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Assessing Water Resource Carrying Capacity and Sustainability in the Cele–Yutian Oasis (China): A TOPSIS–Markov Model Analysis

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Abstract: This study employs the *Driving Force–Pressure–State–Response* (*DPSR*) framework to establish an evaluation index system for the water resource carrying capacity (*WRCC*) in the Cele–Yutian Oasis (China). Utilizing the TOPSIS and obstacle degree models, we analyze the trends in the WRCC and its main hindrance factors in the Cele–Yutian Oasis from 2005 to 2020. Additionally, we employ the Markov model to investigate the dynamic changes in the land use types. The findings reveal that the most unfavorable WRCC status occurred in 2007, with a Grade IV rating (a mild overload). By 2020, the WRCC improved to a Grade III rating (critical), indicating a positive trajectory. However, persistent challenges for water resources remain, with a prolonged critical state. Over the past 15 years, the grassland area has decreased by 15.18%, and the forest area has decreased by 50%. The dynamic degree of grassland, forests, and water bodies is negative, signifying shifts to other land types, with water bodies undergoing the most significant change at −10.16%. Based on the outcomes of these two models, we propose regionally tailored measures to support sustainable development. These research results provide a scientific foundation for optimal water resource allocation and sustainable development in the Cele–Yutian Oasis Economic Belt.

Keywords: water resource carrying capacity; TOPSIS model; barrier degree; Markov model; Celle–Yutian Oasis

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1. Introduction

Water resources constitute essential natural assets pivotal for both economic and social advancement [1–3]. Nevertheless, the relentless surge in economic and social progress and expedited industrialization and urbanization coupled with persistent population expansion have precipitated an incessant upswing in the demand for water resources [4,5]. At the same time, water pollution and scarcity issues are becoming increasingly serious, which is to the detriment of sustainable development initiatives and effective water resource utilization [6]. Especially in the desert regions of the northwest, access to water resources is key to driving economic, social, and ecological development [7]. Hence, it is necessary to conduct a rigorous scientific assessment of the water resource carrying capacity to foster a robust growth in desert oasis economies, to safeguard ecological environments, and to promote the sustainable utilization of water resources [8].

In assessing the water resource carrying capacity, the initial step entails the selection of the appropriate indicators to be evaluation factors. Different scholars have different perspectives on the study of the water resource carrying capacity, resulting in a variety of indicator systems [9]. For example, Gao et al. [10] developed a regional water-resource-carrying-capacity evaluation indicator system encompassing four dimensions: the water resource quantity, virtual water, ecological environment, and socioeconomic factors. Liu et al. [11] examined the selection of the water-resource-carrying-capacity indicators in Tibet based on the three functions of water resources, namely, production, living, and ecology, and the PSR model, and they explored the coupling and coordination relationship between the three subsystems. Dang et al. [9] used the *DPSR (Driving Force–Pressure–State–Response)* framework to comprehensively evaluate the water resource carrying capacity of Longnan City. The *DPSR* model has several advantages, including comprehensiveness, systematicity, clear logic, and strong practicality, making it a favored choice among scholars. The water resource carrying capacity refers to the maximum capacity of the industrial, agricultural, and urban scales as well as the population that a region can bear without damaging its society and ecosystem, which is a comprehensive indicator that is adaptable to social, economic, and scientific and technological development [12–14]. The methods to evaluate the water resource carrying capacity include the TOPSIS method, fuzzy comprehensive evaluation method, principal component analysis method, system dynamics method, and multiobjective linear programming method [15–19]. For example, Li et al. [20] used an improved TOPSIS model to comprehensively evaluate the water resource carrying capacity in Jiangsu Province, and they used the obstacle degree model to diagnose the obstacles to the water resource carrying capacity. Ren et al. integrated a fuzzy comprehensive evaluation with the analytic hierarchy process to assess the water resource carrying capacity of Datong City [21]. Li et al. [22] proposed a water resource allocation method based on the characteristics of the crop and livestock water demand combined with the agricultural water resource carrying capacity. Xu et al. [23] predicted the dynamic changes in the water resource carrying capacity based on a system dynamics model with different development modes. Although these methods have been widely used in the evaluation of the water resource carrying capacity, there are still some problems. For example, the analytic hierarchy process and fuzzy comprehensive evaluation can be susceptible to subjective preferences when assigning indicator weights, while system dynamics modeling demands a multitude of variables and parameters, resulting in intricate model development. In comparison, the TOPSIS method is simple and intuitive, can consider multiple criteria, and can handle fuzzy and uncertain problems.

Researchers from around the world have made progress in studying the water resource carrying capacity, but there are still some problems and deficiencies that need to be addressed. Some of these are that (1) water-resource-carrying-capacity research primarily concentrates on individual projects and that comprehensive studies encompassing the socioeconomic aspects, ecology, and environment are limited. Particularly, there is a dearth of research that explores the influence of human activities on the water resource carrying capacity [24]. (2) The studies mostly pertain to developed provinces, river basins, or prefecture-level cities, with less focus on individual oases [25]. (3) Previous studies predominantly centered on uncovering the year-to-year fluctuations in water resources within the water resource carrying capacity, with comparatively limited exploration into the profound effects of dynamic alterations in various evaluation factors on the water resource carrying capacity [26]. (4) Fewer studies have been conducted to evaluate regional sustainable development using both the water resource carrying capacity and land use change trends. Spatiotemporal variations are high in land use and water-cycle processes. Moreover, inadequate vegetation restoration and excessive human intervention can lead to dramatic shifts in the present land use. The impact of land use on the water resource carrying capacity is further enhanced by human activities. Therefore, the scientific quantification of the dynamic relationship between the water resource carrying capacity and land use types is a prerequisite for protecting oasis ecologies and ensuring healthy sustainable development.

In light of the aforementioned challenges and requirements, this study primarily concentrates on the Cele–Yutian Oasis (China) Economic Belt, which is characterized by somewhat delayed economic development. It is located at the northern foot of Kunlun Mountain and the southern edge of Taklimakan Desert, with an extremely arid continental desert climate. The spatial and temporal distribution of water resources in the oasis is uneven, mainly in agriculture, the low utilization rate of irrigation water, the prominent shortage of water resources, and the weak potential of sustainable development. This study aims to establish a water-resource-carrying-capacity evaluation index system grounded in the *DPSR* framework. The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) model is used to calculate the water resource carrying capacity of the Cele–Yutian Oasis from 2005 to 2020, and the impact of the major obstacle factors is evaluated based on the obstacle degree model system. In addition, the Markov model is introduced to calculate the dynamics among the different land use types. Through a comprehensive analysis of the water resource carrying capacity and land use transitions, this study assesses the state of sustainable development in the Cele–Yutian Oasis and puts forward constructive recommendations. The results of this study provide a solid theoretical foundation for the efficient allocation and judicious utilization of water resources in desert oases.

2. Research Area and Research Methods

2.1. Research Area Overview

Cele–Yutian Oasis (80°50′ E–82° E longitude, 36°50′ N–37°20′ N latitude) is located on the southern edge of the Tarim Basin, with an area of approximately 8257 square kilometers. It ranks as one of the world's most remote regions from the ocean (Figure 1). The mean annual temperature in this region stands at 11.8 degrees Celsius, with a precipitation of 35 mm and an evaporation of 2480 mm. The evaporation is more than 70 times the precipitation, resulting in an extremely harsh environment. The oasis is home to rivers such as the Keriya River, Cele River, Pisgah River, and Nur River. The water in these rivers mainly comes from the melting of mountain snow and ice, with over 70% of the annual runoff occurring during the hot season from June to August. Agriculture is significant to the oasis, contributing over 30% to the GDP. However, due to uneven seasonal distribution of water resources, inadequate agricultural irrigation facilities, low water resource utilization efficiency, and unreasonable water resource development and utilization patterns, the oasis has severe water shortages and unsustainable use patterns.

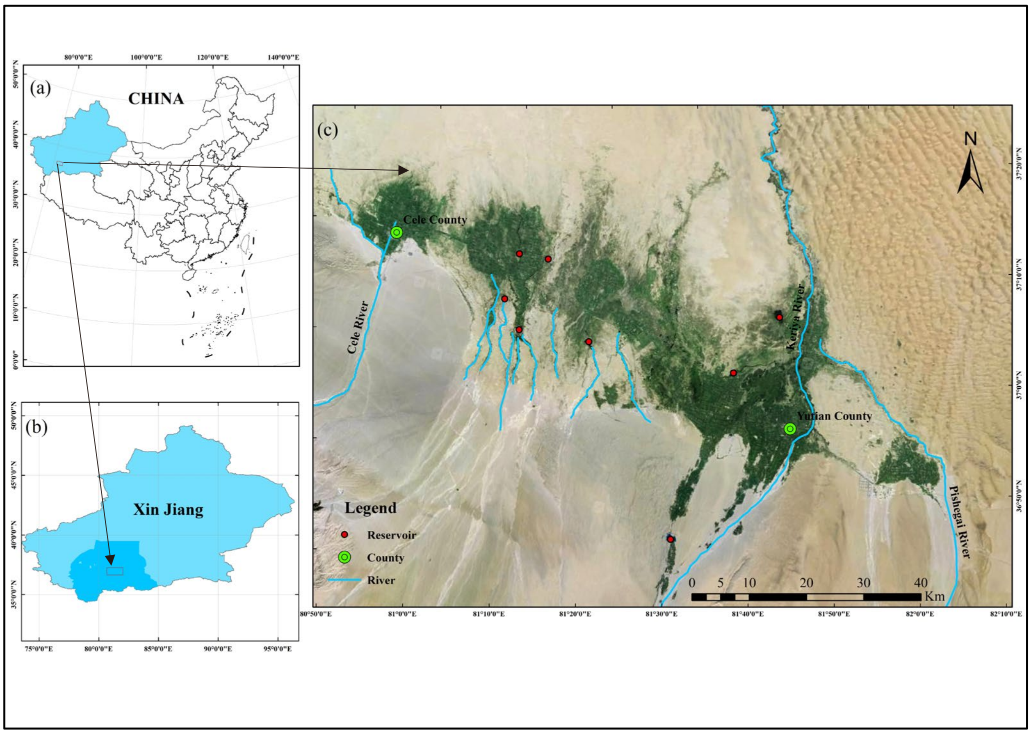

Figure 1. Location of study area. (**a**,**b**) http://datav.aliyun.com/portal/school/atlas/area_selector (accessed on 1 July 2022). (**c**) https://www.ovital.com/ (accessed on 1 July 2022).

2.2. Data Source

The data used in this study includes meteorological data, population data, economic data, and hydrological data. The meteorological data came from the historical meteorological data of two stations, Cele and Yutian. The population, economic, and hydrological data came from the "China County Statistical Yearbook", "Xinjiang Water Resources Bulletin", and "Hotan Statistical Yearbook" (2005–2020). The land use data came from Geo-Remote Sensing Ecology Website (gisrs.cn), and the land use data at three time points, 2005, 2010, and 2020, were downloaded.

2.3. Research Methods

2.3.1. Construction of Water-Resource-Carrying-Capacity Index System

In the process of water-resource-carrying-capacity evaluation, it is very important to establish a suitable evaluation index system, which needs to consider all relevant factors and their mutual influence. The selection of evaluation index system in this paper followed the principles of scientificalness, representativeness, and operability, and it referred to the evaluation index system of sustainable use of water resources. Based on the *DPSR* model, this study constructed an evaluation index system for the water resource carrying capacity of the Cele–Tarim Oasis. The *DPSR* model is based on the PSR model, which was proposed by Canadian statisticians David J. Rapport and Tony Friend in 1979 [27,28]. The *DPSR* model is based on causal relationships and comprehensively reflects the interaction and relationship between human beings and the natural environment [29–31]. In the *DPSR* model, *D* (*driving force*) represents the influence of external factors and internal dynamics on the water resource system, including population growth, economic development, climate change, and water resource management policies. The driving force reflects the dynamics and trends of water resource system development. *P* (*pressure*) represents the pressure and impacts faced by the water resource system, including water resource demand, water pollution, and water ecological destruction. Pressure reflects the pressures and challenges borne by the water resource system. *S* (*state*) represents the current situation and characteristics of the water resource system, including the availability of water resources, water quality, and water ecological health. *State* reflects the actual situation and status of the water resource system. *R* (*response*) represents the measures and response strategies taken in response to the pressures and challenges faced by the water resource system.

Based on existing research [32–34] and combined with the actual situation of Cele–Yutian Oasis, this article selected 16 indicators from 4 levels to evaluate the water resource carrying capacity of the oasis. The specific indicator system and weights were calculated using the entropy weight method, as shown in Table 1.

Table 1. Evaluation indicator system and weights of water resource carrying capacity in Cele–Yutian Oasis.

Target Layer	Ruler Layer	Indicator Layer	Code	Number	Unit	Indicator Properties	Weights
Water resource carrying capacity	*Driving*	Total population	×1	10^4	person	–	0.086
		Natural population growth rate	×2	/	‰	–	0.041
		Total GDP	×3	/	CNY	+	0.081
		Per capita GDP	×4	/	CNY	+	0.039
		Urbanization rate	×5	/	%	–	0.058
	Pressure	Water resources per capita	×6	/	m^3/person	+	0.051
		Domestic water quotas	×7	/	m^3/d	+	0.061
		Sewage Discharge	×8	10^4	m^3	–	0.051
	State	Total water supply	×9	10^8	m^3	+	0.114
		Water use in agriculture	×10	10^8	m^3	–	0.059
		Industrial water consumption	×11	10^8	m^3	–	0.026
		Ecological water use	×12	10^8	m^3	+	0.052
		Total groundwater	×13	10^8	m^3	+	0.064

Table 1. *Cont.*

Target Layer	Ruler Layer	Indicator Layer	Code	Number	Unit	Indicator Properties	Weights
Water resource carrying capacity	*Response*	Sewage treatment capacity	×14	10^4	m^3	+	0.115
		Length of water pipeline	×15	/	km	+	0.056
		Water supply capacity of built storage projects	×16	10^4	m^3	+	0.046

2.3.2. Entropy Weight Method

The entropy weight method calculates the information entropy of indicators considering the information and differences between indicators. The information entropy quantifies the contribution of indicators to decision making, making the allocation of weights more reflective of the importance and differences of indicators. The main calculation process is as follows [35,36]:

(1) Standardization of data

Firstly, a raw data matrix is created:

$$A = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} \\ x_{21} & x_{22} & \cdots & x_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} \end{bmatrix} \tag{1}$$

where x_{ij} represents the j-th indicator of the i-th year.

(2) Because of the different dimensions of the original evaluation data, this paper adopted the range normalization method to standardize the original evaluation data matrix.

For the positive indicators, bigger value represents better indicator:

$$X_{ij}(+) = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} \tag{2}$$

For the reverse indicators, smaller value represents better indicator:

$$X_{ij}(-) = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})} \tag{3}$$

The decision matrix is obtained after data standardization:

$$M = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1j} \\ X_{21} & X_{22} & \cdots & X_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ X_{i1} & X_{i2} & \cdots & X_{ij} \end{bmatrix} \tag{4}$$

(3) Calculate the proportion of the j-th indicator p_{ij}:

$$p_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} (\mathrm{i} = 1, 2, \ldots, \mathrm{m}) \tag{5}$$

(4) Calculate the entropy of the j-th indicator e_j:

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \tag{6}$$

(5) Calculate information entropy redundancy d_j:

$$d_j = 1 - e_j \tag{7}$$

(6) Determine the weights of indicators W_j:

$$W_j = \frac{1 - e_j}{\sum_{j=1}^{m} d_j} \tag{8}$$

where p_{ij} is the probability of the j-th factor in year i, e_j is the entropy value of the j-th indicator, and W_j is the normalized weight of the j-th indicator.

2.3.3. TOPSIS Model

The TOPSIS method, also known as the "Technique for Order Preference by Similarity to an Ideal Solution", is an evaluation method that determines the relative superiority or inferiority of multiple evaluation objects by their relative closeness to the ideal solution. It has a flexible and convenient calculation process that yields precise and rational evaluation outcomes, aligning well with the focus of this paper's research. The specific calculation steps of this method are as follows [37]:

$$Z_{ij} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1j} \\ Z_{21} & Z_{22} & \cdots & Z_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ Z_{i1} & Z_{i2} & \cdots & Z_{ij} \end{bmatrix} = \begin{bmatrix} W_1 X_{11} & W_2 X_{12} & \cdots & W_j X_{1j} \\ W_1 X_{21} & W_2 X_{22} & \cdots & W_j X_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ W_1 X_{i1} & W_2 X_{i2} & \cdots & W_j X_{ij} \end{bmatrix} \tag{9}$$

Determine the positive and negative ideal solutions. If the value of Z_{ij} has a larger value in the decision matrix Z_{ij}, it represents a better solution.

Positive indicator are as follows:

$$\begin{cases} Z^+ = \left(Z_1{}^+,\ Z_2{}^+, \ldots Z_j{}^+\right) = \left\{maxZ_{ij} \middle| \mathrm{j} = 1,2,\ldots 16\right\} \\ Z^- = \left(Z_1{}^-,\ Z_2{}^-, \ldots Z_j{}^-\right) = \left\{minZ_{ij} \middle| \mathrm{j} = 1,2,\ldots 16\right\} \end{cases} \tag{10}$$

Negative indicators are as follows:

$$\begin{cases} Z^+ = \left(Z_1{}^+,\ Z_2{}^+, \ldots Z_j{}^+\right) = \left\{minZ_{ij} \middle| \mathrm{j} = 1,2,\ldots 16\right\} \\ Z^- = \left(Z_1{}^-,\ Z_2{}^-, \ldots Z_j{}^-\right) = \left\{maxZ_{ij} \middle| \mathrm{j} = 1,2,\ldots 16\right\} \end{cases} \tag{11}$$

Calculate the distance to the positive ideal solution ($D_i{}^+$) and the distance to the negative ideal solution ($D_i{}^-$) for each indicator:

$$D_i{}^+ = \sqrt{\sum_{j=1}^{16} \left(Z_{ij} - Z_j{}^-\right)^2}\ i = 1,2,\ldots,n \tag{12}$$

$$D_i{}^- = \sqrt{\sum_{j=1}^{16} \left(Z_{ij} - Z_j{}^-\right)^2} i = 1,2,\ldots,n \tag{13}$$

Calculate the closeness C_i:

$$C_i = \frac{D_i{}^-}{D_i{}^- + D_i{}^+} \tag{14}$$

The closer C_i is to 1, the better the assessment is.

In this paper, the closeness of each year could be used to judge the level of water resource carrying capacity and thus the carrying capacity status. Based on the results of previous studies [11,38] combined with the socioeconomic and natural ecological conditions of the Celle–Yutian Oasis, the five-level evaluation classification criteria of water resource carrying capacity were established as follows.

2.3.4. Obstacle Degree Model

Using the obstacle degree model, we conducted an obstacle degree index evaluation for various indicators of water resource carrying capacity in the Cele–Yutian Oasis and identified the obstructive factors [39]. With respect to this, factor contribution (F_{ij}), deviation degree (I_{ij}), and obstacle degree (p_{ij}) were introduced, and the calculation formula is as follows:

$$F_{ij} = W_j \, I_j \tag{15}$$

$$I_{ij} = 1 - X_{ij} \tag{16}$$

$$p_{ij} = \frac{F_{ij} I_{ij}}{\sum_1^n (F_{ij} I_{ij})} \times 100\% \tag{17}$$

where W_j is the weight of each indicator and X_{ij} is the value of a single indicator after standardization.

2.3.5. Land Use Transfer Matrix

Compared to the well-established research on traditional land carrying capacity, the study of water resource carrying capacity is relatively new and continuously evolving in terms of theoretical methods. Despite this, significant progress has been made. However, there is still a need for further research on the evolving patterns of spatial and temporal transfer of regional water resource carrying capacity.

To address these knowledge gaps, it is imperative to consider the coupled relationship between water resource carrying capacity and land resource carrying capacity in oasis regions. By integrating the management and sustainable use of both water and land resources, a more holistic approach can be taken to ensure the preservation and sustainable supply of resources within these limited ecological regions.

Oasis regions are characterized by the close interconnection and interaction between their water resources and land resources. By recognizing and exploring the interdependence of these factors, it becomes possible to implement better strategies for the management and protection of oasis ecosystems. This integrated approach helps to achieve sustainable utilization of water and land resources, ensuring their long-term availability.

(1) Markov model

The mutual conversion of land use types is mainly achieved through the use of land use transfer matrix [40]. The land use transfer matrix is an application of the Markov model in analyzing land use changes. It provides a comprehensive depiction of the direction and quantity of land use type transitions within the region. This method finds extensive application in land use change research and effectively illustrates the spatiotemporal evolution of land use patterns [41,42].

$$S_{ij} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \vdots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \tag{18}$$

where S_{ij} is the $n \times n$ matrix; S is the area; n is the number of land types; and i and j are the land types at the beginning and end of the study period, respectively.

(2) Land use dynamic index

The annual change rate of land use types can be obtained by calculating the dynamic index of a single land use type using this expression [43]:

$$K = \frac{U_b - U_a}{U_b} \frac{1}{T} \times 100\% \tag{19}$$

where K is the dynamic index of land use type movement; U_a and U_b are the area of a land type at the beginning and at the end of the study period, respectively; T is the length of the study; and when the time period of T is set to be years, K is the annual rate of change of a land use type during the study period.

3. Results and Discussion

3.1. Evaluation of Water Resource Carrying Capacity in Cele–Yutian Oasis

3.1.1. Time-Variation Model for Water Resource Carrying Capacity in the Cele–Yutian Oasis

Based on the comprehensive evaluation findings of the water resource carrying capacity in the Cele–Yutian Oasis spanning from 2005 to 2020 (refer to Figure 2 and Table 2), it is evident that, despite a general upward trajectory, the region still resides in a critical carrying state. The overall situation regarding the water resource carrying capacity remains far from optimistic. This is consistent with the research results of Wei [44] and Zhao et al. [45]. The main reason for this is that the Cele–Yutian Oasis has a fragile ecological environment, an uneven spatial and temporal distribution of water resources, and limited resources [46]. Amidst the rapid national economic growth, a local infrastructure lag and the overexploitation of water resources caused a sharp drop in the water resource carrying capacity from 2005 to 2007. Since 2010, intensive national support for Southern Xinjiang's economic and social development has led to enhanced infrastructure, industrial upgrades, resource recycling, and positive shifts in the water resource carrying capacity. Nonetheless, 2018 marked a nadir due to accelerated urbanization. A significant portion of arable land was transformed into construction zones, diminishing the agricultural land, while desert grasslands were converted to agricultural land, substantially heightening the water resource demand in agriculture. By observing the changes in the trend of the positive ideal solution and negative ideal solution, we found that the positive ideal solution gradually decreased from 0.24 in 2005 to 0.18 in 2020, indicating that the water resource carrying capacity is gradually approaching the positive ideal solution. On the contrary, the value of the negative ideal solution first decreased and then increased, reaching a minimum of 0.14 in 2008, and it has been increasing since then, indicating that the water resource carrying capacity is gradually moving away from the negative ideal solution. Overall, the water resource carrying capacity of the Cele–Yutian Oasis is trending positively, yet it remains in a critical state with a relatively limited water resource capacity. Therefore, the water-resource-carrying-capacity situation in this oasis is still severe, and further measures need to be taken to improve the water resource utilization efficiency and to protect water resources.

3.1.2. Evaluation of the Water-Resource-Carrying-Capacity Subsystem in the Cele–Yutian Oasis

(1) *Drive force subsystem*

According to Figure 3, the value of the *drive force subsystem* shows a steady increase from 0.17 in 2005 to 0.92 in 2020, and the composition of the *drive force subsystem* consists of demographic and economic indicators, with a significant growth in the total population and per capita GDP. The acceleration of the urbanization process, the significant contribution of agriculture to the oasis' GDP, and the rapid growth of the secondary industry all indicate an increasing influence of the *drive force subsystem* on the water resource carrying capacity.

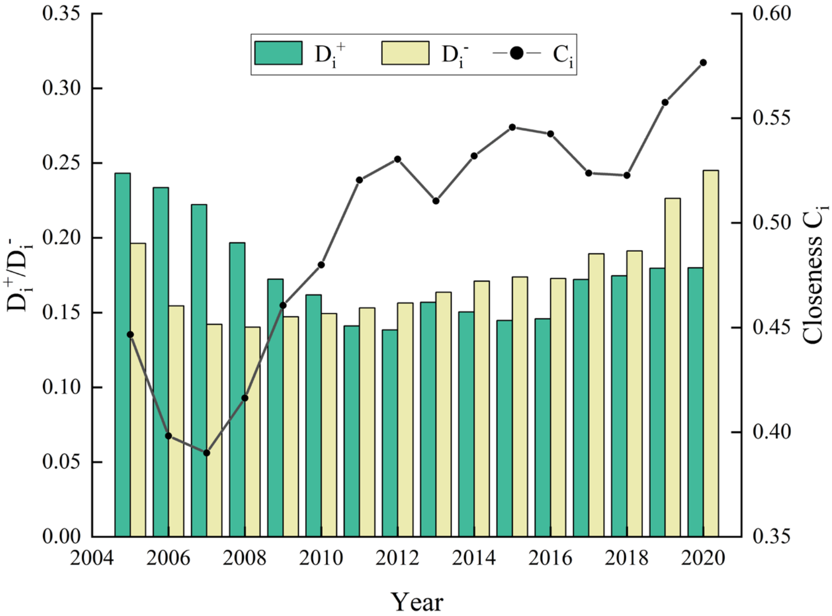

Figure 2. Comprehensive evaluation of water resource carrying capacity in Cele–Yutian Oasis from 2005 to 2020.

Table 2. Classification standards for water resource carrying capacity in Cele–Yutian Oasis.

Level	**V**	**IV**	**III**	**II**	**I**
Level Description	Severe overload	Mild overload	Critical	Good	Excellent
C_i	(0–0.2)	(0.2–0.4)	(0.4–0.6)	(0.6–0.8)	(0.8–1.0)

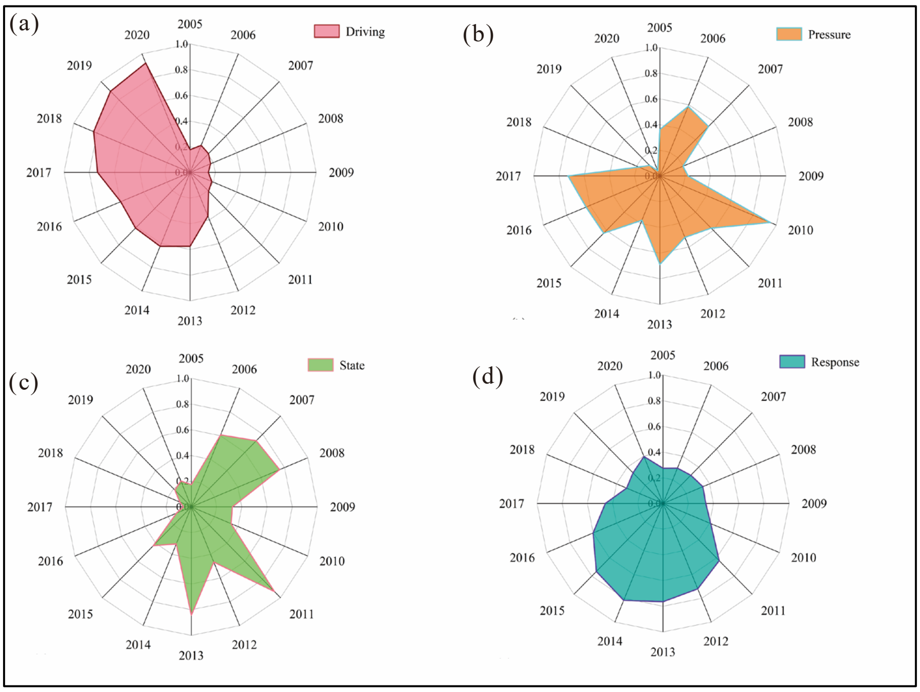

Figure 3. Changes in water-resource-carrying-capacity subsystem from 2005 to 2020. (**a**) *Driving subsystem* (**b**) *Pressure subsystem* (**c**) *State subsystem* (**d**) *Response subsystem*.

(2) *Pressure subsystem*

The *pressure subsystem* shows a strong fluctuation trend, reaching its peak value of 0.94 in 2010. This is mainly due to a 25% decrease in the water volume of the oasis' river channels compared to previous years. Within the *pressure subsystem*, the reduction in the total water resource quantity resulted in a corresponding decline in per capita water resources. Furthermore, as residents' living standards have improved, the volume of domestic sewage discharge has also increased, significantly impacting the *pressure subsystem* of the water resource carrying capacity in the Cele–Yutian Oasis.

(3) *State subsystem*

During the period of 2005 to 2020, the calculated values of the *state subsystem* fluctuated, with the minimum value occurring in 2018 at 0.09, while the maximum value occurred in 2011. Since 2011, climatic changes have increased the water inflow of the river, leading to a significant increase in the ecological water consumption and total water supply, thereby reflecting an improved condition within the *state subsystem*. Overall, the *state subsystem* shows significant fluctuations, which are closely related to the fragile ecological environment of the oasis.

(4) *Response subsystem*

The *response subsystem* demonstrates stability with minimal fluctuations in its impact on the water resource carrying capacity. As the oasis' economy and society rapidly develop, improvements in sewage treatment, the water supply network, and water storage facilities address water scarcity from extreme weather, ensuring an overall improved water resource carrying capacity. In conclusion, compared to the evaluation index system established by the *DPSR* framework and Liu et al. [15], Zhang et al. [47] established an evaluation index system for the water resource carrying capacity that encompasses water resources, society, the economy, and the ecological environment. This comprehensive system takes into account multiple factors in water resource management, including human activity drivers, water resource pressures, water body conditions, and government and societal response measures. This enables the model to provide a comprehensive analysis of water resource management. In addition, the *DPSR* model establishes a logical and clear framework that can help researchers and managers understand and analyze the key factors and relationships in water resource systems. Through a model analysis, it is possible to better understand the impact of different policies and management interventions on water resource systems and to promote sustainable water resource planning and management.

3.2. Determination of the Obstacles to the Carrying Capacity of Water Resources in the Cele–Yutian Oasis

3.2.1. Index Obstacle Degree Analysis

After using the obstacle degree model to calculate the obstacle factors of the water resource carrying capacity of the Cele–Yutian Oasis, ranking the calculation results, and screening the top five obstacle factors, the results are shown in Table 3.

According to the index obstacle degree calculations, between 2005 and 2014, the primary factors hindering the water carrying capacity of the Cele–Yutian Oasis were the sewage treatment volume ×14, per capita GDP ×3, and total water supply ×9. These factors exhibited obstacle degrees exceeding 12%. The main reason for this is that the economic development of the Cele–Yutian Oasis is relatively slow, and although limited water resources are used extensively for agricultural irrigation, the utilization rate of agricultural water resources is low. In addition, the lack of effective domestic sewage and industrial wastewater purification facilities has led to the direct discharge of some sewage into the ecological environment, making it the main factor that affects water security. From 2015 to 2020, the main obstacle factors changed to the total population ×1 and industrial water supply ×11. This is mainly due to the accelerated urbanization process and the transformation of the agricultural sector. The rise in living standards among the population has resulted in a strained supply of water resources. Additionally, the continued growth of the industry has led to a significant consumption of agricultural water resources, with the industrial water supply emerging as the primary obstacle factor.

Table 3. Top five obstacles in the Celle–Yutian Oasis from 2005 to 2020.

Annum	Ranking of Indicators									
	1	Obstacle Degree	2	Obstacle Degree	3	Obstacle Degree	4	Obstacle Degree	5	Obstacle Degree
2005	x 14	19.00%	×3	13.46%	×9	12.78%	×13	10.70%	×7	9.41%
2006	×14	21.01%	×3	13.46%	×9	12.40%	×7	11.25%	×15	9.62%
2007	×14	21.43%	×3	14.73%	×9	10.79%	×7	10.28%	×15	9.45%
2008	×14	19.73%	×9	13.75%	×3	13.10%	×13	11.09%	×7	9.06%
2009	×14	19.73%	×9	12.23%	×3	11.68%	×13	8.25%	×7	7.98%
2010	×14	17.35%	×9	14.24%	×3	11.38%	×13	9.42%	×7	7.73%
2011	×14	24.20%	×3	15.03%	×9	11.20%	×12	10.69%	×1	8.93%
2012	×14	18.77%	×9	16.23%	×9	16.23%	×5	8.48%	×13	8.31%
2013	×14	15.43%	×5	14.31%	×3	11.98%	×1	11.85%	×8	8.77%
2014	×14	13.80%	×1	12.3%	×9	10.16%	×13	9.95%	×5	9.76%
2015	×1	15.53%	×5	11.29%	×9	11.19%	×12	9.24%	×14	8.08%
2016	×1	14.93%	×9	10.52%	×11	10.37%	×12	10.33%	×8	8.06%
2017	×1	18.00%	×11	12.92%	×12	9.70%	×8	7.75%	×16	7.0%
2018	×1	16.78%	×11	10.11%	×13	10.05%	×8	9.13%	×12	8.64%
2019	×1	17.57%	×13	11.24%	×6	10.78%	×11	10.49%	×8	9.53%
2020	×1	19.83%	×11	13.09%	×8	11.90%	×13	11.65%	×6	10.25%

3.2.2. Obstacle Analysis of Subsystems

The analysis of the obstacle degrees within the subsystems reveals varying trends in the challenges to the water resource carrying capacity of the Cele–Yutian Oasis across different years, as shown in Table 4. Before 2011, the *state subsystem* was the main obstacle to the water resource carrying capacity, whereas since 2011, the *drive force subsystem* has become the main obstacle. This shift primarily stems from the implementation of poverty alleviation policies in the developed coastal areas since 2011. This has triggered the expansion of industrial enterprises within the oasis, resulting in heightened industrial water consumption and significant water resource depletion. Simultaneously, advancements in healthcare, population growth, rapid urbanization, and the influx of rural labor into towns have contributed to a continuous rise in the total water usage of the residents.

Table 4. Obstacle degree of the Cele–Yutian Oasis subsystem from 2005 to 2020.

Annum	*Drive Force*	*Pressure*	*State*	*Response*
2005	0.198	0.234	0.327	0.194
2006	0.235	0.225	0.336	0.189
2007	0.254	0.248	0.347	0.203
2008	0.252	0.288	0.373	0.247
2009	0.259	0.276	0.348	0.241
2010	0.259	0.276	0.342	0.242
2011	0.376	0.293	0.270	0.161
2012	0.308	0.282	0.273	0.212
2013	0.433	0.315	0.304	0.271
2014	0.358	0.308	0.292	0.250
2015	0.416	0.300	0.274	0.244
2016	0.382	0.249	0.205	0.213
2017	0.440	0.268	0.216	0.229
2018	0.366	0.283	0.218	0.264
2019	0.346	0.279	0.204	0.288
2020	0.386	0.291	0.197	0.314

3.3. Analysis of Land Use Transfer Mode

Based on the land use distribution maps obtained from remote sensing interpretation in 2005, 2010, and 2020 (Figure 4) as well as the proportion of land use types (Table 5) and the land use transfer matrix (Table 6), the main land use types are grassland, cropland, woodland, water bodies, construction land (urban and rural residential areas), and unused land. Excluding unused land, the Cele–Yutian Oasis consists mainly of grassland, cropland, and woodland. Between 2005 and 2020, both grassland and woodland exhibited a declining trend in their area. The grassland area saw the most significant decrease, plummeting from 35.68% in 2005 to 20.50% in 2020, marking a substantial decline of 15.18%. In comparison, the woodland area decreased by more than half, dropping from 3.19% in 2005 to 1.43% in 2020. Conversely, the cropland area experienced an upward trajectory, increasing from 8.31% in 2005 to 10.39% in 2020. Notably, a substantial portion of grassland has been converted into cropland, aligning with the findings of the research of Gao et al. [48], especially in areas surrounding urban areas. This is mainly due to the increase in population-accelerated urbanization, making flat grassland more suited for construction. At the same time, grassland and woodland far from urban areas have been used extensively for cultivation due to easier access to water resources, expanding along rivers and reservoirs. Furthermore, in the middle reaches of the Keriya River, a substantial portion of grassland on the eastern bank has undergone a transformation into desert and saline–alkali land. This is mainly due to the population growth and the unreasonable development and utilization of water resources. This has led to a decrease in ecological flow in the river, an increase in groundwater depth in the middle and lower reaches, and a reduction in vegetation.

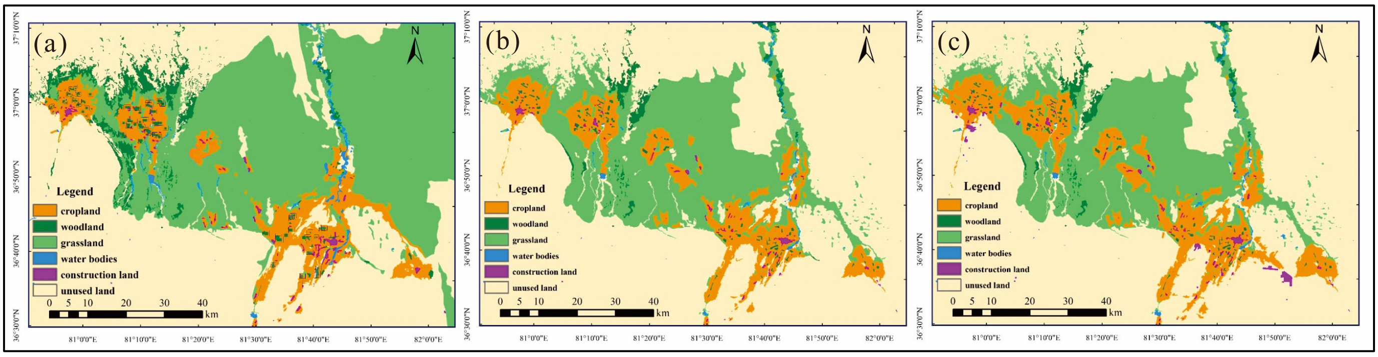

Figure 4. Land use types in 2005, 2010, and 2020. (**a**) Land use types in 2005 (**b**) Land use types in 2010 (**c**) Land use types in 2020.

Table 5. Area and share of each land use type in the Cele–Yutian Oasis in 2005, 2010, and 2020.

Land Use Type	2005		2010		2020	
	Area (km^2)	**Percentage (%)**	**Area (km^2)**	**Percentage (%)**	**Area (km^2)**	**Percentage (%)**
grassland	2947.42	35.70%	1789.68	21.67%	1693.22	20.51%
cropland	686.49	8.31%	715.28	8.66%	857.95	10.39%
woodland	262.93	3.18%	118.98	1.44%	118.44	1.43%
water bodies	52.50	0.64%	19.77	0.24%	21.27	0.26%
construction land	23.74	0.29%	25.10	0.30%	45.46	0.55%
unused land	4283.92	51.88%	5588.19	67.68%	5520.66	66.86%

Table 6. Land use transfer matrix of Cele County in Hetian Oasis from 2005 to 2020 (km^2).

Land Use Types 2005	Land Use Types 2020					
	Grassland	**Cropland**	**Woodland**	**Water Bodies**	**Construction Land**	**Unused Land**
grassland	1350.24	154.27	3.25	10.82	1.76	1426.14
cropland	75.69	530.71	9.52	28.33	3.24	38.81
woodland	0.77	46.92	14.39	5.49	0.08	0.47
water bodies	151.09	20.37	0.16	65.23	0.39	25.69
construction land	13.56	3.83	0.00	2.93	13.70	18.48
unused land	101.87	101.81	18.14	5.61	2.03	4011.39

Over the past 15 years (Table 7), grassland, forests, water bodies, and unused land have all seen negative changes, indicating various conversions to other land use types. Water bodies, showing the most significant dynamics at −10.16%, are particularly susceptible to transformation, which is linked to the fragile oasis ecosystem. Conversely, cultivated and construction land areas have increased, mainly due to the cropland conversion of grassland and forest land. The growth in construction land is concentrated around towns, taking advantage of the flat terrain of cultivated land, especially during urbanization. In summary, the land use patterns reflect a decrease in grassland, forests, and water bodies along with an increase in cultivated and construction land areas. These shifts primarily resulted from population growth, rapid urbanization, and unsustainable water resource utilization.

Table 7. Land use dynamic index in Cele–Yutian Oasis from 2005 to 2020.

2005–2020	Land Use Types					
	Grassland	**Cropland**	**Woodland**	**Water Bodies**	**Construction Land**	**Unused Land**
Area of change (km^2)	−1254.2	171.46	−144.49	−31.23	21.72	1236.74
Dynamic index (%)	−4.94%	1.33%	−8.13%	−9.79%	3.19%	1.49%

3.4. Sustainability Analysis

The evaluation results of the TOPSIS model and Markov model of the land use type transfer show that the overall level of the water resource carrying capacity of the Cele–Yutian Oasis is level III (a critical state); the worst water resource carrying capacity appears in 2007, with a close degree value of 0.39, and the best water resource carrying capacity appears in 2020. The closeness value is 0.57. On the whole, the carrying capacity of water resources shows a benign development trend, but the situation of the water resource carrying capacity in the future is still severe. As can be seen from the weight results of Table 1, the sewage treatment capacity ×14, total water supply ×9, total population ×1, and total GDP ×3 have a great impact on the water resource carrying capacity, which are 0.115, 0.114, 0.086, and 0.081, respectively. This is precisely in line with the results of the index barrier calculation (the sewage treatment capacity ×14, gross domestic product per capita ×3, and total water supply ×9); the three barrier factors have a barrier of more than 12%. According to the analysis results of the land use transfer matrix from 2005 to 2020, grassland, forests, and water bodies are rapidly shrinking, with a dynamic attitude of −4.93%, −8.19%, and −10.16%, respectively, and the reduced part is basically completely used as cultivated land and building land. This is in line with the obstacles to the carrying capacity of water resources. In recent years, the acceleration of urbanization, industrialization, and the rapid growth in the population have brought serious challenges to the sustainable development of the oasis. Due to the fragile ecological environment of the oasis, in future development planning, the government of Cele and Yutian should take a series of countermeasures to promote the sustainable development of the oasis:

(1) Establish a scientific and rational water resource management system, formulate and implement policies for the rational allocation of water resources, and strengthen water resource monitoring and forecasting.

(2) Vigorously promote water-saving equipment, plan population distribution reasonably, enhance the awareness of water conservation, introduce advanced water-saving irrigation technology, reduce the total consumption of water resources, and thereby improve the efficiency of water resource utilization.
(3) Strengthen environment-friendly construction, protect and restore water sources and wetland systems, strengthen the construction of sand control projects, and protect the surrounding ecological areas and residential areas from harm.
(4) Give full play to the role of water conservation projects; regulate the uneven distribution of water resources through the construction of reservoirs, various canal systems, and other engineering projects; and by prioritizing drinking water and ecological water use, allocate industrial and agricultural water use to achieve the rational allocation of water resources.
(5) Strengthen the prevention and control measures for water pollution; control the discharge of industrial wastewater, domestic sewage, pesticides, and fertilizers; increase the intensity of sewage treatment; and improve the reuse rate of wastewater.

Coupled with the dynamic change in the water resource carrying capacity and land interest type, it is first necessary to design a scientific and reasonable research program; select indicators to follow the principles of science, representativeness, operability, and regionalism; establish an appropriate evaluation index system of the water resource carrying capacity; and then combine the Markov model to assist in evaluating regional sustainable development. This evaluation model is especially suitable for the long-term analysis of desert oases, river basins, etc. This evaluation research method will open up new ideas and methods for the evaluation of the regional water resource carrying capacity and sustainable development analysis, and it is of great significance for promoting the efficient and sustainable utilization of water resources and land and for coordinating regional development.

4. Conclusions

This study selected the Cele–Yutian Oasis, located in the arid desert area, as the research area. By introducing the *DPSR* model, TOPSIS model, and obstacle degree model, the water resource carrying capacity of the oasis from 2005 to 2020 was evaluated, and the main obstacle factors were calculated. At the same time, the Markov model of the land use type transfer matrix was used to compare and analyze the distribution of and changes in the surface coverage types in the oasis. The following conclusions were drawn from the comprehensive research results:

(1) From 2005 to 2020, the water resource carrying capacity of the Cele–Yutian Oasis generally improved. The lowest point occurred in 2007, with a proximity value of 0.39, categorizing it as level IV (a mild overload). By 2020, the highest proximity value reached 0.58, but the carrying capacity still remained at level III (critical), indicating a persistently severe water resource situation.
(2) The analysis results of the carrying capacity of the subsystems show that, from 2005 to 2020, the influence of the *drive force subsystem* decreased, the influence of the *pressure subsystem* and the *state subsystem* fluctuated, and the influence of the *response subsystem* increased and then decreased, reaching a maximum value of 0.98 in 2014.
(3) The results of the analysis of the obstacle degree subsystem show that the *drive force subsystem* gradually replaced the *state subsystem* as the main obstacle subsystem affecting the Cele–Yutian Oasis between 2005 and 2020; the main obstacle factors affecting the water resource carrying capacity included the amount of sewage treatment, the gross domestic product per capita, and the total water supply.
(4) During the period of 2005 to 2020, the results of the land use transfer matrix show that the grassland area decreased by 15.18% and that the forest area decreased by half. The dynamics of grassland, forests, and water bodies are all negative, indicating that these three types of land have been transferred to other types of land in different ways, with the largest change occurring in water bodies, with a dynamic value of −10.16%.

This study comprehensively considers factors such as water resources, society, the economy, and ecology and analyzes the changing patterns of the water resource carrying capacity and land use types. To further improve the water resource carrying capacity, it is advisable for local governments to strongly embrace the key concept of "determining land, people, and production based on water." This requires the implementation of strategies aimed at optimizing the allocation of water resources, actively promoting the development of water-saving industries, and ultimately achieving the efficient utilization of water resources.

However, this study only focuses on the current annual water resource carrying capacity and dynamic attitude of the land use change in the study area. If the water resource carrying capacity and the evolution trend of the land use type can be simulated and predicted in the future, it will be beneficial to the optimal allocation and sustainable development of regional water resources, which will be the focus of our follow-up research.

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