DYNAMIC EVALUATION AND REGULATION OF WATER CARRYING STATE USING A COUPLED ITERATIVE METHOD

by

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The water carrying capacity and the water carrying state are two similar concepts, and there are no clear boundaries between them, so there exists confusion during the evaluation process. Additionally, current evaluation methods cannot meet the dynamic change requirements under different control measures. This study emphasizes the difference between the two concepts and points out that the core of the water carrying capacity is the determination of thresholds. In contrast, that of the water carrying state is a state evaluation. A coupled iterative model is proposed based on the extended Fourier amplitude sensitivity test algorithm and a modified state-space method. In order to evaluate and regulate the water carrying state dynamically, the iterative calculation is introduced into the evaluation of the water carrying state. During the iterative process, the water resources in the non-overloaded area are allocated to the surrounding adjacent overloaded areas until the water resource carrying state of the original overloaded area reaches an acceptable level, and the total amount of water resources allocation during multiple iterations is given. In this study, we take Jilin Province as the research object. We hope that the iterative coupling model of the water carrying state proposed in this paper can be widely applied in the future.

Key words: *water carrying capacity, dynamic evaluation and regulation, coupling iterative model, Jilin Province*

Introduction

Water carrying state and water carrying capacity are two very similar concepts, and there are confusions during the evaluation process. However, there is a slight difference between them. In short, the latter emphasizes the maximum scale of the economy or population that the number of water resources in a particular area can support. The core of water carrying capacity is the determination of thresholds [1, 2]. In 2019, some researchers clearly gave the meaning of the state of water resources carrying, and they believed that water carrying status is a comprehensive indicator for judging the interaction between water resources carrying subjects (water resources systems) and carrying objects (economic and social systems, ecological environment systems) in the process of social development [3]. Quite obvious, the core of water carrying status is state evaluation. As an important part of sustainable development, effective management of water resources has always been the focus of academic re-

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search [4-6]. Because of the confusion between water carrying capacity and water carrying state, a large part of the research on the evaluation of the water carrying capacity studies belongs to the research of water carrying state in nature.

With the increasing awareness of water resources management, more and more methods have been introduced in the research of water carrying capacity and water carrying states. For example, system dynamics methods [7], cloud models [8], cellular automata [9], neural networks [10], evidence integration credal classification algorithm [11], robust finite horizon filtering for stochastic uncertain data [12], and distributed state estimation [13]. A complete review on various methods is available in [14].

Even though there are many methods currently, it is still difficult for the current methods to meet the requirements of real-time dynamic evaluation [15, 16]. In the past, most researches focused on the evaluation of the current state of water resources carrying and gave corresponding suggestions based on the evaluation results, but few studies tracked and evaluated the state of water resources carrying after taking these recommendations. Therefore, it is necessary to introduce an iterative idea into the assessment of water carrying.

Data and methods

Study area

This study selected Jilin Province of China as the study area. Jilin Province is located in northeastern China, between 121°38’ E to 131°19’ E and 40°52’ N to 46°18’ N. It has nine cities under its jurisdiction: Baicheng, Songyuan, Changchun, Siping, Jilin, Liaoyuan, Tonghua, Baishan, and Yanbian. The location of Jilin Province in the country and the geographic locations of the nine cities are shown in fig. 1. It is worth noting that Jilin is the only city in China with the same name as the province. Therefore, in this research, if we say *Jilin Province*, it means Jilin Province; otherwise, Jilin refers to Jilin City.

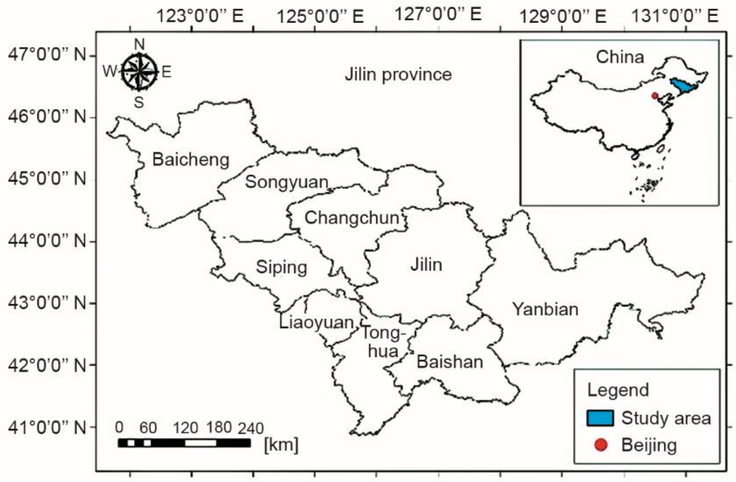

Figure 1. The geographic location of Jilin Province

Data description

The selection of evaluation indicators is directly related to whether the evaluation results are reasonable, so the selection of indicators is very important.

In this study, the indicators were selected from two aspects: water resource pressure force and water resources support force. In terms of support force, the selection of indicators is mainly based on the amount of water available in the region. The amount of water available in a region is based on the total amount of water resources in the region. The total amount of water that can be provided to ecological, production, and living space for water consumption under certain requirements. The selection of indicators in terms of water resource pressure is mainly based on regional water consumption. Regional water consumption is the total amount of ecological water, domestic water and production water in the region, which is closely related to population, economy, and ecological environment. The meaning of each indicator is shown in tab. 1.

Table 1. Index system for evaluating water carrying state

	Indicators	Mark	Indicator illustrator
Support force	Total water resources	I1	Surface and underground water production from precipitation
	Surface water resources	I2	The total surface runoff generated by precipitation in a certain period of time
	Groundwater resources	I3	Amount of water stored below the surface
	Water resources per capita	I4	Water resources per capita
	Precipitation	I5	The depth of liquid and solid precipitation that has fallen from the sky to the ground within a year without accumulating on the horizontal plane without evaporation, infiltration and loss
	Storage capacity of large and medium-sized reservoirs	I6	Reflect the storage capacity of the regional reservoir
Pressure force	Population density	I7	Population living on per unit area of land
	Surface water development rate	I8	Surface water supply as a percentage of surface water
	Groundwater development rate	I9	Ratio of groundwater supply to groundwater resources
	Water consumption per 10000 Yuan of agricultural output value	I10	Water resources consumption for 10000 Yuan of agricultural output value
	GDP per capita	I11	Reflect the level of regional economic development
	Water consumption per 10000 Yuan of GDP	I12	Water resources consumption per 10000 Yuan of GDP
	Water consumption per 10000 Yuan added value	I13	Water resources consumption per 10000 Yuan of industrial added value
	Water consumption per capita	I14	Amount of water used per capita in the area

It is worth noting that the indicators are mainly water quantity indicator, while, water quality indicators, such as the natural degradation of water environmental pollutants and the discharge of water environmental pollutants, are also very good indicators that can evaluate water carrying state. However, because it does not meet the principle of availability when selecting indicators, this study did not select such indicators.

This study uses 2017 as the base year for evaluation. The data used in this research are from the Jilin Provincial Statistical Yearbook, the Jilin Provincial Water Resources Bulletin, the Jilin Provincial Long-Term Water Supply and Demand Planning, the Chinese Academy of Sciences Resource Environment Cloud Platform, the EARTHDATA database, *etc.*

Methodology

Based on the understanding of water carrying state in this study, we propose a coupled iterative model for optimizing the carrying state of water resources. The flow chart of the model is shown in fig. 2.

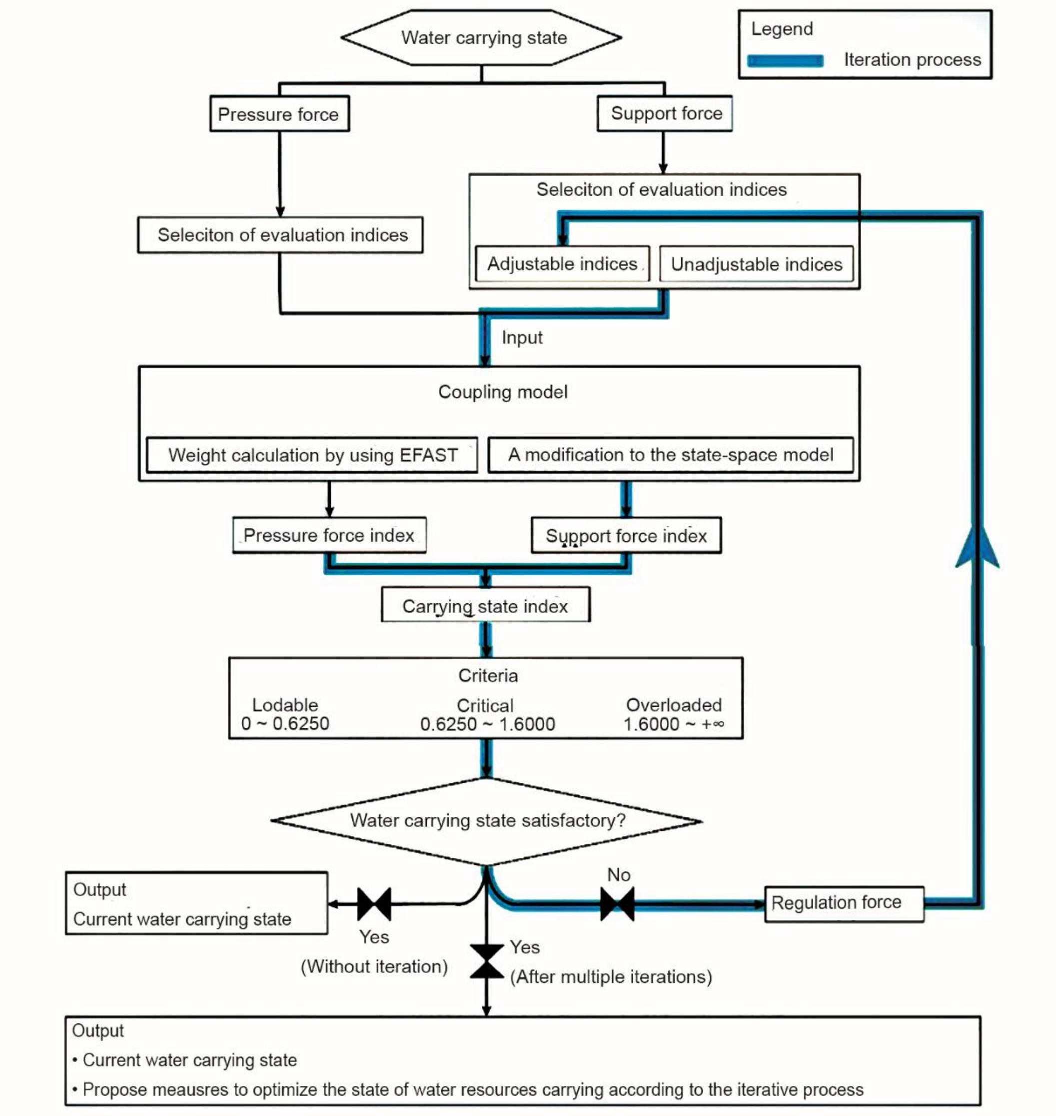

Figure 2. Flow diagram of the coupled iterative model

In this study, when the water carrying state index is greater than 1.6000, the water carrying state is defined as an overload state; when the water resource carrying state index being 1.6000-0.6250, the water carrying state is defined as a critical state and when the water resource carrying state index is less than 0.6250, we define that the current cater carrying state is loadable.

The weights of indicators have been calculated by using extended Fourier amplitude sensitivity test (EFAST) algorithm. The EFAST method is a global sensitivity analysis method based on variance decomposition, which is proposed by combining Sobol's method and Fourier amplitude sensitivity test method, that is, the sensitivity of the model output result can be reflected by the variance of the model result. In this method, the sensitivity of the model is divided into the sensitivity of the individual parameters acting independently and the sensitivity of the interactions between the parameters. Studies have shown that calculating weights using the EFAST algorithm is more scientific [17]. The EFAST algorithm is completed in SIMLAB software (https://ec.europa. eu/jrc/en/samo/simlab).

Water pressure force index and support index have been calculated by using a modified state-space method. State space method is a method of problem representation and solution based on solution space. The current state space method is:

$$SSI = \sqrt[n]{I_1 I_2 ... I_n} \tag{1}$$

where SSI is the state space index, and I_1 ... I_n – the value of the index I_1 ... I_n.

This study has modified the current state space method. Positive indicators are standardized by eq. (2), and negative indicators are standardized by:

$$V_i = \frac{I_i}{I_{\max}} \tag{2}$$

$$V_i = \frac{I_{\min}}{I_i} \tag{3}$$

where V_i is the result after the i^{th} evaluation index is standardized, I_i – the value of the index i, $I_{\min}$ – the minimum value of the index, and $I_{\max}$ – the maximum value of the index.

In fact, the balance between the various indicators should also be fully considered. In this study, the cosine of the angle between the multidimensional vector and the optimal vector formed by each evaluation index was used as a correction parameter to modify the current state space method. Therefore, the calculation process of our modified state space method is:

$$SSI = \frac{\sqrt[n]{V_1 V_2 ... V_n}}{\sqrt{n}} \frac{V_1 + V_2 + ... + V_n}{\sqrt{V_1^2 + V_2^2 + ... + V_n^2}} \tag{4}$$

The coupling model based on EFAST algorithm and modified state space method is as follows, eq. (5). The EFAST algorithm and improved state space method coupling model were used to calculate water pressure force index and water support force index:

$$PFI \text{ or } SFI = \frac{\sqrt[n]{V_1 w_1 V_2 w_2 ... V_n w_n}}{\sqrt{n}} \frac{V_1 w_1 + V_2 w_2 + ... + V_n w_n}{\sqrt{(V_1 w_1)^2 + (V_2 w_2)^2 + ... + (V_n w_n)^2}} \tag{5}$$

In the process of water carrying state index calculation, the ratio of water pressure force index and water support index is used as the water carrying status index:

$$WCSI = \frac{PFI}{SFI} \tag{6}$$

where WCSI is the water carrying state index.

When the water pressure force index exceeds 1.6000 times the water support force index, the water resource carrying state is considered to be overloaded. When there are overload areas in the evaluation area, from a geographical point of view, a certain proportion of water resources in the nearby carrying state index is less than 0.6250 is introduced as the regulation force to couple the EFAST algorithm with the improved state space method. However, if loadable areas are quite far from the overloaded areas, a certain proportion of water resources in the nearby carrying state index is in the range of 0.6250-1.6000 will also be introduced. The model performs repeated iterative calculations. When the carrying state index of the original overload area is between 0.6250 and 1.6000, the iteration is stopped, and the iterative process is arranged to give the minimum amount of water resources allocation. The water carrying state can be roughly divided into three scenarios, fig. 3.

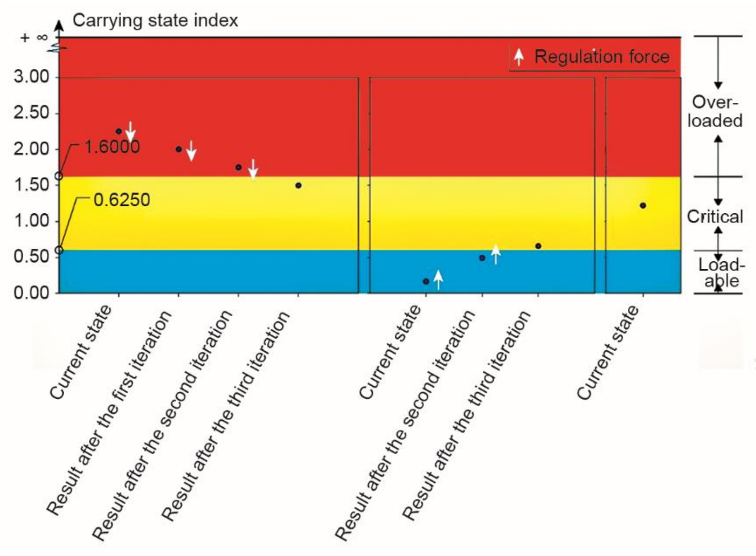

Figure 3. Changes of carrying state index of scenario hypothesis during iteration

Results

Results of weight calculation

Through EFAST algorithm, the weight of each indicator in terms of water resources support force is calculated, as shown in tab. 2. Since I2 (surface water resources) has the largest weight in the calculation of the support force index, that is, if the water support force of Jilin Province is to be regulated, the best way is to regulate the number of surface water resources.

Table 2. Results of weight calculation for support force indicators

I1	I2	I3	I4	I5	I6
0.1609	0.3061	0.1264	0.0191	0.1752	0.2123

Similarly, through the EFAST algorithm, the weights of various indicators in terms of water pressure force are obtained, as shown in tab. 3. It can be seen that among the indicators of water resource pressure in Jilin Province, I8 (surface water development rate) has the largest weight.

Table 3. Results of weight calculation for pressure force indicators

I7	I8	I9	I10	I11	I12	I13	I14
0.1425	0.3863	0.1600	0.0926	0.0131	0.0931	0.0782	0.0342

Water carrying index by city in Jilin Province

Figure 4 shows the water carrying state of each city in Jilin Province obtained in this study. Of all the nine cities: there are two cities with a water carrying state index greater than 1.6000, respectively, Liaoyuan and Songyuan. In other words, Songyuan and Liaoyuan belong to water resource overload areas.

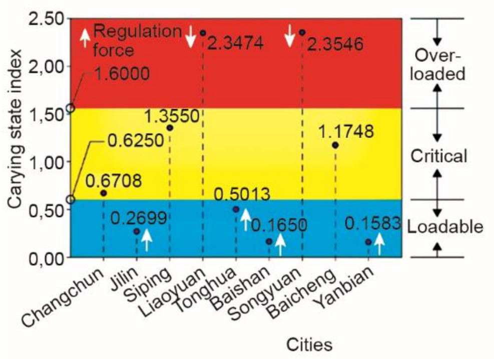

Figure 4. Evaluation results of water carrying status in Jilin Province

Plan of regulation and control for water carrying state

Judging from the weights of various indicators of water resources support, the most effective way and also a practical way is to adjust the number of surface water resources. According to the evaluation results of this study, there are two cities with overloaded water resources in Jilin Province, namely Liaoyuan and Songyuan, taking into account the geographical location and the state of water resources carried by the surrounding cities. In this study, it is planned to distribute surface water from Changchun to Songyuan, and distribute surface water from Jilin to Liaoyuan.

The distribution of water resources in Jilin Province is extremely unbalanced in space, and the spatial distribution of water resources is poorly co-ordinated with the regional economic and social development. The Jilin Provincial Water Resources Department, as the water resources management department of Jilin Province, has been very concerned about the development and utilization of water resources in Jilin Province. In recent years, the Jilin Provincial Water Resources Department has implemented two major water conservancy projects [18, 19], namely the Songyuan Irrigation District Water Supply Project, the Central City Water Diversion Project, fig. 5. The annual water transfer volume of the two projects is 1.040 billion cubic meters and 898 million cubic meters, respectively.

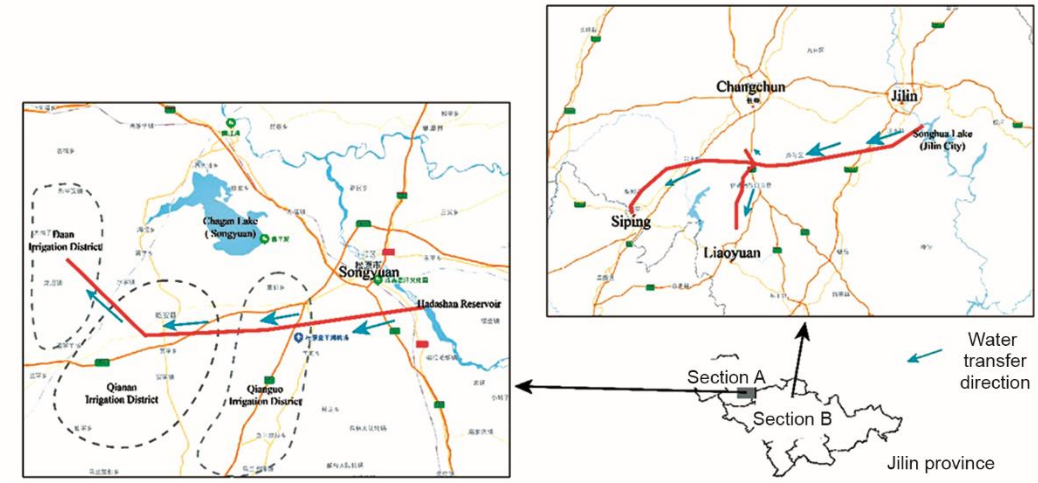

Figure 5. Water resource allocation plan of Jilin Province

Change of carrying state index of each city during iteration

According to the spatial deployment process of water resources and the coupled iterative model proposed in this study, the change process of the carrying state index and support force index in the iterative process of Changchun, Jilin, Songyuan and Liaoyuan is obtained, as shown in fig. 6. Obviously, during the overall iteration process, the water carrying index of Songyuan and Liaoyuan gradually decreased, and the water carrying index of Changchun and Jilin gradually increased.

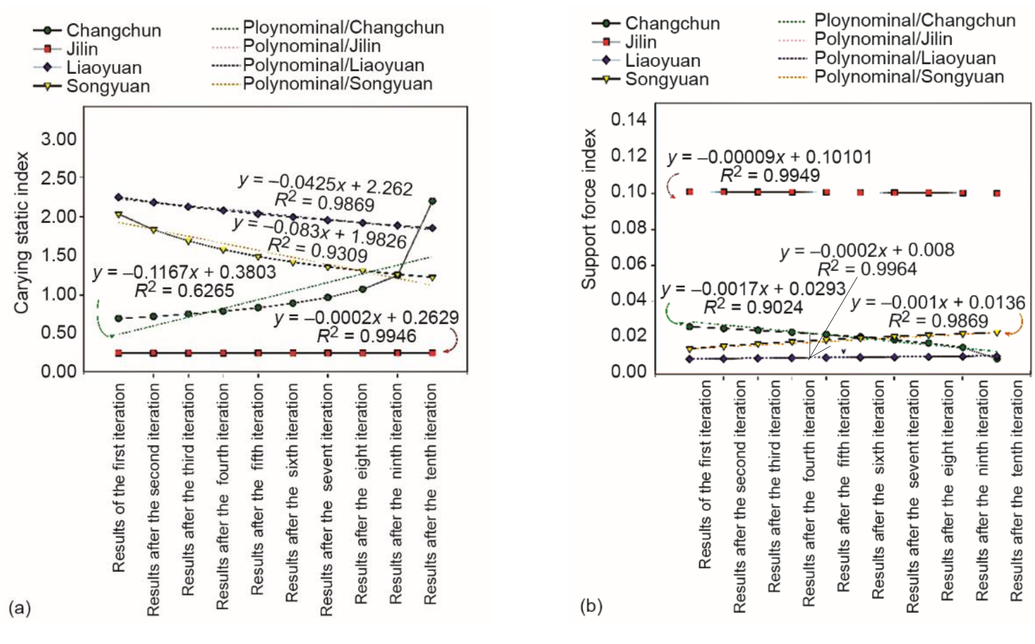

Figure 6. Carrying state index (a) and support force index (b) changes during iteration

Conclusion

Current research on water carrying state tends to ignore the reevaluation of the state after taking corresponding measures. In other words, it is still unclear to determine the extent to which the water carrying state can be improved after taking the related measures. Current evaluation methods cannot satisfy the urgent need for dynamic evaluation and regulation. This study proposes a coupled iterative method of dynamic water carrying state evaluation and regulation innovatively. This study takes Jilin Province of China as the research object, uses the EFAST algorithm to calculate evaluation indicators' weight, and improves the existing state-space method. The coupling model of EFAST algorithm and the improved state-space method is applied to the water carrying state of Jilin Province. The evaluation and iterations were carried out according to different water resources deployment schemes to calculate changes in the state of water carrying capacity after deployment. It is hoped that the coupled iterative model proposed in this study can be widely used in the evaluation of water carrying status or water carrying capacity in the future.

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