Water Resources Carrying Capacity Assessment in Dali Prefecture Based on T-S Fuzzy Neural Network Model

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Abstract: Water resources carrying capacity (WRCC) assessment is an effective way to evaluate the coordinated development of water resources, economic society and ecological environment, thus, it is significant to study WRCC to realize the harmony among water resources, economy and society in region. In this paper, an index system for evaluating WRCC, which represents the natural attributes and the managerial attributes of water resource, was constructed. Moreover, the T-S Fuzzy Neural Network Model was applied to evaluate WRCC of resource-oriented, management-oriented and comprehensive in Dali Prefecture, respectively. The results showed that evaluation results of WRCC of resource-oriented, management-oriented and comprehensive were different from each other obviously. Evaluation results of comprehensive WRCC accords with the fact. The WRCC in research region was averaged overall. WRCC in Heqing county, Eryuan county, Yangbi county, Dali city, Binchuan county, Xiangyun county and north of Midu county and Weishan county was already in a critical status, but that in the other area of Dali Prefecture was in non-overloading status.

1. Introduction

Water resource carrying capacity (WRCC) is a new concept proposed with the rise of the idea of sustainable development in the 20th century and people’s increasing recognition of the correlation between sustainable development and water resources. It is a comprehensive indicator for coordinated development between water resources and economic, social and ecological development [1], and it is a manifestation and application of the idea of sustainable development in the realm of water resources. Thus, studying on WRCC is of great importance for harmonious development between human and water resources.

It has been 30 years since the research on WRCC started. The research history shows that it is closely related to the development of water resource management, and as new problems in water resource management come into being, WRCC has been assigned new meanings. The 1980s witnessed the development phase of Chinese water resources management. In that decade, the major problem in water resource management was water shortage. Thus, research groups like the Xinjiang Water Resources Soft Science Research Group [2] have started research on WRCC, especially the social and
economic impacts of WRCC from the perspective of water volume. The period from the late 1980s to the late 1990s was the fast development of water resource management in China. In that period, the major problems of water resource management were regional severe and disordered development of water resources which led to ecological deterioration. Therefore, studies on WRCC by Xu [3], Ruan [4], Jia [5], Ji [6] as well as the “Ninth Twelve-Year Plan” key scientific breakthrough project “Water resource carrying capacity and sustainable development in Shiyang River Basin” introduced the factor of ecological environment into WRCC and recognized that WRCC is a complex system that involves water resource system – social economic system – ecological environmental system. From the early 2000s to the 2010s, modern water resource management entered the early stage. The fast social and economic development, rapid growth of population, water shortage, environmental pollution and climate changes are imposing more and more challenges to water resource management. In this period, studies on WRCC by Wang [7], Chen [8], Li [9], Hui [10], Wang [11], Feng [12], Liu [13], Huang [14], Duan [15] et al. focused on the intercorrelation among the multiple purposes, dynamic nature, and the system of “water resource- economy & society & ecological environment” of WRCC; the concepts and methods grew mature and developed into three concepts and three methods [1]. Since the start of 2010 to now, modern water resource management in China have been in a new stage, during which the strict policy of “three red lines” for water resource management was established as the problems of water resource shortage, water pollution and water environment degradation became increasingly grave. In this context, studies by Jiang [16], Li [17], Zhou [18], Lan [19], Li [20], Deng [21], the “research on early warning of the resource environment carrying capacity” initiated by the National Development and Reform Commission of China as well as the “national monitoring and early-warning mechanism of water resource carrying capacity” initiated by the Water Conservancy Bureau of China all introduced the “three red lines” to research on WRCC.

As the water use control indicator in the “three red lines” is not determined according to the local water resource conditions, but is identified by the water coordination conditions and the water resource needs of the society, what this indicator reflects is the WRCC under the total water use control, i.e. the management-oriented WRCC. On the contrary, the WRCC evaluation without considering the limits set by the “three red lines” is called the resource-oriented WRCC. The WRCC evaluation that combines these two could reflect the WRCC under the natural water resource conditions and total water use control, thus is called comprehensive WRCC. These three WRCC indicators show different meanings, few studies have been devoted to their comparison so far. Therefore, by establishing a WRCC indicator system that covers both the natural resource attributes and the managerial attributes, this study takes Dali Prefecture in Yunnan as a study case, and analyzes the three WRCC indicators (resource-oriented WRCC, management-oriented WRCC and comprehensive WRCC) to provide a basis for evaluation of the regional WRCC.

2. Overview of the study area
Dali Bai Autonomous Prefecture is located in the central west of Yunnan, ranging from 98°52′~101°03′E and 24°40′~26°42′N, covering an area of 29459 km². Areas under its administration include 12 counties (and cities): Dali City, Xiangyun County, Midu County, Binchuan County, Yongping County, Yunlong County, Eryuan County, Heqing County, Jianchuan County, Yangbi County, Weishan County, Nanjian County (Figure 1). Dali Prefecture has a complex mixture of landforms and distinct altitudes ranging from 730 m to 4,295 m. On the west of Cangshan Mountain are high mountains and valleys; between Cangshan Mountain and Xiangyun County are medium-scale mountains and slopes, with hills covering 93.4% of the area and the abatement taking up 6.6%. As the area is located in the low latitudes and has high altitudes, it is subject to low-latitude plateau monsoon climate: little temperature differences among seasons, as stated in a Chinese classic – “all four seasons are like the spring with mild temperatures that are neither too hot nor too cold”. The Dali Prefecture has distinct climate features, i.e. the temperature decreases and the precipitation increases as the altitude rises; the rainfall ranges from 357 mm to 796 mm from one county (city) to another, and the average temperature shifts between 13.7 °C to 20.0 °C. Many rivers run through this area, distributing
in a feather shape and belonging to four basins (Yangtze River, Hong River, Lancang River, Nu River) and five basins (upper stream of Jinsha River, Yuanjiang River, Lixian River, Lancang River, Nu River). Erhai lake – the second largest lake in Yunnan Province is located in this area.

3. Materials and Methods

3.1. Materials

The materials used in this study include: (1) the 2015 Water Resource Bulletin of Dali Prefecture, Yunnan; (2) the water resource related indicators in Yunnan in 2015, including the total water use control indicator, target water qualification rate of water function area, the limited COD discharge, the limited ammonia nitrogen discharge stipulated in “Opinions for Implementing the strictest water resource management policies issued by the provincial government of Yunnan (Yunnan government 2012: 126)”; (3) the monitored data about the 40 drainage outlets and 27 water functional zones by the Hydrological and Water Resource Bureau in Yunnan.

3.2. T-S fuzzy neural network model

3.2.1. T-S fuzzy neural network. The T-S neural network combines the features of fuzzy logic and the learning approximation of neural networks; it is a fuzzy system that updates automatically and modifies the membership functions of fuzzy subsets constantly [22]. The network consists of an input layer, a fuzzy layer, a fuzzy rule calculation layer and an output layer. It is defined by the “if-then” rule, and under the rule of $R_i$, the deduction process is as follows:

$$ y_i = p_{x_i} + p_{x_1} + \ldots + p_{x_k} \quad (i = 1, 2, 3, \ldots, k) $$

where $A'_i$ is a fuzzy set of the fuzzy system, $p'_j$ is a parameter of the fuzzy system $((j = 1, 2, 3, \ldots, k))$, $y_i$ is the output obtained by the fuzzy rule.

Assume the input variable $x = [x_1, x_2, \ldots, x_k]$, then the construction process of the T-S neural network model:

(1) Input $uA'_j$, the membership grade of the variable, to calculate

$$ uA'_j = e^{\frac{(x_i - c'_j)}{b'_j}} \quad j = 1, 2, \ldots, k; i = 1, 2, \ldots, n $$

where $c'_j$ and $b'_j$ are the center and width of the membership grade function, $k$ is the number of
the input parameters, n is the number of fuzzy subsets.

(2) Perform fuzzy calculation on the membership grade \( uA_j \);

\[
\omega = uA_j(x_1) \times uA_j(x_2) \times \cdots \times uA_j(x_k) \quad i = 1, 2, \ldots, n
\]  

(3) Calculate the output value \( y_i \).

\[
y_i = \frac{\sum_{i=1}^{n} \omega_j (p_j^i + p_j^i x_i + \cdots + p_j^i x_k)}{\sum_{i=1}^{n} \omega_j}
\]

3.2.2. Learning Method. The parameters for learning include \( c_j \), the center of the membership functions of nodes on the second layer of the premise network, and \( b_j \), the width, as well as \( p_j(k) \), the consequent network. The error back propagation algorithm of the BP neural network.

(1) error calculation function

\[
e = \frac{1}{2} (y - y_e)
\]

where \( e \) is the error, \( y_d \) is the expectation, and \( y_e \) is the actual output of the network.

(2) learning algorithm of the coefficients of the neural network

\[
p_j(k) = p_j(k - 1) - \alpha \frac{de}{dp_j}
\]

\[
\frac{de}{dp_j} = \frac{(y - y_e)\omega_j}{\sum_{i=1}^{n} \omega_j x_j}
\]

where \( p_j \) is the coefficient of neural network, \( \alpha \) is the learning rate of the network, \( x_j \) is the input parameter of the network, \( \omega \) is the continued product of the membership grades of parameters.

(3) learning algorithm of parameter adjustment

\[
c_j(k) = c_j(k - 1) - \beta \frac{de}{dc_j}
\]

\[
b_j(k) = b_j(k - 1) - \beta \frac{de}{db_j}
\]

where \( c_j \) and \( b_j \) represent the center and width of the membership grade function.

4. Construction and grading of the WRCC indicator system and its spatial distribution features

4.1. Construction of the evaluation indicator system

The key for evaluation of the WRCC is to establish a scientific and rational evaluation indicators system [15]. However, no evaluation indicator system in this regard has been established yet. Given the importance of WRCC and following the principles of objectivity, systematism and easy access, this study selected 6 indicators for WRCC evaluation from the angle of resources and management. Among the indicators selected, three are resource-oriented(R): water resource utilization ratio(WR), COD over-discharge ratio(COD), ammonia nitrogen over-discharge ratio(NH3-N); three are management-oriented(M): total water use ratio(W), ratio of water function zones that meet the water quality standards(WQR), the effective irrigation of farmland(IR). All indicators are presented in Table 1.
Table 1. The indicators system for evaluation of water resource carrying capacity

| indicators attribute | Calculation formula | Meaning |
|-----------------------|--------------------|---------|
| W M                   | Comparable water use volume/ control indicator of total water use | Reflecting the total water use control conditions in a certain region |
| WQR M                 | Number of water functional zones that meet water quality meeting standards/ expected number of water functional zones that meet water quality standards | Reflecting the river water quality meeting the requirements for water resource development, ecological and environmental protection |
| IR M                  | Irrigation area/farmland area | Reflecting the agricultural and water conservancy infrastructure in a certain region |
| WR R                  | Actual total water-use volume/total volume of water resources | Reflecting the water resource development level and use potential of a region |
| COD R                 | COD discharge volume/ limited COD discharge volume | Reflecting the water pollution load of a certain region |
| NH3-N R               | NH3-N discharge volume/Limited NH3-N discharge volume | Reflecting the water pollution load of a certain region |

The control indicator of total water use adopts an annual average among years, the actual water use volume $W_i$ differs as the water inflow frequency in different years (the water-rich and water-deficient conditions). Thus, to make the total water use volume and the control indicator of total water use comparable, the total water use volume of a region for a year should adopt the annual average value of different years according to the regional rainfall frequencies, labelled as comparable water use volume $\bar{W}_i$. The conversion steps are as follows:

Step 1: calculate the water volume conversion coefficient under typical water inflow frequencies. As stipulated in “Overall Planning of Water Resources in Yunnan”, under the four rainfall frequencies $P=25\%$, $P=50\%$, $P=75\%$, and $P=95\%$, the available water supply volume for counties are $W_{25\%}$, $W_{50\%}$, $W_{75\%}$, and $W_{95\%}$, respectively. The available water supply $W_{50\%}$ under the frequency $P=50\%$ is used as the approximate annual average, and according to the formula below, the water use volume conversion coefficient of four typical frequencies are $K_{25\%}$, $K_{50\%}$, $K_{75\%}$, and $K_{95\%}$:

$$
\begin{align*}
K_{25\%} &= \frac{W_{50\%}}{W_{25\%}} \\
K_{50\%} &= 1 \\
K_{75\%} &= \frac{W_{50\%}}{W_{75\%}} \\
K_{95\%} &= \frac{W_{50\%}}{W_{95\%}} 
\end{align*}
$$

Step 2: calculate the conversion coefficient $K_p$ of the annual water use volume, which is obtained by interpolating the water-rich and -deficient frequencies $p$, as shown in the following equation:

$$
K_p = K_{dp} + \frac{(K_{up} - K_{dp})}{(up - dp)}(p - dp)
$$

where $dp$ and $up$ are the lower limit and upper limit that are closest to the annual rainfall frequency $p$; $K_{dp}$ and $K_{up}$ are the corresponding water use volume conversion coefficients under the typical frequencies $dp$ and $up$.

For regions where the rainfall frequency $p$ is lower than 25\% or larger than 95\%, the conversion coefficient $K_p$ is obtained through linear extension and interpolation of the typical water use volume conversion coefficient of the corresponding node.

Step 3: calculate the comparable water use volume of a year under evaluation $\bar{W}_i$. The comparable water use volume $\bar{W}_i$ is the product of multiplying the annual total water use volume $W_i$ by the water use volume conversion coefficient $K_p$, i.e.:
The comparable water use volume \( \bar{W}_i \) can be obtained using Eq. (12). The total water use ratio thus can be obtained by using the formula in Table 1.

### 4.2. Indicator grading

According to the indicator grading system [23] in “Outline for national water resource carrying capacity monitoring and early-warning technology (Revision)” issued by the national water conservancy bureau, the evaluation indicators are divided into four grades: non-overloading status, critical status, overloading status, serious overloading status; the grading thresholds stipulated in this document are adopted for the thresholds for the total water use ratio, ratio of water function zones that meet the water quality standards, the COD over-discharge ratio, and the \( \text{NH}_3\text{-N} \) over-discharge ratio. As studies by Wang and Zhang [24] found, the water resource use ratio thresholds for Yangtze River and Pearl River are 31% and 32%, respectively. The adopted threshold for overloading in this study is 30%, the thresholds for no-overloading and severe overloading are 20% and 40%. The grading threshold for effective irrigation of farmland uses the value stated in paper [25]. The thresholds of evaluation indicator are showing in Table 2.

| Indicator | Non-overloading status | Critical status | Overloading status | Serious overloading status |
|-----------|------------------------|-----------------|--------------------|--------------------------|
| \( W \)   | < 0.9                  | <1              | <1.2               | ≥1.2                     |
| WQR       | >80%                   | >60%            | >40%               | ≤40%                     |
| IR        | <50%                   | <60%            | <90%               | ≥90%                     |
| WR        | <20%                   | <30%            | <40%               | ≥40%                     |
| COD       | <1.1                   | <1.2            | <3                 | ≥3                       |
| \( \text{NH}_3\text{-N} \) | <1.1                 | <1.2            | <3                 | ≥3                       |

### 4.3. Spatial distribution features of evaluation indicators

Figure 2a shows the spatial distribution of total water use ratio (\( W \)) in 2015 in different counties in Dali Prefecture, Yunnan. As the figure shows, the total water use ratio presents a “low-high-low-high” pattern from northwest to southeast of the region. One high value zone is in Yangbi, Eryuan and Heqing; another high value zone is in Nanjian county. Two high value centers are in Heqing county and Yangbi county, with values higher than 0.9, indicating that the water use volume in these regions in 2015 is close to the controlled total water use volume. Two low-value regions are in Jianchuan, Yunlong and Yongping in northwest Dali Prefecture and Weishan, Midu and Xiangyun in eastern Dali Prefecture. The total water use ratio of Midu and Xiangyun is the smallest, below 0.5, indicating that the water-use volume of these regions in 2015 is smaller than the controlled total water use volume and thus the water is sufficient.

With regard to the WQR (Figure 2b), there is a low-value belt ranging from Heqing in the north to Yangbi and Dali in the center and then to Midu in the southeastern area, where the proportion is lower than 0.9. Two low-value centers are in Yangbi and Midu, with an average value lower than 0.7, indicating that the water quality of these areas in 2015 is not good. The average value for other areas on both sides of this belt is larger or equal to 1, indicating that the actual water quality of water functional areas meets the target standards.

Figure 2c shows the spatial distribution of effective irrigation of farmland (IR). As the figure shows, areas with high values of effective irrigation of farmland are along the belt connecting Dali, Xiangyun, Binchuan and Jianchuan, with an effective irrigation ratio between 0.5 and 0.6; while the value for other areas is between 0.3 and 0.5. The low-value area is mainly in Yunlong county, with an effective irrigation ratio lower than 0.3. The water resource use ratio (WR) of Dali Prefecture in 2015 is not high (Figure 2d), with a ratio lower than 40% for all counties. The ratio increases from west to east, and in Yunlong, the westmost
county, the ratio is only 2.8%; counties in central regions including Jianchuan, Heqing, Eryuan, Yangbi, Yongping, Weishan, Midu and Nanjian has a ratio between 5% and 20%; the three counties in the east, Binchuan, Dali and Xiangyun, has a ratio larger than 30%, with Binchuan marking the largest ratio – 38%.

The COD over-discharge ratio (COD) decreases radiating outwards with Dali and Yangbi as the center, presenting a linear and radiating pattern (Figure 2e). The highest COD over-discharge ratio is in Dali and Yangbi, between 1.15 and 1.2; the value in other areas is between 0.9 and 1, with the two low-value centers at Yunlong and Nanjian.

Figure 2f shows the spatial distribution of ammonia nitrogen over-discharge ratio (NH3-N). As the figure shows, ammonia nitrogen over-discharge concentrates in Weishan County, with an over-discharge ratio between 1.1 and 1.5; the value for most of the other regions is between 0.9 and 1.0. The lowest ammonia nitrogen over-discharge occurs in Nanjian County, with a value lower than 0.8.

5. WRCC evaluation of Dali

5.1. Construction of the neural network

For evaluation of three WRCC indicators for Dali prefecture, three T-S neural networks are constructed, as Table 3 shows.

| Model title                        | Evaluation indicator | Network                                                                 |
|------------------------------------|----------------------|-------------------------------------------------------------------------|
| Resource-oriented evaluation model | WR, COD, NH3-N       | \( f = T - SANN \) \{ \begin{align*} p_i (i = 0,1,\cdots,3) \\ e < 10^{-3} \end{align*} \} |
| Management-oriented evaluation model| W, WQR, IR           | \( f = T - SANN \) \{ \begin{align*} p_i (i = 0,1,\cdots,3) \\ e < 10^{-3} \end{align*} \} |
Comprehensive evaluation model \( \text{WR, COD, NH}_3\text{-N, W, WQR, IR} \) \( f = T - \text{SANN} \)

\[
I - M - O : 6 - 13 - 1 \quad \\substack{p_i (i = 0, 1, \ldots, 6) \vspace{0.2cm} \\sum_{i=0}^{6} p_i = 1 \vspace{0.2cm} e < 10^{-6}}
\]

\text{a. The Input layer, medium layer and output layer of the neural network;}
\text{b. the coefficient in the network;}
\text{c. the training error.}

5.2. Design of training samples of the neural network
As it is difficult to obtain the real WRCC evaluation indicators, the training samples are obtained through linear interpolation according to the grading standards. 50 samples are produced via linear interpolation according to each grade of evaluation threshold, thus a total of 200 samples. Table 4 shows the correlation between the training samples and the output values.

| No. of training samples | WRCC status       | output |
|-------------------------|-------------------|--------|
| 1-50                    | No-overloading    | (1,2)  |
| 51-100                  | critical state    | (2,3)  |
| 101-150                 | Overloading       | (3,4)  |
| 151-200                 | Severe overloading| (4,5)  |

Through repetitive training, the learning rate is set as 0.05, the training epoch is 500. The absolute error between the output and the expected output of all the three T-S neural networks is between 0% and 5.0%, indicating that the training has high accuracy and meets the requirements, so the network could be used for WRCC evaluation in Dali prefecture.

5.3. Result analysis and discussions

5.3.1. Result analysis. Figure 3 shows the evaluation results of the three WRCC indicators using the T-S neural network. Evaluation of these three indicators shows distinct spatial distribution features.

Figure 3a shows the resource-oriented WRCC conditions of Dali Prefecture in 2015. Figure 3a shows that the WRCC evaluation value in the eastern area is higher than that in the western area. The high-value center is in Binchuan County, eastern Dali and northern Xiangyun County, with a value larger than 3.0, indicating that the water resources in this region is in an overloading status. The high-value center is in eastern Heqing County, eastern Eryuan County, southern Xiangyun County, northern Midu County, northern Yangbi County, with a value between 2 and 3, indicating that the water resources in this region is in a critical status. The value for the rest regions is below 2 and decreases from east to west, indicating that the water resources in this regin is in the non-overloading status, and the western region is better than the eastern counterpart.

As the spatial distribution of management-oriented WRCC evaluation result shows (Figure 3b), a high-value belt occurs from Heqing County in northern Dali Prefecture to Dali, Yangbi County in central Dali Prefecture, to Midu and Nanjian in southeastern Dali Prefecture. The value in Heqing County, Dali City and Yangbi County reaches 2~3, indicating that the water resources in this region is in a critical status; the value for other counties (cities) is below 2, indicating that the water resources in this region is in a non-overloading status. Two low-value centers are in Xiangyun County and Yunlong County, indicating that the WRCC in these two counties is good.

Figure 3c shows the comprehensive WRCC evaluation result. The distribution of WRCC value presents a “low-high-low” pattern from southeast to northwest. High values occur in Heqing, Eryuan, Yangbi, Dali, Binchuan, Xiangyun, northern Weishan, northern Midu, between 2 ~ 3, indicating that the water resources in this region in 2015 is in a critical status. The central Nanjian and western Yunlong mark the lowest value, indicating that the WRCC in this region is good.
5.3.2. Discussions. The water resource volumes, the control indicator of total water use, the GDP anomaly percentage of Dali Prefecture are shown in Figure 4. Figure 4a shows that more water resources do not mean a larger value of the control indicator of total water use. Areas like Dali City, Xiangyun County, Binchuan County that have a lower volume of water resources (negative anomaly) have a larger value of the control indicator of total water use (positive anomaly), while counties like Yangbi County, Yunlong County, Jianchuan County that have more water resources have a lower value of the control indicator of total water use (negative anomaly). For the rest six counties follow the pattern that fewer water resources match a lower value of the control indicator of total water use, but the anomaly percentage does not show a strict positive correlation. For instance, Midu County that has the least water resources volume have the fourth largest value of the control indicator of total water use.

The control indicator of total water use and GDP anomaly percentage distribution diagram (Figure 4b) shows that the control indicator of total water use is in good correlation with the GDP. Except Eryuan County and Heqing County, the rest ten counties (cities) follow the rule that a higher GDP matches a higher value of the control indicator of total water use, but the correlation is not strictly positive. For instance, Yangbi County which has the lowest GDP has the second largest value of the control indicator of total water use.

To sum up, the control indicator of total water use of all counties in Dali prefecture is not assigned according to the natural water resources, but is more correlated to the regional economic conditions. As a result, the value of the control indicator of total water use is higher in areas with stronger economic strengths. Therefore, in the WRCC evaluation system, if only the control indicator of total water use is adopted, the conclusion would be that areas with less water resources have stronger economic strength, which is not consistent with the actual regional conditions and will does disservice to sustainable development of the region. For instance, Xiangyun County of Dali Prefecture has the second least volume of water resources, but the value of the control indicator of total water use ranks the second, following Dali City. If only the control indicator of total water use is considered (as Figure 3b shows), most areas in Xiangyun County is in a non-overloading status, but the water resource utilization ratio has already exceeded 30%. Besides, Xiangyun County is an agriculture-dominated county and in its major irrigation areas, crops like rice, corn and wheat are grown. If the water use volume is not controlled in the future, the increasing volume of water used will lead to more pollution, which will undermine the sustainable development of Xiangyun County.

Then, is it appropriate to evaluate the WRCC of Dali prefecture only according to the natural water resources (resource-oriented attributes)? As Figure 3a shows, if only the natural water resource conditions are considered for WRCC evaluation (i.e. the resource-oriented WRCC), Dali City, Binchuan County and Xiangyun County are all in an overloading status. According to the water control regulations in “implementation opinions for long-term effective monitoring and early-warning water resource carrying capacity mechanism” released by the General Office of the CPC Central Committee and the State Council in 2017, new water supply applications for these areas will be declined in the future, which will hold back the economic growth in these regions. This is not
consistent with the actual conditions of Dali Prefecture for the following three reasons: first, in light of the location and landform, Dali City has four basins and five rivers, steep mountains and scarce abatements; most abatements distribute along the watersheds, but the abatement areas are where agricultural, industrial production and urban residences are located. The unique location and landform of Dali Prefecture inevitably lead to a mismatch between water resources and the economic conditions. Therefore, it is not proper to evaluate the WRCC of a region only according to the resource-oriented indicators. Secondly, with regard to the natural conditions and major functions of the region, Dali, Binchuan and Xiangyun are located in two abatement areas (Dali Abatement and Xiangyun Abatement) among the eight abatement areas and two irrigations areas (Binchuan Irrigation Area and Xiangyun Irrigation Area) among the 12 irrigation areas. The land is flat with rich cultivated land, good light and heat conditions, making the most promising area in Dali Prefecture, a key development area of Yunnan and a major agricultural production area in China. Therefore, if only the resource-oriented indicators are adopted to identify it as an overloading area, setting limitations for its development will go against the national and provincial development strategies for this area. Last, according to the Statistical Annual Book of Yunnan in 2016 [26], the population, GDP and cultivated land area of Dali, Binchuan and Xiangyun take up 42.1%, 59.2% and 37.6% of the total of Dali Prefecture, making the most prosperous areas of Dali Prefecture and the major economic engines of this area in the future. Dali City is the capital of Dali Prefecture, the economic, political and cultural center of Dali Prefecture. If evaluated by the resource-oriented indicators, Dali City is an overloading area and thus its economic development will be severely decreased, which goes against the actual conditions of this area.

If the comprehensive WRCC indicator is adopted (Figure 3c), all these three areas are in a threshold overloading state. This conclusion preserves the space for economic development of Dali Prefecture, urges the area to advance conservation and protection of water resources, which will promote regional economic transformation and high-quality development of Dali Prefecture. Thus, evaluation by the comprehensive WRCC indicator is more consistent with the actual conditions of Dali Prefecture and can be promoted among similar regions.

![Figure 4. Anomaly percentage of the control indicators of total water use, water resource volume and GDP in each county of Dali Prefecture](image-url)

6. Conclusion
WRCC evaluation will facilitate coordinated development of water resources, population growth and economic development, with great importance for regional sustainable development. On the basis of evaluation systems that cover both resource-oriented and management-oriented indicators, a T-S fuzzy neural network is used to perform resource-oriented, management-oriented and comprehensive WRCC evaluation. The three evaluation results are compared, the applicability is discussed and the following conclusions are reached:

1) Evaluation based on these three evaluation indicators varies markedly. In light of the
resource-oriented WRCC, Binchuan County, western Dali City and Xiangyun County are in an overloading status in 2015, southern Heqing County, eastern Eryuan County, southern Xiangyun County, northern Midu County and northern Yangbi County are in a critical status, other areas are in a non-overloading status. According to the management-oriented WRCC, Heqing County, Dali City and Yangbi County are in a critical status, while others are in a non-overloading status; the comprehensive WRCC evaluation shows that eight counties including Heqing, Eryuan, Yangbi, Dali, Binchuan, Xiangyun, northern Weishan and northern Midu are in a critical status, while others are in a non-overloading status.

(2) Dali Prefecture is located in the watershed of four basins and five river systems, with steep mountains and few abatements. The unique location and landform there lead to a mismatch between water resources and economic conditions, and it is not proper to rely solely on the resource-oriented WRCC indicators or the management-oriented WRCC indicators to evaluate the WRCC of this area. Evaluation based on the comprehensive WRCC indicators can reflect the natural resource conditions, the water resource management requirements, and especially suitable for the WRCC evaluation of the region under the condition that the local water resources do not match the economic conditions. The evaluation results are consistent with the actual conditions, and the evaluation conclusions will facilitate sustainable and high-quality development of this area.

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