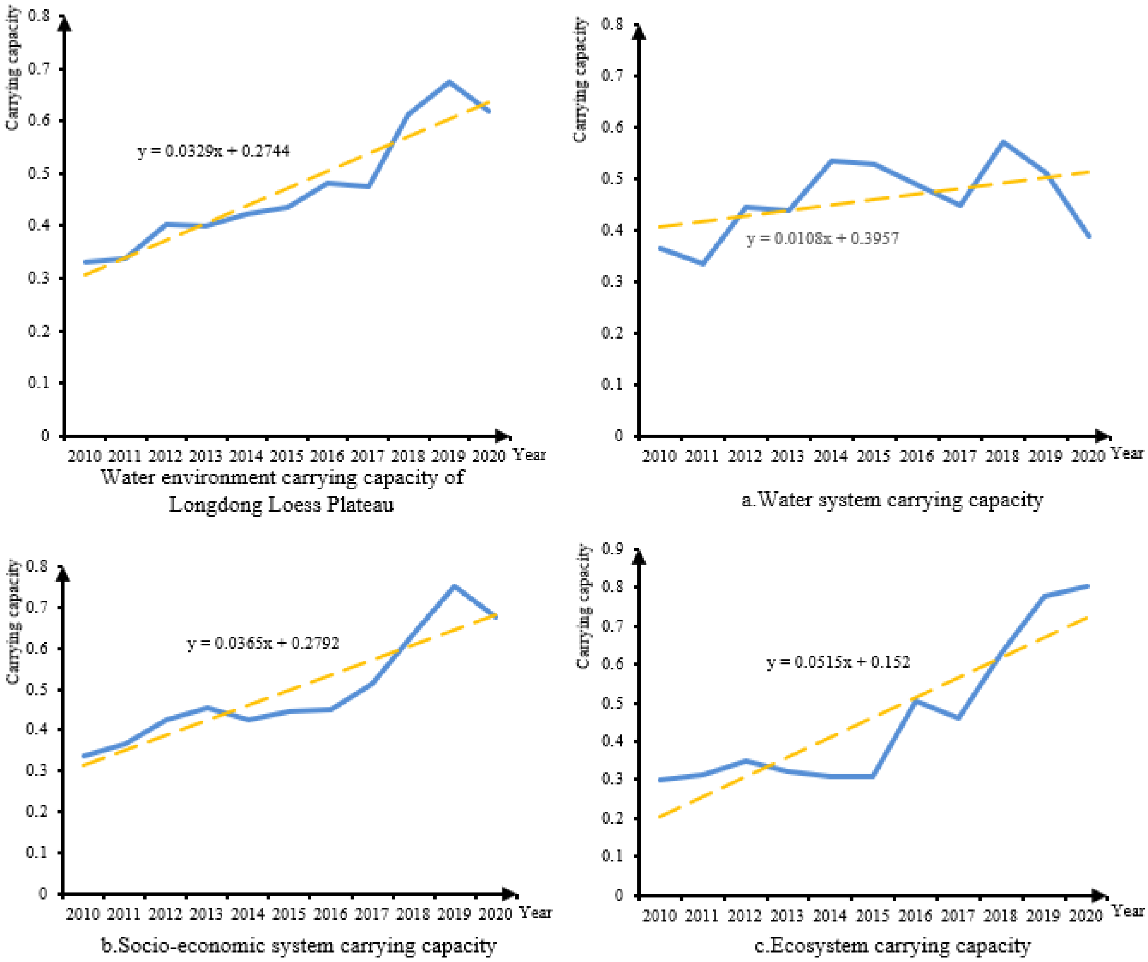

Figure 3. WRCC and subsystem carrying capacity in the Longdong Loess Plateau.

As indicated in **Table 3** and the map illustrating the WRCC in the Longdong Loess Plateau region, the overall WRCC in the region exhibited an upward trend with fluctuations from 2010 to 2020. The carrying capacity increased from 0.333 in 2010 to 0.675 in 2019, representing a growth of 0.342. The WRCC level increased from level III (normal) to level V (excellent). During the study period, the minimum carrying capacity value occurred in 2010 at 0.333, corresponding to level III (normal), whereas the maximum value occurred in 2019 at 0.675, corresponding to level V (excellent).

Overall, the WRCC in the Longdong Loess Plateau area from 2010 to 2020 can be divided into three stages. The first stage encompasses 2010-2013, which is characterized by a rise and subsequent decline in WRCC, starting from 0.333 in 2010, reaching 0.402 in 2012, and then declining to 0.397 in 2013. Despite these fluctuations, the overall carrying capacity exhibited an upward trend. This can be attributed to increased government attention to environmental protection, more investment in environmental conservation, and significant achievements in environmental protection. Notable projects such as the QingYang Yanghuang irrigation project, the northern terraces construction project, the southern solid ditch loess protection project, the eastern ZiWuLing construction and protection project, and soil and water conservation, forest planting, environmental treatment in Pingliang City have effectively prevented soil erosion and environmental pollution, improved environmental quality, and ultimately led to a rapid increase in the WRCC.

The second stage spans from 2014 to 2017, during which the WRCC exhibited a steady rise, increasing from 0.424 in 2014 to 0.474 in 2017, which represents a 0.05 increase. The overall capacity remained at level of IV (good), indicating the establishment of sustainable development strategies and practices. The Ministry of Ecology and Environment of the People's Republic of China issued the 2015 National Advanced Pollution Prevention and Control Demonstration Technology List (Water Pollution Control Field) and the National Directory of Environmental Protection Technologies Encouraged to be Developed (Water Pollution Control Field) announcements in 2015, which encouraged the promotion of water pollution control technologies that are innovative, with stable control effects and are economically reasonable and feasible, and the Gansu Provincial Government focused on the promotion and application of the technologies that are suitable for the conditions of the local development, which demonstrates that environmental protection measures implemented by the Government have proved to be effective, and that the positive results of environmental protection are becoming increasingly significant.

The third stage spans from 2017 to 2020, where the WRCC exhibited a rapid increase, rising from 0.474 in 2017 to 0.619 in 2020, which represented a 0.145 increase. The highest value of 0.675 was observed in 2019. The overall carrying capacity remained at a level of V (excellent). This can be attributed to the national and local governments' prioritization of ecological conservation while coordinating social and economic development. Efforts were made to establish an ecologically sound society, improve laws and regulations, strengthen environmental protection inspections, and promote integrated protection and systematic management of mountains, water, forests, lakes, grasslands, and sand. These initiatives effectively enhanced the quality and stability of the ecosystem, thereby facilitating the steady improvement of the regional water environment carrying capacity.

Regarding the WRCC, the environment, and the social and economic subsystems, there was a significant change in the subsystems of WRCC. From 2010 to 2020, the carrying capacity of the water resources subsystems increased from 0.365 to 0.389, with an overall increase and a maximum value of 0.573 in 2018. The carrying capacity of the water resources subsystem exhibited an increase during the 2011-2012, 2013-2014, and 2017-2018 periods. These increases indicate stable supply and demand of water resources alongside economic and social development. However, there was a sharp decrease in the carrying capacity of the water resources subsystems during the 2010-2011, 2012-2013, 2014-2017, and 2018-2020 periods. According to the statistical data of each county, the per capita water consumption and utilization rate of water resources in the Loess Plateau area of Longdong showed an upward trend, while the proportion of surface water resources showed a downward trend. This indicates the overuse of water resources in the region, resulting in water pollution and environmental impacts (Zhang et al., 2020). Regarding the socio-economic subsystem, its carrying capacity significantly increased from 0.335 in 2010 to 0.677 in 2020. This indicated a stable growth at the regional economic level, providing consistent financial investment and support for ecological and environmental protection projects, thus ensuring the effective improvement of the regional water environment carrying capacity. For the ecological environment subsystem, its carrying capacity grew rapidly from 0.302 in 2010 to 0.803 in 2020. This demonstrates that since 2010, the management and protection of the ecological environment subsystem in the Longdong Loess Plateau area have been effective, particularly through the implementation of projects focused on soil and water conservation, pollution control, the Yang Huang Irrigation project, solid ditch protection on the plateau, and the protection of the ZiWuLing region. These projects, which were aimed at preserving the ecological environment and were complemented by construction projects, have played an instrumental role in promoting the growth of the carrying capacities of the subsystems. However, it takes a certain amount of time to accumulate the results of ecological management, and a certain amount of ecological damage occurs at the initial stage of implementation, so the carrying capacity of the ecological environment subsystem declined significantly in 2012–2015.

5.1.2. Assessment of the WRCC in each county and district

The ideally positive and negative distances of the WRCC evaluation indexes and the WRCC results for each county and district in the Longdong Loess Plateau area from 2010 to 2020 were calculated using the SPSS Pro software. The results are presented in **Table 4**.

Table 4. Evaluation of WRCC of different counties in the Longdong Loess Plateau region.

District	2010				2015				2020			
	D +	D-	C	Rank	D +	D-	C	Rank	D +	D-	C	Rank
Jingchuan County	0.582	0.627	0.518	3	0.536	0.667	0.555	1	0.516	0.714	0.581	1
Kongtong District	0.547	0.644	0.541	1	0.550	0.611	0.526	2	0.563	0.648	0.535	2
Lingtai County	0.701	0.511	0.421	5	0.685	0.537	0.439	5	0.715	0.521	0.421	5
Chongxin County	0.554	0.632	0.533	2	0.610	0.570	0.483	3	0.602	0.603	0.500	3
Huan County	0.831	0.411	0.331	12	0.821	0.421	0.339	12	0.810	0.436	0.350	12
Huachi County	0.757	0.519	0.407	6	0.774	0.492	0.389	8	0.769	0.500	0.394	7
Qingcheng County	0.739	0.440	0.373	8	0.740	0.407	0.355	11	0.756	0.417	0.356	11
Xifeng District	0.697	0.591	0.459	4	0.704	0.588	0.455	4	0.712	0.559	0.440	4
Zhenyuan County	0.811	0.459	0.361	9	0.788	0.463	0.370	9	0.771	0.486	0.387	8
Ning County	0.815	0.430	0.346	10	0.786	0.459	0.369	10	0.797	0.458	0.365	9
Zhengning County	0.810	0.415	0.339	11	0.761	0.489	0.391	7	0.784	0.435	0.357	10
Heshui County	0.738	0.496	0.402	7	0.745	0.501	0.402	6	0.755	0.499	0.398	6

Table 4 summarizes the rankings of the WRCC in the counties of the Longdong Loess Plateau region in different years. From 2010 to 2020, Jingchuan County, Kongtong District, Chongxin County, and Xifeng District consistently ranked among the top four areas in terms of WRCC, reaching a level of IV (good). This indicates that these counties have a good WRCC and can meet the demands of social and economic development. They also possess potential for further development and utilization, making them capable of reliably providing water resources for regional growth. On the other hand, Huan County and Qingcheng County consistently ranked last, with their WRCC being classified as a level III (normal). This suggests that there is a

significant gap between water resource supply and demand in these two counties, which is further exacerbated by an unstable ecosystem, average WRCC, and poor water resource protection.

In 2010, seven counties (Jingchuan County, Kongtong District, Chongxin County, Lingtai County, Xifeng District, Huachi County, and Heshui County) exhibited high WRCC at a level of IV (good), whereas the remaining five counties had lower WRCC at a level of III (normal). By 2015, six counties (Jingchuan County, Kongtong District, Chongxin County, Lingtai County, Xifeng District, and Heshui County) maintained high WRCC at the level of IV (good). However, the WRCC of Huachi County decreased to 0.389, whereas the remaining five counties remained at a level of III (normal). In 2020, the WRCC of five areas (Jingchuan County, Kongtong District, Chongxin County, Lingtai County, and Xifeng District) decreased to level IV. Heshui County's WRCC decreased to 0.398, also at a level of III (normal), along with the other six counties.

Generally, although the overall WRCC in the counties of the Longdong Loess Plateau area has increased from 2010 to 2020, the carrying capacity level remains low and tends to fluctuate. This can be attributed to the reduction of surface water resources, population growth, and expansion of energy resource exploration. The demand for economic development and the need to improve people's livelihoods has come at the expense of weakened environmental protection, resulting in lower WRCC. Among all the regions, Huan County consistently lags behind in terms of WRCC. This can be attributed to various constraints, including geographical location, topography, economic structure, environmental conditions, natural conditions, and the imbalance between the supply and demand of water resources.

5.2. Spatial evolution of WRCC in the Longdong Loess Plateau

Based on the previous spatial analysis method, the global spatial autocorrelation analysis (Global Moran's I) method was used to analyze the overall spatial autocorrelation and clustering pattern of water resources carrying capacity in Longdong Loess Plateau region from 2010 to 2020, and the cold hotspot analysis (Getis-Ord Gi* index) method was used to analyze the evolution of spatial distribution and pattern of water resources carrying capacity of the counties and districts in Longdong Loess Plateau region from 2010 to 2020.

5.2.1. Spatial autocorrelation analysis of the WRCC in the Longdong Loess Plateau

Using the spatial autocorrelation analysis method (Global Moran's I), we calculated the global Moran's I index for the WRCC of the Longdong Loess Plateau region from 2010 to 2020. This calculation was conducted to assess its spatial autocorrelation and clustering patterns. The specific results are presented in **Table 5** below.

Table 5. Statistics of the Global Moran's I index of WRCC in the Longdong Loess Plateau region from 2010 to 2020.

Year	**Global Moran's I value**	**Z**	**P**
2010	0.4011	2.5227	0.0116
2011	0.4458	2.7603	0.0058
2012	0.4378	2.7139	0.0067
2013	0.4251	2.6451	0.0082
2014	0.3036	2.0421	0.0411
2015	0.4055	2.6095	0.0091
2016	0.3513	2.2669	0.0234
2017	0.4491	2.7791	0.0055
2018	0.4984	3.0275	0.0025
2019	0.5720	3.4413	0.0006
2020	0.4080	2.6803	0.0074

As summarized in **Table 5**, the minimum value of the global Moran's I index Z for WRCC in the Longdong Loess Plateau region from 2010 to 2020 is 2.0421. This value exceeds 1.96, indicating that all the global Moran's I indexes for WRCC in the region passed the 5% significance test. Therefore, it can be inferred that during the study period, there is a significant positive correlation in the spatial distribution of WRCC in the Longdong Loess Plateau region. Adjacent counties with high or low efficiency exhibit a clustering pattern. However, the overall Moran's I index was low, suggesting that although adjacent counties exhibited a clustering pattern in terms of the spatial distribution of WRCC, the overall degree of clustering is still weak and the ability to exert influence among counties remains low.

Overall, from 2010 to 2020, the Moran's I index for WRCC in the Longdong Loess Plateau area exhibited a steady increase with some fluctuations, rising from 0.4011 in 2010 to 0.4080 in 2020, which represented a 0.0069 increase. However, the minimum value of Moran's I index appeared in 2014 as 0.3036, and the maximum value appeared in 2019 as 0.5720, and there were multiple data fluctuations during the study period, indicating that the overall trend of WRCC in the counties and districts of Longdong Loess Plateau Region is increasingly clustered, and the correlation between WRCC in the counties and districts is getting stronger and stronger, but the degree of clustering shows fluctuating with upward trend, which suggests that it is necessary to continue to strengthen the regional cooperation and exchange, and further improve the regional cooperation. This indicates the need to continue to strengthen regional cooperation and exchanges to further enhance the degree of regional agglomeration.

5.2.2. Analysis of hot spots of WRCC in the Longdong Loess Plateau

Using the hot spot analysis (Getis-Ord Gi* index) calculation method, the Getis-Ord Gi* index values were computed for the Longdong Loess Plateau region in 2010, 2015, and 2020. These values were used to classify the local Getis-Ord Gi* index into different areas, including 99% hot spots, 95% hot spots, 90% hot spots, non-significant areas, 90% cold spots, 95% cold spots, and 99% cold spots. Based on this analysis, a hot spot evolution map depicting the spatial pattern of WRCC in the Longdong Loess Plateau region was generated (**Figure 4**).

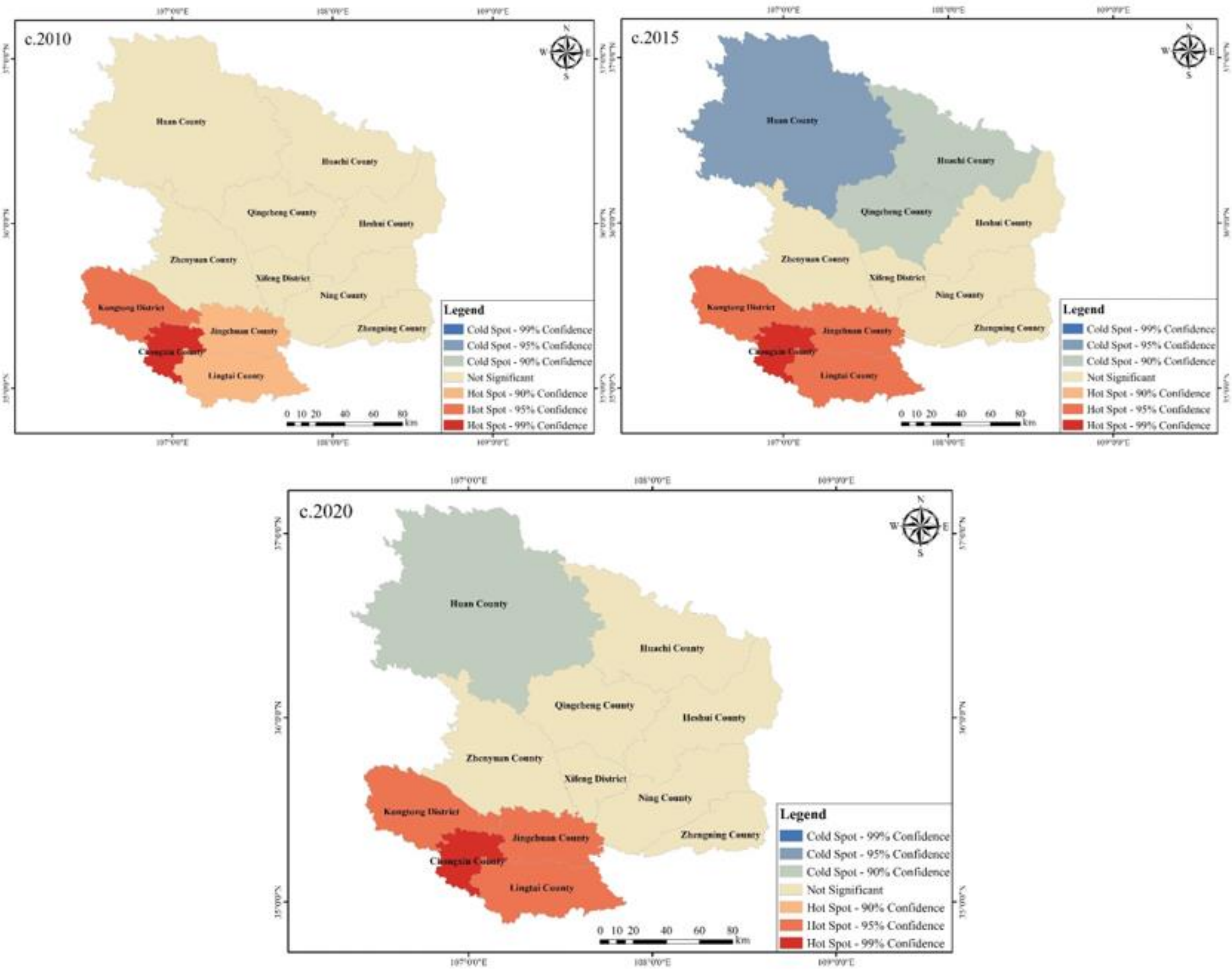

Figure 4. Spatial evolution of cold and hot spots of WRCC in 2010, 2015, and 2020 in Longdong Loess Plateau area.

As shown in **Figure 4**, the Getis-Ord Gi* index values for the WRCC in the Longdong Loess Plateau area in 2010 exhibited different spatial patterns. The values ranged from 99% hot spot, 95% hot spot, 90% hot spot, non-significant, 90% cold spot, 95% cold spot, to 99% cold spot. Among the counties and districts, only Chongxin County fell within the 99% hot spot area. Kongtong District was the only area classified as a 95% hot spot. Lingtai County and Jingchuan County were categorized as 90% hot spots. The remaining counties did not have significant 90% cold spot, 95% cold spot, or 99% cold spot areas. This indicates that in 2010, the spatial clustering of WRCC in the Longdong Loess Plateau area was primarily driven by clusters of high-value areas. These clusters, which were predominantly located in the southwest part of the study area, exhibited a significant trend.

In 2015, the Getis-Ord Gi* index values for the WRCC in the Longdong Loess Plateau region once again exhibited various spatial patterns. As described above, the values encompassed 99% hot spot, 95% hot spot, 90% hot spot, non-significant, 90%

cold spot, 95% cold spot, and 99% cold spot areas. Similar to 2010, Chongxin County fell within the 99% hot spot area. Kongtong District, Lingtai County, and Jingchuan County were classified as 95% hot spots. Huachi County and Qingcheng County were categorized as 90% cold spots. Huan County was the only county that fell within the 99% cold spot area. The remaining counties did not have significant areas of 90% hot spots or 95% cold spots. This suggests that the spatial clustering of the WRCC in the Longdong Loess Plateau area became more pronounced in 2015. High and low-value areas tended to cluster together, with high-value areas primarily located in the southwest part of the study area and low-value areas primarily found in the north. This marks the beginning of the formation of a distribution pattern where the WRCC in the Longdong Loess Plateau area was higher in the south and lower in the north.

In 2020, the Getis-Ord Gi* index values for the WRCC in the Longdong Loess Plateau area exhibited various spatial patterns, including 99% hot spot, 95% hot spot, 90% hot spot, non-significant, 90% cold spot, 95% cold spot, and 99% cold spot areas. Among the counties and districts, Chongxin County was the only one classified as a 99% hot spot area. Kongtong District, Lingtai County, and Jingchuan County fell within the 95% hot spot area. Huan County was the only county categorized as a 90% cold spot area. The remaining counties did not exhibit significant areas of 90% hot spots, 95% cold spots, or 99% cold spots. This suggests that in 2020, the spatial clustering of water resources in the Longdong Loess Plateau area remained evident, exhibiting a concentrated regional distribution of high and low values. The spatial distribution pattern, with cold and hot spot areas being higher in the south and lower in the north, remained fundamentally unchanged.

Overall, from 2010 to 2020, the spatial distribution of hot spot areas of WRCC in the Longdong Loess Plateau area has remained consistent, with only a slight increase from 90% hot spot areas to 95% hot spot areas. The number of cold spot areas has also fluctuated, with a decrease from 99% cold spot areas to 90% cold spot areas. This indicates a more pronounced trend of concentrated distribution for high and low-value areas, with a narrowing gap in carrying capacity levels among counties and districts in cold and hot spots. High-value areas are concentrated in the southern part of the study area, whereas low-value areas are concentrated in the northern region, resulting in a spatial distribution pattern of higher values in the south and lower values in the north. Significant differences in WRCC were identified among counties, which was primarily attributed to economic level, industrial infrastructure, environmental conditions, and population size. Moving forward, the enhancement of the WRCC in the Longdong Loess Plateau area will require extensive green development and circular development efforts.

5.3. Discussion

In summary, the WRCC in the Longdong Loess Plateau area has shown an overall upward trend with fluctuations during the 2010–2020 period. The WRCC levels of counties and districts primarily fell within a level III (normal) and level IV (good) classification. Additionally, we identified a significant difference in the spatial distribution of the WRCC, which was characterized by higher values in the south and lower values in the north. Despite the relative scarcity of systematic and comprehensive studies on WRCC in the Longdong Loess Plateau area, other scholars have conducted related research. Cao et al. (2017) used principal component analysis to comprehensively evaluate the water resources carrying capacity of Gansu Province from 2006 to 2015 from both temporal and spatial perspectives. Principal Component Analysis (PCA) can evaluate water resources carrying capacity by downscaling multiple variables and replacing the original multidimensional variables with a few composite variables, but the clarity of the composite variables decreases when there are both positive and negative indicator options in the PCA, resulting in an unclear significance of the composite evaluation function. Liu et al. (2021) selected the indicators of water resources system and socio-economic system in Gansu Province from 2005 to 2017, and evaluated the water resources carrying capacity of each city in Gansu Province by entropy weight method. The study systematically considered the impact of water resources and socio-economic systems on water resources carrying capacity, but neglected the significant impact of ecological protection on water resources carrying capacity. Shi et al. (2021) selected 14 indicators from four aspects of water resources, residents' life, socio-economics, ecological environment, etc., and determined the weights of the indicators by using the game theory combination weighting method, and analyzed and evaluated the water resources carrying capacity of Gansu Province from 2009 to 2018 by using the TOPSIS comprehensive analysis method, and carried out the evaluation of water resources carrying capacity of the seven secondary river basins in the province respectively. The article uses game theory to combine the G2 assignment method with the CRITIC method to assign weights to the selected indicators, which to a certain extent reduces the error generated when using the two methods alone, but the use of subjective methods still affects the weights of the indicators to a certain extent. The above articles mainly assessed the water resources carrying capacity within the administrative boundaries from the socio-economic system level, but did not consider the water environment carrying capacity situation of the cross-administrative regions with similar ecological environment, economic circle and cultural atmosphere. In this paper, we take the Longdong Loess Plateau region as the research object from the three aspects of water resources, socio-economics and ecological environment, and the conclusions drawn are more reliable and accurate.

6. Conclusions and suggestions

6.1. Conclusions

(1) From 2010 to 2020, the overall WRCC in the Longdong Loess Plateau area exhibited an upward trend with some fluctuations. The overall carrying capacity increased from 0.333 in 2010 to 0.675 in 2019, which represented a 0.342 increase. The WRCC level increased from level III to level V, indicating an improvement from average to good. Throughout the study period, the minimum WRCC value (0.333) was observed in 2010, corresponding to a level III (normal) classification. Conversely, the maximum value (0.675) occurred in 2019, which corresponded to a level V (excellent) classification. The water resource, socio-economic, and ecological environment subsystems all exhibited an increasing trend in carrying capacity, with a substantial overall growth.

(2) From 2010 to 2020, the WRCC of counties and districts in the Longdong Loess Plateau area predominantly fell into level III (normal) and level IV (good) classifications. Jingchuan County, Kongtong District, Chongxin County, Lingtai County, and Xifeng District consistently exhibited high WRCC at level IV (good). Zhenyuan County, Ning County, Zhengning County, and Qingcheng County consistently displayed low WRCC at level III (normal). Huachi County and Heshui County experienced a decline in WRCC, shifting from level IV (good) to level III (normal). Huan County consistently exhibited the lowest WRCC, remaining at level III (normal) throughout the entire study period.

(3) From 2010 to 2020, the spatial distribution of WRCC in the Longdong Loess Plateau area exhibited a significant positive correlation. That is, adjacent counties with high or low WRCC exhibited a clustering distribution pattern. High-value clusters were concentrated in the southern part of the study area, whereas low-value clusters were concentrated in the northern region, resulting in a spatial distribution pattern characterized by higher values in the south and lower values in the north.

6.2. Suggestions

Based on our findings, as well as the socio-economic and ecological environment conditions and the current state of water resources in the counties in the Longdong Loess Plateau area, we propose measures and recommendations to enhance the WRCC in the region:

(1) The Longdong Loess Plateau region, where water resources are unevenly distributed and the spatial correlation of regional water resources carrying capacity is not strong, should prioritize and optimize regional water diversion planning based on the water diversion planning of different river basins across the country. The key is to consider the overall characteristics of surface water and groundwater in the region. Strengthening the comprehensive utilization of water resources, enhancing the coordination between surface water and groundwater, promoting the conversion of surface water and groundwater, and improving the recycling of water resources are top priorities.

(2) The Longdong Loess Plateau region has a large amount of water consumption in agriculture and industry, and the phenomenon of water resource wastage is relatively serious, water conservation measures should be implemented in the agricultural sector, the industrial structure should be optimized, priority should be given to the development of green and low-water-consuming industries, and attention should be paid to the development of tertiary industries such as eco-tourism and logistics, so as to increase their proportion in the composition of the industry as a whole. In addition, it should also increase the publicity of water conservation, enhance the awareness of water conservation, and improve the efficiency of water resources utilization.

(3) Strengthening the protection of the ecological environment is paramount. Improving environmental quality, increasing investment in environmental protection, enhancing water quality monitoring and pollution control measures, and expanding forest coverage and urban greening are essential steps. These actions will facilitate the

creation of a virtuous cycle between water resources and the environment, thus enhancing the self-healing capacity of water resources.

6.3. Research prospect

In this paper, the entropy weight TOPSIS method was used to measure the water resources carrying capacity of the Longdong Loess Plateau region, and the spatial distribution and regional evolution of water resources carrying capacity were analyzed using spatial analysis methods, with a view to providing scientific support for decision-making on sustainable development in the region and even the world region. However, the potential driving mechanism and influencing factors of water resources carrying capacity were not analyzed, so we hope to continue to analyze the driving mechanism of regional water resources carrying capacity in future studies.

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