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Evaluation of the water resource carrying capacity in Heilongjiang, eastern China, based on the improved TOPSIS model

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ABSTRACT

Assessments and analyses of the water resource carrying capacity provide practical guidance for regional water resource planning and water resource management. The water resource carrying capacity index system and the corresponding level criteria are constructed from the perspective of the carrying capacity subsystem. Additionally, a water resource carrying capacity model is constructed using the improved TOPSIS method. Finally, a comprehensive evaluation and analysis of the water resource carrying capacity in the study area from 2009 to 2018 is conducted, with the eastern part of Heilongjiang as a case study. The results show that the combination of the improved AHP and the anti-entropy weighting method can avoid the bias caused by subjective factors in the traditional AHP and the bias caused by the randomness of data in the entropy weighting method, yielding accurate estimates of the water resource carrying capacity. A new method of assigning weights in TOPSIS models is developed. In addition, the water resource carrying capacity of the studied cities is generally in state III (Moderate) in the eastern region of Heilongjiang, and the multiyear average value obtained from the comprehensive evaluation is 0.4581. The Qitaihe and Hegang areas have higher water resource carrying capacities than other areas. Overall, water resource and societal factors have an obvious influence on the water resource carrying capacity in the eastern region of Heilongjiang, and these factors vary in different areas. The water supply modulus and proportion of water used for agricultural irrigation have the greatest effects on the water resource carrying capacity in the study area.

1. Introduction

Water resources play an irreplaceable role in the development of society and in ensuring socioeconomic, environmental and food security (Yi et al., 2018). However, shortages and uneven spatial and temporal distributions of water resources have seriously restricted the sustainable development of regional economies and societies (Jian et al., 2019). With economic development and population growth, the contradiction among rapid economic development, ecology and the sustainable utilization of water resources has become increasingly prominent (Song et al., 2010). The water resource carrying capacity refers to the maximum support capacity of regional water resources for socioeconomic development under the principle of sustainable development in a certain period of time for a given standard of living and certain production technology conditions; thus, this index integrally reflects the coordination between regional water resources and socioeconomic and environmental factors (Liu et al., 2017). When the water resource carrying capacity exceeds a certain threshold, it will seriously limit the sustainable development of the economy and society and have a direct impact on food and ecological security (Qi et al., 2021). Therefore, a

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reasonable evaluation of the carrying capacity of regional water resources is important for ensuring the coordinated development of socioeconomics, the environment and food security (Li et al., 2022; Yang et al., 2021).

In studies of the water resource carrying capacity, determining the relevant carrying capacity indicators is a key step, however, many qualitative and quantitative indicators are used in studies of the water resource carrying capacity. These indicators stem from many fields and are influenced by factors such as the economy, society and ecology. Additionally, water resources, society, the level of economic development and the environment differ in different areas (Bu et al., 2020; Ren et al., 2016; Wang et al., 2022b). Therefore, when establishing a water resource carrying capacity evaluation index system, the system should correspond to the actual local conditions in the study area as much as possible. Traditional evaluations of the water resource carrying capacity are based on the water quantity, water quality, balanced supply and demand, etc. (Zhang and Dong, 2022), and less consideration is given to ecological factors, which makes it difficult to reflect the influence of ecosystems on the water resource carrying capacity (Wang et al., 2022a). Therefore, water resource carrying capacity studies that consider ecological factors need to be developed.

Many research methods have been used to study the water resource carrying capacity, and they can be broadly divided into two categories: indicator evaluation methods and system dynamics methods (Dai et al., 2022; Zhou et al., 2017). The indicator evaluation methods mainly use indicators to establish evaluation systems to evaluate the water resource carrying capacity; this approach has become generally accepted and widely used. The most common indicator evaluation methods are principal component analysis (Liu and Wang, 2013), fuzzy comprehensive evaluation models (Wu et al., 2021), set-pair analysis (Chen, 2014), traditional trend analysis (Song et al., 2010), etc. However, the principal component analysis method is associated with some uncertainties when determining the principal components and the weights of contributions (Long et al., 2022). In the fuzzy comprehensive evaluation method, the determination of indicator weight vectors is subjective, which results in a certain bias in the evaluation results (Li and Chen, 2021). In set-pair analysis, it is difficult to reflect the moderating effects among subsystems (Zhang et al., 2020). The traditional trend analysis method lacks a systematic analysis of the interactions among factors, which makes it difficult to provide an objective description of the actual situation (Wang et al., 2021). The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method involves a ranking approach to approximates the most ideal solution, and solutions are evaluated based on the distance between an estimated solution and the ideal solution (Dai et al., 2010; Hwang and Yoon, 1981). However, the traditional TOPSIS method has obvious shortcomings related to the assignment of weights and the ranking of advantages and disadvantages, as affected by subjective factors (Dingrong et al., 2022; Sun et al., 2021); thus, the application of the TOPSIS method is somewhat limited. To better apply the TOPSIS model and obtain more reasonable weights, scholars have used the analytical hierarchy process (AHP) (Lixiang et al., 2022), entropy weighting method (Wang and Kong, 2021), coefficient of variation method (Chen, 2019) and other approaches to optimize the TOPSIS method. Notably, the AHP is a decision-making method that combines qualitative and quantitative analysis, but it is influenced by human experience and subjective factors, which in turn lead to certain errors (Ge et al., 2022). The entropy weighting method, on the other hand, is based on a system of evaluation indicators that are used to determine the weight values, providing high objectivity. Thus, the entropy weighting method combined with the AHP can yield accurate weights. However, the traditional AHP can be unstable in consistency tests, and the traditional entropy weighting method may also produce unreliable weights because of the randomness of the data (Cui et al., 2018).

In this study, the actual conditions in the study area are considered, and representative evaluation indexes are selected to construct a water resource carrying capacity evaluation system to reflect the real water resource carrying capacity in the study area as much as possible. Additionally, to solve the problems associated with the weights in the TOPSIS method, the influence of subjective factors on the weights is reduced, and the rationality of the allocation method is improved. The optimal transfer matrix-based improved AHP method is used to calculate the subjective weights, the anti-entropy weighting method is used to calculate the objective weights, and the final weights are obtained by a linear combination of subjective and objective weights. The improved TOPSIS model is used to assess the water resource carrying capacity in the eastern region of Heilongjiang, to quantitatively study the status of the water resource carrying capacity and analyze the changes in and factors that affect the water resource carrying capacity in the study area.

2. Materials and methods

2.1. Study area

The eastern region of Heilongjiang is located between 130° ~ 135°E and 45° ~ 48°N (Fig. 1), with a total area of approximately 98,300 km^2 and a total population of approximately 7,241,000 (Chen et al., 2020). This area mainly includes the five prefecture-level cities of Hegang, Jiamusi, Jixi, Shuangyashan, and Qitaihe. The region has a temperate continental monsoon climate with cold and dry winters and rainy and warm summers, with an average annual temperature of 2.5–3.6 °C, annual precipitation totaling 500–600 mm (Chunyan et al., 2018) and an average multiyear water resource volume of approximately 19.77 billion m^3, including 15.1 billion m^3 of multiyear surface water resources and 9.23 billion m^3 of multiyear underground water resources on average (Jiang et al., 2020). In recent years, the Sanjiang Plain area has faced problems such as lagged development for water conservation facilities, inefficient use of surface water, severe groundwater overdraft, and unreasonable allocation of agricultural water and soil resources (Qian, 2020). Especially in agriculture, the effective utilization coefficient of irrigation water is low, and there is still a significant gap with developed countries in terns of the water use efficiency, with much room for improvement (Yu, 2021). There are large-scale plans to reclaim farmland on the Sanjiang Plain in the future. It is also a large test for the supply capacity of water resources in the region. Therefore, this case study serves as a hydrological assessment of the eastern region of Heilongjiang, where agricultural water consumption accounts for more than 90% of total water consumption, as dominated by consumption for large-scale rice cultivation. The water resource carrying capacity in the eastern region of Heilongjiang influences the scales of socioeconomic development and agricultural production in the region; it also affects the water supply capacity of the region. Therefore, it is important to research the water resource carrying capacity of the region.

3. Research methodology

3.1. Evaluation index system for the water resource carrying capacity

In studies of the water resource carrying capacity, the selection of an appropriate evaluation index system is important, and all relevant factors and their mutual effects need to be considered (Lv et al., 2011; Ren et al., 2021). In this paper, considering the abundant of water resources in the eastern region of Heilongjiang, stable social development, the predominantly agricultural economy and the active agricultural activities, a water resource carrying capacity index system with 16 indicators at 4 levels is established with reference to the existing research results (Qu and Zhang, 2017), as shown in Table 1. To reflect the changes in the water resource carrying capacity in the study area, a 10-year period is chosen as the time range for the study, and the study time period is 2009–2018. The actual conditions in the study area and the accuracy and accessibility of the data during this period are considered. The research data were obtained from the Heilongjiang Province Water

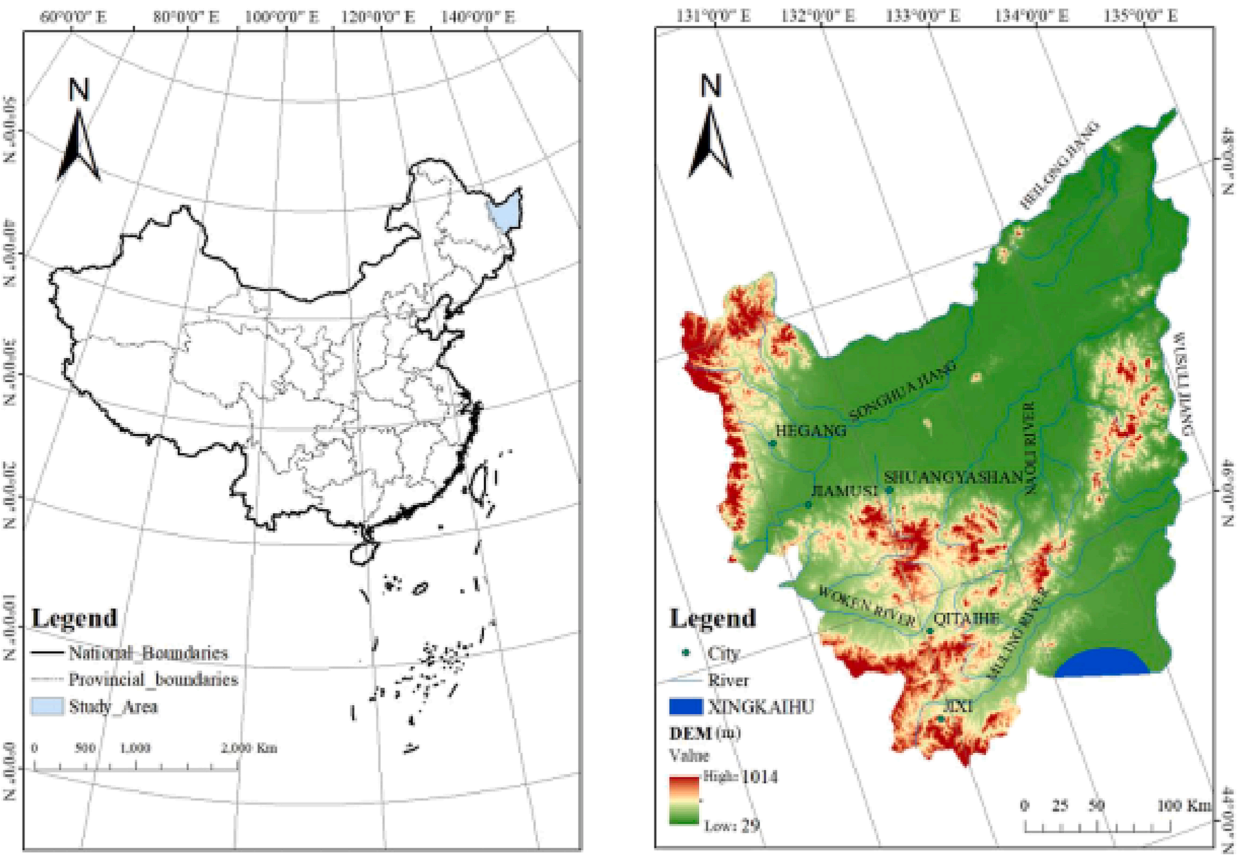


Fig. 1. Map of the eastern region of Heilongjiang Province.

Table 1
Comprehensive evaluation index system for the water resource carrying capacity.

Guideline levels	Indicator levels	Calculation methods	Indicator attributes	Unit
Water resource subsystems	Per capita water resources (R_1)	Total water resources/Total population	Positive	m^3/person
	Per capita water resource usage (R_2)	Total water consumption/Total population	Negative	m^3/person
	Water production coefficient (R_3)	Total water resources/Total annual rainfall	Positive	–
	Water supply modulus (R_4)	Total water supply/Total area of the region	Negative	$10^4m^3/km^2$
Social subsystems	Urban per capita daily domestic water consumption (R_5)	Total urban daily water consumption/Total urban population	Negative	L·(d·person)
	Population growth rate (R_6)	Net annual growth in headcount/Average annual headcount	Negative	‰
	Total annual production water consumption (R_7)	Statistics	Negative	10^8m^3
	Total annual domestic water consumption (R_8)	Statistics	Negative	10^8m^3
Economic subsystems	Per capita GDP (R_9)	Total GDP/Total population	Negative	10^4RMB/person
	Proportion of primary industry (R_{10})	Total agricultural GDP/Total GDP	Negative	%
	Water consumption per 10 thousand RMB GDP (R_{11})	Total water consumption/Total GDP	Negative	$m^3/10^3$RMB
	Proportion of water used for agricultural irrigation (R_{12})	Total agricultural irrigation water consumption/Total water consumption	Negative	%
Ecological subsystems	Ecological water consumption (R_{13})	Statistics	Negative	10^8m^3
	Daily sewage treatment capacity (R_{14})	Statistics	Positive	10^4m^3/d
	Urban greening coverage rate (R_{15})	Urban green area/Total urban area	Positive	%
	Percentage of groundwater extraction (R_{16})	Statistics	Negative	%

Resource Bulletin and the Heilongjiang Province Economic and Social Development Statistics Database.

3.2. Evaluation method

In the improved TOPSIS method, the improved AHP-anti-entropy weighting approach is applied to determine the relevant weights, and the specific calculation steps are as follows.

3.2.1. Determination of subjective weights

In this paper, the AHP is improved by using the optimal transfer matrix (Lu et al., 2017) to avoid the instability problem in the consistency test in the traditional AHP (Wang and Wang, 2018), and the specific calculation steps are as follows.

(1) Define the problem and build a hierarchical model

The water resource carrying capacity evaluation index system is divided into 3 levels: the top level is the target level (water resource carrying capacity), the second level is the guideline level (corresponding to the evaluation index), and the third level is the indicator level (corresponding to the evaluation object), as listed in Table 1.

(2) Construct the decision matrix

To calculate the relevant weights, the AHP method requires the relationships between indicator pairs to be determined by constructing a judgment matrix (Ruan et al., 2019). The judgment matrix reflects the importance of each element, and the order of importance of each evaluation index is determined by comparing the indicators. The '1-9′ scale method is used to construct the judgment matrix $A = (a_{ij})_{t\times t}$. The specific meaning of the '1-9′ scale is shown in Table 2.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{bmatrix}_{t\times t} \tag{1}$$

In the formula, a_{ij} denotes the valuation obtained by comparing elements a_i and a_j with the '1-9' scale method and t is the number of ranks of the matrix.

(3) Transform the judgment matrix into an antisymmetric matrix $B = (b_{ij})_{t\times t}$

$$b_{ij} = \lg a_{ij} \tag{2}$$

In the formula, lg is the logarithmic function (log10).

(4) Establishment of the optimal transfer matrix

The optimal transfer matrix $C = (c_{ij})_{t\times t}$ is obtained by solving for the antisymmetric matrix B, which in turn can be used to construct the optimal transfer matrix $E_{ij} = (e_{ij})_{t\times t}$.

$$c_{ij} = \frac{1}{t}\sum_{k=1}^{t}\left(b_{ik} - b_{jk}\right) \tag{3}$$

$$e_{ij} = 10^{C_{ij}} \tag{4}$$

(5) Determine the index weights

The square root method is used to obtain the weight coefficient $F=(f_{ij})_{t\times t}$.

$$f_i = \left(\prod_{j=1}^{t} e_{ij}\right)^{\frac{1}{t}} \tag{5}$$

The weights g_i are further calculated to obtain the following expression.

$$g_i = \frac{f_i}{\sum_{i=1}^{t} f_i} \tag{6}$$

3.2.2. Determination of objective weights

In this paper, the anti-entropy weighting method is used to calculate the objective weights, thus avoiding the issues encountered in the traditional entropy weighting method, which is prone to producing extreme weights due to the excessive sensitivity of the disorder degree of indicators (Ding et al., 2019). The specific calculation steps are as follows.

(1) Construction of the evaluation index matrix

With m indicators and n evaluation objects, the raw data matrix $X=(x_{ij})_{m\times n}$ is constructed, where x_{ij} denotes the i-th evaluation index and the j-th evaluation object's original data. The specific formula for matrix X is as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} \\ x_{21} & x_{22} & \cdots & x_{2j} \\ \vdots & \vdots & & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} \end{bmatrix}_{m\times n} \tag{7}$$

(2) Standardization of data

The positive and negative indicators are normalized to obtain separate standardized results, and the corresponding formulas are

$$\text{Positive indicator}: \ y_{ij} = \left(x_{ij} - x_{jmin}\right)/\left(x_{jmax} - x_{jmin}\right) \tag{8}$$

$$\text{Negative indicator}: \ y_{ij} = \left(x_{jmax} - x_{ij}\right)/\left(x_{jmax} - x_{jmin}\right) \tag{9}$$

Calculate the anti-entropy of each evaluation index h_j'

$$h_j' = -\sum_{k=1}^{n} p_{jk}\ln\left(1 - p_{jk}\right) \tag{10}$$

In formula $p_{jk} = y_{jk}/\sum_{k=1}^{n} y_{jk}$, ln is a logarithmic function (log e).

(3) Determine the objective weights of indicators

The anti-entropy values are normalized to obtain the anti-entropy of each evaluation index weight, which is the objective weight.

$$r_j = h_j'/\sum_{j=1}^{m} h_j' \tag{11}$$

3.2.3. Improved TOPSIS model

The improved TOPSIS model is constructed based on the subjective and objective weights obtained, as follows.

(1) Construction of the weighted normalized evaluation matrix

The original data are processed with equations (8) and (9) to obtain the dimensionless matrix z_{ij} and the final weights of indicators are determined with the improved AHP–anti-entropy weighting method. Then, the dimensionless evaluation matrix is weighted to construct the weighted normalized evaluation matrix.

$$W = (w_{ij})_{mn} = (\omega_{ij} z_{ij})_{mn}$$

$$i = 1,2,\ldots,m; j = 1,2,\ldots,n; \tag{12}$$

where ω_{ij} is the final weight value obtained through a linear combination of subjective weight g and objective weight r, $\omega_{ij} = \Delta g + (1-\Delta) r$, Δ is the combination coefficient, $(0 < \Delta < 1)$, and in general, Δ takes a value of 0.5 (Chen et al., 2019; Yu et al., 2020).

(2) Determine the positive and negative ideal points

The positive ideal point is based on the set of values of each indicator that yields the best result, and the negative ideal point is based on the set of values of each indicator that yields the worst result. After the original data are transformed to become dimensionless, the positive and negative ideal points of the positive and negative indicators can be calculated using the following formula.

$$\begin{cases} w_j^+ = \max\left\{w_{1j}, w_{2j}, \cdots, w_{mj},\right\} \\ w_j^- = \min\left\{w_{1j}, w_{2j}, \cdots, w_{mj},\right\} \end{cases} \tag{13}$$

In the formulas, w_j^+ is the positive ideal point and w_j^- is the negative ideal point.

(3) Calculating the integrated metric distance

The distance of each evaluation index from the positive and negative ideal points is calculated as follows.

$$D_j^+ = \sqrt{\sum_{i=1}^{m}\left(w_{ij} - w_j^+\right)^2} \tag{14}$$

$$D_j^- = \sqrt{\sum_{i=1}^{m}\left(w_{ij} - w_j^-\right)^2} \tag{15}$$

Table 2
1–9 proportion scale table.

Numerical scale	Definition
1	Equal significance between the two factors
3	Slight significance of one factor over the other
5	Strong significance of one factor over the other
7	Dominance of one factor over the other
9	Absolute dominance of one factor over the other
2,4,6,8	Intermediate values between those defined above

(4) Calculation of closeness

The closeness reflects the proximity of each scheme to the optimal scheme. The higher the value of closeness is, the better the scheme used to evaluate the water resource carrying capacity is. The formula for the closeness H of each evaluation scheme is:

$$H_j = D_j^- / \left(D_j^+ + D_j^-\right) \tag{16}$$

3.2.4. Establishing the level of the water resource carrying capacity

To reflect the evaluation results more directly, the water resource carrying capacity is divided, with different grades corresponding to different water resource carrying capacity. Based on international and national standards, the socioeconomic development and water resource conditions in the study area and the results of existing studies, the grading criteria for the water resource carrying capacity (Ge et al., 2021; Zhao et al., 2018) in the study area were determined, as shown in Table 3. Finally, the water resource carrying capacity grades in of the study area are obtained with the improved TOPSIS approach, as shown in Table 4.

The closeness values are divided into 5 grades. A grade I water resource carrying capacity is excellent; notably, water resources are in a strong state with no pressure, water resource development and utilization are low, and the development potential is high. In grade II, water resources are in a weak state of no pressure, and water resources are available to meet development needs. A grade III water resource carrying capacity is moderate, water resources and social and economic development are in a balanced state, the use of water resources is limited to a certain scale, and there is some potential for future development. Grade IV water resources are in a certain pressured state, the water resource carrying capacity has reached a certain threshold, and further development and utilization are generally limited. The grade V water resource carrying capacity is very poor, water resources are in a high pressure state, the water resource carrying capacity is close to maximized, and potential water resource-related development and utilization are extremely limited. In some cases, the supply of water resources cannot meet the needs of society and the economy, affecting the social, economic and ecological development of the city.

Table 3
Evaluation criteria for the water resource carrying capacity in the eastern region of Heilongjiang.

Indicator levels	I	II	III	IV	V	IV
Per capita water resources (R_1)	≧2400	1800 ~ 2400	1000 ~ 1800	500 ~ 1000	300 ≃ 500	<300
Per capita water resource usage (R_2)	<500	500 ~ 1000	1000 ~ 1200	1200 ~ 1500	1300 ≃ 1500	1500<
Water production coefficient (R_3)	≧0.6	0.5 ~ 0.6	0.4 ~ 0.5	0.3 ~ 0.4	0.2 ≃ 0.3	<0.2
Water supply modulus (R_4)	<1	1 ~ 3	3 ~ 10	10 ~ 15	12 ≃ 15	15<
Urban per capita daily domestic water consumption (R_5)	<130	130 ~ 150	150 ~ 170	170 ~ 300	190 ≃ 300	300<
Population growth rate (R_6)	<2	2 ~ 4	4 ~ 6	6 ~ 10	8 ≃ 10	10<
Total annual production water consumption (R_7)	<40	40 ~ 45	45 ~ 50	50 ~ 65	60 ≃ 65	65<
Total annual domestic water consumption (R_8)	<5	5 ~ 6	6 ~ 8	8 ~ 10	9 ≃ 10	10<
Per capita GDP (R_9)	≧80000	7000 ~ 30,000	4000 ~ 7000	3000 ~ 4000	0 ≃ 3000	≧0
Proportion of primary industry (R_{10})	<5	5 ~ 10	10 ~ 15	15 ~ 30	20 ≃ 30	30<
Water consumption per 10 thousand RMB GDP (R_{11})	<20	20 ~ 50	50 ~ 100	100 ~ 300	200 ≃ 300	300<
Proportion of water used for agricultural irrigation (R_{12})	<10	10 ~ 20	20 ~ 40	40 ~ 60	50 ≃ 60	60<
Ecological water consumption (R_{13})	<1	1 ~ 2	2 ~ 3	3 ~ 5	4 ≃ 5	5<
Daily sewage treatment capacity (R_{14})	≧15	7.5 ~ 10	5 ~ 7.5	2.5 ~ 5	0 ≃ 2.5	≧0
Urban greening coverage rate (R_{15})	≧50	20 ~ 40	10 ~ 20	5 ~ 10	0 ≃ 5	≧0
Percentage of groundwater extraction (R_{16})	<10	10 ~ 20	20 ~ 30	30 ~ 50	40 ≃ 50	50<

4. Results

4.1. Results of the weight calculations

According to the data from each region and the aforementioned approach, the subjective weights were calculated using the improved AHP, and the objective weights were calculated using the anti-entropy weighting method. The final weight results were obtained by linearly combining the calculations. The results of the weight calculations are provided in Table 5.

4.2. Analysis of the results of the water resource carrying capacity evaluation

4.2.1. Temporal variation pattern

The data from each region and the final calculated weights were input into the TOPSIS model to determine the comprehensive evaluation value of the water resource carrying capacity in the eastern region of Heilongjiang Province from 2009 to 2018, as shown in Fig. 2. Additionally, to fully reflect the water resource carrying capacity in the entire study area, the average value of each evaluation indicator in the eastern region of Heilongjiang was calculated as a reference and evaluated. Through the comparative analysis in Table 4, the water resource carrying capacity levels in the eastern region of Heilongjiang in different years were obtained, and the specific results are shown in Table 6.

Table 6 and Fig. 2 indicate that the overall water resource carrying capacity in eastern Heilongjiang was in a relatively stable state from 2009 to 2018 and was mainly classified as grade III (Moderate). The average multiyear water resource carrying capacity from 2009 to 2018 varied from best to worst in the following order: 2016, 2017, 2009, 2015, 2010, 2013, 2018, 2014, 2012, and 2011. The best and worst water resource carrying capacity states were observed in 2016 and 2011, with evaluation values of 0.4783 and 0.4223, respectively. In general, the comprehensive level of the water resource carrying capacity remained relatively stable. The evaluation value was 0.4223 in 2011, which was lower than the average value in other years. Mainly, rainfall

Table 4
Classification standard for the water resource carrying capacity grades.

Grade	Grade description	Closeness	Grade	Grade description	Closeness
I	Excellent	0.7 ~ 1.0	IV	Poor	0.2 ~ 0.3
II	Good	0.5 ~ 0.7	V	Very poor	0 ~ 0.2
III	Moderate	0.3 ~ 0.5			

Table 5
The weights of the evaluation indexes.

Indexes	Subjective weights	Objective weights	Final weights	Indexes	Subjective weights	Objective weights	Final weights
R11	0.0537	0.0579	0.0558	R31	0.0498	0.0520	0.051
R12	0.0485	0.0576	0.0531	R32	0.0419	0.0751	0.059
R13	0.1224	0.0597	0.0911	R33	0.0352	0.0573	0.046
R14	0.1564	0.0584	0.1074	R34	0.0838	0.1021	0.093
R21	0.0368	0.0511	0.0440	R41	0.0137	0.0471	0.030
R22	0.1071	0.0526	0.0799	R42	0.0281	0.1144	0.071
R23	0.0575	0.0555	0.0565	R43	0.0427	0.0549	0.049
R24	0.0968	0.0479	0.0724	R44	0.0254	0.0565	0.041

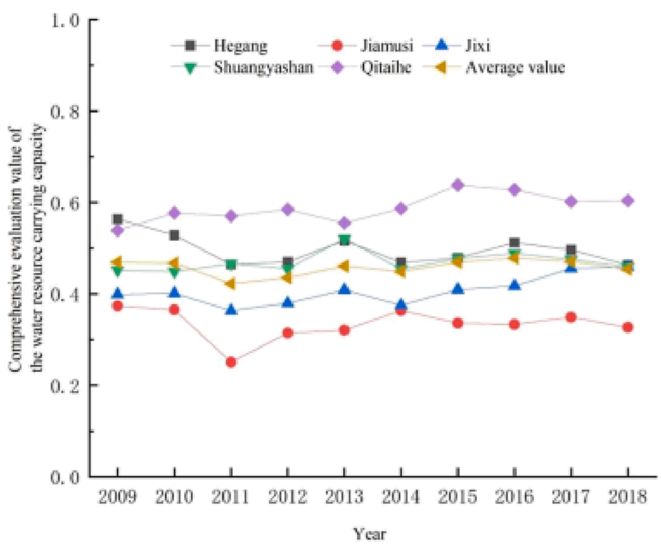


Fig. 2. Comprehensive evaluation value of the water resource carrying capacity.

Table 6
Water resource carrying capacity from 2009 to 2018.

Year	Closeness	Grade	Year	Closeness	Grade
2009	0.4694	III	2014	0.4488	III
2010	0.4674	III	2015	0.4692	III
2011	0.4223	III	2016	0.4783	III
2012	0.4352	III	2017	0.4708	III
2013	0.4608	III	2018	0.4543	III

was relatively low that year, and the total water supply was lower than that in other years. In 2016, the carrying capacity of water resources reached the best state, which was close to grade II (Good). In that year, the per capita water supply was adequate, and the water production coefficient was large (Fig. 3).

4.2.2. Spatial variation pattern

According to the results of the annual water resource carrying capacity evaluation value of each region, the average evaluation value of the water resource carrying capacity of each region for multiyear was calculated. Then, the grades were obtained according to Table 4, and the final results are shown in Table 7 and Table 3. Additionally, the carrying capacity evaluation values of subsystems in different areas were calculated, as shown in Fig. 4.

Table 7 shows similar evaluation results based on the water resource carrying capacity in different parts of the eastern region of Heilongjiang. The Qitaihe and Hegang areas exhibited relatively good water resource carrying capacity evaluation values of 0.5886 and 0.4962, respectively, which were higher than the values in other regions. The pressure on water resources is relatively low in these areas, and the water needs for social and economic development are met, with room for further development. However, the water resource carrying capacity is relatively low in Shuangyashan, Jixi, and Jiamusi, and water resources and socioeconomic development have reached a state of balance. Water resources can meet the basic demands of industrial and agricultural production and everyday life. However, there will be a certain pressure on the water resource carrying capacity if the demand for water resources

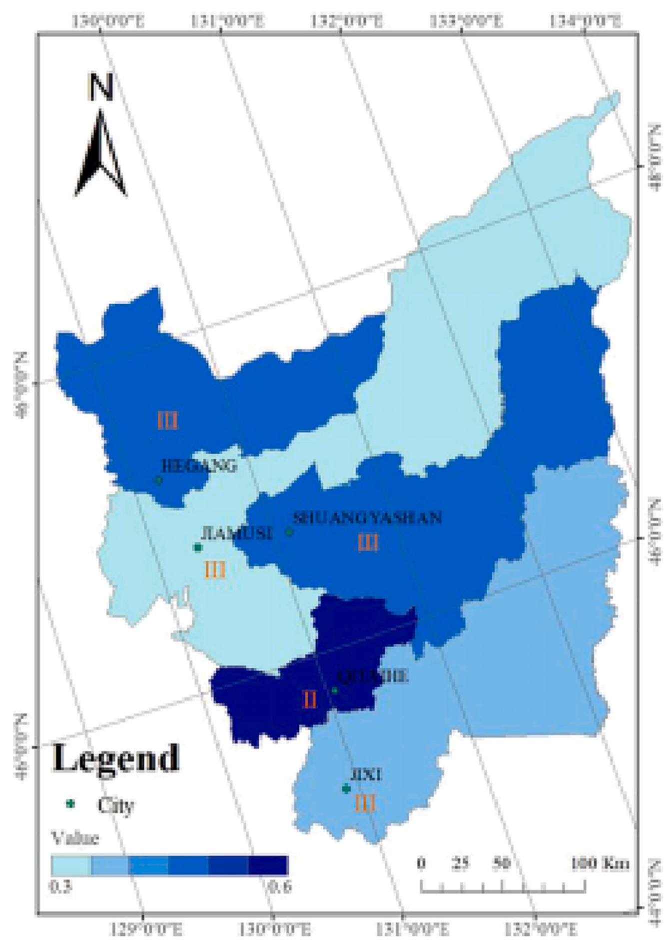
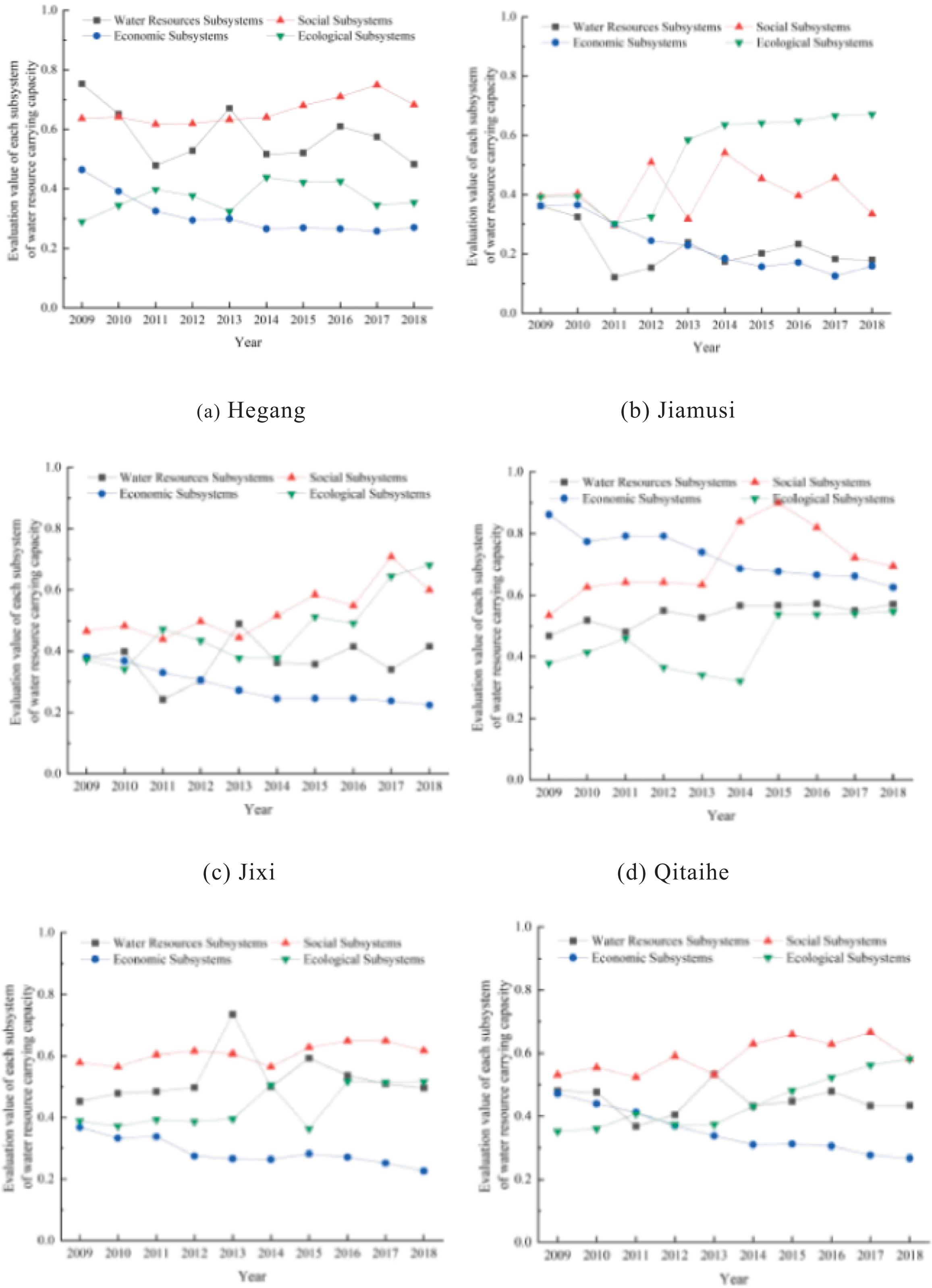


Fig. 3. Spatial distribution of the water resource carrying capacity from 2009 to 2018.

Table 7
Comprehensive evaluation of the water resource carrying capacity from 2009 to 2018 in each region.

Region	Closeness	Grade	Region	Closeness	Grade
Hegang	0.4962	III	Shuangyashan	0.4697	III
Jiamusi	0.3334	III	Qitaihe	0.5886	II
Jixi	0.4069	III	Average value	0.4557	III



(a) Hegang (b) Jiamusi (c) Jixi (d) Qitaihe (e) Shuangyashan (f) The eastern region of Heilongjiang

Fig. 4. Evaluation values of the subsystems of the water resource carrying capacity.

increases.

4.2.3. Variation in each subsystem

The carrying capacity results for each subsystem are shown in Fig. 4. In general, the results in the eastern region of Heilongjiang are relatively good during the study period. The water resource subsystem remained stable overall. The score for the social subsystem was generally good and remained stable. In contrast, the scores were slightly worse for the economic subsystem evaluation, but the trend improved after 2014. Moreover, the scores were relatively good for the ecological subsystem, and the trend has been improving since 2012.

An analysis of the water resource subsystem assessment values was conducted for each region. In terms of the water resource subsystem, the evaluation results vary in different regions in terms of the water resource carrying capacity. The best evaluation value was observed in the Hegang region at 0.5789, which was higher than the average value of 0.4489. This result suggests that the Hegang region is characterized by a better water resource situation than the other regions. The evaluation results in this area fluctuate slightly over the study period but are mainly within the same level. In certain years, the evaluation results were higher or lower, mainly due to the influence of the heterogeneous spatial and temporal distributions of water resources. The evaluation results are similar in different regions in terms of the social subsystem, generally at grade III (Moderate) based on the multiyear average. The evaluation results fluctuate to different degrees at different times in the same region, with an overall upward trend, suggesting that the social development levels are generally similar in the eastern region of Heilongjiang and that social development is steady and progressive. The average evaluation value is 0.3502 for the economic subsystem carrying capacity, and the evaluation grade is III (Moderate). This evaluation result is close to average, but the potential for future economic development is enormous because agriculture is the main industry in the eastern region of Heilongjiang. Other regions also displayed a gradual trend toward enhanced development after the economic adjustment in 2014. As an important city in the eastern region, Jiamusi city has certain development prospects in the future. The average evaluation value is 0.4446 for the ecological subsystem in the eastern region of Heilongjiang, and the corresponding grade is III (Moderate). These results suggest that there has not been much change in the ecological environment in the eastern region of Heilongjiang. During the study period, the evaluation results in each region generally gradually improved. The capacity improved year by year with the enhanced treatment of water and sewage in the ecological environment; additionally, the urban green coverage rate has remained stable, and groundwater exploitation is controlled to some extent. Overall, a good development trend was displayed by the ecological environment in general.

5. Discussion

5.1. Identification of the factors that influence the water resource carrying capacity in the eastern region of Heilongjiang Province

At the guideline level, the weights are calculated for the evaluation indexes in the four subsystems of the water resource carrying capacity evaluation system, and the ratio of each of these weights to the total weight is shown in Fig. 5. The influence of each subsystem on the water resource carrying capacity in the study area is relatively close, and there are no indicators that have a very high impact on the overall water resource carrying capacity, as shown in Fig. 5. Among the subsystems, the water resource subsystem has the largest influence on the water resource carrying capacity, and the ecological subsystem has the smallest influence. The influence is moderate for the social and economic subsystems. These differences are mainly due to the heterogeneous distribution of regional water resources.

At the indicator level, the calculated final weights are ranked and analyzed, and the effects of the indicators on the water resource carrying capacity are compared; the larger a weight value is, the greater the influence of the corresponding evaluation indicator. Fig. 6 shows that the highest weights are assigned to the water supply modulus (R_4) and the proportion of water used for agricultural irrigation (R_{12}). Relatively small weights are observed for the percentage of groundwater extraction (R_{16}) and ecological water use (R_{13}). This is in line with the actual conditions, as the the eastern region of Heilongjiang has abundant water resources, with a high proportion of water used for agriculture and less water used for the ecological environment.

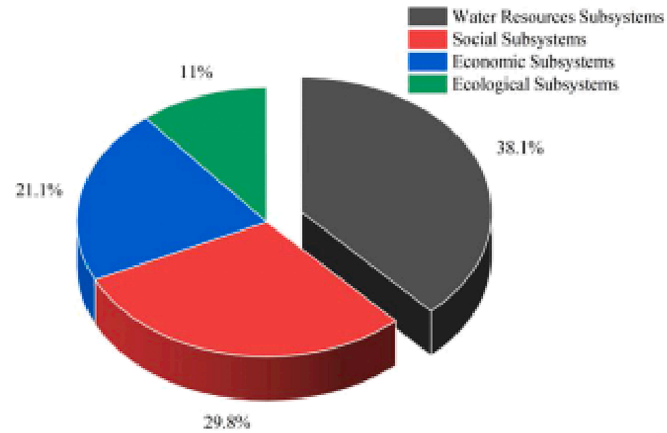


Fig. 5. Weight comparison for the water resource carrying capacity subsystems.

5.2. Analysis of the variability in factors that influence the water carrying capacity of each city

The impact of subsystems in each region on the overall water resource carrying capacity is analyzed in Fig. 4. The greater the proportion of the subsystem evaluation value is, the greater the degree of influence. The Hegang area is most influenced by water resource constraints, and the water resources in this area are relatively abundant. The Jiamusi region is most significantly affected by ecological factors. From the results, the value of ecosystem evaluation is increasing in the Jiamusi region, mainly due to the improvement of the sewage treatment capacity and the stabilization of the urban greening rate. Shuangyashan and Jixi are most influenced by social factors, and the population growth rate is the most important factor. Qitaihe is most influenced by economic

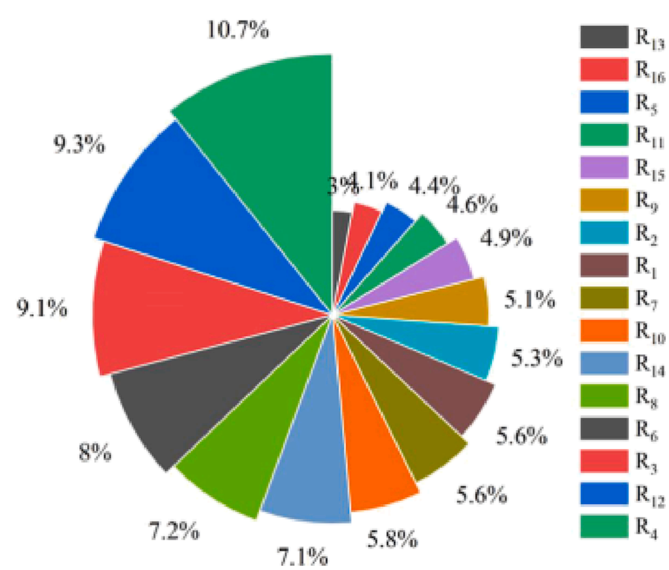


Fig. 6. Importance of water resource carrying capacity evaluation indicators.

factors, including economic and industrial structures. Moreover, there is much room for industrial adjustment in Qitaihe.

5.3. Comparative analysis

5.3.1. Weight comparison of water resource carrying capacity

In water resource carrying capacity evaluations, the weights of evaluation indexes affects the accuracy and reasonableness of the final results. Therefore, the weights are calculated with the AHP-entropy method (unmodified weight) and compared with those obtained with the improved AHP-anti-entropy weight method, as shown in Fig. 7.

As shown in Fig. 7, the weights calculated with the unimproved method display obvious variation, with weights ranging from 0.01 to 0.138. The weights obtained after the improvement are more evenly distributed, with weights ranging from 0.3 to 0.107. Without improvement, the weights of the proportion of water used for agricultural irrigation (R_{12}) and the daily sewage treatment capacity (R_{14}) were 12.6% and 13.8%, respectively, and that for ecological water consumption (R_{13}) was 1%. After improvement, the weights of R_{12}, R_{14} and R_{13} were 9.3%, 7% and 3%, respectively. The improved method avoids the appearance of excessive weights and is more accurate and reasonable. It ensures that more realistic results of water resource carrying capacity evaluation can be obtained.

5.3.2. Comparative analysis

In general, the water resource carrying capacity was classified as good in the eastern region of Heilongjiang during the study period, reaching grade III (Moderate); additionally, the water resource carrying capacity remained stable in general. To verify the reliability of the evaluation results of the model proposed in this paper, the results were analyzed by comparing them with those previously obtained using a gray correlation model (Kang and Song, 2014) and a projection pursuit model (Jiang et al., 2011), and the results are shown in Table 8.

As shown in Table 8, the overall evaluation result of the water resource carrying capacity in the eastern region of Heilongjiang is grade III (Moderate), which is basically similar to the research results of the previous studies. However, there are some differences in the evaluation results for Shuangyashan. The results of the projection pursuit model for Shuangyashan are II (Good), and the research period is 2008, thus, considering the difference in study period, the results are relatively close, indicating that the model in this paper is reasonable and that the evaluation results are reliable.

6. Conclusions

In this study, according to the characteristics of the study area, the proportion of primary industry and the proportion of water used for agricultural irrigation were selected as evaluation indicators to construct the evaluation system. Sixteen indicators were identified from four perspectives, namely, water resources, society, the economy and ecology, to build a comprehensive evaluation system of the water resource carrying capacity, and the eastern part of Heilongjiang was selected as the study area. An evaluation based on the TOPSIS model was adopted, and the weights were determined by combining the improved AHP and the inverse entropy weighting method. This approach avoids the instability problem in the consistency test in the traditional AHP and the extreme weighting problem in the traditional entropy weighting method, thus yielding more accurate and reasonable weights and more realistic evaluation results for the water resource carrying capacity.

The overall evaluation result is grade III (Moderate) for the water resource carrying capacity in eastern Heilongjiang, ranging from grade II (Good) in Qitaihe city to grade III (Moderate) in other areas. Overall, the water resource and societal factors have an obvious influence on the water resource carrying capacity in the eastern region of Heilongjiang. The influential factors vary in different areas, and the Hegang area is most influenced by water resources. The Jiamusi region is most affected by ecological factors. In addition, social factors have the greatest influence in the Shuangyashan and Jixi regions, while economic factors have the largest influence in the Qitaihe area. The water supply modulus and proportion of water used for agricultural irrigation have a large impacts on the water carrying capacity in the study area.

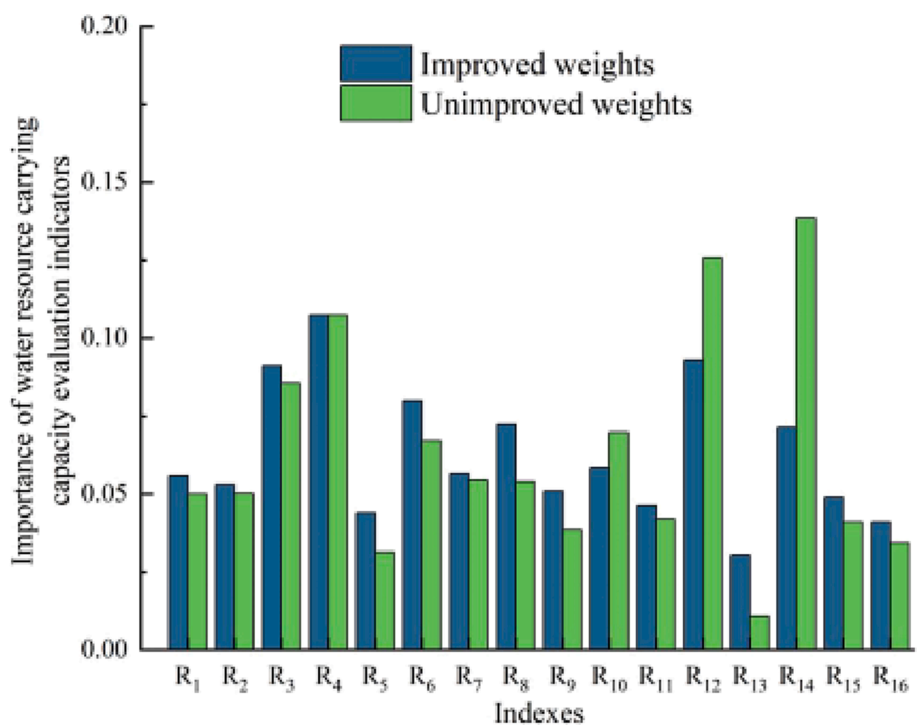


Fig. 7. Comparison of weights of water resource carrying capacity indicators.

Table 8
Comparison of the water resource carrying capacity evaluation results.

Model	Hegang	Jiamusi	Jixi	Shuangyashan	Qitaihe	The eastern region of Heilongjiang
Model evaluation	III	III	III	III	II	III
Grey correlation model	III	III	III	III	II	III
Projection pursuit model	III	III	III	II	II	III

CRediT authorship contribution statement

Bo Lv: Conceptualization, Methodology, Investigation, Writing – original draft, Formal analysis. **Changrong Liu:** Conceptualization, Project administration, Resources, Writing – original draft. **Tianxiao Li:** Conceptualization, Methodology, Investigation, Resources, Funding acquisition. **Fanxiang Meng:** Methodology, Resources, Writing – review & editing, Funding acquisition. **Qiang Fu:** Writing – review & editing. **Yi Ji:** Writing – review & editing. **Renjie Hou:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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