Variable fuzzy evaluation model for water resources carrying capacity in the Tarim River Basin, China

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ABSTRACT

As one of the regions of China with the most serious water shortages, the shortage of water resources and ecological deterioration of the Tarim River Basin have increasingly attracted attention, and management and sustainable utilization of water resources rely mostly on the understanding of their carrying capacity. In the present study, the water resources carrying capacity of the Tarim River Basin was evaluated using a multi-dimensional perspective of natural, social and economic factors based on a variable fuzzy evaluation model for the 2018 hydro-climatic conditions. Evaluation model results rated Aksu, Kizilsu, Kashi and Hotan districts as grade 2, where current use and overexploitation of water resources have reached a relatively high level combined with a limited water resources carrying capacity. Bazhou district, where the water resources carrying capacity is relatively higher, was evaluated and rated as grade 1 by the model. It is urgent to put forward some strategies in order to protect and improve the water resources carrying capacity in the Tarim River Basin, which include promoting more efficient utilization of water conservation schemes, strengthening the long-term investment in environmental protection, improving the ratio of industrial wastewater treatment and reducing the industrial water quota. The results of the present study are aimed to be a beneficial guide in the planning and management of the Tarim River Basin water resources and possibly for other similar river basins.

Key words: analytic hierarchy process, Tarim River Basin, variable fuzzy evaluation model, water resources carrying capacity

HIGHLIGHTS

• It is imperative to evaluate the water resources carrying capacity of Tarim River Basin.
• Comparing other methods, a variable fuzzy evaluation method can evaluate WRCC more regionally.
• The method improved the reliability of evaluation results.
• The results of this study are expected to be beneficial to the planning and management of water resources in the Tarim River Basin.

1. INTRODUCTION

Water is indispensable and a crucial resource for economically sustainable development and the ecological construction of the environment (Liu et al. 2016; Bao & Zou 2018). With the rapid development of modern society and human civilization, the contradiction between the rapid development of the economy and sustainable utilization of water resources has become increasingly prominent (Giri et al. 2016; Cheng et al. 2018).

Data from the United Nations FAO indicates that 1.8 billion people will live in countries or regions with absolute water scarcity and two-thirds of the world population could be in conditions of water stress by 2025 (Men & Liu 2018). According to the China Water Resources website, China is desperately short of freshwater, with a volume of per capita freshwater only one-quarter of the world average (Sun et al. 2014). Among all the 669 cities in China, 440 cities have a lack of water, and 110 have severe water shortages (Sun et al. 2017), especially in the arid and semi-arid regions where water resources shortage is more intense. Taking the Tarim River Basin as an example, the stream flow at a 321 km section of the river downstream was completely cut off in 1970, and Luob Nor and Taitema Nor, located at the tail end of the Tarim River, also dried up in 1972.
due to the intensified exploitation of water and land resources. Furthermore, the groundwater levels in most of the downstream regions decreased by 8–12 m (Xu et al. 2008). Acreage average of land in the Tarim River Basin decreased sharply due to the expansion of the land used for urban and rural construction projects and unregulated land cultivation. Over the period of 1995–2008, all kinds of available acreage of land reduced by 9.57%, desertification was aggravated and land resources were impaired severely (Zhang et al. 2010). These environmental problems led to the degradation of *Populus euphratica* forests over large areas, a heavy reduction in local biodiversity, and the impairment of the structure and functions of the ecosystem. The increasingly deteriorating environment and shortage of water resources in the Tarim River Basin have attracted great attention both locally and internationally. Previous studies on the Tarim River Basin mainly focused on variations in water resources (Chen & Xu 2004), the relationship between groundwater and plant species diversity, climate change and changes of water resource and land cover (Sun et al. 2012) and the utilization and exploitation of water resources (Mao 2001). Some researchers also investigated the relationship between regional economic development and its ecological consequences in terms of the exploitation of the available water resources (Yang & Liu 2014). However, there have been few attempts to study and evaluate the carrying capacity of water resources in the Tarim River Basin. To improve water resources carrying capacity is imperative for the sustainable development of ecology and environment in the Tarim River Basin. Therefore, it is necessary and significant to evaluate and diagnose the regional water resources carrying capacity for guiding the balance between rational utilization of water resources and economic development in the Tarim River Basin.

The concept of water resources carrying capacity (WRCC) was first proposed by a Project Team named Xinjiang Water Resources Soft Science in 1989 (Ren et al. 2016). Regarding the concept of WRCC, some scholars thought that WRCC is the maximum threshold of water resources to sustain human activities (Harris & Kennedy 1999; Li et al. 2000). Others considered WRCC to be water resources that are needed to maintain the coordinated development of the social–economic system (Hunter 1998; Ofoezie 2002). WRCC is also defined as the maximum sustainable socio-economic scale based on available water resources and the maintenance of a healthy water environment (Song et al. 2011). In the present study, based on previous research (Qi et al. 2021; Qiao et al. 2021), the WRCC is defined as the maximum amount of water resources that can be used for socio-economic development while being maintained as defined by the healthy social and environmental conditions at the historical stage.

Internationally, breakthroughs have been made in previous research projects that address WRCC. The URS Corporation undertook a study on WRCC in the Florida Keys valley (Clarke 2002) and Harris & Kennedy (1999) focused on WRCC in the areas of agricultural production. Research by other scholars such as Falkenmark (1989) has also dealt with the limitations of WRCC. Studies focusing exclusively on WRCC have been performed predominantly in China. Preliminary studies began in the areas where drought is common. A quantitative study on WRCC along the Urumqi valley was performed (Shi & Qu 1992; Liu et al. 2015). Currently, WRCC studies mainly focus on developing and utilizing water resources, evaluations of WRCC at social and economic scales (Meng et al. 2009), coordinated development of resources, environment, society, and economy (Cheng et al. 2018), evaluating the temporal-scale variation tendency of water environment carrying capacity (Zhang et al. 2019a), allocation of water resources (Meng et al. 2018), water-cycle status (Zhang et al. 2019b) and so on. In addition, methods for evaluating WRCC have been proposed and improved, which mainly include the fuzzy comprehensive evaluation method (Prato 2009; Dang & Liu 2012), system dynamics (Yang et al. 2015), multi-objective decision-making and analysis (Xu & Chen 2000), large-scale system theory (Liu & Borthwick 2011), and the optimization method (Yang et al. 2019). However, the biggest challenge for WRCC research at present is to formulate a method of quantitative assessment of the concept, which can then be used to develop reliable guidelines for water resources management. Comparing other methods, the advantages of the variable fuzzy evaluation method are as follows: (1) reasonable identification of the relative membership degree and relative membership function between sample index and standard interval of each level index; (2) proper determination of the assessment level of each sample; (3) improvement of the reliability and validity of evaluated results through varying model parameters (Chen 2005).

Therefore, the present paper aims to evaluate the WRCC of the Tarim River Basin using a variable fuzzy evaluation model for the 2018 hydroclimatic conditions, where water resources carrying capacity had reached or exceeded classification 2, which could constrain socio-economic development. The study could provide a scientific reference for the rational and efficient utilization and management of water resources in the Tarim River Basin, and also have potential for application in other areas and scales for WRCC and comparison over time.
2. MATERIALS AND METHODOLOGY

2.1. Study area
Tarim River Basin is the longest inland river in China, with the main stream 1,321 km in length (Xu et al. 2013). It has extreme drought and poor formation condition of water resources with an average annual precipitation of $1,055 \times 10^8$ m$^3$, a gross amount of water resource of $446.1 \times 10^8$ m$^3$ and an average annual natural surface runoff volume of $398.3 \times 10^8$ m$^3$. In the past, the Tarim River comprised nine water systems, including the main stream of the Tarim River, the Takla-magan Desert, and the eastern Gobi (Zhang et al. 2015). With historic events and the disturbance of human activities, especially the exploitation of water resources, most water systems have lost their relationship to the main stream. Now there are only three water systems maintaining hydraulic relationships with the main stream: the Hotan River, Yarkant River, and Aksu River together with Kaidu-Konqi River are called the four ‘headstreams’. Kaidu-Konqi River delivers water to the lower reaches of the main stream through the Kuta Main Canal (Zhang et al. 2010). Currently, there are five districts in the Tarim River Basin including the Aksu, Kashi, Kizilsu, Hotan, and Bazhou regions (Figure 1). In the present paper, the carrying capacity of the water resources in the Tarim River Basin was evaluated with a variable fuzzy evaluation model to provide decision makers with a basis upon which to draw up policies on the sustainable exploitation and utilization of these water resources.

2.2. Data collection
There are 95 basic data for ten indicators in this paper: ecological water use ratio, precipitation, irrigation ratio, utilization degree of water resources, water consumption per ten thousand GDP, water supply modulus, water demand modulus, per capita domestic water, water shortage rate, and per capita practical water supply from the Tarim River Basin in 2018. The socio-economic data are all obtained from the Statistical Yearbooks of Xinjiang province. The water resources and ecological environment data are obtained from the Water Resources Bulletin of China (MWRC 2018). The rest of the data are from the Thematic Database for Human–Earth System.

2.3. Methodology
2.3.1. Definition of variable fuzzy aggregation
Definition 1.1: Assume a fuzzy concept $A \equiv \mu_A (u)$ of domain $U$ to be at any point of the relative subjection function axis, ($u \in U$). Then $\mu_A (u)$ represents the relative subjection degree of $u$ to $A \equiv \mu_A (u)$, which shows the attractiveness, and $\mu_A (u)$ is the relative

![Figure 1](image_url)
subjection degree of $u$ to $A^\xi$, which shows the repellency (Chen 2005). Let

$$D_A(u) = \mu_A(u) - \mu_{A^\xi}(u)$$  \hspace{1cm} (1)$$

in which $D_A(u)$ is the relative difference degree of $u$ to $A$.

$$\text{Mapping} \begin{cases} D_A: D \rightarrow [-1, 1] \\ u \rightarrow D_A(u) \in [-1, 1] \end{cases}$$  \hspace{1cm} (2)$$

Equation (2) shows the relative difference function of $U$ to $A$.

According to

$$\mu_A(u) + \mu_{A^\xi}(u) = 1$$  \hspace{1cm} (3)$$

then

$$D_A(u) = 2\mu_A(u) - 1$$  \hspace{1cm} (4)$$

or

$$\mu_A(u) = (1 + D_A(u))/2$$  \hspace{1cm} (5)$$

Definition 1.2: Let

$$\bar{V} = \{ (u, D) | u \in U, D_A(u) = \mu_A(u) - \mu_{A^\xi}(u), D \in [-1, 1] \}$$  \hspace{1cm} (6)$$

$$A_+ = \{ u | u \in U, 0 < D_A(u) \leq 1 \}$$  \hspace{1cm} (7)$$

$$A_- = \{ u | u \in U, -1 \leq D_A(u) < 0 \}$$  \hspace{1cm} (8)$$

$$A_0 = \{ u | u \in U, D_A(u) = 0 \}$$  \hspace{1cm} (9)$$

where $\bar{V}$ is the fuzzy variable aggregation; $A_+$, $A_-$, and $A_0$ represent the attraction domain, the repulsion domain, and the gradual change border, respectively.

Definition 1.3: Assume $C$ to be the variable gene aggregation of $\bar{V}$, which can be described with the following formula:

$$C = \{ C_A, C_B, C_C \}$$  \hspace{1cm} (10)$$

where $C_A$ is the variable model aggregation, $C_B$ is the variable model parameter aggregation, and $C_C$ is the variable aggregation of genes other than the model and parameter. Suppose

$$A^- = C(A_+) = \{ u | u \in U, 0 < D_A(u) \leq 1, -1 \leq D_A(C(u)) < 0 \}$$  \hspace{1cm} (11)$$

$$A^+ = C(A_-) = \{ u | u \in U, -1 \leq D_A(u) < 0, 0 \leq D_A(C(u)) \leq 1 \}$$  \hspace{1cm} (12)$$
\( V \) is the variable domain of fuzzy variable aggregation concerning variable gene aggregation. Suppose

\[
A^{(+)} = C(A^{(+)}_V) = \left\{ u | u \in U, \ 0 < D_A(u) \leq 1, \ 0 < D_A(C(u)) \leq 1 \right\}
\]

\[ (13) \]

\[
A^{(-)} = C(A^{(-)}_V) = \left\{ u | u \in U, \ -1 \leq D_A(u) < 0, \ -1 \leq D_A(C(u)) < 0 \right\}
\]

where \( A^{(+)} \) and \( A^{(-)} \) are the variable domains of variable fuzzy sets \( V \) about the alterable factor aggregate \( C \).

### 2.3.2. Relative difference function

When \( X_0 = [a, b] \), the attraction domain of fuzzy variable aggregation is on the real axis, and \( 0 < D_A(u) \leq 1 \). \( X = [c, d] \) is the interval from up to down, including \( X_0 \) \((X_0 \subset X)\).

According to the definition of variable fuzzy aggregation \( V \), it is obvious that \([c, d]\) and \([a, b]\) are both regions of rejection, excluding the domain of \( V \), namely \(-1 \leq D_A(u) < 0\). Suppose \( M \) is the point value of \( D_A(u) = 1 \) in the attraction domain \([a, b]\), then \( M \) is not always the midpoint value of region \([a, b]\) according to physical analysis.

When \( x \) is the value of any point in the \( X \) interval, and \( x \) is to the left of \( M \), the relative difference function model can be described as follows:

\[
\begin{align*}
D_A(u) &= \left( \frac{x - a}{M - a} \right) ^\beta; \ x \in [a, M] \\
D_A(u) &= -\left( \frac{x - a}{c - a} \right) ^\beta; \ x \in [c, a]
\end{align*}
\]

(15)

when \( x \) is to the right of \( M \), the relative difference function model can be represented as follows:

\[
\begin{align*}
D_A(u) &= \left( \frac{x - b}{M - b} \right) ^\beta; \ x \in [M, b] \\
D_A(u) &= -\left( \frac{x - b}{d - b} \right) ^\beta; \ x \in [b, d] \\
D_A(u) &= -1; \ x \not\in (c, d)
\end{align*}
\]

(16)

(17)

In Equations (15) and (16), \( \beta \) is a non-negative index, and generally \( \beta = 1 \), so the relative difference function is a linear function.

Equations (15) and (16) satisfy: (1) when \( x = a, \ x = b \), \( D_A(u) = 0 \); (2) when \( x = M, \ D_A(u) = 1 \); (3) when \( x = c, \ x = d \), \( D_A(u) = -1 \). After determining \( D_A(u) \), the relative subjection degree \( \mu_A(u) \) can be calculated using Equation (5).

### 2.3.3. Variable fuzzy evaluation model

Suppose there are \( n \) swatch aggregates that can describe the conditions of the WRCC as follows:

\[ X = \{x_1, x_2, \ldots x_n\} \]

(18)

The characteristics of swatch \( j \) can be denoted by the eigenvalue of \( m \) indices:

\[ x_j = (x_{1j}, x_{2j}, \ldots x_{mj})^T \]

(19)

Then, the swatch aggregate can be denoted by the matrix \( m \times n \) index eigenvalue:

\[ X = (x_i) \]

(20)
where $x_{ij}$ is the index eigenvalue of swatch $j$ and index $i; i = 1, 2, \ldots, n$. The swatch aggregate can be identified according to the $m$ indices and the $c$ eigenvalues, and then the $m \times c$ matrix is as follows:

$$Y = (y_{ih})$$

(21)

where $y_{ih}$ is the standard eigenvalue of level $h$ and index $i, h = 1, 2, \ldots, c$.

The attraction domain and the bound domain matrix of variable aggregation about WRCC in any place can be determined by referring to the index standard matrix:

$$I_{ab} = ([a_{ih}, b_{ih}])$$

(22)

$$I_{cd} = ([c_{ih}, d_{ih}])$$

(23)

According to the $c$ levels of WRCC, the matrix of $M_{ih}$ can be represented as follows:

$$M = M_{ih}$$

(24)

It is necessary to determine whether the swatch eigenvalue $x_{ij}$ is to the left or right of $M_{ih}$ according to Equations (22)–(24), and then the difference degree $D_A(x_{ij})_h$ can be calculated by Equations (15)–(17), and the relative subjection degree $\mu_A(x_{ij})_h$ matrix of level $h$ can be calculated using Equation (5).

$$[U_h] = (\mu_A(x_{ij})_h)$$

(25)

The fuzzy evaluation model cited in the references will be applied (Chen 2005).

$$ju'_h = \frac{1}{1 + \left\{ \frac{\sum_{i=1}^{m} w_i \left( 1 - \mu_A(x_{ij})_h \right)^p}{\sum_{i=1}^{m} w_i \mu_A(x_{ij})_h^p} \right\}^{\alpha/p}}$$

(26)

where $ju'_h$ stands for the comprehensive relative subjection degree that is not unitary; $\alpha$ is the rule parameter of model optimization; $w_i$ is the index weight; $m$ is the identification index number; and $p$ is the distance parameter, with $p = 1$ and $p = 2$ representing the Hamming distance and Euclid distance, respectively.

The comprehensive relative subjection degree matrix that is not unitary can be calculated from Equation (26),

$$U' = (ju'_h)$$

(27)

The comprehensive relative subjection degree matrix that is unitary can be described as follows:

$$U = (ju_h)$$

(28)

where

$$ju_h = ju'_h / \sum_{h=1}^{c} ju'_h$$

(29)

According to the inapplicability of the greatest subjection degree of the fuzzy concept under the classification condition, the swatch can be evaluated according to the level eigenvalue put forward in the paper.

$$H = (1, 2, \ldots, c) \cdot U$$

(30)
2.3.4. Indicator system of WRCC

WRCC is a concept with twin attributes, involving both nature and society. Obviously, this means that the system is complex and large scale, with numerous contributing factors, such as population, resources, the environment, ecology, society, economy, technology, etc. The principles of choosing evaluation indicators and building indicator systems are crucial for the reliability of results. Based on the exploitation and utilization situation of water resources in the Tarim River Basin and referring to other researchers’ results (Huang & Ma 1990; Tian et al. 2021), ten evaluation indicators were chosen and the indicator systems were built to evaluate WRCC of the Tarim River Basin (Table 1).

Classification methodology and the determination thresholds are very important for evaluating the results of WRCC, and it is necessary to follow the principles of comprehensiveness, scientificity, operability and timeliness when defining different classes. Referring to other researchers’ evaluation standards for WRCC and considering the situations of local areas (Jin et al. 2018; Zhang et al. 2019a), three classes were defined for the significance of seven evaluation factors to WRCC in the Tarim River Basin. The indices of each class are listed for each factor (Table 2). \( V_1 \) represents the best situation, which shows that the water resources still have great potential, and the degree of water resource utilization and the scale of development are small. \( V_3 \) represents the worst situation, in which WRCC is close to full and more exploitation of the water resource will lead to a shortage in the water resource and deterioration of the environment; \( V_2 \) is between \( V_1 \) and \( V_3 \), where the scales of water resource exploitation and utilization have reached a certain level, but there is still potential for further exploitation and utilization.

**Table 1 | The ten indicators of WRCC and the basic data in the Tarim River Basin**

| Indicators                                      | Formulas                                      | Unit      |
|------------------------------------------------|-----------------------------------------------|-----------|
| Ecological water use ratio \( u_1 \)          | Ecological water use/Total water use          | %         |
| Precipitation \( u_2 \)                       | The current year precipitation                | mm        |
| Irrigation ratio \( u_3 \)                    | Irrigation area/Plantation area               | %         |
| Utilization degree of water resources \( u_4 \)| Water utilization value/Gross water resources | %         |
| Water consumption per ten thousand GDP \( u_5 \)| Water consumption/ten thousand GDP            | \( 10^4 \) Yuan/m³ |
| Water supply modulus \( u_6 \)                | Water supply/Land acreage                    | \( 10^4 \) m³/km² |
| Water demand modulus \( u_7 \)                | Water demand/Land acreage                    | \( 10^4 \) m³/km² |
| Per capita domestic water \( u_8 \)           | Consumption of domestic water/Gross population| L/person·d |
| Water shortage rate \( u_9 \)                 | Water shortage value/Gross water demand      | %         |
| Per capita practical water supply \( u_{10} \)| Water supply/Gross population                | m³/person  |

**Table 2 | The classification of each evaluation indicator**

| Evaluation indicators                     | \( V_1 \) | \( V_2 \) | \( V_3 \) |
|-------------------------------------------|----------|----------|----------|
| Ecological water use ratio/%              | >5       | 5–1      | <1       |
| Precipitation/(mm)                        | >450     | 450–300  | <300     |
| Irrigation ratio/%                        | <20      | 20–60    | >60      |
| Utilization degree of water resources/%   | <30      | 30–70    | >70      |
| Water consumption per ten thousand GDP/(\( 10^4 \) Yuan/m³) | <70      | 70–130   | >130     |
| Water supply modulus/(\( 10^4 \) m³/km²)  | <1       | 1–15     | >15      |
| Water demand modulus/(\( 10^4 \) m³/km²)  | <1       | 1–15     | >15      |
| Per capita domestic water/(L/person·d)    | <70      | 70–130   | >130     |
| Water shortage rate/%                    | <0       | 0–5      | >5       |
| Per capita practical water supply/(m³/person) | >4,500   | 4,500–2,500 | <2,500  |
3. RESULTS AND DISCUSSIONS

3.1. Results of WRCC in the Tarim River Basin

According to Table 2, the status index eigenvalue and the index standard value matrix can be calculated as follows:

\[
X = \begin{bmatrix}
0.12 & 0.04 & 0.39 & 0.5 & 0.39 \\
117.5 & 98.5 & 91 & 59.4 & 36.5 \\
94.87 & 97.2 & 96.83 & 91.87 & 76.82 \\
17.61 & 135.85 & 38.99 & 151.12 & 39.16 \\
1222 & 1328.46 & 531 & 1524.89 & 1977.76 \\
1.68 & 8.47 & 1.17 & 8.56 & 1.86 \\
4.05 & 17.58 & 2.93 & 21.91 & 4.7 \\
142 & 72.54 & 115 & 92.56 & 80.15 \\
58.33 & 51.85 & 60 & 60.53 & 60.48 \\
3964 & 4253.31 & 2051 & 2644.03 & 1991.57
\end{bmatrix}
\]

\[
Y = \begin{bmatrix}
5 & 5 - 1 & < 1 \\
< 20 & 20 - 60 & > 60 \\
< 30 & 30 - 70 & > 70 \\
< 70 & 70 - 130 & > 130 \\
< 1 & 1 - 15 & > 15 \\
< 1 & 1 - 15 & > 15 \\
< 70 & 70 - 130 & > 130 \\
< 0 & 0 - 5 & > 5 \\
< 4500 & 4500 - 2500 & < 2500
\end{bmatrix}
\]

where \( i = 1, 2, \ldots, 10 \) indicates the index number; \( j = 1, 2, \ldots, 5 \) is the subsection mark; and \( h = 1, 2, 3 \) is the level number. Consulting the index standard value matrix \( Y \) and the actual situation of the Tarim River Basin, the attraction domain matrix, bound matrix, and point value \( M_{ih} \) can be determined as follows:

\[
I_{ab} = \begin{bmatrix}
[5, 9] & [1.5] & [0.1] \\
[450, 600] & [300, 450] & [0, 300] \\
[0.20] & [20, 60] & [60, 100] \\
[0.50] & [30, 70] & [70, 100] \\
[0.20] & [20, 100] & [100, 400] \\
[0.1] & [1.15] & [15, 29] \\
[0.1] & [1.15] & [15, 29] \\
[0.70] & [70, 130] & [130, 190] \\
[0.0] & [0.5] & [5, 9] \\
[4500, 7000] & [2500, 4500] & [0, 2500]
\end{bmatrix}
\]

\[
I_{cd} = \begin{bmatrix}
[0.9] & [0.9] & [0.5] \\
[50, 600] & [0.100] & [0.100] \\
[0.60] & [0.100] & [20, 100] \\
[0.70] & [0.100] & [30, 100] \\
[0.100] & [0.1200] & [100, 2000] \\
[0.15] & [1.29] & [0.29] \\
[0.15] & [1.29] & [0.29] \\
[0.100] & [0.190] & [80, 300] \\
[0.5] & [0.20] & [0.59] \\
[2000, 7000] & [0.4500] & [0.4000]
\end{bmatrix}
\]

\[
M = \begin{bmatrix}
7 & 20 & 0 \\
500 & 400 & 150 \\
10 & 40 & 80 \\
15 & 45 & 90 \\
9 & 50 & 200 \\
0 & 6 & 23 \\
0 & 8 & 25 \\
30 & 100 & 160 \\
0 & 2 & 7 \\
5000 & 3500 & 1000
\end{bmatrix}
\]

The position of \( x_{ij} \), calculated according to \( I_{ab}, I_{cd}, \) and \( M \), is to the left or right of \( M_{ih} \). The difference degree \( D_A(x_{ij})_h \) was then calculated with Equations (15) or (16), and the relative subjection degree \( \mu_A(x_{ij})_h \) was determined with Equation (5).
When $j = 1, 2, \ldots, 5$, the relative subjection degree matrix corresponding to $h = 1, 2, 3$ is as follows:

$$[U_1] = \begin{bmatrix}
0.012 & 0.004 & 0.039 & 0.050 & 0.039 \\
0.084 & 0.061 & 0.051 & 0.012 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0.913 & 0 & 0.388 & 0 & 0.386 \\
0.476 & 0.233 & 0.494 & 0.230 & 0.469 \\
0.391 & 0.000 & 0.431 & 0 & 0.368 \\
0 & 0.458 & 0.000 & 0.124 & 0.331 \\
0 & 0 & 0 & 0 & 0 \\
0.393 & 0.451 & 0.010 & 0.129 & 0
\end{bmatrix}$$

$$[U_2] = \begin{bmatrix}
0.060 & 0.020 & 0.195 & 0.250 & 0.195 \\
0.196 & 0.164 & 0.152 & 0.099 & 0.061 \\
0.064 & 0.035 & 0.040 & 0.102 & 0.290 \\
0.294 & 0 & 0.800 & 0 & 0.805 \\
0 & 0 & 0 & 0 & 0 \\
0.568 & 0.863 & 0.517 & 0.858 & 0.586 \\
0.718 & 0.408 & 0.638 & 0.233 & 0.764 \\
0.400 & 0.542 & 0.750 & 0.876 & 0.669 \\
0 & 0 & 0 & 0 & 0 \\
0.768 & 0.623 & 0.410 & 0.572 & 0.398
\end{bmatrix}$$

$$[U_3] = \begin{bmatrix}
0.940 & 0.980 & 0.805 & 0.750 & 0.805 \\
0.892 & 0.828 & 0.803 & 0.698 & 0.622 \\
0.628 & 0.570 & 0.579 & 0.703 & 0.921 \\
0 & 0 & 0 & 0 & 0.115 \\
0.243 & 0.210 & 0.459 & 0.148 & 0.007 \\
0.056 & 0.282 & 0.039 & 0.285 & 0.062 \\
0.135 & 0.629 & 0.098 & 0.846 & 0.157 \\
0.700 & 0 & 0.350 & 0.126 & 0.002 \\
0.007 & 0.072 & 0 & 0 & 0 \\
0.012 & 0 & 0.650 & 0.452 & 0.669
\end{bmatrix}$$

Consulting other experts’ results and referring to the analytic hierarchy process (Minatour et al. 2016), the unitary vectors were obtained as follows:

$$w = [0.004, 0.003, 0.125, 0.205, 0.173, 0.182, 0.041, 0.123, 0.027, 0.117]$$

With the variable fuzzy evaluation model of Equation (26), the relative subjection degree of WRCC at different levels in the Tarim River Basin can be calculated. From $[U_2]$, the relative subjection degree vector with $j = 3$ can be calculated as follows:

$$[(\mu_2)]_3 = (0.195, 0.152, 0.040, 0.800, 0.304, 0.517, 0.638, 0.750, 0, 0.410)$$

Let the distance parameter $p = 1$, and the model optimization principle parameter $\alpha = 2$, so when $j = 3, h = 2$, the variable fuzzy evaluation model of Equation (26) can be expressed as follows:

$$3u_2' = \frac{1}{1 + \left[ \sum_{i=1}^{10} w_i (1 - \mu_A (x_{13})_2) \right]} \left[ \sum_{i=1}^{10} w_i \mu_A (x_{13})_2 \right]$$

In the above formula, $3u_2' = 0.397$ can be calculated in the same way. When $h = 1, 2, 3$, the relative membership degree is as follows:

$$3u_1' = [0.158, 0.0397, 0.389]$$
When \( j = 1, 2, \ldots, 5 \), the relative subjection degree that is not unitary for WRCC can be obtained as follows:

\[
U' = \begin{bmatrix}
0.320 & 0.118 & 0.158 & 0.048 & 0.159 \\
0.328 & 0.247 & 0.397 & 0.253 & 0.403 \\
0.307 & 0.315 & 0.389 & 0.376 & 0.365
\end{bmatrix}
\]

After normalization, the relative subjection degree matrix is as follows:

\[
U = \begin{bmatrix}
0.335 & 0.174 & 0.168 & 0.071 & 0.171 \\
0.344 & 0.364 & 0.420 & 0.374 & 0.434 \\
0.321 & 0.462 & 0.412 & 0.555 & 0.394
\end{bmatrix}
\]

Using Equation (30), the level eigenvalue vector of WRCC can be calculated as follows:

\[
H = (1, 2, 3) \cdot \begin{bmatrix}
0.335 & 0.174 & 0.168 & 0.071 & 0.171 \\
0.344 & 0.364 & 0.420 & 0.374 & 0.434 \\
0.321 & 0.462 & 0.412 & 0.555 & 0.394
\end{bmatrix}
\]

\[
= (1.986, 2.288, 2.244, 2.484, 2.223)
\]

The results for the water resources carrying capacity in the Tarim River Basin are shown in Table 3.

Based on the standard water resources evaluation in China (Wang et al. 2014; Ai et al. 2020), each factor can be endowed with a different weight, as follows:

\[
w = [0.05, 0.15, 0.1, 0.2, 0.05, 0.08, 0.07, 0.05, 0.1, 0.15]
\]

The results, which have been recalculated with Equation (26), are shown in Table 3.

As shown in Table 3, when the weight is changed, the eigenvalues vary within a certain range, which indicates that the variable fuzzy evaluation model is less disturbed by human disturbance, so the evaluation results are regional and objective. To obtain more-regional results, it is necessary to recalculate them, endowing different values to \( \alpha \) and \( p \) (Table 4). It is obvious that when endowing different values to \( \alpha \) and \( p \), the eigenvalue keeps to a stable zone, and the assessment class does not vary with the change of \( \alpha \) and \( p \), which verifies the validity of the variable fuzzy model (Chen 2005).

### 3.2. WRCC analysis in the Tarim River Basin

From the level eigenvalue for WRCC calculated by comparing the four groups of parameters, it is obvious that the evaluation results are stable and that the reliability of the model is high. From these results (Tables 3 and 4), it is indicated that the WRCC of the Aksu, Kizilsu, Kashi and Hotan districts are not optimistic, with evaluation classes of \( V_2 \). Consequently, the potential for water resource exploitation is low. Therefore, it is high time to strengthen water resource management, to improve water resource utilization efficiency, and to raise the consciousness of the population to save water to improve the carrying capacity of their water resources. However, the situations in Bazhou are more positive, with evaluation classes of \( V_1 \). It is obvious that

| Sub-area | Weight 1 | Weight 2 | Stable zone | Assessment class |
|----------|----------|----------|-------------|-----------------|
| Bazhou   | 1.986    | 1.852    | 1.852–1.986 | 1               |
| Aksu     | 2.288    | 2.031    | 2.031–2.288 | 2               |
| Kizilsu  | 2.244    | 2.042    | 2.042–2.244 | 2               |
| Kashi    | 2.484    | 2.210    | 2.210–2.484 | 2               |
| Hotan    | 2.223    | 2.009    | 2.009–2.223 | 2               |
the water resource potential of the district is relatively high, and the water resources can still sustain future economic development and environmental protection. Overall, it is necessary to strengthen the integrated management of the water resources to utilize them scientifically and sustainably.

3.3. Discussion

WRCC focuses on the interaction between the water resources system and the socioeconomic system, and how to evaluate WRCC scientifically is a hot topic of research at present. Previous studies provided valuable references for WRCC mainly focusing on methods such as the System Dynamics Model (Song et al. 2011; Yang et al. 2015; Sun & Yang 2019), AHP method (Lu et al. 2017), the Cloud Model (Cheng et al. 2018), Spatial Durbin model (Wang et al. 2019), Fuzzy Comprehensive Evaluation Model (Meng et al. 2009), ecological footprints (Wang et al. 2013) and so on. However, the above studies cannot always ensure the accuracy of the results, because they have only been based on a weight system or a model. In this paper, the WRCC was evaluated quantitatively for the Tarim River Basin in 2018 using a variable fuzzy evaluation model, which can reasonably identify the relative membership degree and the relative membership function. The assessment level of each sample was kept in a certain range by varying the model and its parameters, which indicated that the reliability of evaluation results can be improved. Our results reveal that the WRCC of the Tarim River Basin is not optimistic with evaluation classes of $V_2$ excluding Bazhou with evaluation classes of $V_1$. In addition, the assessment classifications did not change when endowing different parameters, which indicates that the variable fuzzy evaluation model can reasonably identify the relative membership degree and the relative membership function between the sample index and the standard interval of each level index, and the results are more reliable and referable.

Future study of the WRCC should focus on: (1) measuring spatiotemporal variations of WRCC in different regions of China from the perspective of heterogeneous resource endowment; (2) simultaneously considering the driving factors affecting WRCC; (3) analyzing the spatial spillover effects of WRCC using the Spatial Durbin model; (4) providing new insights from inter-city comparisons.

4. CONCLUSIONS

The Tarim River Basin has extreme drought and poor formation conditions for water resources, and improving the efficiency of water resources is an inevitable approach for exploitation and utilization of water resources. The variable fuzzy evaluation model can reasonably identify the relative membership degrees and relative membership functions between the sample index and standard interval of each level index, and properly determine the assessment level of each sample by varying the model and its parameters. This study evaluated the WRCC of the Tarim River Basin using this method. The main conclusions and strategies are as follows:

(1) WRCC of the Aksu, Kizilsu, Kashi and Hotan districts are not optimistic, with evaluation classes $V_2$, and the current water exploitation and utilization have reached relatively high levels, although there is still some exploitation potential. The situations in Bazhou are more positive, with evaluation classes $V_1$, because Bazhou has implemented the strictest water resources management system according to the established ‘three red lines’ control indicators since 2014.

(2) The prediction shows that the water demand for the development of new industrialization and new urbanization in Bazhou will rise by 290.15 million m$^3$ and 69.33 million m$^3$. The water consumption of ecological environment protection and restoration is required to be 55 million m$^3$. In order to achieve the above requirements, the agricultural water
consumption of the whole of Bazhou should be reduced by 1.151 billion m³ and 1.399 billion m³ compared with the current situation. Therefore, great efforts must be taken to improve water utilization efficiency, optimize water structure, strictly control the total scale of irrigation area, and effectively reduce agricultural water consumption.

(3) The Hotan area is located in the southern edge of the Taklimakan Desert, and is subject to serious sandstorm damage. It is requisite to continue to strengthen the construction of soil and water conservation engineering, increasing the scale of windbreak and sand-fixation forest construction, paying attention to grassland protection. As a typical source area of Tarim River, the Aksu area has rare precipitation, and the ecological environment is vulnerable. It is urgent to increase the ecological water consumption for ecological protection and restoration of ecological destruction.

(4) The spatial and temporal distribution of water resources is uneven in Kezhou. In order to improve the water supply capacity, it is imperative to accelerate the advancement of the Altash and Karabeli hydro-junction projects. In the Kashgar area, due to the large quota of agricultural irrigation water, ecological water utilization will be overloaded. Therefore, important measures should be taken in order to ensure the sustainable utilization and development of water resources including promoting water-saving agriculture, strengthening the management of industrial wastewater and improving the ratio of industrial wastewaster treatment.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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