Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-15

DOI: *10.15244/pjoes/196248* ONLINE PUBLICATION DATE:

Original Research

Spatiotemporal Heterogeneity and Driving Mechanisms of Water Resources Carrying Capacity Based on Ecological Civilization: A Case Study of Yunnan, China

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Received: 01 August 2024
Accepted: 20 November 2024

Abstract

Water resource carrying capacity (WRCC) is an important index used to measure the sustainable development of a system. Under the background of ecological civilization, research on the spatiotemporal differentiation of regional WRCC and its driving mechanism remains insufficient. The sustainable social and economic development in Yunnan Province still faces water resource challenges for multiple reasons, such as engineering, water shortage, and water pollution. Therefore, based on the analysis of regional water resource endowment and utilization during 2010–2021 in Yunnan Province, this study explores the spatiotemporal variation of regional WRCC and its driving mechanism. First, a comprehensive evaluation index system covering water resources, society, economy, and ecological environment is constructed, with a total of 20 indicators. Then, an improved TOPSIS WRCC evaluation model is constructed based on subjective and objective comprehensive weighting methods. Finally, the geographically and temporally weighted regression (GTWR) model is introduced to examine the driving analysis of WRCC. Results show the following: (1) The WRCC of Yunnan Province depicts an overall increasing trend from the year 2010 to 2021. (2) The WRCC of Yunnan Province has remarkable spatial heterogeneity, and the water resource subsystem is still the major driving force.

Keywords: water resources carrying capacity, improved TOPSIS, spatiotemporal heterogeneity, driving mechanism

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Introduction

Water is an indispensable natural resource for human survival and sustainable social and economic development [1]. With the rapid population increase, large-scale industrialization, and economic globalization, water shortage and water pollution have become global problems [2, 3]. Specifically in China, water problems have become increasingly prominent due to recent large-scale urbanization and rapid economic development, thus causing obstacles to sustainable social and economic development [4, 5]. As an important index to measure the degree of sustainable development of water resource systems, water resources carrying capacity (WRCC) is widely used to explore the relationship between water resources and sustainable social and economic development [6-8]. With the proposal and in-depth implementation of ecological civilization construction, water resources environmental protection has received more attention and investment, and the water resources environment has undergone significant changes [9, 10]. Therefore, in the background of ecological civilization construction, it is particularly important to evaluate the supporting capacity of water resources for economic and social development by carrying out research on WRCC. It is not only a scientific basis for formulating ecological civilization construction plans but also an important means to guide the rational allocation of water resources, promote eco-environmental protection, and promote sustainable economic and social development.

The concept of carrying capacity can be traced back to 1978 [11], when the theory was first applied to the study of population ecology. The concept of WRCC was first proposed by the Xinjiang Water Resources Research Group in 1989 and defined as the amount of water that can be exploited and utilized under the constraints of natural and socioeconomic conditions [12]. WRCC is often linked to sustainable development theory [13-16] and has the concept of nature and society [17, 18]. At present, although a unified definition of WRCC is yet to be achieved, its connotation emphasizes the meaning of "water resources supporting capacity" under the premise of sustainable water resources development and utilization [19, 20]. In terms of quantitative research, WRCC evaluation index systems are usually designed first with different theoretical frameworks [21-24], and then various evaluation models for calculation are designed [25, 26]. At present, scholars have proposed a series of WRCC evaluation methods from different perspectives. Common methods include principal component analysis [27], a technique for order preference by similarity to ideal solution (TOPSIS) [28, 29], the analytic hierarchy process (AHP) [30], the fuzzy comprehensive evaluation method [31], the ecological footprint (EF) model [32], the system dynamics (SD) model [33], etc. Each approach has its advantages and limitations. For example, the EF model emphasizes the natural characteristics of water resources but does not consider the impact of human and social activities. At the same time, TOPSIS maximizes raw data information but gives equal weight to all indicators. Fuzzy comprehensive evaluation can deal with fuzzy evaluation objects, but the process is relatively complicated. The SD model can simulate the complex process of water resources and social economy on a large time scale, but the setting of parameters is subjective. Constructing an evaluation index system based on research background is also the focus of WRCC research. For example, Liu et al. evaluated WRCC in Central Asia from the viewpoints of economic and technological conditions and social welfare [8]. Qiu et al. selected evaluation indicators from the perspective of global climate change and human activities to construct a WRCC evaluation model [34]. Wang et al. constructed the initial index database based on water resources endowment and availability of index data in the study area [35]. Some scholars classify the indicators from the bearing subject and bearing object perspective to evaluate the WRCC status [36].

The above results show that a lot of research has been carried out on WRCC in different aspects, but there are still some problems. In the background of ecological civilization construction, green development is an inherent requirement for sustainable economic and social development and is an important symbol of high-quality development [37, 38]. However, the existing research has not clearly constructed the WRCC index system from the perspective of the background of ecological civilization construction. At the same time, the current evaluation of WRCC usually focuses on the regional evaluation of a certain year. Still, it ignores the spatiotemporal evolution characteristics, regional heterogeneity, and its driving mechanism in the spatiotemporal dimension [39, 40] and only focuses on the identification of obstacle factors [41-43].

Based on the above problems, this study innovatively constructed the WRCC evaluation index system based on the background of ecological civilization construction and carried out the spatiotemporal evaluation and driving mechanism of WRCC through the improved TOPSIS evaluation method. The main contributions of this research are as follows: (1) With Yunnan Province taken as an example, a WRCC evaluation index system covering water resources, society, economy, and ecological environment was constructed to comprehensively reflect the supporting capacity of the regional water resources system in the spatiotemporal dimension from the perspective of sustainable economic and social development. The index system was constructed based on regional water resources endowment, with a focus on the measures and effects of ecological environmental protection of the inflow in recent years. (2) Based on the comprehensive weighting of AHP and the entropy weight method, an improved TOPSIS evaluation method was constructed, making up for the shortage of the traditional TOPSIS evaluation method, giving the same weight to indicators.

(3) The temporal and spatial evolution of WRCC in Yunnan Province from the year 2010 to 2021 was studied. (4) The driving mechanism of regional WRCC was explored by introducing the GTWR model, which provided a certain reference value for an in-depth understanding of the relationship between WRCC and regional industrial development and the promotion of sustainable development and utilization of water resources.

The total amount of water resources in Yunnan Province is abundant. Still, for a long time, the contradiction between the supply and demand of water resources in the province has been prominent [44] because of natural causes, such as the uneven spatial distribution of water resources and frequent natural disasters [45], human factors, such as engineering water shortage and water pollution, and the impact of unbalanced economic development among regions. Sustainable socioeconomic development faces the challenge of water resources. Therefore, a study on the spatiotemporal differentiation of WRCC and its driving mechanism for Yunnan Province is crucial to the following: (1) determining the sustainable development trend of water resource utilization in the background of ecological civilization construction, (2) clarifying the relationship between water resources and economic and social development, and (3) helping coordinate the balanced development of water resources and industrial economy.

Overview of the Study Area

Yunnan Province is located in the southwestern part of China (Fig. 1). It is located on a low-latitude plateau with a slope from northwest to southeast. The whole province belongs to the tropical and subtropical plateau monsoon climate, with dry and wet seasons and considerable vertical changes. Yunnan Province is rich in water resources, with an average annual precipitation of 1,258 mm. The province has 298 tributaries of Grades 1-5 over 100 km^2, which are divided into six major river systems: Jinsha River, Lancang River, Honghe River, Zhujiang River, Nujiang River, and Irrawaddy River. It has more than 40 plateau lakes, such as Dianchi Lake, Erhai Lake, and Fuxian Lake, with a lake area of 1,140 km^2 and a water collection area of more than 9,000 km^2, accounting for 0.29% and 2.31% of the province's total water storage of nearly 30 billion cubic meters. In terms of total water resources and per capita water resources, Yunnan Province is rich in water resources. Still, the scarcity of water resources has gradually intensified due to multiple reasons, such as uneven spatial and temporal distribution, engineering water shortage, water pollution, and uneven social and economic development among regions [46].

The data sources of the indicators designed in this study are divided into two categories. One type of indicator data is direct statistical data, mainly from statistical yearbooks and communiques, etc., specifically from the Yunnan Statistical Yearbook, the Yunnan Water Resources Bulletin, the Yunnan Ecological Yearbook, and the city yearbooks of some cities in Yunnan Province from the year 2010 to 2021 (e.g., the Kunming Yearbook and the Nujiang Yearbook). The second index data type is calculated from basic data, such as water resources per unit area, water storage per capita, economic density, water consumption rate for the ecological environment, etc.

Fig. 2 shows the spatiotemporal changes in water resources in Yunnan Province from 2010 to 2021. In terms of time, the per capita water resources of 16 cities in Yunnan Province did not change much

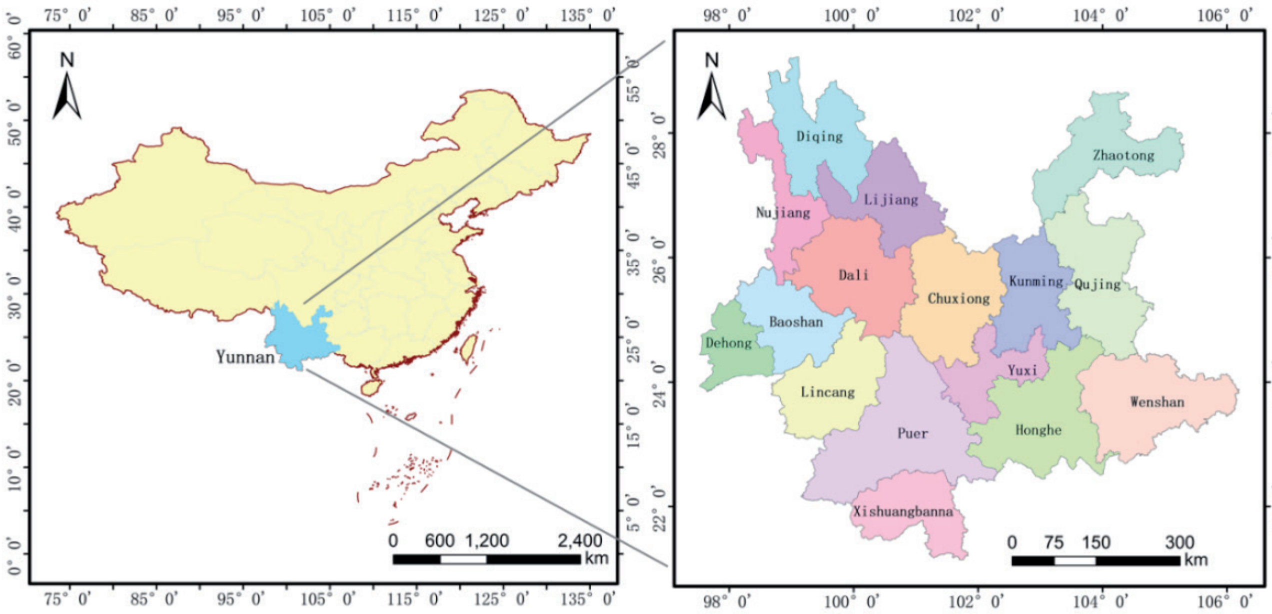

Fig. 1. Location and administrative division map of the study area.

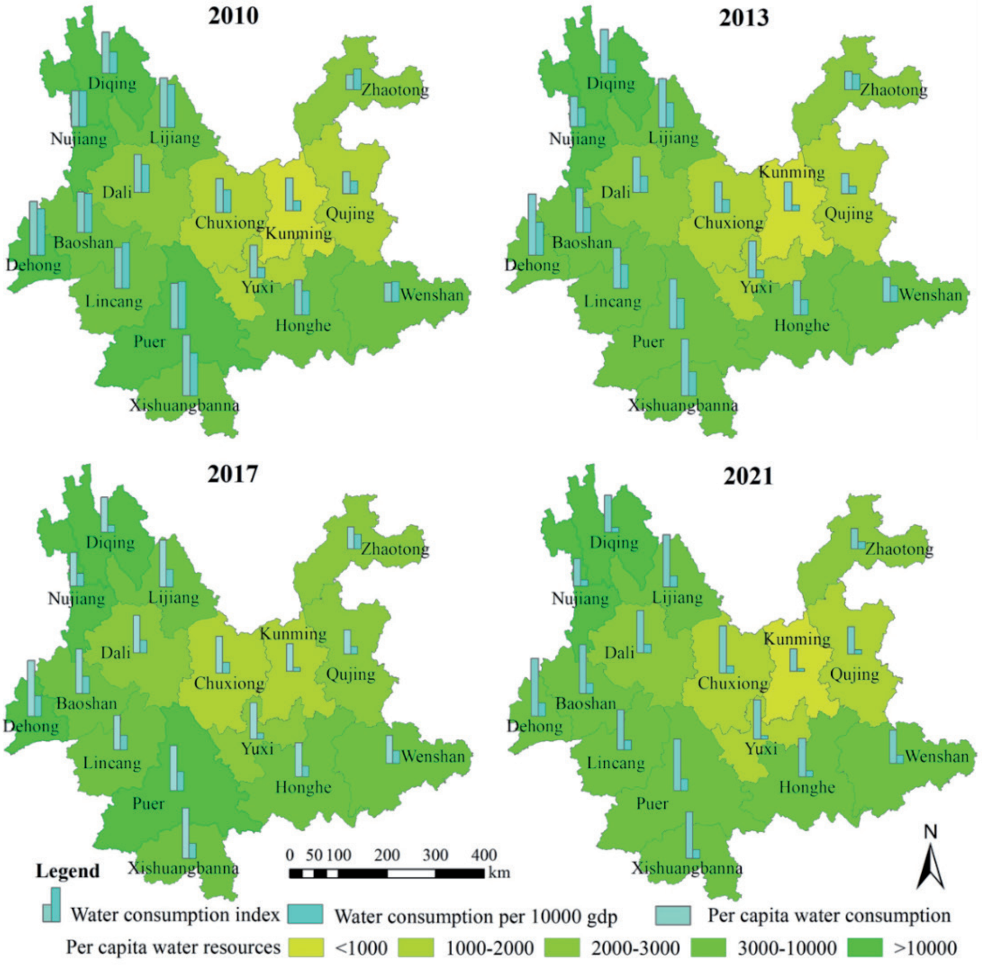

Fig. 2. Spatiotemporal changes in water resource conditions and utilization in Yunnan Province.

from 2010 to 2011. In the spatial dimension, the regions with low per capita water resources are concentrated in Kunming, Qujing, Chuxiong, Yuxi, Dali, and Zhaotong in central Yunnan Province. Among them, Kunming's per capita water resource, which belongs to a severe water shortage area, is less than 1,000 m^3 all year round. The per capita water resources of Qujing, Yuxi, and Chuxiong, which belong to areas of moderate water shortage, are 1,000-2,000 m^3 all year round. The per capita water resources of Dali and Zhaotong, which are mild water shortage areas, are 2000-3000 m^3 all year round. In particular, the per capita water resources of Nujiang and Diqing are higher than 20,000 m^3 all year round, which is much higher than other regions. The per capita water consumption of Lijiang, Puer, Xishuangbanna, and Dehong is relatively high, with an annual per capita water consumption exceeding 500 m^3. At the same time, the water consumption of Zhaotong and Wenshan is relatively low, with an annual per capita water consumption below 200 m^3. From the time dimension, each city's per capita water consumption has a small change, and most regions showed an increasing trend from 2010 to 2011. From the spatial dimension, the water consumption per 10,000 yuan of GDP of Lijiang, Puer, Lincang, Xishuangbanna, and Dehong is generally higher than that of other cities; the water consumption per 10,000 yuan of GDP in 2010 was higher than 400 $m^3/10^4$ yuan, while that of Kunming, Qujing, and Yuxi is relatively lower, i.e., only approximately 100 $m^3/10^4$ yuan. In terms of time dimension, the water consumption per 10,000 yuan of GDP in 16 cities of Yunnan Province showed a downward trend from 2010 to 2011. The average water consumption per 10,000 yuan of GDP in 16 cities of Yunnan Province was 290 $m^3/10^4$ yuan in 2010 and dropped to 77 $m^3/10^4$ yuan, a 73.4% drop, in 2021.

Methodologies

Construction of the Evaluation Index System of WRCC

The selection of evaluation factors for WRCC directly affects the scientific and rational evaluation results [24]. Given that WRCC is a complex system involving water resources, social economy, and ecological environment, the research on WRCC in this study is based on its connotation, and it discusses the main influencing factors in the complex system and builds an evaluation index system of WRCC. The objective of this study is to evaluate the carrying capacity of water resources in Yunnan Province. According to the thought of hierarchical analysis, the four subsystems of the water resources subsystem, social subsystem, economic subsystem, and ecological environment subsystem are determined as the criterion layer. Representative indicators are selected in the four subsystems of the criterion layer to construct the WRCC evaluation index system, as shown in Table 1. The selection of indicators is mainly based on the important findings, regional characteristics, and data availability of domestic and foreign studies [24, 47, 48]. In particular, in the index screening process, this study focused on the measures and effects of ecological environmental protection of incoming water in recent years and selected relevant indicators to be incorporated into the index system to pay attention to the spatiotemporal evolution of regional WRCC under the concept of ecological civilization development.

Index Weight Calculation Method

This study adopts subjective and objective comprehensive weighting methods to improve the accuracy of weighting and reduce the error caused by the single weighting method. The AHP is used for subjective weighting, and the entropy weight method is used for objective weighting.

AHP

AHP is a widely used method for determining subjective weights. As a subjective weighting method, it uses a mathematical transformation to quantify problems that are clear but difficult to quantify through the subjective drive. Its calculation process includes establishing a hierarchical structure model, constructing a judgment matrix, calculating the weight of each index, and testing for consistency. Given its advantages of simple operation, practicability, and strong adaptability, it is widely used in determining the weights of a comprehensive evaluation index [29, 30, 49].

Table 1. Evaluation index system of WRCC in Yunnan Province.

Criterion layer	Index layer	Units	Attribute	Comprehensive weight
Water resources subsystem	Water resources per unit X1	10^4 m^3/km^2	+	0.054
	Precipitation X2	mm	+	0.036
	Water resources per capita X3	m^3/person	+	0.121
	Modulus of water resources supply X4	10^4 m^3/km^2	+	0.093
	Water storage per capita X5	m^3/person	+	0.053
	Utilization ratio of water resources X6	%	−	0.048
Social subsystem	Population density X7	person/km^2	−	0.055
	Urbanization rate X8	%	+	0.049
	Water consumption per capita X9	m^3/person	−	0.052
	Natural rate of population growth X10	%	−	0.021
Economic subsystem	GDP per capita X11	10^4 yuan/ person	+	0.054
	Economy density X12	10^4 yuan / km^2	+	0.062
	Water consumption per 10,000 RMB of GDP X13	m^3/10^4 yuan	−	0.064
	Water consumption per hectare for agricultural irrigation X14	m^3/hm^2	−	0.042
	Water consumption rate X15	%	−	0.044
Ecological environment subsystem	Ecological water use rate X16	%	+	0.055
	Industrial wastewater emissions X17	ton/m^3	−	0.020
	Forest coverage rate X18	%	+	0.020
	Rate of urban sewage treatment X19	%	+	0.042
	Green coverage rate of built-up area X20	%	+	0.016

Note: "+" denotes a positive indicator, and "–" denotes a negative indicator.

Entropy Weight Method

Information entropy is a measure of uncertain systems in information theory. The entropy weight method is used to calculate the entropy weight of each index by using information entropy according to the variation degree of each index. The greater the information, the smaller the uncertainty and entropy, and vice versa. The entropy weight method determines that the weight is not disturbed by the positive and negative properties of the index [43]. The calculation steps are as follows:

Step 1: Build the raw metric data matrix *V*.

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix} \quad (1)$$

where v_{ij} is the value of index *j* of region *i*.

Step 2: Calculate the proportion of index *j* of region *i* to the sum of the index of all regions.

$$P_{ij} = v_{ij} / \sum_{i=1}^{m} v_{ij} \quad (2)$$

where P_{ij} is the weight of V_{ij}.

Step 3: Calculate the entropy of the *j* factor.

$$e_j = -\frac{1}{lnm} \sum_{i=1}^{m} P_{ij} lnP_{ij} \quad (3)$$

where e_j is the entropy value of the factor *j*.

Step 4: Calculate the *j* factor entropy weight.

$$W_{fj} = \ (1 - e_j) / \ (n - \sum_{j=1}^{n} e_j) \quad (4)$$

where W_{fj} is the entropy weight of the *j* index.

Comprehensive weighting is combined with subjective and objective weighting. This study chooses the product method to obtain a combined weight value. The *j* index weight calculated by AHP and the entropy weight method is W_{aj} and W_{fj}, respectively, and then the combined weight is shown in Formula (5).

$$w_j = \frac{(w_{aj} * w_{fj})^{0.5}}{\sum_{j=1}^{n} (w_{aj} * w_{fj})^{0.5}} \quad (5)$$

Improved TOPSIS Evaluation Model

In 1981, Hwang and Yoon proposed the TOPSIS evaluation model, namely, the “ranking method of approaching ideal solutions,” which belongs to a method of multiobjective decision-making. The principle is to rank the advantages and disadvantages of evaluation objects by calculating the distance between evaluation objects and the best and the worst ideal solutions [50-52]. First, the model calculates the positive ideal solution (optimal) and the negative ideal solution (worst) according to the data of each object to be evaluated. Second, the distance between each object to be evaluated and the positive and negative ideal solutions are calculated, respectively. Finally, all the objects are sorted to reflect the quality of the evaluation results. The TOPSIS model has no strict restrictions on the number of samples, the number of indicators, and the distribution form of data, and it maximizes the use of raw data to evaluate the regional resource and environmental carrying capacity, which can comprehensively and objectively reflect the dynamic and changing trend of regional resource carrying capacity [43, 51].

Step 1: Construction of a standardized evaluation matrix

The original evaluation matrix constructed by the evaluation index of WRCC in Yunnan Province is V (Formula [1]). The range normalization method was adopted to normalize the original data and obtain the standardized evaluation matrix *R* (8). For the processing method of positive indicators, see Formula (6); for the processing method of negative indicators, see Formula (7).

$$r_{ij} = \frac{v_{ij} - min\,(v_{ij})}{max(v_{ij}) - min\,(v_{ij})} \quad (6)$$

$$r_{ij} = \frac{max(v_{ij}) - v_{ij}}{max(v_{ij}) - min\,(v_{ij})} \quad (7)$$

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (8)$$

where *R* is the standardized evaluation matrix, r_{ij} is the standardized value of the *j* index in the *i* region, *m* is the number of evaluation areas, and *n* is the number of evaluation indicators.

Step 2. Construction of an evaluation matrix based on combination weights

The weighted standardized evaluation matrix *A* is constructed with combined weight w_j, and the calculation formula is as follows:

$$A = (a_{ij})_{m \times n} = (w_j \times R_{ij})_{m \times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \quad (9)$$

where *A* is the weighted standardized evaluation matrix, a_{ij} is the weighted standardized value of the *j* index in the *i* region, and w_j is the combined weight of the *j* index.

Step 3. Determination of positive and negative ideal solutions

Set *A*+ as the maximum value of the *j* index of the *i* region in the evaluation data; *A*− is the minimum value of the *j* index for the *i* region in the evaluation data.

Positive ideal solution $A^+ = (a_{i1}^+, a_{i2}^+, a_{i3}^+, \dots, a_{in}^+)$ (10)

where $a_{ij}^+ = \max(a_{ij})$, $1 \le i \le m$, j = 1, 2, 3, …, n.

Negative ideal solution $A^- = (a_{i1}^-, a_{i2}^-, a_{i3}^-, \dots, a_{in}^-)$ (11)

where $a_{ij}^- = \min(a_{ij})$, $1 \le i \le m$, j = 1, 2, 3, …, n.

Step 4. Calculation of Euclidean distance

Euclidean distance is D_i^+, D_i^- between each index, and the positive and negative ideal solutions were calculated, respectively. D_i^+ is the distance between the index value of the region and a_{ij}^+, and D_i^- is the distance between the index value of the region and a_{ij}^-. The calculation formula is shown in Equations (12) and (13).

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(a_{ij}^+ - a_{ij}\right)^2} \tag{12}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(a_{ij}^- - a_{ij}\right)^2} \tag{13}$$

Step 5: Calculation of closeness

In this study, closeness represents the carrying capacity of water resources to judge the level of WRCC. C_i is set as the degree to which the WRCC of the i region is close to the optimal carrying capacity, and the value range is between [0,1]. The larger C_i is, the closer the WRCC of the year is to the optimal carrying capacity level. When $C_i = 1$, WRCC is the highest. When $C_i = 0$, the carrying capacity of water resources is the lowest. The calculation formula is shown in Equation (14).

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

GTWR

In previous studies, geographically weighted regression models can explore the nonstationarity of spatial relationships by incorporating spatial geographic location information into regression equations, using the changes in parameter estimates that change with spatial geographic location [53, 54]. However, this method does not consider the time dimension or solve the problem where the regression coefficient changes with time. The GTWR model solves this limitation by combining time and space to solve the problem of space–time instability [21, 55, 56], making the estimated results of the model more appropriate and effective. The GTWR model has been widely used to measure the influence of explanatory variables on dependent variables.

The mathematical expression of the GTWR model is as follows:

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i, t_i)\, x_{ik} + \varepsilon_i \tag{15}$$

Where y_i is the observed value, (u_i, v_i, t_i) is the space–time coordinate of the i observation point, $\beta_0(u_i, v_i, t_i)$ is the constant term of regression, $\beta_k(u_i, v_i, t_i)$ is the regression coefficient of the k variable at the i observation point, and p is the total number of variables. x_{ik} is the value of the k independent variable at the i observation point, and ε_i is the random error at the i observation point.

Results and Analysis

Temporal Evolution Characteristics of WRCC

Based on the improved TOPSIS evaluation model, the index data of 16 cities in Yunnan Province from 2010 to 2011 were substituted to calculate the comprehensive evaluation score of WRCC. The larger the score is, the better the carrying capacity is, and vice versa. Fig. 3 shows the change in WRCC of 16 cities in Yunnan Province from 2010 to 2021. In general, under the background of ecological civilization construction, the WRCC in the whole province showed an upward trend. The WRCC of Yunnan Province increased from 0.34 in 2010 to 0.43 in 2021, an increase of 24%, and reached a peak of 0.43 in 2021. From the spatial dimension of the 16 cities, the WRCC generally shows a fluctuating upward trend, which means that under the promotion of sustainable development, the cities have made remarkable achievements in the development and utilization of water resources and water ecological protection. Among the 16 cities, Kunming has the highest WRCC, followed by Nujiang and Diqing, with average values of 0.46, 0.45, and 0.43, respectively. The amount of precipitation and water resources per capita in Kunming is small, and the natural water resources endowment is poor. Still, strict measures have been taken to protect water resources. Furthermore, the water consumption per 10,000 yuan of GDP, water consumption rate, water consumption rate for the ecological environment, and sewage treatment have maintained a high level. The WRCC of Lijiang, Puer, and Lincang is low, with an average value of 0.35. In particular, the WRCC of Lijiang has the highest growth rate, reaching 41% and showing good momentum for development. Nujiang and Diqing have the lowest growth rate of WRCC, which has not changed much over the years, mainly because Nujiang and Diqing have good natural water resource endowment, and these two cities have a small social population scale, low water consumption of residents, and small industrial water consumption. Multiple factors have kept their WRCC at a high level.

The changes in the four subsystems of WRCC in 16 cities of Yunnan Province are shown in Fig. 4. As shown in Fig. 4a), the water resources subsystem carrying capacity (WRSCC) of 16 cities in 2010 was the highest. Statistics show that the average annual precipitation of the province in 2010 was 1,185 mm, the highest level in recent years, and the annual per

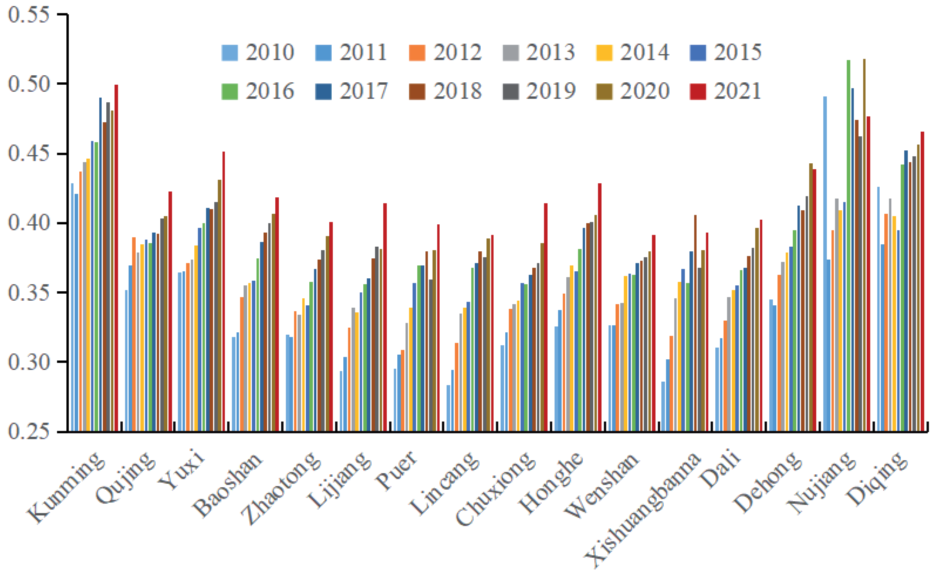

Fig. 3. Evaluation score of WRCC in Yunnan Province based on combined weight TOPSIS.

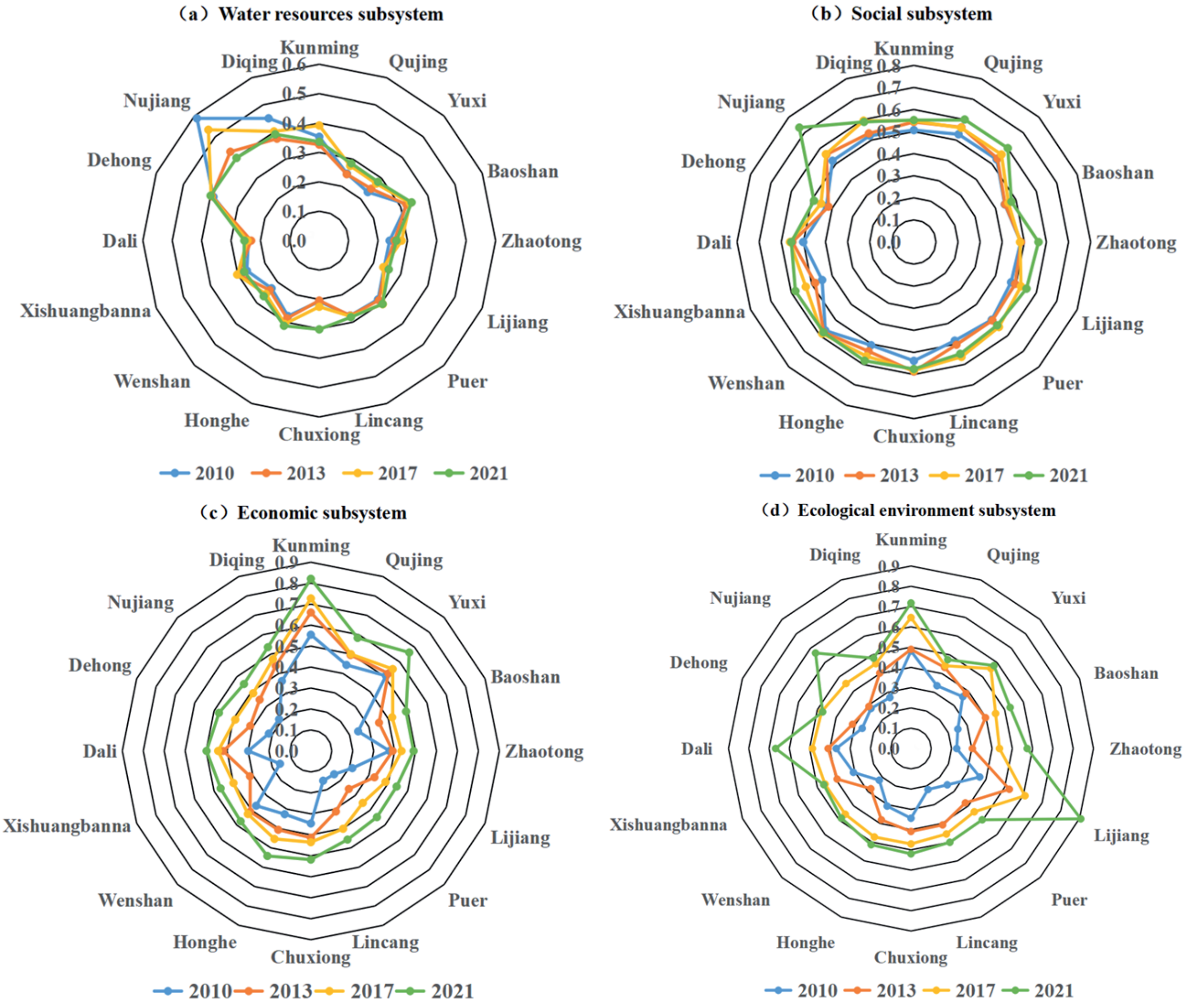

Fig. 4. Variation of the WRSCC in Yunnan's 16 cities from 2010 to 2021.

capita water resources were 9,550 m^3, the highest level in recent years. In terms of spatial dimension, the WRSCC in Nujiang, Dehong, and Diqing ranks in the top three, with an average value of 0.47, 0.39, and 0.38, respectively, mainly because these regions are rich in water resources and thinly populated, with an annual average per capita water resource of 35,285.92, 9,527.75, and 26,935.50 m^3. The WRSCC in Chuxiong was the worst, with an average value of 0.22, mainly due to poor water resource endowment. The annual average per capita water resources was only 1,598 m^3, and the annual average precipitation was only 803 m^3; much lower than other cities. In the social subsystem (Fig. 4b), the social subsystem carrying capacity (SSCC) of 16 cities showed an overall increasing trend, with the average value increasing from 0.50 in 2010 to 0.57 in 2021, with a growth rate of 14.1%. Statistics show that in addition to the natural population growth rate, which has shown a downward trend in recent years, the population density and urbanization level of the other 16 cities have shown an upward trend, and the per capita water consumption has decreased year by year. In the spatial dimension, the SSCC of Nujiang increased most remarkably, i.e., from 0.52 in 2010 to 0.73 in 2021, with a growth rate of 40.1%. By contrast, the social subsystems of Wenshan, Kunming, Baoshan, Puer, and Chuxiong did not increase remarkably, with growth rates of less than 10%. The reason is that while the population density and urbanization level increase year by year, the per capita water consumption and the natural growth rate of the population show a downward trend year by year. Fig. 4c shows that the economic subsystem carrying capacity (ESCC) of 16 cities showed a steady upward trend, increasing from 0.31 in 2010 to 0.52 in 2021, with a growth rate of 69.2%. The regional differences between the 16 cities are evident; Kunming (0.70), Qujing (0.51), and Yuxi (0.56) have the best ESCC performance. The three regions represented by the central Yunnan region have developed economies and concentrated and complete industries; the water consumption per 10,000 yuan of GDP is considerably lower than that of other cities, and the water use efficiency is the highest. For example, Kunming's average annual water consumption per 10,000 yuan of GDP (48.4 m^3) was much lower than that of the whole province (155.1 m^3). Puer (0.31) ranked last due to agriculture and industry's relatively backward water use efficiency and the highest water consumption rate. As shown in Fig. 4d, different regions' ecological and environmental subsystem carrying capacity (EESCC) presents a rising trend, but the regional differences are crucial. The average value of EESCC increased from 0.30 in 2010 to 0.57 in 2021, with a growth rate of 86.5%. This trend shows that promoting the concept of sustainable development leads to more attention to water ecological protection, and the ecological water consumption rate, forest coverage rate, and urban sewage treatment rate have increased year by year. In the spatial dimension, the EESCC of Kunming, Nujiang, Dali, and Lijiang is considerably better than that of other cities, among which the average EESCC of Kunming is the highest (0.59), mainly because Kunming, as a provincial capital, invests substantially in water ecological environment protection and strives to build a leading demonstration city in ecological civilization construction. By contrast, the average EESCC of Zhaotong, Lincang, Wenshan, and Dehong is lower than 0.4 due to large wastewater discharge, low ecological water consumption, and insufficient sewage treatment capacity. In particular, Zhaotong EESCC has the highest growth rate, increasing from 0.23 in 2010 to 0.57 in 2021, with an increase rate of 154.3%, showing good development momentum.

Discussion

In this study, the spatiotemporal differentiation and driving mechanism of WRCC in Yunnan Province from the year 2010 to 2021 were analyzed. To further improve the level of WRCC in Yunnan Province, we should focus on the following aspects for future development: First, the results show that WRCC in Yunnan Province has considerable spatial and temporal heterogeneity, and the development measures should be formulated in accordance with the regional characteristics. Each region should closely combine the characteristics of socioeconomic development with water resource endowments to address the current deficiencies. Specifically, the central region of Yunnan Province has a concentrated population, a developed economy, less rainfall, and an uneven spatial and temporal distribution. Therefore, the construction of water source projects, such as water diversion in central Yunnan, should be accelerated to optimize the spatial and temporal allocation of water resources further and ensure water supply for urban life and industry. In western Yunnan Province, the utilization rate of water resource development is low, the development of water resources is difficult, and the storage capacity of reservoirs is insufficient. Therefore, the construction of small- and medium-sized water source projects can be accelerated, small water conservancy facilities in mountainous areas can be developed, and the capacity building of soil erosion control and water conservation can be strengthened. The southern region of Yunnan Province is prone to flood disasters and weak in resistance to drought disasters; thus, the construction of large-scale irrigation areas and reservoirs must be accelerated, the water supply structure must be improved, the urban and rural water supply guarantee rate must be increased, and industrial and agricultural production must be ensured. Second, some cities in western and southern Yunnan Province are rich in water resources, and the forest coverage rate is higher than the provincial average; however, their economic development is seriously lagging behind. Therefore, the pace of economic development must be accelerated by coordinating ecological environmental protection and promoting

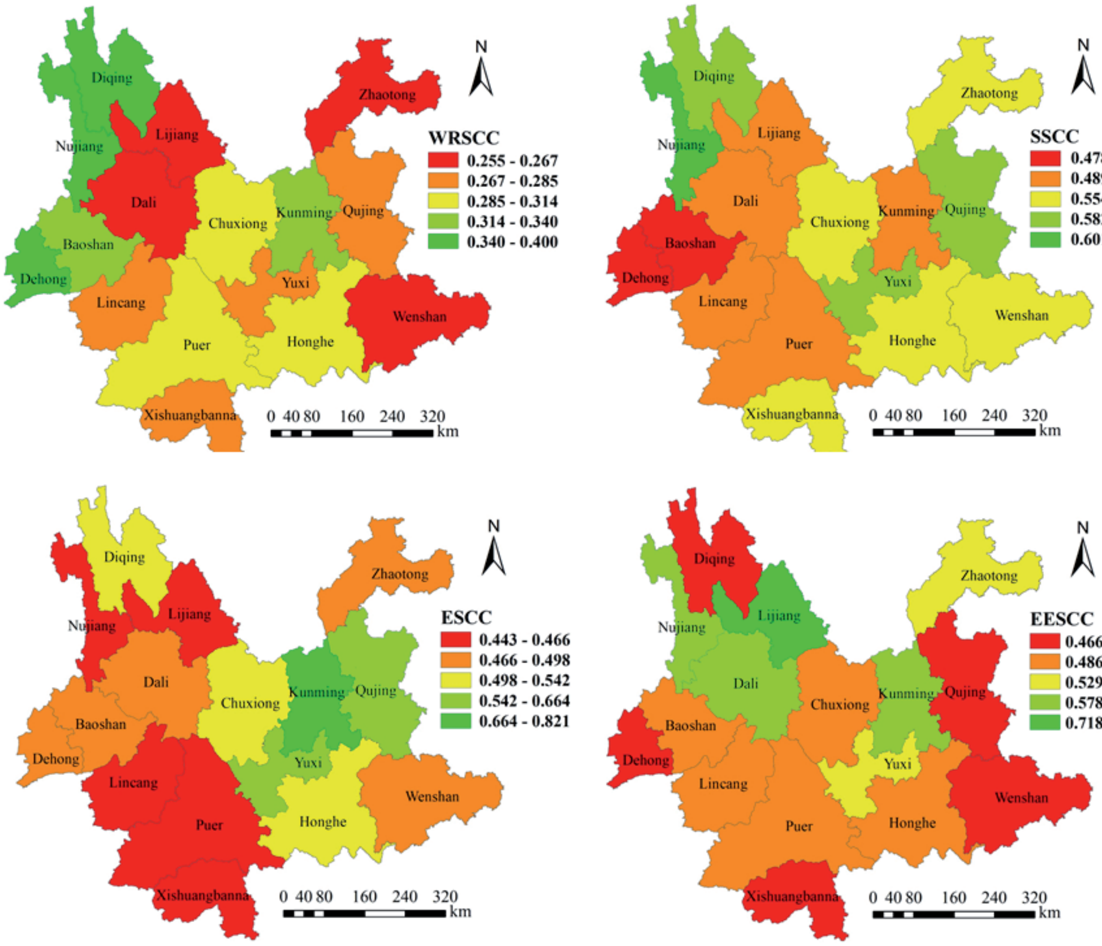

Fig. 5. Spatial distribution of four subsystems carrying capacity in Yunnan's 16 cities in 2021.

the efficient use of water resources. At the same time, the eastern and western regions of Yunnan Province should further clarify industrial planning according to their own characteristics and give full play to the radiating and driving role of the industries in the central urban agglomeration of Yunnan Province through regional industrial construction to form a coordinated and complementary development trend. Third, under the concept of sustainable development, although great progress has been made in the protection of the water ecological environment, industrial wastewater discharge remains high in some areas, and ecological water security and urban sewage capacity remain insufficient. Thus, standards for urban sewage treatment must be strictly discharged, the construction and renovation of sewage collection and treatment facilities must be strengthened, and the comprehensive water ecological treatment project must be actively promoted. In addition, given the relatively backward concept of water use in Yunnan Province, the consciousness of water saving remains relatively weak; thus, consciousness for water saving must be strengthened further, water resources management systems must be improved, and water resources management must be strengthened.

Spatial Characteristics of WRCC

To reveal the spatial characteristics of WRCC and the carrying capacity of four subsystems in Yunnan Province, this study takes the year 2021 as an example and divides it into five levels by the natural breakpoint method based on the principle of minimum intraclass difference and maximum interclass difference [57, 58]. As shown in Fig. 5, WRCC in Yunnan Province has a large spatial heterogeneity. The WRSCC in Diqing, Nujiang, Baoshan, and Dehong in western Yunnan Province and Kunming in central Yunnan Province is considerably higher than that in other regions because the western region of Yunnan Province has large rainfall, a small population, and abundant water resources per capita. Its natural water resources conditions are remarkably better than those in other regions. In particular, the per capita water resources of Nujiang and Diqing in 2021 are 26,563 and 22,792 m^3, respectively. The water resources subsystem of Kunming in the central region has a higher carrying capacity than other regions because of its perfect water supply engineering infrastructure and strong supporting capacity for regional social and economic development, with a water supply modulus of 8.87×10^4 m^3/km^2.

By contrast, the Dali water resources subsystem has the lowest carrying capacity in 2021, and its precipitation and per capita water resources are low, i.e., 849 mm and 2032 m³, respectively. Regarding the social subsystem, Nujiang has the best performance because it is located in the western backward area, with a small population size and low per capita water consumption. In 2021, the population density was only 37.8 person/km², far lower than the province's average of 119.9 person/km². By contrast, Baoshan, also in the western region, performed the worst, mainly due to the slow urbanization process, with an urbanization rate of only 36% in 2021, lower than the province's 50% level. In addition, Baoshan's high per capita water consumption is an important reason for its low carrying capacity. The carrying capacity of the economic subsystem is best concentrated in Kunming, Qujing, and Yuxi, which are in the middle of Yunnan Province. The region is the most economically developed in Yunnan Province, accounting for 28.3% of Yunnan's land area and generating 63.8% of the province's GDP. In comparison, the entire western region accounts for less than 20% of the province's GDP. In addition, along with economic development, the water resource utilization efficiency in central Yunnan Province is high. For example, Kunming's water consumption per 10,000 yuan of GDP in 2021 was 26 m³, far lower than the province's average level of 77 m³. By contrast, the economic development of western Yunnan Province is backward, and the ESCC performance is poor. Regarding ecological and environmental subsystems, Lijiang has the best EESCC performance. It is a famous tourist city with good ecological and environmental quality, and its ecological and environmental water consumption rate reaches 10.4%, much higher than the provincial average of 3.1%. In addition, the high forest green and urban vegetation coverage are important reasons for the high EESCC. By contrast, the poor EESCC performance in Diqing, Dehong, Qujing, and Baoshan is mainly due to these regions' low eco-environmental water consumption rate and the high industrial wastewater discharge index.

WRCC Driver Mechanism

This study uses the GTWR model to explore the driving force of WRCC. Fig. 6 shows the evolution of different driving forces (water resources, social, economic, and eco-environmental subsystems) in Yunnan Province. From the perspective of time, the main driving force of WRCC development in Yunnan Province has not changed much. Although the driving intensity of the water resource subsystem has decreased somewhat from 2010 to 2021, it has always been the main driving force. With time, the driving

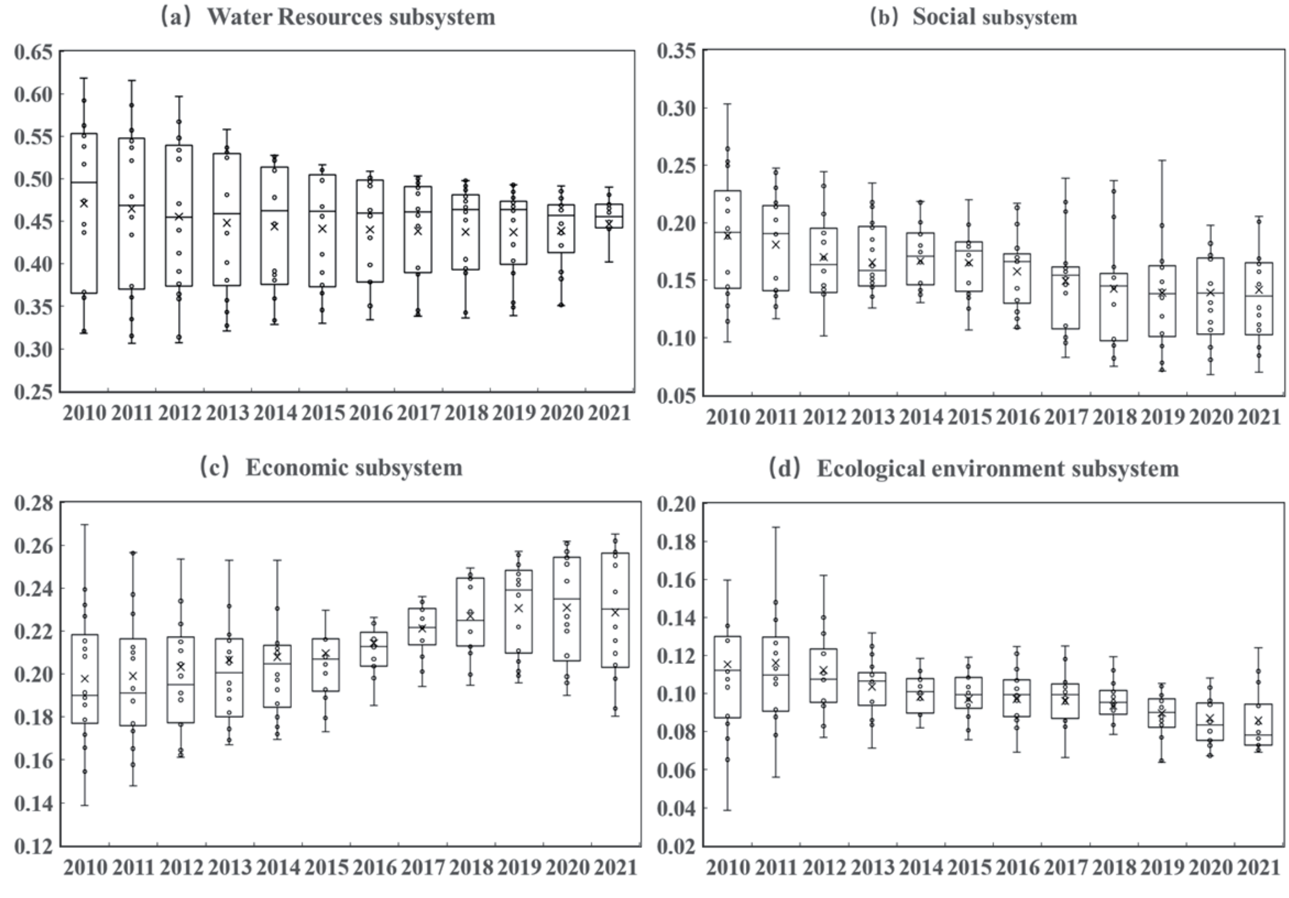

Fig. 6. Temporal evolution of the driving intensity of WRCC subsystems in Yunnan.

intensity of the social subsystem and the ecological environment subsystem gradually decreases, while the driving intensity of the economic subsystem gradually increases. The subsystems of water resources, society, and ecological environment decreased slightly, while the driving intensity of the economic subsystem increased overall. Regarding spatial differentiation, the uncertainty of the water resources subsystem decreases gradually over time, indicating that its driving force on WRCC in each city tends to be stable. The main reason is that with the gradual improvement of water conservancy infrastructure, the level of water resources development and utilization gradually improved, and the natural change of water resources has less and less impact on WRCC. The uncertainty of the ecological environment subsystem also tends to decrease gradually, which is lower than that of the water resource subsystem, indicating that its driving force tends to be concentrated. The uncertainty of the social subsystem develops in waves, gradually decreasing before 2015 and gradually increasing after 2015. The main reason is that the population distribution of Yunnan Province and the natural population growth rate of different cities have shown great differences in recent years. After decreasing in the early stage, the uncertainty of the economic subsystem increased after 2016, indicating that its driving force among cities is first concentrated and then dispersed, indicating that the economic development differentiation among cities has remained in recent years.

The difference in the driving intensity of different subsystems in 16 cities of Yunnan Province is shown in Fig. 7. From the year 2010 to 2021, the main driving force of the 16 cities has always been the water resources subsystem, but the driving intensity of other subsystems has changed considerably. The evolution of driving force can be divided into five categories: (1) In Kunming, Yuxi, and Chuxiong in the central region of Yunnan Province, the driving force of the economic subsystem tends to be stable, and the driving force of the social subsystem becomes stronger. (2) In Qujing, Wenshan, Honghe, and Xishuangbanna in the eastern

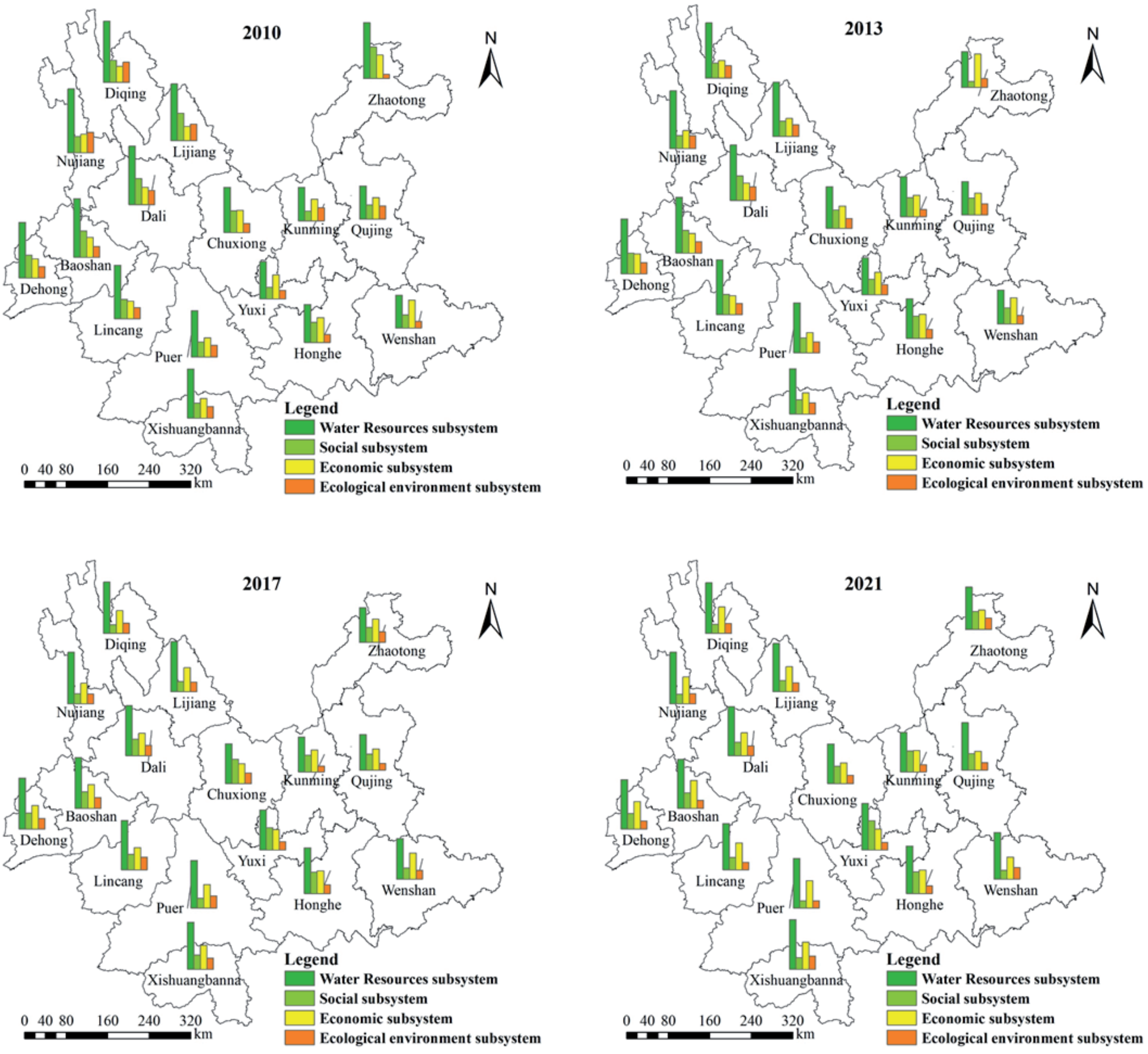

Fig. 7. Spatial evolution of the driving intensity of WRCC subsystems in Yunnan.

and southern parts of Yunnan Province, the driving forces of the economic and social subsystems tend to be stable and have minimal change. (3) In Zhaotong in the northeastern part of Yunnan Province, the driving force of the social and economic subsystems decreased. In contrast, the driving force of the ecological subsystems gradually increased. (4) In Lijiang, Dali, Lincang, Baoshan, Dehong, and Puer in the western part of Yunnan Province, the driving force of the economic subsystem was remarkably enhanced, while the driving force of the social subsystem gradually decreased. (5) In Diqing and Nujiang in the northwestern part of Yunnan Province, the driving force of the ecological subsystem gradually decreased, while the driving force of the economic subsystem increased remarkably.

In general, the main driving force of WRCC has obvious regional characteristics. Compared with other regions, the driving force of the social and economic subsystems in central and eastern Yunnan Province is stronger. The driving force of the economic subsystem in southern and western Yunnan Province is remarkably higher than that of the social and ecological subsystems, and the driving force of the water resource subsystem is remarkably higher than that of central and eastern Yunnan Province. Specifically, the central and eastern regions of Yunnan Province have a flat terrain, a developed economy, and a strong population-gathering ability. The western region of Yunnan Province is rich in water resources and has superior ecological and environmental conditions, but its economic development level is low. Overall, regional development has some commonalities; that is, although the driving force of the water resources subsystem is reduced, it remains the main driving force of each city. In addition, the driving force of the ecological environment subsystem is gradually stabilizing, mainly due to the concept of sustainable development. The state has invested a substantial amount of money in water pollution control and urban sewage treatment, increased the construction of environmental protection infrastructure, and continued to improve the urban water ecological environment.

Conclusion

Under the background of ecological civilization construction, this study analyzed the natural conditions, development, and utilization of water resources in Yunnan Province. On the basis of the panel data of 16 cities in Yunnan Province from 2010 to 2021, a comprehensive evaluation index system of WRCC was constructed, and the spatiotemporal evolution characteristics of WRCC were analyzed using the improved TOPSIS evaluation model. The GTWR model identified the driving force of WRCC evolution. The main conclusions can be summarized as follows:

(1) Based on the analysis of natural conditions and the development and utilization status of water resources in Yunnan Province, a WRCC evaluation index system consisting of four subsystems and 20 indicators was determined. Based on the evaluation index system, the traditional TOPSIS evaluation model was improved with the comprehensive weighting method. Based on the model, the WRCC of Yunnan Province from 2010 to 2021 was evaluated in terms of time and space.

(2) The results of the WRCC evaluation show that from the perspective of sustainable development, the WRCC of Yunnan Province and 16 cities show an overall upward trend from the year 2010 to 2021, with the highest growth rate of 41% in Lijiang and the lowest growth rate in Nujiang, which is largely unchanged in 2021 compared to 2010. From the subsystem perspective, affected by natural precipitation, the WRSCC in 15 cities (except Nujiang) developed in waves, and the trend of WRSCC in Nujiang decreased considerably. SSCC, ESCC, and EESCC all showed an increasing trend in 16 cities.

(3) In the spatial dimension, the natural water resource endowment in western Yunnan Province is good, and the water conservancy infrastructure in Kunming in central Yunnan Province is perfect; thus, its WRSCC has optimal performance. Nujiang and Diqing in the western region have backward economic development, a small population size, and low per capita water consumption, and the carrying capacity of the social subsystem is the best among the cities. The carrying capacity of the economic subsystem is the best in the central region of Yunnan Province, which has a developed economy and a high efficiency of water resource utilization. As a tourist city, Lijiang has the best EESCC performance, and its ecological water consumption and forest coverage rates are high in the province.

(4) The main driving forces of WRCC development have remarkable spatiotemporal heterogeneity. From the perspective of time, the main driving force of Yunnan's WRCC has always been water resources. The driving intensity of the social subsystem and the ecological environment subsystem has gradually decreased, while the driving intensity of the economic subsystem has gradually increased. From the perspective of space, the driving force of the social and economic subsystems in the central and eastern regions of Yunnan Province is stronger than that of other regions. The driving force of the economic subsystems in the southern and western regions of Yunnan Province is remarkably higher than that of the social and ecological subsystems, and the driving force of the water resources subsystems is remarkably higher than that of the central and eastern regions.

Acknowledgments

This research was funded by the Project of the Evaluations on Mineral Exploration Resources and Environmental Carrying Capacity in Yunnan province (No. 202103741).

Conflicts of Interest

The authors declare no conflicts of interest.

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