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Analysis of Water Resource Carrying Capacity and Obstacle Factors Based on GRA-TOPSIS Evaluation Method in Manas River Basin

Anfuding Gulishengmu [1,2], Guang Yang [1,2,*], Lijun Tian [3], Yue Pan [1,2], Zhou Huang [1,2], Xingang Xu [1,2], Yongli Gao [4] and Yi Li [5]

[1] College of Water Conservancy & Architectural Engineering, Shihezi University, Shihezi 832000, China
[2] Key Laboratory of Cold and Arid Regions Eco-Hydraulic Engineering of Xinjiang Production & Construction Corps, Shihezi 832000, China
[3] Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[4] Department of Earth and Planetary Sciences, University of Texas at San Antonio, San Antonio, TX 78249, USA
[5] College of Water Resources and Architectural Engineering, Northwest Agriculture and Forestry University, Yangling 712100, China
* Correspondence: mikeyork@163.com; Tel.: +86-15009930733

Abstract: The investigation of water resource carrying capacity (WRCC) in oasis cities in Northwest China is useful for guiding the sustainable development of arid regions. To quantify the WRCC of Shihezi, an oasis city in the Manas River Basin (MRB), Northwest China, a total of 21 indicators from three subsystems were selected to construct an evaluation index system based on the theory of the water resource–socio-economic–ecological complex system. Our study utilized a combination of the CRITIC method and the entropy weight method to determine the synthesis weight, the GRA-TOPSIS approach to comprehensively evaluate the WRCC, and the obstacle degree model to identify its main obstacle factors. Our results showed that the WRCC of Shihezi showed an increasing trend from 2011 to 2020, with the compositive index increasing from 0.3454 to 0.5210. The carrying capacities of the ecological environment and socio-economic subsystems were generally on the rise, but the rate of change was relatively gentle from 2017 to 2020. The carrying capacity index of the water resource subsystem dropped significantly from year to year from 2016 to 2020. The irrigation coverage rate, the proportion of agricultural water, water consumption per 10,000 CNY of GDP, the modulus of water production, water resource development and its utilization ratio, the water supply modulus, and the proportion of ecological water were the seven most significant obstacles. Our findings could serve as scientific references for enhancing WRCC and promoting the sustainable development of oasis cities in arid regions.

Keywords: water resource carrying capacity (WRCC); CRITIC method; GRA-TOPSIS method; obstacle factor; Manas River Basin (MRB)

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1. Introduction

Water resource carrying capacity (WRCC) refers to the reasonable scale of water resources that can support regional sustainable economic, social, and ecological development [1]. The evaluation and analysis of WRCC are key to solving the contradiction between the supply of and demand for regional water resources and maintaining coordinated economic, social, and ecological development [2]. WRCC significantly impacts the prevention of environmental degradation and the spatial balance of water resources. Therefore, an in-depth study of regional WRCC and an accurate assessment can promote the full scientific utilization of regional water resources and the sustainable development of the regional social economy [3,4].

The concept and research of WRCC first began abroad. In the 1990s, Engelman et al. [5] selected factors such as population size, growth rate, distribution, and consumption pattern, and analyzed the contradiction between supply and demand of the tertiary industry and freshwater resources according to the influence of the selected factors on WRCC. In the 21st century, research on WRCC mainly focuses on assessing and managing urban water resource security and intelligent city water. Michiel et al. [6] studied the evaluation and management systems of urban water resource security and proposed that urban WRCC guarantees urban water resource security. In 2015, Steven H. A. Koop et al. [7] established an international evaluation index system for climate change, urbanization, and water pollution, which made research more inclined toward clean city water. WRCC research in China has shifted from the water resource system to the water resource–economic society–ecological complex system [8] Yue et al. [9] built a rating index system of Wuhan's water ecological carrying capacity based on DIPSIR and used the TOPSIS method to conduct a quantitative evaluation of the city's water ecological carrying capacity. Based on the interaction of the water resource–socio-economic–ecological complex system, Yang et al. [10] comprehensively evaluated the carrying capacity of water resources in Gongyi City, and analyzed the key factors affecting the carrying capacity of urban water resources by combining the state-space and hierarchical analysis methods. Zeng et al. [11] proposed a hybrid land–water–environment (LWE) model to identify the ecological risks and impacts of agroforestry ecosystems under uncertain meteorological and precipitation conditions. Ma et al. [12] calculated the WRCC of Yunnan Province from 2005 to 2018 using the GRA-TOPSIS method and obstacle degree model, and diagnosed the main obstacle factors. Zeng et al. [13] developed a hybrid stochastic-fuzzy model with a Green-Z scenario (HFSG) to alleviate the conflict between regional irrigation production and environmental protection under the pressure of water and soil resources. Yang et al. [14] applied the CRITIC-GR-TOPSIS method to conduct a comprehensive evaluation of WRCC in Yantai City from 2003 to 2018. In addition to the above research methods, regional WRCC research mainly uses the principal component analysis method, the fuzzy comprehensive evaluation method, the multi-criteria compromise solution sorting method, and the grey correlation degree [15,16].

The Manas River Basin (MRB) is located in the arid area of Northwest China, an important development area on the north slope of the Tianshan Mountains' economic belt. The water resource is the main limiting factor that restricts the evolution and development of ecological and economic systems. In recent years, with the rapid development of industrial and agricultural production and urban construction, regional water resources have been developed and utilized to a greater degree [17]. Furthermore, the "three red lines" of water resources have restricted the reduction of water supply from sewage resources, resulting in an increasingly severe water shortage phenomenon [18]. For example, the regional water supply in 2018 was 13.89×10^8 m^3, but the total water demand of various industries was 19.47×10^8 m^3. Thus, the water shortage was as high as 5.58×10^8 m^3. The contradiction between the supply and demand of water resources is increasingly prominent, and significantly restricts sustainable economic, social, and ecological development [19]. Therefore, our study took Shihezi, an oasis city in the MRB, as an example and constructed a comprehensive evaluation index system of WRCC based on the theory of the water resource–socio-economic–ecological complex system. In order to provide scientific reference for the rational allocation, exploitation, and sustainable development of water resources in oasis cities, we determined the synthesis weight by combining the CRITIC method [20] and the entropy weight method [21], and evaluated the WRCC of Shihezi oasis city using the GRA-TOPSIS method. Additionally, the obstacle degree model was used to diagnose the main obstacle factors. The specific framework of this study is shown in Figure 1.

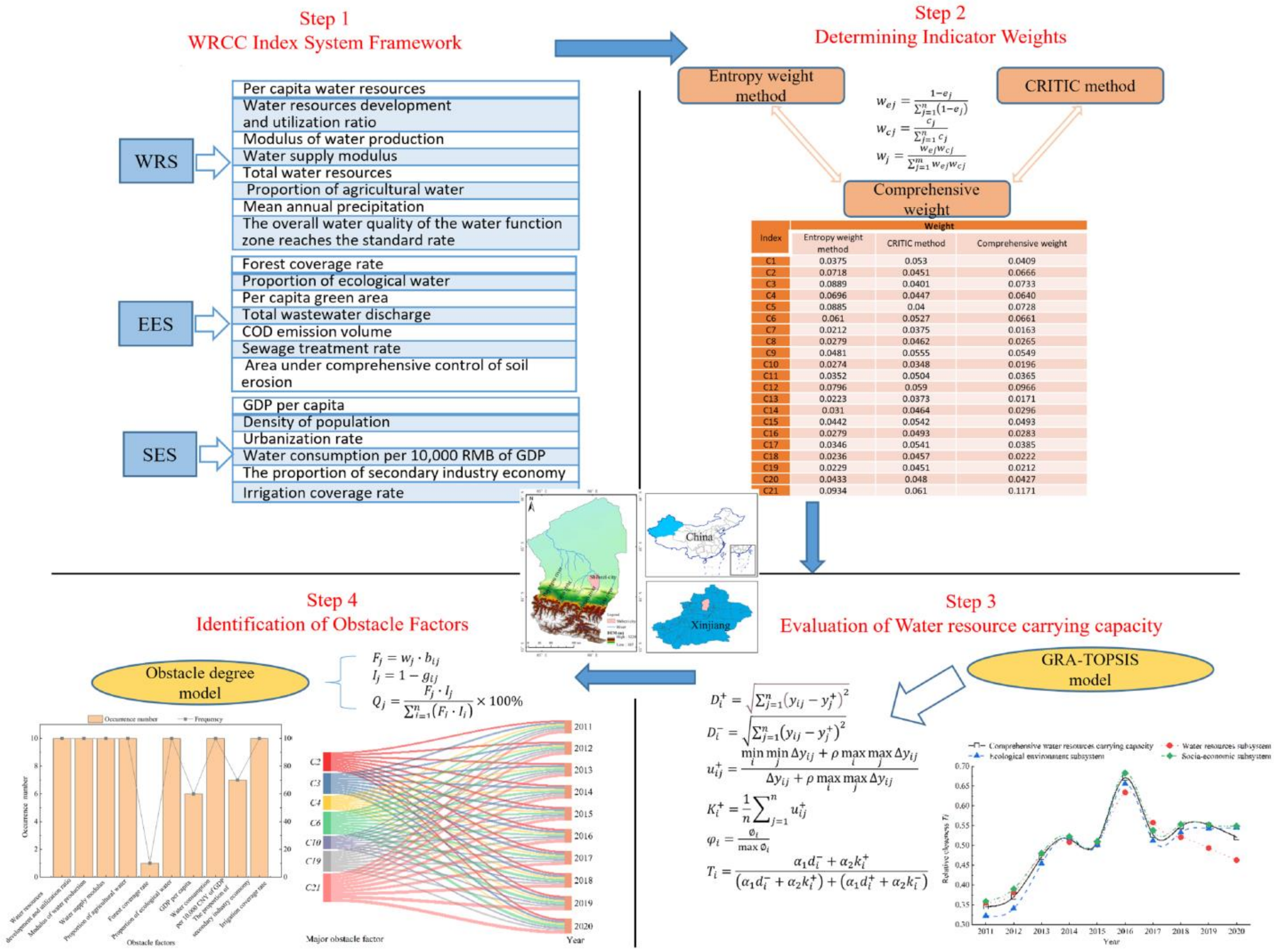

Figure 1. General framework of this paper.

2. Methods

2.1. Overview of the Study Area

Shihezi city is located in the middle part of the northern foot of the Tianshan Mountains in Xinjiang, in the MRB, on the southern edge of the Junggar Basin (Figure 2). The study area (43°26′–45°20′ N, 84°58–86°24′ E) covers an area of 7529 km^2. The territory has four rivers (Manas, Ningjia, Taxi, and Bayingou), forming six irrigated areas (Shihezi, Mosowan, Xiaidi, Anjihai, Jingou, and Ningjia). The average annual runoff of the four rivers in 1956–2020 was 20.811 $\times$ 10^8 m^3, and the region's annual divisible water volume was 12.17 $\times$ 10^8 m^3. The study area has a typical continental semi-arid climate. The average precipitation from 2009 to 2019 was 260.7 mm, while the average annual evaporation was 1500 mm. In recent years, the rapid development of the industrial and agricultural economies has aggravated the problem of water resources in Shihezi. The deterioration in water quality and the scarce quantity of water are growing increasingly severe, posing a threat to the long-term growth of the area's economy and society.

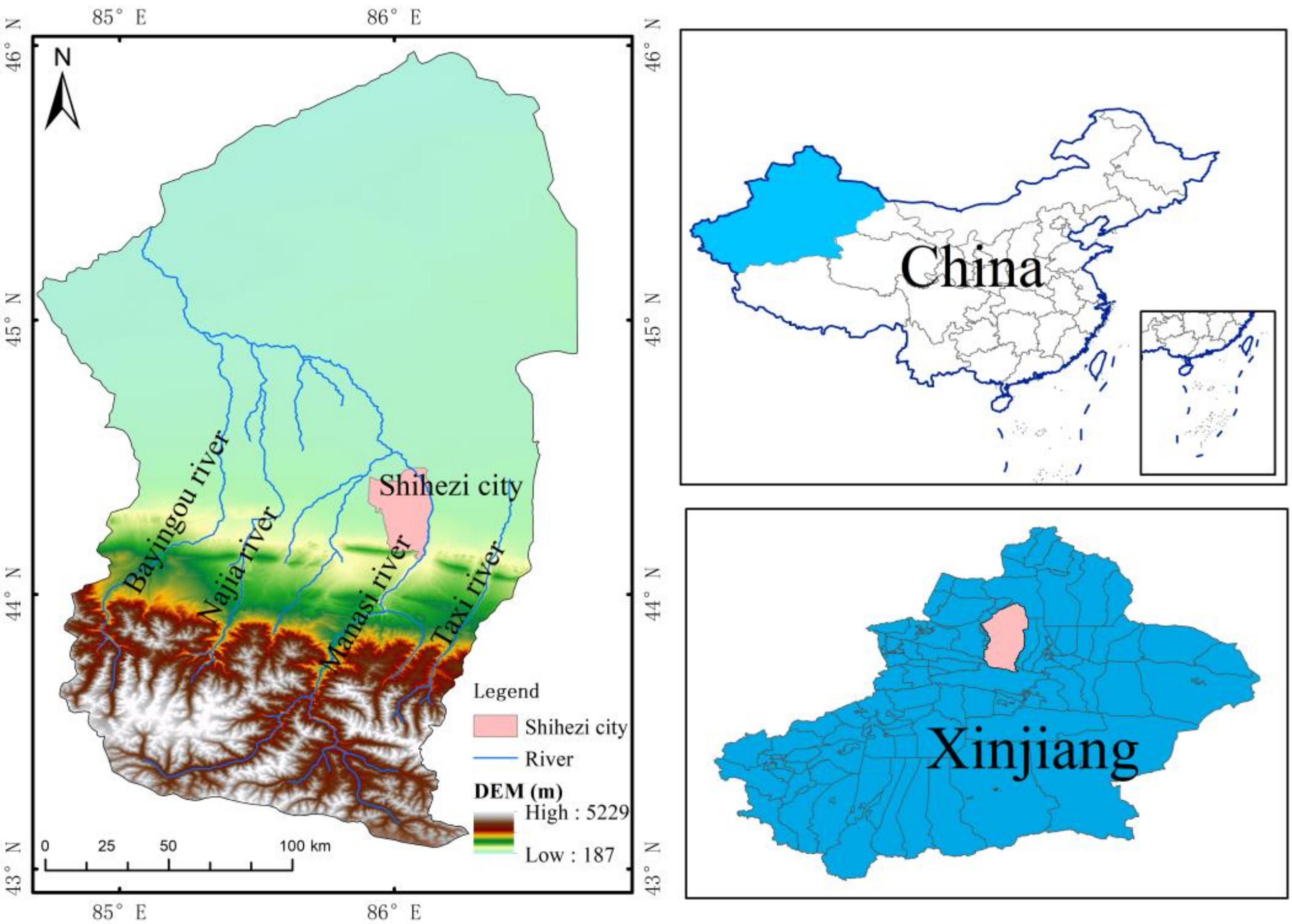

Figure 2. Geographical map of the study area.

2.2. Data Sources

The data were mainly sourced from the "*Xinjiang Statistical Yearbook*" (2011–2020), the "*Xinjiang Production and Construction Corps Statistical Yearbook*" (2011–2020), (http://tjj.xinjiang.gov.cn/ (accessed on 1 April 2021); http://www.yearbookchina.com (accessed on 7 April 2021)) the "Statistical Bulletin of Xinjiang Production and Construction Corps on National Economic and Social Development" (2011–2020), the "Shihezi Water Conservancy Annual Report" (2011–2020), and the "Xinjiang Water Resources Bulletin" (2011–2020).

2.3. Research Methods

2.3.1. Index Standardization

The min–max normalization method is adopted to carry out the linear transformation of the original data and realize dimensionless processing of the original data. The calculation formula is as follows:

Standardization of positive indicators:

$$g_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \tag{1}$$

Standardization of reverse indicators:

$$g_{ij} = \frac{\max x_j - x_j}{\max x_j - \min x_j} \tag{2}$$

where: g_{ij} is the standardized value of the index; x_{ij} is the original data of the j evaluation index in the i year; and $\max x_j$ and $\min x_j$ are the maximum and minimum values of the j evaluation index, respectively.

After the index standardization, we construct the decision matrix G.

$$G = (g_{ij})_{m \times n}(i = 1, 2, \cdots, m; j = 1, 2, \cdots, n) \tag{3}$$

2.3.2. Determination of Indicator Weights

The CRITIC method, proposed by Diakoulaki in 1995, is an objective weight method. This method determines the objective weight of each indicator by calculating the variability and conflict of evaluation indicators, which can ensure that the information in the original data of each indicator can be fully divided and utilized [22]. The single CRITIC method does not fully consider the discrete types among indicators, but the entropy weight rule effectively makes up for the deficiency in this method. Therefore, this analysis is based on the combined weight of the entropy weight method and the CRITIC method [23].

(1) Entropy weight method. The entropy weight method is a method used to determine the dispersion degree of an index by using the entropy value, and thus, the index's weight [24]. If the index data value is 0 after standardization, to avoid ln0, the standardized value is replaced by 0.0000001. The specific calculation steps are as follows:

Calculate the proportion q_{ij} of the sample value of the i year in the j index

$$q_{ij} = \frac{g_{ij}}{\sum_{i=1}^{m} g_{ij}} \tag{4}$$

Calculate the entropy e_j of the j index

$$e_j = -k \sum_{i=1}^{m} (q_{ij} \cdot \ln q_{ij}) \tag{5}$$

where: $k = \frac{1}{\ln m}$.

Calculate the weight w_{ej} of the j index

$$w_{ej} = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)} \tag{6}$$

(2) CRITIC method. The CRITIC method comprehensively measures the weight of each indicator through the variability and conflict among indicators [22]. The specific calculation steps are as follows:

Calculate the standard deviation σ_j of the j index.

Calculate the correlation coefficient r_{ij} between the indicators:

$$r_{ij} = \frac{\sum_{i=1}^{m} (g_i - \overline{g_i})(g_j - \overline{g_j})}{\sqrt{\sum_{i=1}^{m} (g_i - \overline{g_i})^2 \sum_{i=1}^{m} (g_j - \overline{g_j})^2}} \tag{7}$$

The conflict between indicators is based on the correlation coefficient between indicators and can be expressed by R_j. The calculation formula is:

$$R_j = \sum_{i=1}^{m} (1 - r_{ij}) \tag{8}$$

Calculate the weight w_{cj} of the j indicator:

$$w_{cj} = \frac{c_j}{\sum_{j=1}^{n} c_j} \tag{9}$$

$$c_j = \sigma_j R_j \tag{10}$$

where: c_j is the amount of information contained in the j index. The larger the value, the greater the amount of information the index contains, and the greater the relative importance of the index.

(3) Portfolio empowerment. The comprehensive weight calculation adopts the "multiplication" integrated method to realize the complementary advantages between the entropy weight and CRITIC methods [23]. The formula for calculating the synthesis weight is as follows:

$$w_j = \frac{w_{ej}w_{cj}}{\sum_{j=1}^{m} w_{ej}w_{cj}} \tag{11}$$

2.3.3. GRA-TOPSIS Model

TOPSIS is a multi-objective decision-making method that sorts evaluation objects based on their proximity to idealized objects [25]. The relative proximity is calculated and sorted by calculating the distance between each evaluation object and positive or negative ideal solutions to judge the relative merits of evaluation objects. The introduction of grey correlation theory into TOPSIS can compensate for the method's shortcomings. The grey correlation method (GRA) is based on the sample data of evaluation indicators [26]. We use grey relational analysis to describe the relationship's strength, magnitude, and order among evaluation indicators. The GRA-TOPSIS method can more systematically and accurately reflect the degree of proximity between alternative schemes and ideal schemes, make the analysis results more reasonable and reliable, and provide a basis for the final decision [27,28]. Based on the GRA-TOPSIS method, this paper builds an evaluation model of WRCC in Shihezi city in the MRB. The specific calculation steps are as follows:

(1) Construct the weighted decision matrix. Establish a normal-weighted decision matrix Y according to the weight of each index:

$$Y = \left(y_{ij}\right)_{m\times n} = \left(w_{ij}\cdot g_{ij}\right)_{m\times n} \tag{12}$$

(2) Determine the positive ideal solution and negative ideal solution of each index.
Positive ideal solution:

$$y_j^+ = \left\{\max y_{ij} \middle| i = 1, 2, \cdots, m\right\} \tag{13}$$

Negative ideal solution:

$$y_j^- = \left\{\max y_{ij} \middle| i = 1, 2, \cdots, m\right\} \tag{14}$$

(3) Determine the European distance between each evaluation object and the positive and negative ideal solutions:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(y_{ij} - y_j^+\right)^2} \tag{15}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}\left(y_{ij} - y_j^+\right)^2} \tag{16}$$

(4) Calculate the grey correlation degree.

Calculate the grey correlation coefficient between the i year sample and the positive ideal solution of the j index:

$$u_{ij}^+ = \frac{\min_i \min_j \Delta y_{ij} + \rho \max_i \max_j \Delta y_{ij}}{\Delta y_{ij} + \rho \max_i \max_j \Delta y_{ij}} \tag{17}$$

$$\Delta y_{ij} = \left|y_j^+ - y_{ij}\right| \tag{18}$$

where: minminΔy_{ij} is the minimum difference between the two levels; maxmaxΔy_{ij} is the maximum difference between the two levels; and ρ is the resolution coefficient, and its value ranges from 0 to 1 (ρ = 0.5 in our study).

Calculate the correlation degree K_i^+ between the i year sample and the positive ideal solution:

$$K_i^+ = \frac{1}{n}\sum_{j=1}^{n} u_{ij}^+ \tag{19}$$

Similarly, the correlation degree K_i^- between the i year sample and the negative ideal solution can be calculated.

(5) Calculate the relative closeness.

The Euclidean distance and correlation degree are treated as dimensionless

$$\varphi_i = \frac{\varnothing_i}{\max\varnothing_i} \tag{20}$$

where: $\varnothing_i$ is the Euclidean distance D_i^+, D_i^-, and the grey correlation degree K_i^+, K_i^-; φ_i is the dimensionless European distance d_i^+, d_i^-, and the grey correlation degree k_i^+, k_i^-.

Calculate the relative stick progress T_i:

$$T_i = \frac{\alpha_1 d_i^- + \alpha_2 k_i^+}{\left(\alpha_1 d_i^- + \alpha_2 k_i^+\right) + \left(\alpha_1 d_i^+ + \alpha_2 k_i^-\right)} \tag{21}$$

where: α_1, α_2 is the bias coefficient, reflecting the bias degree of decision-makers; for $\alpha_1 + \alpha_2 = 1$, the values in this article are $\alpha_1 = 0.6$ and $\alpha_2 = 0.4$. The larger the T_i value, the higher the WRCC in the i year.

2.3.4. Obstacle Degree Model

The change in WRCC is the result of the combined action of various index factors. However, the GRA-TOPSIS method cannot be analyzed concretely to influence the degree of each index factor of WRCC. The obstacle degree model makes a pathological diagnosis of the level or degree of the evaluation target and determines the main obstacle factors by mining the factors that hinder the development trend and degree of things [29]. Therefore, we utilize the obstacle degree model to measure the obstacle degree of the index layer of WRCC, to provide a basis for the future improvement of WRCC. The diagnostic results are of great significance in guiding and adjusting the utilization of regional water resources. The obstacle degree mainly involves three measurement indexes: the factor contribution degree, the index deviation degree, and the obstacle degree [30].

(1) Calculate the factor contribution degree F_j:

$$F_j = w_j \cdot b_{ij} \tag{22}$$

where: w_j is the comprehensive weight of the j single index, and b_{ij} is the weight of the criterion layer to which the i single index belongs.

(2) Calculate the index deviation degree I_j:

$$I_j = 1 - g_{ij} \tag{23}$$

(3) Calculate the degree of computational handicap Q_j:

$$Q_j = \frac{F_j \cdot I_j}{\sum_{j=1}^{n}\left(F_j \cdot I_j\right)} \times 100\% \tag{24}$$

where: Q_j is the obstacle degree (%) of the j index to the carrying capacity of water resources, and its size represents the constraint of the index to the carrying capacity of water resources. The greater the value of Q_j, the greater the constraint.

3. Results and Analysis

3.1. Evaluation Index System

Taking the water resource subsystem, ecological environment subsystem, and social and economic system as the criterion layers of the WRCC of Shihezi. The concept of WRCC considers the comprehensive influence of the water resource system, ecological environment system, and social and economic system. Therefore, when measuring or evaluating the status of regional WRCC, the influences of the regional water resource conditions, social scale, economic structure and technical level, ecological environment, and other factors are mainly considered. Therefore, we selected evaluation indexes from the three subsystems comprehensively. The selection of evaluation indicators followed the principles of comprehensiveness, hierarchy, operability, and data availability [31]. By referring to the evaluation index system and standard of the national WRCC, consulting experts, and referring to relevant research results at home and abroad, and combining these with the actual situation of Shihezi city, a total of 21 indexes were selected to establish the evaluation index system of Shihezi WRCC, as shown in Table 1.

Table 1. Evaluation index system of WRCC in Shihezi.

Target Layer	Standard Layer	Index Layer	Unit	Weight		
				Entropy Weight Method	CRITIC Method	Comprehensive Weight
WRCC	Water Resource Subsystem B1	Per capita water resources C1	m^3/person	0.0375	0.053	0.0409
		Water resource development and utilization ratio C2	%	0.0718	0.0451	0.0666
		Modulus of water production C3	10^4 m^3/km^2	0.0889	0.0401	0.0733
		Water supply modulus C4	10^4 m^3/km^2	0.0696	0.0447	0.0640
		Total water resources C5	10^8 m^3	0.0885	0.04	0.0728
		Proportion of agricultural water C6	%	0.061	0.0527	0.0661
		Mean annual precipitation C7	mm	0.0212	0.0375	0.0163
		The overall water quality of the water function zone reaches the standard rate C8	%	0.0279	0.0462	0.0265
	Ecological environment Subsystem B2	Forest coverage rate C9	%	0.0481	0.0555	0.0549
		Proportion of ecological water C10	%	0.0274	0.0348	0.0196
		Per capita green area C11	m^2	0.0352	0.0504	0.0365
		Total wastewater discharge C12	10^4 t	0.0796	0.059	0.0966
		COD emission volume C13	10^4 t	0.0223	0.0373	0.0171
		Sewage treatment rate C14	%	0.031	0.0464	0.0296
		Area under comprehensive control of soil erosion C15	10^3 hm^2	0.0442	0.0542	0.0493
	Socio-economic subsystem B3	GDP per capita C16	yuan	0.0279	0.0493	0.0283
		Density of population C17	person/km^2	0.0346	0.0541	0.0385
		Urbanization rate C18	%	0.0236	0.0457	0.0222
		Water consumption per 10,000 CNY of GDP C19	m^3	0.0229	0.0451	0.0212
		The proportion of secondary industry economy C20	%	0.0433	0.048	0.0427
		Irrigation coverage rate C21	%	0.0934	0.061	0.1171

3.2. Evaluation of WRCC of Oasis Cities in MRB

As shown in Figure 3, we analyzed the changes in the regional WRCC as follows:

(1) Analysis of changes in comprehensive WRCC. The comprehensive WRCC of Shihezi in the MRB showed a partial decrease in some years but, on the whole, showed an upward trend. The relative sticking progress increased from 0.3454 in 2011 to 0.5210 in

2020, with an annual average growth rate of 1.76%. The changes in the regional research period can be roughly divided into two stages combined with the relative progress:

The first stage was from 2011 to 2016, and the WRCC showed a fluctuating upward trend. The relative sticking progress increased from 0.3454 to 0.6714, with an annual average growth rate of 6.52%. Compared with the previous period, the WRCC decreased slightly in 2014–2015 and significantly increased in 2015–2016. At this stage, Shihezi vigorously implemented new urbanization construction and adjusted the regional economic structure. The proportion of the tertiary industry in the region's total GDP increased from 31.46% in 2011 to 41.39% in 2016, and the sewage treatment rate increased from 31.8% to 70%. The second stage was from 2016 to 2020. The regional WRCC shows a trend of fluctuation decline, and the relative closeness degree decreases from 0.6714 to 0.5210. It is worth noting that the carrying capacity decreased from 0.6714 in 2016 to 0.5275 in 2017 and showed a slight upward trend for two consecutive years. Under the combined pressure of water resources, ecological environment, and the economy and society, the WRCC showed a downward trend.

(2) Analysis of bearing capacity changes in each subsystem. From 2011 to 2020, the carrying capacity of the water resource subsystem in Shihezi showed a trend of first rising, and then, decreasing. From 2011 to 2016, the relative closeness degree ranged from 0.3552 to 0.6342, with a maximum increase of 26.2%. During 2016–2020, the carrying capacity of the water resource subsystem decreased from 0.6342 to 0.4632. The carrying capacity of the eco-environmental subsystem showed an upward trend on the whole, with an annual average growth rate of 16.14% from 2011 to 2016. In 2016–2017, the carrying capacity of the eco-environmental subsystem showed a significant decrease and an annual growth trend from 2017 to 2020. The carrying capacity of the socio-economic subsystem of Shihezi showed a fluctuating upward trend from 2011 to 2017. During 2015–2017, there was a significant fluctuation, with an increased rate of 33.83% during 2015–2016 and a decrease rate of 21.18% during 2016–2017. From 2018 to 2020, the changing trend of the socio-economic subsystem was relatively flat.

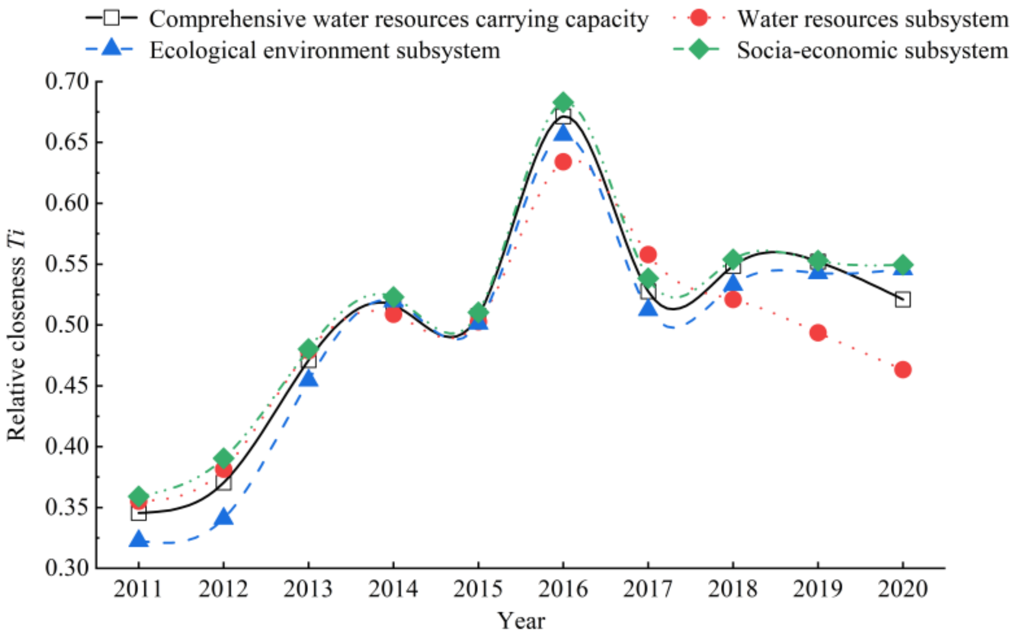

Figure 3. The comprehensive WRCC of Shihezi from 2010 to 2020 and the evaluation results of the carrying capacity of each subsystem.

3.3. Obstacle Factor Analysis of WRCC of Oasis Cities in MRB

The obstacle degree model was used to estimate the obstacle degree of the WRCC of Shihezi, an oasis city in the MRB, during 2011–2020. The WRCC is characterized by the

21 indicators of obstacle degree $Q_j \geq 5\%$ and its frequency of determining the primary and secondary relationships of the obstacle factors. The frequencies of the ten main obstacle factors are shown in Figure 4.

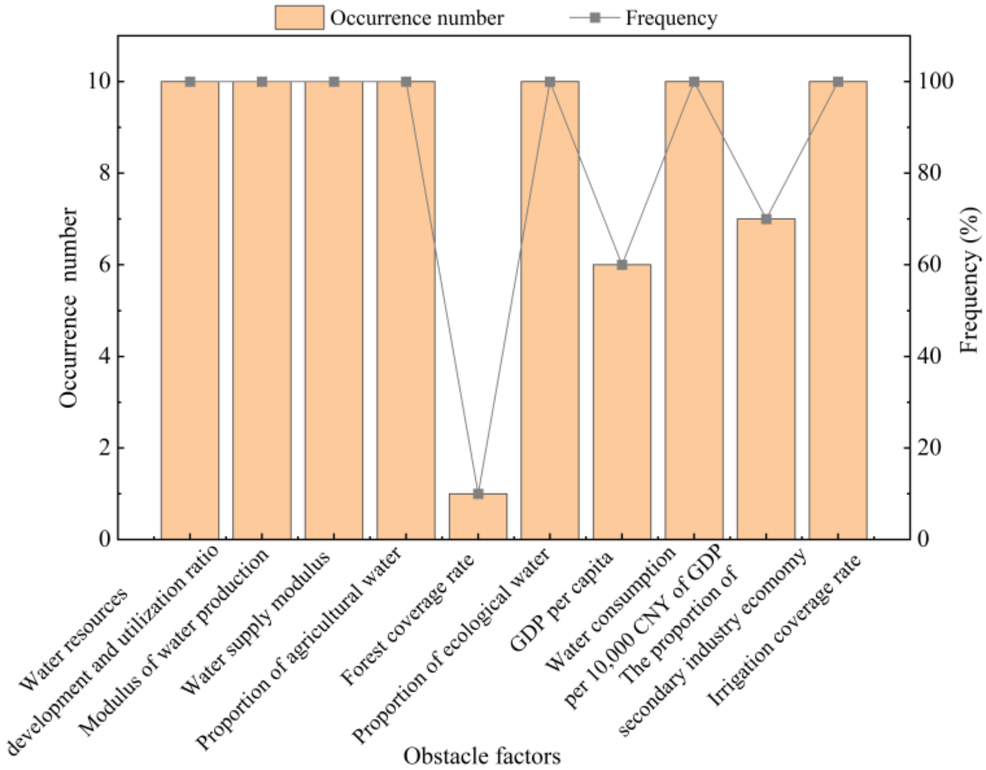

Figure 4. Frequency diagram of main obstacles to WRCC in Shihezi.

As can be seen from Figure 3, the obstacle degree of water resource development and its utilization ratio (C2), the modulus of water production (C3), the water supply modulus (C4), the proportion of agricultural water (C6), the proportion of ecological water (C10), water consumption per 10,000 CNY of GDP (C19), and the irrigation coverage rate (C21) are all greater than 5% for ten consecutive years. Regarding the proportion of secondary industry economy (C20), the frequency of obstacle degree greater than 5% was 70%, the frequency of GDP per capita (C16) was 60%, and the frequency of forest coverage rate (C9) was 10%. After comparison, the final diagnosis of water resource development and its utilization ratio (C2), the modulus of water production (C3), the water supply modulus (C4), the proportion of agricultural water (C6), the proportion of ecological water (C10), water consumption per 10,000 CNY of GDP (C19), and the irrigation coverage rate (C21) are the main obstacle factors affecting regional water resource carrying capacity. Among them, four belong to the water resource subsystem, one to the ecological environment subsystem, and two to the economic and social subsystem.

Figure 5 shows the relationship between the WRCC of Shihezi from 2011 to 2020 and the main obstacle factors. It can be seen that the most significant obstacle factor for the overall obstacle degree of Shihezi from 2011 to 2020 is irrigation coverage, with a moderate obstacle degree of 12.28% in ten years. This is followed by the proportion of agricultural water consumption, with a moderate obstacle degree of 9.68%. The smallest is the ecological water proportion at 5.68%. From 2011 to 2020, irrigation coverage was the first obstacle affecting the WRCC of Shihezi. Additionally, it has been increasing year by year since 2017. Water consumption per 10,000 CNY of GDP ranked as the second obstacle factor in 2011–2012 and 2014–2016. However, from 2017 to 2020, its obstacle degree decreased yearly. In this stage, the obstacle degree of agricultural water consumption proportion increased yearly, becoming the second largest obstacle affecting regional WRCC. By 2020, its obstacle degree was 12.36%, and the 2015–2020 modules of water production ranked third, from 8.82% in 2015 to 9.57% in 2020. Although the proportion of ecological water use is smaller than other obstacle factors, its obstacle degree has been increasing yearly since 2017.

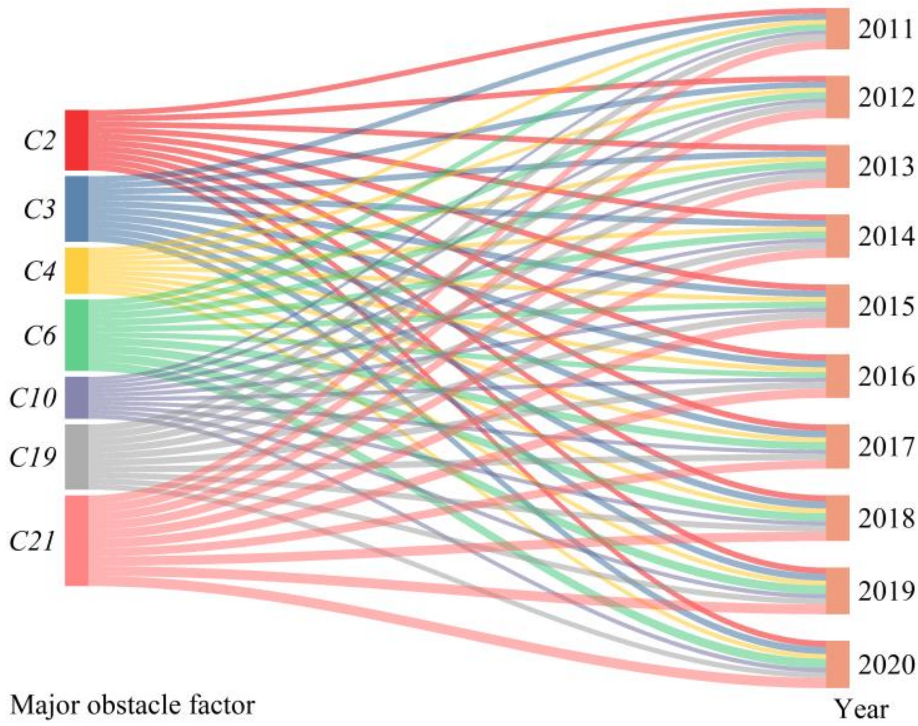

Figure 5. Analysis of the main obstacles to the WRCC of Shihezi from 2011 to 2020.

4. Discussion

(1) Discussion on the changes in the comprehensive carrying capacity of water resources. Based on the existing research, this paper constructs a comprehensive evaluation index system based on the theory of the water resource–socio-economic–ecological hybrid system. It uses the GRA-TOPSIS model to quantify the WRCC of Shihezi city. The evaluation results show that the WRCC of Shihezi increased from 2011 to 2016 and fluctuated from 2016 to 2020, which is consistent with the research results of Cheng et al. [32] on the water resource vulnerability of the northern slope of the Tianshan Mountain Cluster. The higher the carrying capacity, the lower the vulnerability. The WRCC of Shihezi showed a fluctuating downward trend from 2016 to 2020, which may be closely related to the regional resource situation and development status at this stage. At this stage, except for an increase of 38.9% compared with the annual average level in 2016, the inflow of river water within the region decreased year by year from 2017 to 2020. The average rainfall was 28.2% less than the annual average, and the population and COD emissions increased year by year. Moreover, WRCC is a coupling system of water resources, the ecological environment, and the economy and society, and each factor has mutual restrictions and influence. If the index value of positive factors decreases or the value of pressure factors increases, the regional water resource carrying capacity will decrease.

(2) Discussion of main obstacle factors. The obstacle degree model identifies the main obstacle factors affecting regional carrying capacity, including the irrigation coverage rate, the agricultural water proportion, water consumption per 10,000 CNY of GDP, the water production modulus, the ecological water proportion, etc. This is mainly because agriculture is still the main body of urban development in Shihezi, and the area of agricultural farmland is large. The average ratio of regional agricultural water consumption to total water consumption was 90.06% from 2011 to 2020. However, the average GDP generated by agriculture only accounts for 19.97% of the total regional GDP. Figure 6 shows a change

chart of agricultural water consumption and production value in Shihezi from 2011 to 2020. Its development has a significant impact on the carrying capacity of water resources. At the same time, Shihezi is located in an arid area, which has a relatively significant disadvantage in water resource endowment and is subject to the inherent constraints of resources. In addition, the reduction in regional water resource supply under total water consumption control will increase the bearing pressure of the water resource subsystem, thus affecting the comprehensive bearing capacity of the whole region. Therefore, local governments must take measures to adjust the water use structure, implement land reclamation plans, and implement water resource protection policies.

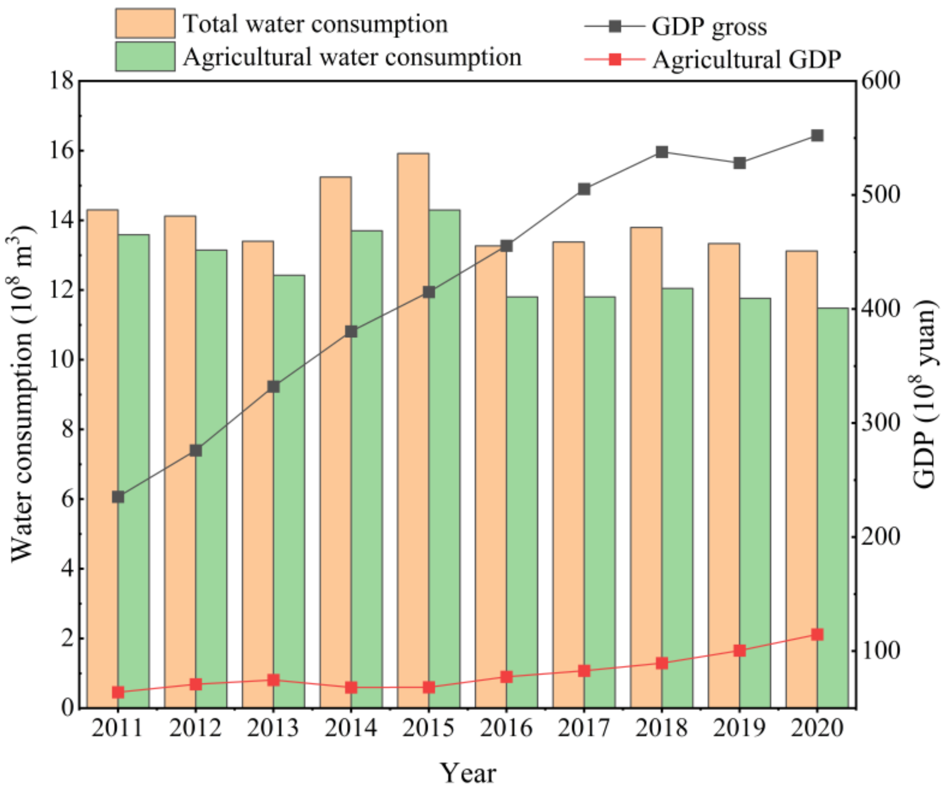

Figure 6. Comparison of agricultural water use and production with total water use and total production value of Shihezi from 2011 to 2020.

5. Conclusions

(1) Combining CRITIC and GRA-TOPSIS can be an effective means of comprehensive evaluation of urban WRCC. This method can coordinate the relationships between water resources, the ecological environment, and socio-economic carrying capacity through the data analysis of indicators, to make the evaluation results more realistic and reasonable.

(2) The WRCC of Shihezi City in the MRB showed an upward trend from 2011 to 2020. There is little difference between the carrying capacity of socio-economic and ecological environment subsystems. However, there is a great difference between them and the water resource subsystem, which affects further improvement of the comprehensive WRCC of Shihezi. Therefore, Shihezi should pay attention to the coordinated development of the three subsystems of the region to improve the regional WRCC.

(3) According to the results of the obstacle degree model, regional water resources and socio-economic factors have more significant impacts on carrying capacity than ecological and environmental factors. They have become the main obstacle factors affecting the comprehensive WRCC of Shihezi. Therefore, they should serve as references and crucial points for further improving the WRCC of Shihezi city in the MRB.

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