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Water resource optimization bi-level coupling model and carrying capacity of a typical plateau basin based on interval uncertainty stochastic programming

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ABSTRACT

The bi-level programming coupling model of uncertainty constraints and interval parameter programming is developed to optimize the allocation of water resources and conduct a comprehensive analysis of water resource carrying capacity. The model uses an uncertainty credibility number set and interval value to deal with uncertain factors, and analyses the water resources allocation of Longchuan River in central Yunnan. The competition mechanism and polynomial variation improved algorithm are used to analyze the water consumption, economic benefits and satisfaction in different planning periods when $\lambda = 0.7$, 0.8, 0.9, 1.0. The results show that the uncertain bi-level coupling model can cause changes in water allocation, pollutant discharge, system efficiency, etc., and can also effectively balance the mutual constraints between economic benefits and environmental pollution discharge, ensuring a good development trend in the planning year. The water diversion from other basins such as the Central Yunnan Water Diversion Project was transferred to Longchuan River Basin to increase the water supply, and the carrying capacity was further improved, with an increase of water resources by 25.9%. The model research has certain practical and strategic significance for maintaining the sustainable development of the ecological environment in the Longchuan River Basin

Key words: Bi-level programming, Improved sparrow search algorithm, Longchuan River, Model integration, Water resources

HIGHLIGHTS

- A bi-level programming coupling model of uncertainty-constrained programming and interval parameter programming is established.
- Competition mechanism and polynomial mutation improved algorithm is introduced.
- Select typical watersheds in central Yunnan, China, and solve the optimization model.
- Through the comprehensive analysis of water resources carrying capacity, the ideal evaluation results are obtained.

1. INTRODUCTION

Water is a precious resource for the sustainable development of the country. Global climate change and human activities directly threaten the water environment, increase the vulnerability of freshwater resources, and

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accelerate the contradiction between the supply and demand of water resources and also the shortage of water resources (Wang *et al.* 2022c). Climate change has aggravated the uneven spatio-temporal distribution of water resources and made it more difficult to allocate water resources. China's water resources are very scarce, the structure of water use is unreasonable, the water management system is not perfect, there are conflicts of interest, backward management and other issues, which have led to the increasingly prominent contradiction between supply and demand of water resources. Therefore, it is particularly important to establish an efficient water resources optimal allocation model to solve the complex water resources planning problem (Dong & Wang, 2012; Martinsen *et al.*, 2019).

The traditional research on the optimal allocation of water resources in China mainly involves cities (Meng *et al.*, 2020; Wei *et al.*, 2020; Chen *et al.*, 2021a), river basins (Han *et al.*, 2018; Banadkooki *et al.*, 2022; Wan *et al.*, 2023), cross-basins (Tian *et al.*, 2019; Kazemi *et al.*, 2020; Sun *et al.*, 2021) and optimal allocation of water resources based on the concept of sustainable development (Hu & Li, 2014). In the previous objective function settings, Zhang *et al.* (2020b) and Zhou (2022) mainly considered the minimum shortage of water resources, the maximum ecological and economic benefits as the goal, and coordinated the different water needs of various sources for residents' living, industrial production, agricultural irrigation, environmental protection, to achieve the optimal allocation of water resources between regions and basins. Kazemi *et al.* (2022) and Li *et al.* (2022a, 2022b) usually take the maximum water supply or water storage as the objective function of cross-basin water resources, and establish a multi-objective optimization model with the constraints of cross-basin project scale, multi-reservoir joint adjustment, and reasonable compensation mechanism, so that the cross-basin water resources optimization decision can be further developed. According to the research results of Hao *et al.* (2022) and Dou *et al.* (2022), the objective function is usually established under the conditions of maximum water demand, minimum water shortage, low water cost and others. In the case of the ecological environment as the key consideration, there are few studies on the setting of pollutant discharge as the objective function. For the optimal allocation model, there are many studies on the establishment of a single uncertain factor model, such as considering parameter calibration (Khosrojerdi *et al.*, 2019), interval boundary (Bekri *et al.*, 2015), fuzzy random (Banihabib *et al.*, 2019) and one-way evaluation after allocation. Compared with the research on multiple uncertain factors, Chen *et al.* (2021b) illustrated the effectiveness of the developed multi-level model through a practical case of the Wuhan metropolitan area. Li *et al.* (2021) and Bi *et al.* (2022) established a multi-objective water resources optimal allocation model based on an improved intelligent population optimization algorithm with economic, social and ecological benefits as objective functions, strengthening the comparative evaluation research before and after planning. It is a great progress in the research of optimal allocation of water resources.

In the cross-field, the optimal allocation of water resources breaks through the research on the traditional model, combining the environmental construction, the relationship mechanism between decision-makers and managers and the optimal calculation of data. Through the complex dynamic and stable evolution strategy (Lu *et al.*, 2022), the combination of the water environment mechanism model (Genova & Wei, 2023), and the introduction of low-carbon economic development (Wang *et al.*, 2022a), the gaps in water resources planning and management evaluation were filled.

Considering comprehensively, the bi-level programming model is established by the connection and influence of the upper structure and the lower structure. This model uses the intelligent optimization algorithm to obtain the global optimal solution and applies it to the actual case. The establishment of this model provides a scientific basis for studying the efficient use of water resources, water environment security and promoting socio-economic development.

2. RESEARCH MODELS AND ALGORITHMS

2.1. Bi-level programming model

The bi-level programming model is the most common mathematical model in the bi-level decision-making programming problem (Yao *et al.*, 2019; Gong *et al.*, 2022), focusing on solving problems such as system optimization in the hierarchical level of the bi-level programming structure. Both the upper structure and the lower structure can be regarded as two decision-making systems, each with its own objective function and constraint conditions, which influence each other and are independent of each other. The lower structure refers to a decision variable given by the upper structure, using the lower objective function and constraint conditions to solve an optimal solution, and then feedback to the upper structure to solve the overall optimal solution within the scope. The specific BP model calculation such as Formulas (1)–(4):

$$\min Z(x, y) = (Z_1(x, y), \cdots, Z_n(x, y)) \tag{1}$$

$$s.t. \quad G(x, y) \le 0 \tag{2}$$

$$\min z(x, y) = (z_1(x, y), \cdots, z_m(x, y)) \tag{3}$$

$$s.t. \quad g(x, y) \le 0 \tag{4}$$

where x is the upper structure decision variable, y is the lower structure decision variable, $Z(x, y)$ is the upper structure objective function, $z(x, y)$ is the lower structure objective function, $G(x, y)$ is the upper structure constraint condition, $g(x, y)$ and is the lower structure constraint condition.

According to the process of adopting the optimal solution, the upper structure influences the lower structure by setting x decision variables. The lower structure is a function of the variable $y = y(x)$ of the upper structure, and the specific steps are as follows:

Step 1. Calculate the upper structure solution Z'_i and the lower structure solution Z''_i, respectively.

Step 2. Through the influence and relationship of the upper and lower structure objective function, the upper structure objective function critical value Z'_U and the lower structure objective function critical value Z'_L are determined.

Step 3. Solve the membership degree of the objective function of the upper and lower structure, and use the optimal membership function formula (Calvete & Galé, 2010), to solve the maximum value $\max \varpi$ of the membership function, ϖ which represents the satisfaction value.

2.2. Uncertainty-constrained programming model

The uncertainty constraint programming model (Zhang & Huang, 2011; Chen *et al.*, 2022) is to express the balance relationship between the system function and the credibility constraint condition through the uncertainty set, that is, the constraints between the water unit and the water resource demand, to make a trade-off judgment. The specific UCP model calculation is as follows: Equations (5)–(7):

$$\text{System functions:} \quad \min P = \sum_{j=1}^{n} \alpha_j x_j \tag{5}$$

$$\text{Constraint conditions:} \quad C\left\{\sum_{j=1}^{n} \beta_{ij} x_j \le a_i i\right\} \ge \lambda_i \quad i = 1, 2, 3, \cdots, m, \quad x_j \ge 0, j = 1, 2, \cdots, n, \tag{6}$$

$$C(r \leq \zeta) = \begin{cases} 1 & r \leq v' \\ \dfrac{2v - v' - r}{2 \times (v - v')} & v' < r \leq v \\ \dfrac{r - v}{2 \times (v - v)} & v < r \leq v \\ 0 & r > v \end{cases} \tag{7}$$

where x_j represents the objective function decision variable; α_j, β_{ij}, and $\underset{i}{a}$ represent function coefficients; C is the set of uncertain reliability applied to the study area when the reliability is $r \leq \zeta$, ζ is the function uncertainty variable, r is the real number, and $\sum_{j=1}^{n} \beta_{ij} x_j = S$ is set, then the constraint condition is expressed as $C\{S \leq a_i\} \geq \lambda_{i,}\ i = 1, 2, 3, \cdots, m$. According to the research results of relevant scholars, according to the concept of credibility (Zhang *et al.*, 2020a), the credibility value of the system function should be greater than 0.5, and each constraint satisfaction interval should be [0.5, 1].

2.3. Interval parameters programming

In complex water resources management, the parameters of the water resources system, social economic system and ecological environment system are affected by society, economy, technology and policy, and the influence factors are difficult to be expressed by uncertainty set. The interval parameter programming method (Zarghami *et al.*, 2015; Fu *et al.*, 2018) makes up for the defects of the uncertainty set, and uses interval values to express, the specific model is calculated as Equations (8) and (9) (Fu *et al.*, 2016):

$$\text{System functions:} \quad \min P = \sum_{j=1}^{n} \alpha_j^* x_j^* \tag{8}$$

$$\text{Constraint conditions:} \quad \beta_{ij}^* x_j^* \leq a_i^*, \quad i = 1, 2, 3, \cdots, m, \quad x_j \geq 0, j = 1, 2, \cdots, n, \tag{9}$$

where x_j^* represents the objective function decision variable; α_j^*, β_{ij}^*, and a_i^* represents function coefficients.

2.4. Establishment of interval uncertainty bi-level programming optimization model

Based on the method steps of the uncertainty constraint programming model, interval parameter programming and bi-level programming, based on the bi-level programming model, the uncertainty constraint programming model and the interval parameter programming method are integrated to construct the regional water resources, social economy and ecological environment evaluation index parameters, objective function and constraint condition optimization model. The model is the interval uncertainty bi-level programming optimization model. The specific model calculation is as follows: Equations (10)–(17):

1. The upper structure takes the minimum pollutant emissions as the objective function:

   Objective function:

$$\min P^* = \sum_{h=1}^{9} \sum_{k=1}^{3} \sum_{l=1}^{3} W_{h,k,l}^* \times e_{h,k,l}^* \times \left\{ \begin{array}{l} D_{h,k,l}^* \times (1 - \varepsilon_{h,k,l}^*) + N_{h,k,l}^* \times (1 - \phi_{h,k,l}^*) \\ +M_{h,k,l}^* \times (1 - \eta_{h,k,l}^*) + A_{h,k,l}^* \times (1 - \mu_{h,k,l}^*) \end{array} \right\} \tag{10}$$

Constraint conditions:

(1) Ammonium nitrogen, nitrate nitrogen, total nitrogen, total phosphorus emission constraints:

$$\begin{cases} \sum_{h=1}^{9}\sum_{k=1}^{3}\sum_{l=1}^{3} W^*_{h,k,l} \times e^*_{h,k,l} \times \rho^*_{h,k,l}(\mathrm{NH}_4^+{-}\mathrm{N}) \times (1-\varepsilon^*_{h,k,l}) \le w^*_l(\mathrm{NH}_4^+{-}\mathrm{N}) \\ \sum_{h=1}^{9}\sum_{k=1}^{3}\sum_{l=1}^{3} W^*_{h,k,l} \times e^*_{h,k,l} \times \rho^*_{h,k,l}(\mathrm{NO}_3^-{-}\mathrm{N}) \times (1-\phi^*_{h,k,l}) \le w^*_l(\mathrm{NO}_3^-{-}\mathrm{N}) \\ \sum_{h=1}^{9}\sum_{k=1}^{3}\sum_{l=1}^{3} W^*_{h,k,l} \times e^*_{h,k,l} \times \rho^*_{h,k,l}(\mathrm{TN}) \times (1-\eta^*_{h,k,l}) \le w^*_l(\mathrm{TN}) \\ \sum_{h=1}^{9}\sum_{k=1}^{3}\sum_{l=1}^{3} W^*_{h,k,l} \times e^*_{h,k,l} \times \rho^*_{h,k,l}(\mathrm{TP}) \times (1-\mu^*_{h,k,l}) \le w^*_l(\mathrm{TP}) \end{cases} \tag{11}$$

(2) Regional discharge constraints:

$$\sum_{h=1}^{9}\sum_{k=1}^{3}\sum_{l=1}^{3} W^*_{h,k,l} \times e^*_{h,k,l} \le E^*_l \tag{12}$$

(3) Ecological environment water consumption constraints:

$$\begin{cases} C\left\{\sum_{k=1}^{3} \theta^*_{h,l} W^*_{h,k,l} \le W^*_{h,3,l}\right\} \ge \lambda^* \quad h = 1, 2, 3, \cdots, m, \\ \sum_{k=1}^{3} \theta^*_{h,l} W^*_{h,k,l} + (1-2\lambda^*)\theta^*_{h,l} \le W^*_{h,3,l} \end{cases} \tag{13}$$

where P^* represents the amount of pollutant discharge, t; $W^*_{h,k,l}$ represents the amount of water resources allocated, 10,000 m^3; h is the number of water use areas, including Nanhua County, Chuxiong City, Mouding County, Lufeng County, Yuanmou County, Yao'an County, Dayao County, Yongren County and Wuding County; k is the number of water used by the department, $k = 1,2,3$, which respectively represent domestic water, production water and ecological environment water; l is the number of planning years, $l = 1, 2, 3\ldots$; $e^*_{h,k,l}$ represents the pollution discharge coefficient; $\rho^*_{h,k,l}(\mathrm{NH}_4^+{-}\mathrm{N})$ indicates the discharge concentration of ammonium nitrogen, $\mathrm{mg \cdot L^{-1}}$; similarly, $\rho^*_{h,k,l}(\mathrm{NO}_3^-{-}\mathrm{N})$, $\rho^*_{h,k,l}(\mathrm{TN})$, $\rho^*_{h,k,l}(\mathrm{TP})$ represent the discharge concentration of nitrate nitrogen, total nitrogen and total phosphorus, respectively, $\mathrm{mg \cdot L^{-1}}$; $\varepsilon^*_{h,k,l}$, $\phi^*_{h,k,l}$, $\eta^*_{h,k,l}$, $\mu^*_{h,k,l}$ represent the removal rate of each pollutant discharge index; w^*_l indicates the total discharge amount of the pollution discharge index in the setting l planning year, t; E^*_l indicates the total discharge amount of sewage in the planning year, million m^3; $\theta^*_{h,l}$ represents the proportion coefficient of ecological environment water consumption to the allocated of water resources.

2. The objective function of the lower structure is to maximize social and economic benefits:

Objective function:

$$\max Q^* = \sum_{h=1}^{9}\sum_{k=1}^{3}\sum_{l=1}^{3} (b^*_{h,k,l} - c^*_{h,k,l}) \times W^*_{h,k,l} - \sum_{c=1}^{9}\sum_{u=1}^{3}\sum_{t=1}^{3} d^*_{h,k,l} \times W^*_{h,k,l} \times e^*_{h,k,l} \tag{14}$$

Constraint conditions:

(1) Water supply capacity constraints in water area:

$$\sum_{h=1}^{9}\sum_{k=1}^{3} W^{*}_{h,k,l} \leq w^{*}_{w,l} \tag{15}$$

(2) Domestic water constraints in water area:

$$\begin{cases} C\left\{ \sum\limits_{h=1}^{9}\sum\limits_{l=1}^{3} p^{*}_{h,k,l} \times \varphi^{*} \times 365 \leq W^{*}_{h,k,l} \right\} \geq \lambda^{*} \\ \sum\limits_{h=1}^{9}\sum\limits_{l=1}^{3} p^{*}_{h,k,l} \times \varphi^{*} \times 365 + (1 - 2\lambda^{*}) \times 365 \times \left(\sum\limits_{h=1}^{9}\sum\limits_{l=1}^{3} p^{*}_{h,1,l} \times \varphi^{*} - \sum\limits_{h=1}^{9}\sum\limits_{l=1}^{3} p^{*}_{-h,k,l} \times \varphi^{*} \right) \leq W^{*}_{h,k,l} \end{cases} \tag{16}$$

(3) Constraints on water consumption per 10,000 yuan of industrial output value:

$$\sum_{h=1}^{9}\sum_{l=1}^{3} B^{*}_{h,k,l} \times \xi'_{L} \leq \sum_{h=1}^{9}\sum_{l=1}^{3} W^{*}_{h,k,l} \leq \sum_{h=1}^{9}\sum_{u=1}^{3} B^{*}_{h,k,l} \times \xi'_{U} \tag{17}$$

where Q^{*} represents socio-economic benefits, 10,000 yuan; $b^{*}_{h,k,l}$ represents water supply benefit coefficient, yuan/m^3; $c^{*}_{h,k,l}$ represents water price, yuan/m^3; $d^{*}_{h,k,l}$ represents the water cost coefficient, yuan/m^3; $w^{*}_{w,l}$ represents the total amount of water supply, t; $p^{*}_{h,k,l}$ represents the total urban population, 10,000 people; φ^{*} represents urban domestic water consumption, m^3/d, $B^{*}_{h,k,l}$ represents gross industrial production, 10,000 yuan; ξ'_{U} and ξ'_{L} represent the upper and lower limits of water consumption per 10,000 yuan of industrial output value, m^3/10,000 yuan.

2.5. Model algorithm solution

There are various model algorithms employed to solve many engineering problems (Deb *et al.*, 2002; Reyes-Sierra & Coello, 2006; Yang & Deb, 2014; Wang *et al.* 2022b; Zhao *et al.*, 2022), among them, the solution of single-objective optimization algorithm is a scalar, and the solution of multi-objective optimization algorithm is a vector. The size of the vector cannot be compared by simple magnitude. Therefore, based on the original algorithm of the sparrow search algorithm (Li *et al.* 2022a), the algorithm-solving process is improved, the competition mechanism (Zeng *et al.*, 2021) and polynomial mutation (Wen *et al.*, 2021) is introduced, and the non-dominated vector sorting is used for size comparison.

The competition mechanism is mainly to provide pairs of competing candidates in the sparrow population to speed up population renewal, and obtain the Pareto frontier $f_1, f_2, f_3, \ldots f_n$ index ranking to achieve the maximum search value. Comparing the obtained index with the crowding degree distance of population individuals, select m population individuals as optimal individuals to compete with each other. After multiple competitions, two individuals k and h are randomly selected from the set to calculate the angle with the individual L in the given population. The smaller the angle is, the higher the calculation accuracy will be. Competition is shown in Figure 1.

The main purpose of polynomial mutation is to further update the sparrow position and regain the optimal solution when the sparrow search algorithm has a local optimal solution. Specific variations such as Equation (18):

$$\begin{cases} x' = x + \sigma(u - u') \\ \sigma = \begin{cases} [2u + 2 \times (1 - 2u)(1 - \tau_1)^{\kappa+1}]^{\frac{1}{\kappa+1}} - 1 & u \leq 0.5 \\ 1 - \left[2(1 - u) + 2\left(u - \frac{1}{2}\right) \times (1 - \tau_2)^{\kappa+1}\right]^{\frac{1}{\kappa+1}} & u > 0.5 \end{cases} \end{cases} \tag{18}$$

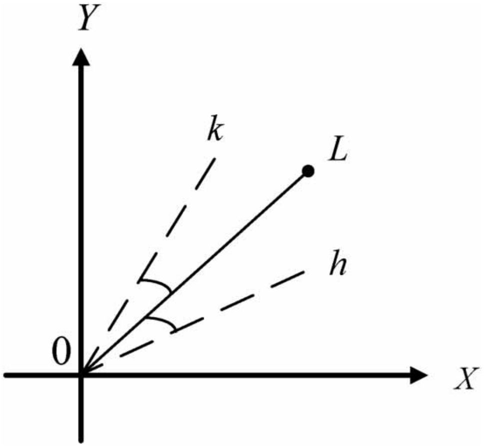

Fig. 1 | Individual competition reference of population.

Among them, κ is an exponential distribution, and the larger the index value, the closer the mutant individual is to the previous generation. According to multiple checks and references to relevant literature, the value of κ is set to 20, and the improved algorithm has the ability to obtain the optimal solution. u is the upper limit of sparrow position, u' is the lower limit of sparrow position, τ_1 and τ_2 are random numbers in the range of [0, 1].

2.6. Model ideas

The research of the water resources optimization coupling model is carried out on the basis of basic theory and system analysis. The effective use of water resources supports the sustainable development of the social economy and is also an important part. Based on the study of water resources, population, economy and environment in the region, the results of optimal allocation of water resources are obtained through carrying capacity evaluation and supply and demand balance analysis.

In the process of water resources allocation, we should not only aggregate environmental, economic and social factors into a single-objective function to form a bi-level programming model, but also integrate uncertain constraint programming and interval parameter programming into the model framework. Considering that the environmental impact in the process of water resources utilization (especially the emission of ammonium nitrogen, nitrate nitrogen, total nitrogen and total phosphorus) has become a restrictive factor for the effective utilization of water resources, the minimum target of pollutant emission in the process of water resources allocation and utilization is taken as the upper structure of the model. At the same time, considering that the distribution of water resources allocation income is the focus of maintaining social stability and promoting the coordinated development of river basins, the goal of maximizing the social and economic benefits of water resources allocation is introduced as the lower structure of the model. However, in the process of water resource allocation, the minimum discharge of pollutants and the maximization of social and economic benefits are used as the objective functions, and the results of water resource allocation often conflict with each other. In order to cope with the conflict of interests between different decision-makers, in the process of uncertainty bi-level programming, the upper structure model should fully consider the decision of the lower structure, and then adjust and optimize its own allocation plan. According to its own development needs, the optimal decision-making scheme is made, the global optimal solution is obtained, and the carrying capacity of water resources in the basin is analyzed, including the balance of supply and demand of water resources and the evaluation of the development trend of carrying capacity.

Model construction ideas are shown in Figure 2.

3. CASE ANALYSIS

3.1. Overview of the study area

The Longchuan River Basin is located in Chuxiong Yi Autonomous Prefecture of Yunnan Province on the central Yunnan Plateau. It is a first-class tributary on the right bank of the lower section of Jinsha River. The catchment area of the basin is 9,225 km^2, accounting for 32.4% of the land area of Chuxiong Prefecture. These include Zidian River, Longchuan River, Qinglong River, Xijing River, Mouding River, Pudeng River, Dragonfly River and other major rivers. From a spatial point of view, the terrain of the basin is closed, the altitude is low, and the climate becomes very dry. It is the area with the least rainfall in the Yunnan-Guizhou Plateau. The general trend is more in the south than in the north, with more mountains and fewer flat dams. The horizontal distribution is complex and the vertical zoning is obvious.The distribution of water resources is extremely uneven, and the water resources zoning of the comprehensive planning of the basin is shown in Figure 3. The water resource system of the Longchuan River Basin is relatively complex. There are large and small reservoirs and other water supply projects newly built and expanded in the basin. The current status of relevant areas in the basin and the main planning projects are shown in Figure 4.

The multi-year average precipitation in the Longchuan River Basin is 876.2 mm, the multi-year average evaporation is 1,160.1–2,226.8 mm, and the multi-year average temperature is 14.8–21.5 °C. The highest monthly average temperature appears in June when the temperature is 20.9 °C, the lowest monthly average temperature appears in January when the temperature is 8.2 °C, the extreme maximum temperature is 32.4 °C, the extreme minimum temperature is –4.8 °C, the multi-year average relative humidity is 57–75%, the multi-year average sunshine is 2,177–2,593 h, the multi-year average wind speed is 1.5–3.3 m/s, and the average maximum wind speed is 21.0 m/s (wind direction NE).

The Longchuan River length of 272.5 km was selected for the annual water quality evaluation. Among them, rivers with Classes II–III water quality account for 27.7%, rivers with Class IV water quality account for 50.7%, and rivers with Class V and inferior V water quality account for 21.6%. In the wet season, rivers with Class II-III water quality account for 27.7%, and rivers with water quality Class V and inferior V account for 72.3%. In the dry season, rivers with Classes II–III water quality account for 70.1%, rivers with Class IV water quality account for 8.3%, and rivers with Class V and inferior V water quality account for 21.6%. In the Longchuan River Basin, the pollutants in the mainstream mainly come from chemical substances and heavy metal pollution. In the tributaries, the water quality of the Zidian River and Xijing River reached Class II, and the water quality of the Qingling River reached Classes II–III. Due to the small number of factories, mines and other enterprises, and human activities having little impact, the water quality of the tributaries is relatively good, which can basically meet the requirements of water supply along the river.

3.2. Evaluation index analysis

According to the design principles of the index system, follow the scientific, practical, feasible, representative, and policy relevance, and include the main influencing factors in the system as much as possible. Preliminary selection of 16 index factors affecting water resources–social economy–ecological environment in the Longchuan River Basin. Specific indicators are shown in Table 1.

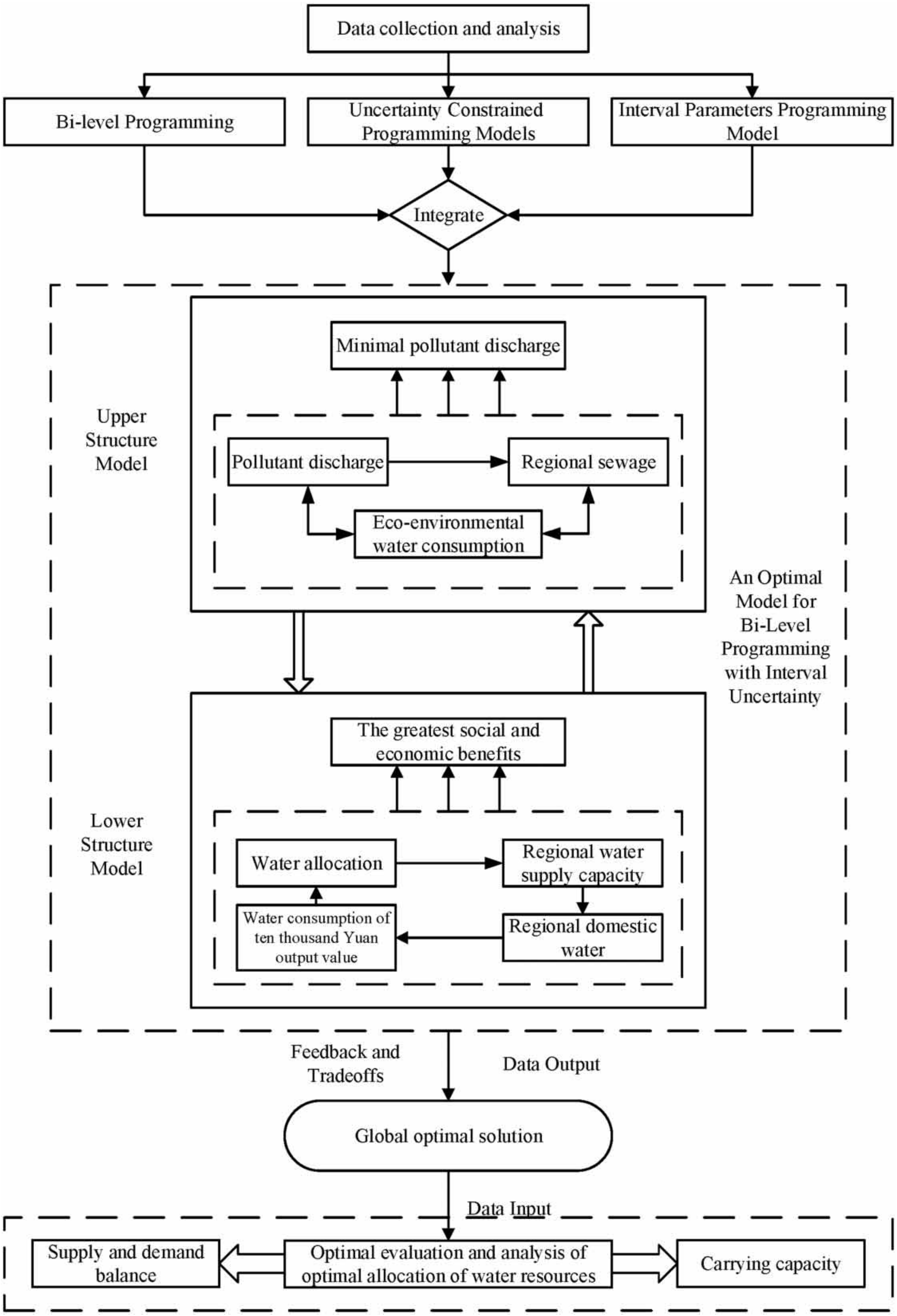

Fig. 2 | Model construction idea diagram.

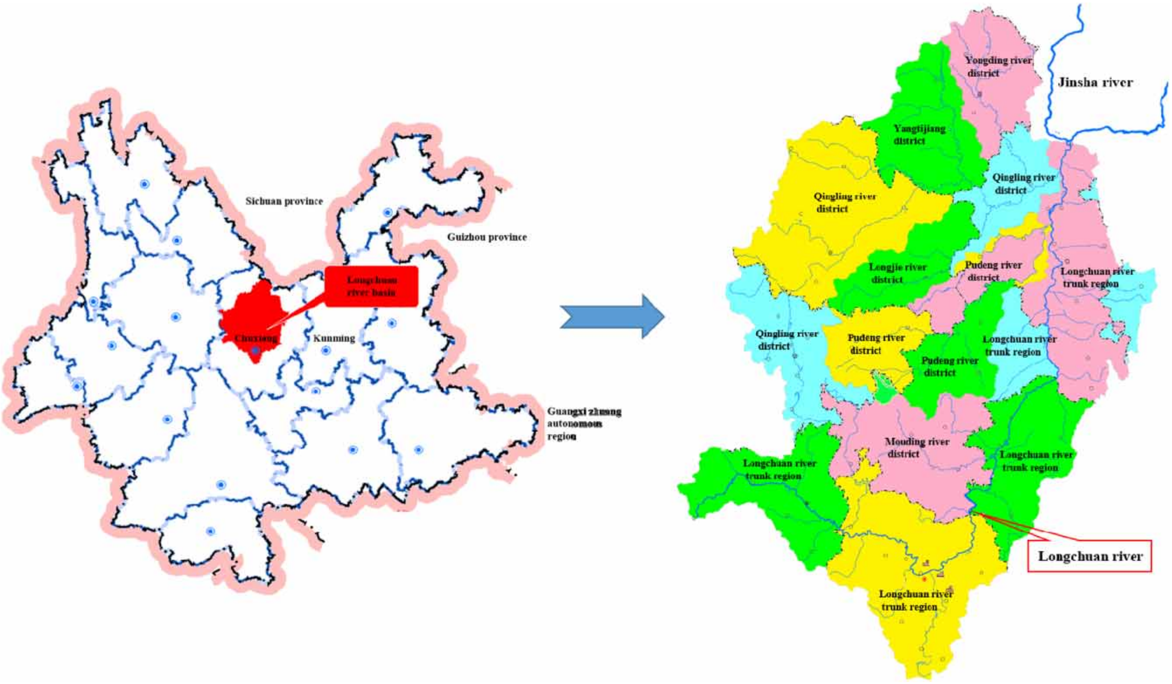

Fig. 3 | Location of the Longchuan River and water resources zoning of the basin comprehensive planning.

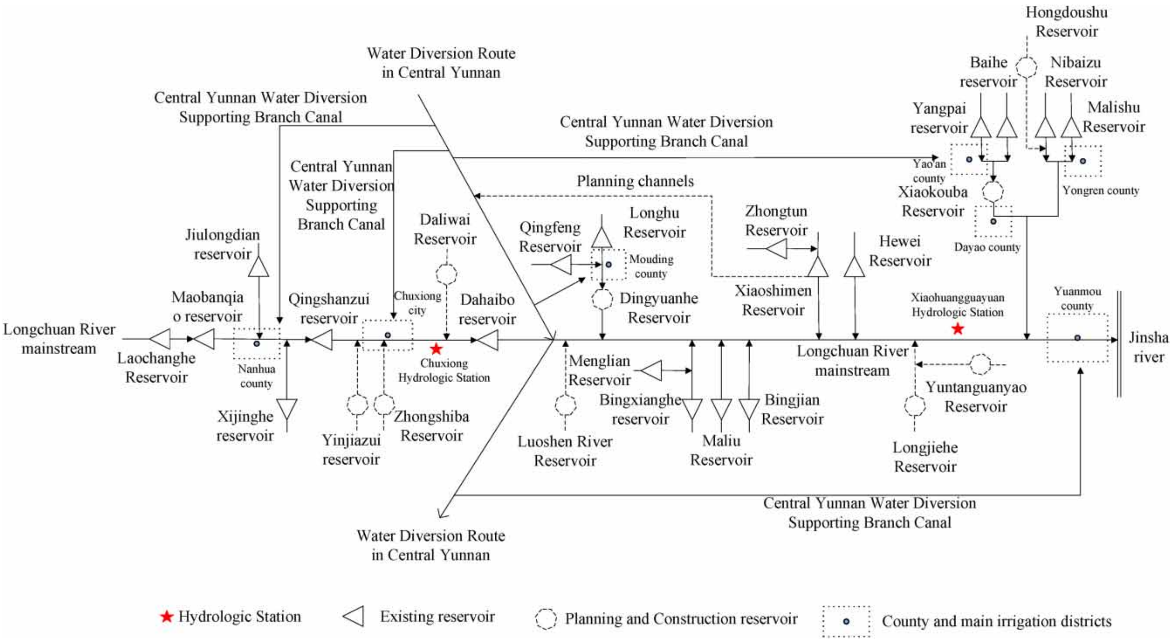

Fig. 4 | Generalized network of the water resources system in the Longchuan River Basin.

Table 1 | Evaluation index and weight of water resources in the Longchuan River Basin.

Index system	Specific indicators	Indicator symbol	Index weight
Water resources system	Water resources per unit area of watershed	X_1	0.059
	Per capita water resources	X_2	0.061
	Water Transfer Per Unit Area Outside Watershed	X_3	0.091
	Water consumption of 10,000 yuan industrial output value	X_4	0.046
	Ecological environment water consumption per capita	X_5	0.038
	Per capita water storage capacity	X_6	0.083
Social and economic systems	Per capita GDP	X_7	0.062
	GDP per water	X_8	0.057
	Urbanization rate	X_9	0.089
	Effective irrigation area	X_{10}	0.079
Ecological and environmental systems	NH_4^+-N	X_{11}	0.059
	NO_3^--N	X_{12}	0.067
	TN	X_{13}	0.061
	TP	X_{14}	0.071
	Ratio of man-made sewage discharge to river runoff	X_{15}	0.040
	soil erosion rate	X_{16}	0.037

3.3. Data analysis

Considering the intersection and complexity of the comprehensive system of water resources–society–economy–ecological environment and other comprehensive systems, referring to factors such as ecological environment compensation mechanism, taking the comprehensiveness, dynamic and static, comparability of basic data as the principle, setting the minimum pollutant discharge and maximum economic benefit as the upper and lower structure objective functions, selecting 2000, 2004, 2010, and 2020 as the current status year as the basis, 2025, 2030, and 2035 as the planning year. Nanhua County, Chuxiong City, Mouding County, Lufeng County, Yuanmou County, Yao'an County, Dayao County, Yongren County, and Wuding County in typical plateau areas are determined as water-using areas. The current annual water supply and consumption data of the living, production and ecological conditions in these nine regions mainly come from the Water Resources Bulletin, Environmental Bulletin and Statistical Yearbook, which are used as input and output in the coupling model. Missing data were obtained by interpolation and fitting through theoretical analysis and linear analysis.

With the rapid development of the social economy, in the next 20 years, the amount of water resources in the Longchuan River Basin has changed, which is reflected in the changes in multi-year average total water demand, supply and shortage. The predicted values of 2025, 2030, and 2035 are shown in Table 2.

Table 2 | The balance between supply and demand of water resources in the Longchuan River Basin.

	The first supply demand balance			The second supply demand balance			The third supply demand balance		
Year	Water supply	Water need	Water scarcity	Water supply	Water need	Water scarcity	Water supply	Water need	Water scarcity
2025	6.26	11.29	5.03	7.55	10.51	2.96	10.2	10.51	0.31
2030	6.67	12.36	5.69	7.25	11.27	4.02	11.04	11.27	0.23
2035	7.09	12.93	5.84	7.96	12.26	4.3	11.35	11.7	0.35

4. RESULTS AND DISCUSSION

4.1. Analysis of water use department under different credibility

Under the effects of reducing demand and increasing supply, the contradiction between supply and demand of water resources is solved through the implementation of a water diversion project in the outer basin. The water resources allocation of the outflow water diversion project in the Longchuan River Basin presents an increasing trend as time goes on. It can be seen from the increased credibility value that the water resources allocation shows a decreasing trend, which is mainly reflected in the continuous expansion of the corresponding water resources demand caused by the development of the city scale, urbanization rate and population increase of the water use region. Therefore, when the credibility value of water resource allocation increases, there will be an upward trend over time, and the greater the degree of reliability, the stronger the risk. In the case of water resource constraints, the tighter the constraints, the lower the amount of allocated water resources, on the contrary, the higher the amount of allocated water resources. During the planning period, the changes of various water consumption departments at different levels of credibility are as follows: the proportion of domestic water consumption in 2025, 2030, and 2035 are [41.19%, 41.25%], [40.96%, 41.02%], and [40.95%, 40.99%]; the proportion of industrial water consumption in 2025, 2030, and 2035 are [42.55%, 42.57%], [42.45%, 42.48%] and [41.79%, 41.99%]; the proportion of ecological environment water consumption in 2025, 2030, and 2035 are [16.18%, 16.26%], [16.50%, 16.59%] and [17.02%, 17.26%] respectively. The comparison results are shown in Figure 5.

4.2. Analysis of pollutant discharge

In different planning periods, analyzing the types of pollutants $NH_4^+{-}N$, $NO_3^-{-}N$, TN and TP showed no significant difference between months and months throughout the year ($P > 0.05$). Compared with the corresponding mean values of water quality parameters, in the second quarter of the year, $NH_4^+{-}N$ reached the water quality II standard, $NO_3^-{-}N$ was within the standard value range, TN was greater than the water quality standard, and TP reached the water quality III standard; in the third quarter, $NH_4^+{-}N$ reached the surface environmental quality class II standard, $NO_3^-{-}N$ and TN had no change, and TP also rose to the surface water quality class II standard.

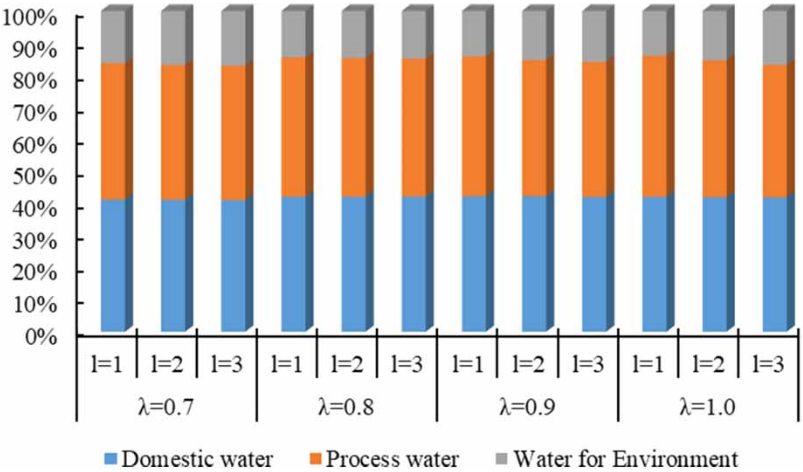

Fig. 5 | The proportion of different water departments in different credibility levels during the planning period.

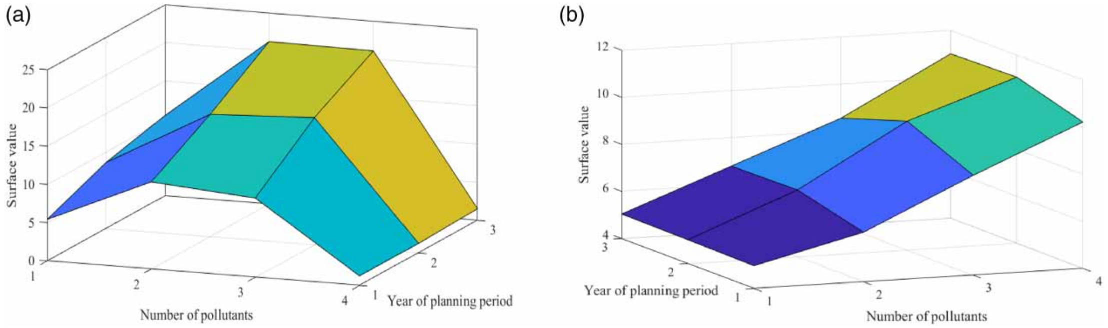

Fig. 6 | Emissions of pollutants in different planning periods under different credibility levels in the lower structure. (a) Emissions of various pollutants in different planning periods and (b) emissions of pollutants with different credibility in different planning periods.

In general, the total amount of discharge increases significantly as the planning period moves forward, indicating that the total allocation of water resources during the planning period is also increasing; from the perspective of credibility, the allocation of water resources becomes smaller as the value of the credibility increases, which leads to a decrease in the discharge of pollutants. It can be seen from Figures 6 and 7, from the perspective of water use in the basin, that the amount of water resources allocated to domestic water and production water produces higher pollutant emissions, mainly nitrogen, phosphorus and other nutrients, mainly related to farmland, engineering construction and other affected areas.

4.3. System benefit analysis

The upper and lower structures are reflected by the global satisfaction value ϖ. Under different credibility conditions, the satisfaction value decreases with the increase of credibility. The value of credibility λ is divided into 0.7, 0.8, 0.9, and 1.0. The smaller the value is, the lower the credibility condition of the system is, so as to obtain higher satisfaction, and the overall satisfaction range is [0.69,0.72], which balances the relationship between the upper and lower structures. In addition, in different planning periods, with different reliability values selected, the obtained system benefit intervals are [616.73,756.93], [489.98, 628.18], [329.06, 469.32], [218.48, 310.37] billion yuan. The development trend of system benefit is opposite to the value of credibility, the higher the credibility, the lower the benefit. When $\lambda = 0.7$, the maximum advantages of system benefits can

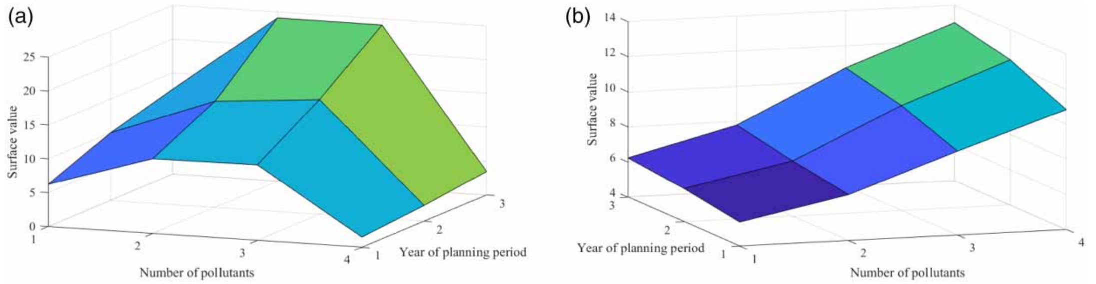

Fig. 7 | Emissions of pollutants in different planning periods under different credibility levels in superstructure. (a) Emissions of various pollutants in different planning periods and (b) emissions of pollutants with different credibility levels in different planning periods.

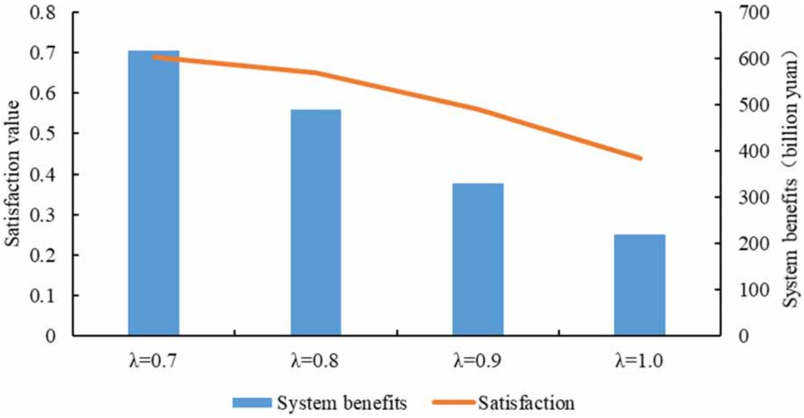

Fig. 8 | Comparison of system benefit and satisfaction value results of the lower structure system.

be fully utilized, thereby reducing the risk of system constraints. Otherwise, the opposite is true. Considering comprehensively, it is particularly important to balance system benefit, satisfaction and reliability under the dual effect of uncertainty constraint programming and interval parameter programming. The calculation results of the system benefit and satisfaction value are shown in Figures 8 and 9.

4.4. Compared with the results of single-layer model

The upper structure and the lower structure are used as objective functions to establish two single-level objective programming optimization models. That is, the uncertain water resources single-level planning model with the minimum pollutant emission and the uncertain water resources single-layer planning model with the maximum social and economic benefits. The two single-level programming models are compared with the uncertain bi-level programming model, and the results are shown in Table 3. The upper structure model only considers the

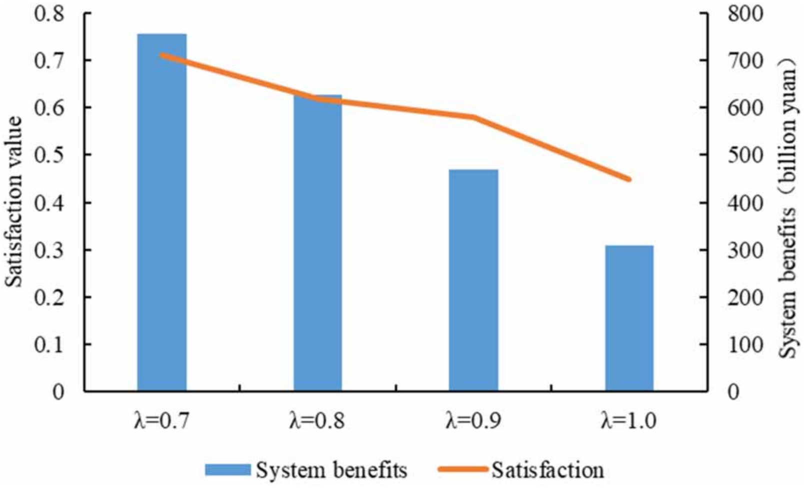

Fig. 9 | Comparison of system benefit and satisfaction value results of the upper structure system.

Table 3 | Comparison of system benefits and total pollutant emissions between single-level and bi-level models.

	$\lambda = 0.7$		$\lambda = 0.8$		$\lambda = 0.9$		$\lambda = 1.0$	
Different credibility Numerical value	**Upper limit**	**Lower limit**	**Upper limit**	**Lower limit**	**Upper limit**	**Lower limit**	**Upper limit**	**Lower limit**
	A single-level programming model with the goal of minimizing pollutant emissions							
System benefits (billion yuan)	687.39	597.88	621.54	553.61	599.12	500.93	563.75	486.54
Total amount of pollutant discharged (million tons)	3.96	3.87	3.89	3.84	3.85	3.83	3.82	3.80
	A single-level programming model aiming at maximizing social and economic benefits							
System benefits (billion yuan)	758.73	740.22	741.92	727.78	729.62	719.46	711.06	698.96
Total amount of pollutant discharged (million tons)	4.16	4.13	4.14	4.10	4.11	4.08	4.09	4.05
	Uncertainty bi-level programming model							
System benefits (billion yuan)	709.06	668.05	682.73	643.695	669.57	612.15	635.43	582.55
Total amount of pollutant discharged (million tons)	4.06	4.00	4.02	3.97	3.98	3.95	3.96	3.91

watershed environment. The optimal solutions of the model optimization have the lowest pollutant emissions and system benefits, and the water supply of the water sector is also allocated according to the minimum demand. The lower structure model is from the perspective of social and economic benefits. The final optimization results are distributed according to the maximum economic benefits and the highest supply and demand requirements of the water sector. At the same time, it brings environmental pollution and leads to an increase in pollutant emissions. The uncertainty bi-level programming optimization model takes into account the requirements of environmental pollutant discharge and socio-economic system benefits. The results can provide reasonable water resources allocation schemes, economic allocation schemes, environmental governance schemes and water supply and demand requirements for different decision-making management departments and water use departments. In general, the upper structure model reflects the optimization of the water environment; the lower structure model reflects the promotion of economic and social development in the basin; the bi-level programming model provides the best solution results in both environmental and economic aspects.

4.5. Comprehensive evaluation of carrying capacity

According to the geological geomorphology, meteorological data, precipitation, evaporation and drought data of the Longchuan River Basin, the basin has a typical dry-hot Yuanmou Valley climate, and is located in the arid area of central Yunnan. Considering the water diversion scenario without and with external basin, the results of water resources carrying capacity are shown in Table 4 and Figure 10.

4.5.1. Without external basin water diversion scenario

In the absence of water diversion from external basins, the carrying capacity of water resources tends to slow down from 2020, and the development trend gradually reaches the ultimate carrying capacity state, which indicates that the potential of water resources development is relatively small. The ratio of the total water supply of Longchuan River Basin in 2000 to that in 2004 was 1:1.08, and the amount of water transferred from the external basin was 0.15 billion m^3, accounting for 0.27% of the total water supply, a very small proportion. The current

Table 4 | Comprehensive evaluation results of influencing factors.

Year	2000	2004	2010	2020	2025	2030	2035
*P**	−2.551	−2.048	−0.566	2.270	2.545	2.811	3.040
P	−2.361	−1.933	−0.541	2.978	3.321	3.541	3.977

Note: *P** indicates a water diversion scenario without external basins, *P* indicates a water diversion scenario with external basins.

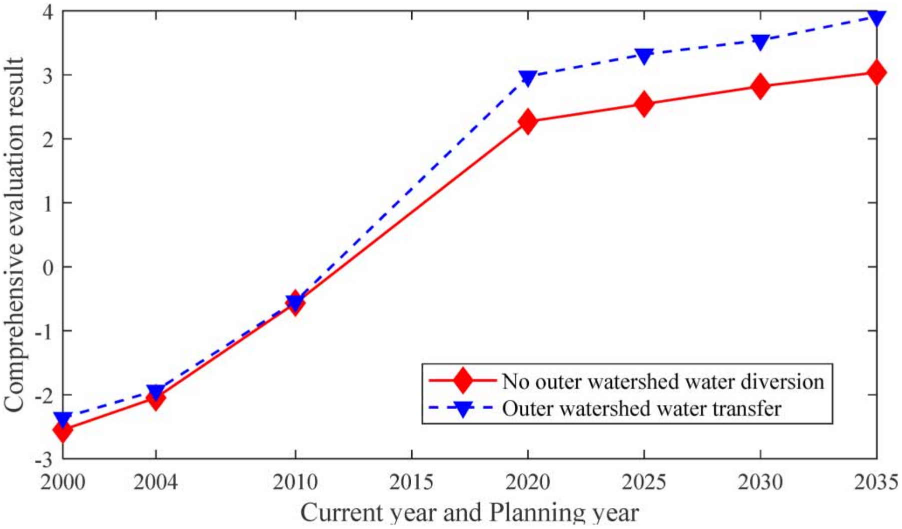

Fig. 10 | Comparison of comprehensive evaluation results of water resources carrying capacity in the Longchuanjiang River Basin.

situation mainly relies on regional self-owned water source projects to meet the water demand of the region, mainly water storage projects, followed by water diversion projects. The water supply structure model is basically the same, and the water allocation for living, production and agriculture has increased by 0.081 billion m^3, 15.9 million m^3, and 19.1 million m^3. Among them, the effective irrigated area reached 978,000 mu in 2004. Compared with the effective irrigated area in 2000, the agricultural water consumption decreased by 2.6%, indicating that it is impossible to rely on the existing water source projects to balance the annual water demand, and it is necessary to increase the utilization of water resources and increase the water supply to ensure the needs of social and economic development.

Since the economy of the Longchuan River Basin is relatively developed in central Yunnan, the water use efficiency is relatively high, and the utilization of water conservancy projects is high, indicating that the utilization of water resources has brought a greater degree of development to the economy. If the original water resources are maintained, it will lag behind the economic development of this region in the future.

4.5.2. With external basin water diversion scenario

In 2000, the development and utilization of water resources in the Longchuan River Basin reached 34.6%. The development of water resources was based on the principle of restricting the excessive growth of water use and combining quota management with total volume control. Water use efficiency was given priority, and the water supply capacity of projects was supplemented. In 2020, the development and utilization of water resources reached 56.4%, exceeding the internationally recognized 40% reasonable development level. In the case of without water diversion from the external basin, the total amount of water consumption is strictly limited, considering from the perspective of water saving measures, water allocation mainly tends to focus on water use efficiency. In 2030, the development and utilization of water resources will drop to the same level as in 2010, due to the construction of water diversion in central Yunnan and the construction of key small and medium-sized water source projects in this area. The water supply in the external basin will increase from 183 million m^3 in 2020 to 315.7 million m^3 in 2030, an increase of 297.4 million m^3. The amount of water transferred has accounted for 35.0% of the total water supply in the basin, the irrigation area has increased by 49,800 mu, and the utilization coefficient of irrigation water is 0.70–0.71. During this 10-year period, the added value ratio of domestic water, production water and ecological water reaches 1:5.73:0.12, so the increased amount of water diversion and allocation is 0.434 million m^3, 248.8 million m^3 and 0.052 million m^3. Production of water accounts for the main part of the water diversion, and under the condition of ensuring the production of water, it promotes social economy and drives the overall rise of water resources in the basin.

According to the comprehensive development trend of Figure 9, it can be seen that the carrying capacity of water resources is gradually increasing, with a score of 3.541. Compared with the scenario without water diversion from external basins, the comprehensive evaluation value of water resources carrying capacity is increased by 0.73, an increase of 25.9%, which shows that the carrying capacity of water resources has been improved on the basis of the basin limit. The Central Yunnan water diversion projects are in line with the goal of focusing on cities and towns, taking into account the water demand for agriculture and the ecological environment, improving the ecological environment, human activities and economic development methods, and providing a guarantee for the protection of water resources in the Longchuan River Basin.

5. CONCLUSIONS

Uncertainty-constrained programming and interval parameter programming are introduced into the bi-level programming model to propose an optimal uncertainty water resource coupling model. The new bi-level model is applied to nine water use areas in the Longchuan River Basin, and the water resources optimization study was carried out in the three planning periods of 2025, 2030, and 2035. The results showed that:

(1) The bi-level programming optimization model with interval uncertainty can reflect the characteristics and interaction effects of multi-level and multi-objective in complex water resources systems. In this study, the model was introduced into the water resource allocation system of typical river basins in the Yunnan plateau region, uncertainty-constrained planning and interval parameters was integrated into the model, which not only solves the problem of strong directivity of a single aspect in the single-level planning model, but also improves the accuracy and reliability of the bi-level programming model in dealing with the multi-objective complex relationship of water resources.

(2) The model uses the sparrow search algorithm, introduces competition mechanism and polynomial variation, and obtains the optimal solution after improvement, to obtain the optimization results of pollutant discharge, system benefit and satisfaction.

(3) The bi-level programming model is often used to solve the multi-objective optimization problem. From the perspective of the integrity of the model, the constraints and connections between the upper structure, the lower structure and the regional water use departments are solved. At the same time, the bi-level programming model also has the function of comparing the economic benefits and satisfaction of the system in water resources allocation, and can provide practical solutions for the harmonious development of the region in the future.

(4) The comparison and analysis of the optimization results with the single-level planning model show that the bi-level planning model comprehensively considers the pollutant discharge targets in the environment, and regional, social and economic development goals, and takes into account the two-way results of the single-level planning model under different credibility levels, which is more advantageous than the single directionality of the two single-level planning models, and can provide a practical plan for the harmonious development of the region in the future.

(5) The carrying capacity evaluation method can explain the development trend of regional water resources in detail. The comprehensive evaluation results show that the implementation of a cross-regional water diversion project has a certain role in promoting the sustainable and harmonious development of water resources-social economy-ecological environment and other comprehensive systems in the Longchuan River Basin.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: Yunnan Statistical Yearbook: http://stats.yn.gov.cn/tjsj/tjnj/; Yunnan Water Resources Bulletin: http://wcb.yn.gov.cn/html/shuiziyuangongbao/; Yunnan Soil and Water Conservation Bulletin: http://wcb.yn.gov.cn/html/shuitubaochigongbao/.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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