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An ecological interval two-stage fuzzy shadow price model for environmental flow allocation in the Shaying River Basin

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ABSTRACT

In recent years, social water is pressurizing ecological water, causing the environmental flow to not be guaranteed and destroying the ecological environment. This research aims to coordinate social and natural water use to bring about optimal economic benefits, while ensuring environmental flow requirements. In this study, an interval two-stage fuzzy shadow price model (ITS-SPM) has been developed, which combines two-stage programming (TSP) and system of water value to optimize environmental flow. The ITS-SPM is mainly characterized as system benefits constituted by expected water resource benefits and water shortage penalty. This model has removed the uncertainties of economic data and environmental water demand (expressed fuzzy and interval). It has been found that adjusting the social water structure can effectively solve the problem of insufficient ecological flow. The ITS-SPM can make the adjustment of social water use more reasonable, which will produce benefits, unlike the current agricultural water reduction policy. Under the premise of guaranteeing optimal economic benefits, the added value of environmental water use in different scenarios is (social water structure adjustment) as follows: in 2020, it was expected that Shaying River water would increase by at least 13.49%; in 2025, it is expected to increase by at least 33.35%; in 2030, the increase will be by at least 57.54%; and in 2035, it will be by at least 77.50%.

Key words: environmental flow allocation, interval two-stage programming, shadow price, Shaying River Basin, water resource management

HIGHLIGHTS

- Improving the Tennant method to calculate minimum environmental flow.
- Developing a two-stage model of 'society-natural' duality.
- Constructing a water resource value evaluation system: evaluating ecological benefits using the shadow price model (SPM) and evaluating agriculture benefits using the differential water price model (DWPM).
- Developing an interval two-stage fuzzy shadow price model (ITS-SPM).

1. INTRODUCTION

With developing countries witnessing rapid social and economic growth over the years, there has been a gradual deterioration in the natural ecological environment, resulting in the serious problem of social water squeezing ecological water (Hughes 2001; Reggiani & Rientjes 2015; Harbuľáková *et al.* 2016). Environmental water demand is determined by seasonal water shortage in the ecosystem (Li *et al.* 2012). In the social water-use structure, agricultural water consumption is huge, and extensive irrigation methods cause high wastage of water resources (Yue & Zhan 2013; López *et al.* 2019). Unbalanced distribution of water resources will continue to affect social and economic development. In the context of river basin water resource planning, a reasonable setting of the environmental flow threshold and water resource development level is an important way to strengthen water resource management (Li *et al.* 2018; Zhang *et al.* 2020).

Due to increased human influence, the current water ecological environment has gradually evolved into a natural–social dual water function system. Therefore, the current water resource allocation model should gradually change from a social demand pattern to a 'dual' water resource allocation pattern. The water resource system is complex with many uncertain factors, many parameters cannot be expressed in the form of probability distribution and the acquisition of economic and policy data cannot be accurate. At the same time, changes in social activities and the impact of water use on the social economy

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have rendered water resource allocation difficult. In water resource planning, a number of uncertainty optimization methods can be introduced to help water managers face the challenges of uncertainties and their interactions (Kong *et al.* 2016; Zeng *et al.* 2017; Chen *et al.* 2018; Wu & Ma 2018; Wu *et al.* 2020). Therefore, one type of stochastic programming (SP), named two-stage stochastic programming (TSP), can be used to handle uncertainties expressed as probabilistic distributions (Kenneth 2007; Zeng *et al.* 2014a; Budhathoki *et al.* 2020). For example, Zeng *et al.* (2015) developed a mixed inexact–quadratic fuzzy water resource management model (IQT-WMMF) for floodplains, incorporating the techniques of credibility-constrained programming (CP), two-stage programming (TSP), interval-parameter programming (IPP), multi-objective joint probability and quadratic programming within a general framework of limited data availability (Zeng *et al.* 2015; Liu *et al.* 2018). Water resource planning results in economic growth in most cases. However, in collecting important economic data (such as water efficiency), a wide range of data are often used, which will inevitably have an adverse effect on the results. Therefore, evaluating the economic benefits of water use and the losses caused by water shortages will be the focus of the planning model.

Ecological economic benefits include two aspects: natural and social. Through a comprehensive evaluation of the economic benefits of the Everglades ecosystem, ecologist Ruscena Wiederholt discovered that the system offered more ecological benefits than economic benefits (Wiederholt *et al.* 2020). Both ecological and economic benefits often cannot go hand in hand. How to deal with the contradiction between the two is the key. Some of the factors to be considered for evaluating the benefits include climate, the dynamic development of agriculture and farmers' income and expenditure; however, redistribution capacity is limited by the scarcity of water resources, and fluctuations in water prices and other factors cannot be reflected. The differential water price model (DWPM) is often used to optimize the allocation of water resources through the adjustment of economic leverage and formulate matching empirical decisions (Yan *et al.* 2020). Di *et al.* (2020) adopted Kriging interpolation to evaluate the regionalized benefit of China's sloping cropland erosion control during 2011–2015 (Di *et al.* 2020). Taken together, different evaluation indicators and methods need to be selected when evaluating the different aspects of benefits (Olander *et al.* 2018). Researcher Martin Hensher used the shadow price method to estimate economic loss caused by the destruction of the environment (Hensher 2020). Shadow prices reflect the scarcity of resources and the demand for final products in the social economy but cannot reflect economic changes and changes in demand (Shen & Lin 2017; Sidhoum 2018). Therefore, this research has developed a fuzzy shadow price model (SPM) to remove the uncertainties of economic data and more accurately derive the dynamic relationship between the actual water demand and the economy.

Two-stage planning involves the basic concept of retrospection. It can compensate and correct the first-stage water resource allocation decision after the occurrence of a random event, so as to reduce the risks in decision making and obtain the best compromise plan. In addition, the uncertainty of incoming flows will directly affect water resource allocation for the forthcoming year, investigations of incoming flow distribution forecast are relatively rare, and those focused on determining the optimal discharge for water resource utilization benefits are even rare. Therefore, fuzzy planning is used to remove the uncertainty of unknown distribution, and interval planning for setting the upper and lower bounds of data will remove the uncertainty in water resource management. This study intends to consider the natural–society dual water resource allocation model in collaboration and rationally optimize the annual distribution of water environmental flow. The developed model aims to maximize the benefits of the system, comprehensively consider the economic benefits of social water use and ecological water use, build a complete water resource value system and attempt to strike a balance between social water use and ecological water use goals.

2. MATERIALS AND METHODS

2.1. Model framework

Figure 1 presents the framework of ITS-SPM application in the Shaying River Basin. In recent years, climate change and extensive human activities have posed a challenge to the environment. At the same time, the traditional on-demand distribution of water resources no longer meets the needs of current social development. In view of this, TSP was adopted to set a 'dual' (natural and social) water environmental flow allocation model. This model mainly resolves the problems of uncertainty in expected water resources and water shortage risk in the environmental flow distribution system and then

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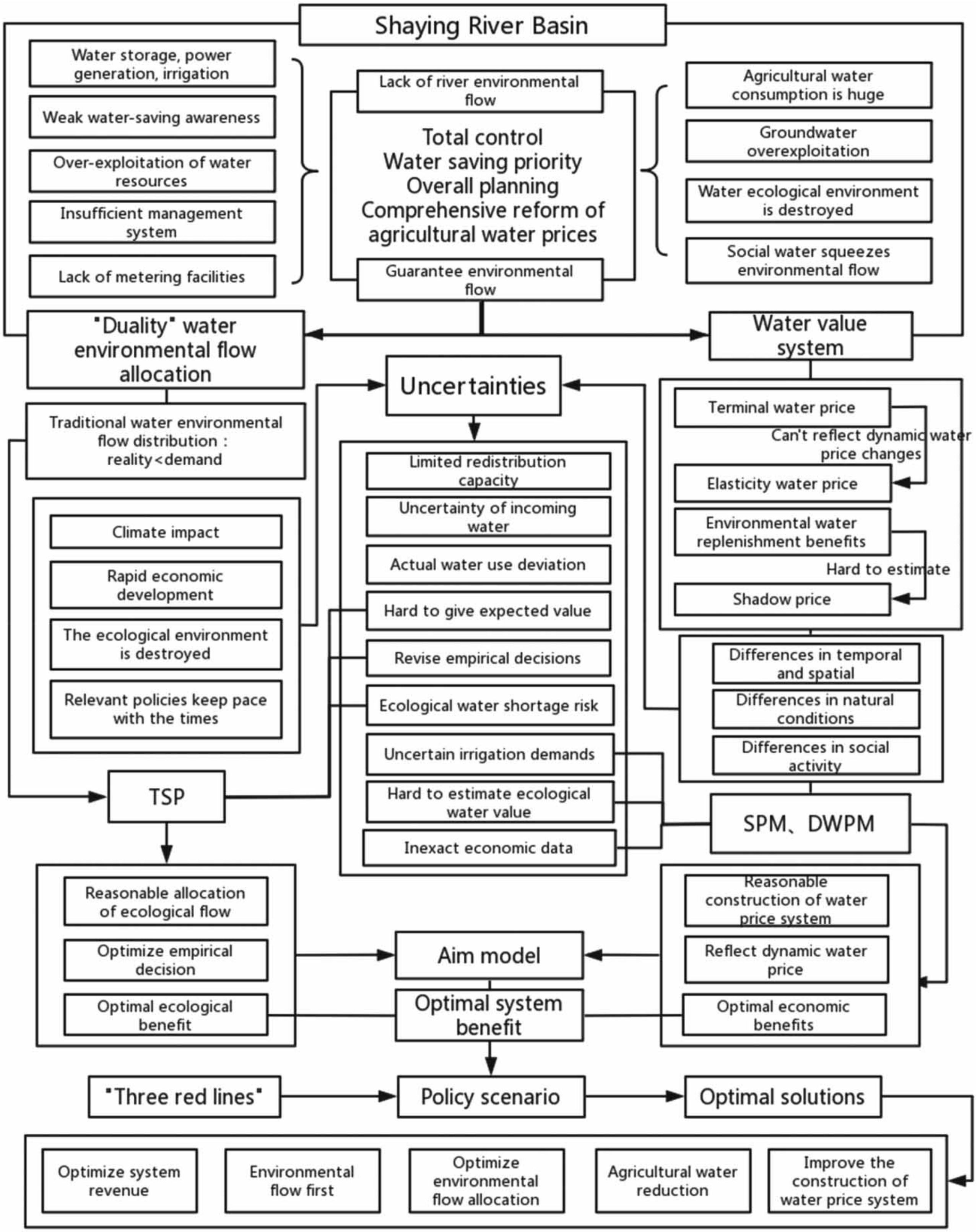

Figure 1 | Framework of ITS-SPM application in the Shaying River Basin.

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gives the final optimization result by continuously modifying the empirical decision. Uncertainties in environmental flow value and economic data in the system are expressed by eco-economic benefits. The evaluation of eco-economic benefits includes two aspects: ecological benefits and social economic benefits, which require different evaluation methods. The ecological aspect is considered by adopting the SPM and the social aspect is considered by adopting the DWPM to jointly set a water resource value system in the water environmental flow distribution system.

By introducing interval parameters to deal with the uncertainties of economic data and water inflow in the two-stage planning model, the uncertainty data are expressed as an interval, and then this interval is introduced into the constraints of the two-stage planning model, which help solve the practical difficulties involved in two-phase planning, leading to the formation of an interval two-stage (ITS) 'dual' water environmental flow allocation model. Finally, an interval two-stage 'dual' water environmental flow allocation model (ITS), the SPM and the DWPM are coupled to generate an interval two-stage fuzzy shadow price model (ITS-SPM).

2.2. Methods

2.2.1. 'Dual' (natural–social) environmental flow allocation model

This model applies the idea of optimizing resource allocation and fully considers the uncertainties caused by inaccurate data in the display situation for water resource system management. On the one hand, it can reflect the complexity response relationship between uncertainty parameters and economic penalties, and on the other hand, it can reflect uncertainties and decision-making goals in the optimization process. Environmental flow planning can help decision makers make reasonable plans for water resources in the river basin under complex economic and system constraints and achieve the goal of coordinating the relationship between economic costs, system efficiency and water supply security. An interval two-stage fuzzy shadow price model (ITS-SPM) is as follows:

$$\begin{aligned}\text{Max}\, f^{\pm} &= \sum_{i=1}^{m}(M_{ic}^{\pm}-P_{0i}^{\pm})\cdot W_{ci}^{\pm}-\sum_{i=1}^{m}M_{ic}^{\pm}\cdot Y_{ci}^{\pm}\\ &\quad+\sum_{i=1}^{m}(M_{ia}^{\pm}-P_{0a}^{\pm})\cdot W_{ai}^{\pm}-\sum_{i=1}^{m}(M_{ia}^{\pm}-P_{1a}^{\pm})\cdot Y_{ai}^{\pm}+\sum_{i=1}^{m}(M_{il}^{\pm}-P_{0l}^{\pm})\cdot W_{li}^{\pm}-\sum_{i=1}^{m}(M_{il}^{\pm}-P_{1l}^{\pm})\cdot Y_{li}^{\pm}\\ &\quad+\sum_{i=1}^{m}(M_{id}^{\pm}-P_{0d}^{\pm})\cdot W_{di}^{\pm}-\sum_{i=1}^{m}(M_{id}^{\pm}-P_{1d}^{\pm})\cdot Y_{di}^{\pm}\end{aligned} \tag{1}$$

Subject to

$$P_{1j}^{\pm}\le P_{0j}^{\pm}\le P_{j\ \max}$$

$$\sum_{i=1}^{12}\sum_{j=1}^{4}W_{i}^{\pm}-\sum_{i=1}^{12}\sum_{j=1}^{4}Y_{ci}^{\pm}\le qc^{\pm}$$

$$W_{ci}^{\pm}+W_{ai}^{\pm}+W_{li}^{\pm}+W_{di}^{\pm}\le qc^{\pm}$$

$$qc^{\pm}\le Q^{\pm}$$

$$W_{i\ \max}\ge W_{ci}^{\pm}\ge Y_{ci}^{\pm}\ge 0$$

where f is the basin water environment system benefits, which is equal to the total returns minus the loss from reduced social activities. Among them, i is the month that the environmental flow of a certain river needs to be allocated; j is the four water demand units of a certain river: c (i.e., ecology), a (i.e., agriculture), l (i.e., life) and d (i.e., industry); $W_{ci}^{\pm}$ is the expected water demand (i.e., first-stage decision variable), the expected allocation of water resources will produce the first stage of benefits; $Y_{ci}^{\pm}$ is the adjusted value of expected water demand (i.e., decision optimization), which leads to the second-stage penalties $\sum_{i=1}^{m}M_{ic}^{\pm}\cdot Y_{ci}^{\pm}$; $P_0^{\pm}$ is the expected price of unit water resources; $P_1^{\pm}$ is the real price of unit water resources; $qc^{\pm}$ is the total amount of water resources available for distribution; $Q^{\pm}$ is the total amount of water resources in the basin.

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2.2.2. Shadow price model

Water resources in the basin are divided into natural and social modes, and four water-use sectors: ecological (natural), agriculture, life and industry (social). Based on the direct consumption coefficient matrix of each sector and the input–output table composed of column vectors, we maximize the net benefit of the total social water as the optimization target and the water resource input–output balance as the constraints of the optimization model and construct a water resource SPM.

$$\text{Max } Z = \sum_{j=1}^{4} H_j X_j, \tag{2}$$

Subject to

$$AX + Y = X$$

$$\sum_{j=1}^{4} K_j X_j \leq W$$

$$H_j = \frac{w_j}{X_j}$$

$$X_l \leq X \leq X_h$$

$$Y_l \leq Y$$

where Z is the total value added of each water sector in the national economy; H is the value-added coefficient of section j; X is the total output of each sector; Y is the product column vector; w_j is the total sector water consumption; K is the direct water-use coefficient; W is the total amount of water resources available for distribution; X_l is the lower bound column vector of total output; X_h is the upper bound column vector of total output; Y_l is the lower bound column vector of products.

2.2.3. Interval two-stage fuzzy SPM

The theory is to add a water value system into the environmental flow allocation model, so as to affect the distribution of environmental flow and ensure the maximization of system income. This research aims to give priority to ensuring high-efficiency domestic and industrial water and making a systematic adjustment between ecological and agricultural water. The algorithm and solution process of the ITS-SPM are as follows.

$$\text{Max } f^{\pm} = \sum_{i=1}^{m} (M_{ic}^{\pm} - P_{0i}^{\pm}) \cdot W_{ci}^{\pm} - \sum_{i=1}^{m} M_{ic}^{\pm} \cdot Y_{ci}^{\pm} + \sum_{i=1}^{m} (M_{ia}^{\pm} - P_{0a}^{\pm}) \cdot W_{ai}^{\pm} - \sum_{i=1}^{m} (M_{ia}^{\pm} - P_{1a}^{\pm}) \cdot Y_{ai}^{\pm} \tag{3}$$

Subject to

$$P_{0a}^{\pm} = (qc^{\pm}/KR^{E_2} Z^{E_3})^{\frac{1}{E_1}}$$

$$\sum_{j=1}^{4} H_j^{\pm} X_j^{\pm} \leq qc^{\pm}$$

$$P_{1j}^{\pm} \leq P_{0j}^{\pm} \leq P_{j\ \max}$$

$$\sum_{i=1}^{12} W_{ci}^{\pm} - \sum_{i=1}^{12} Y_{ci}^{\pm} \leq qc^{\pm}$$

$$W_{ci}^{\pm} + W_{ai}^{\pm} \leq qc^{\pm} - W_{li}^{\pm} - W_{di}^{\pm}$$

$$qc^{\pm} \leq Q^{\pm}$$

$$W_{i\ \max} \geq W_{ci}^{\pm} \geq Y_{ci}^{\pm} \geq 0$$

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where qc is the actual water consumption in irrigated areas; K is the constant; P is the actual water price; R is the average annual evaporation during the growing season; Z is the average annual rainfall during the growing season; E_1 is the elastic coefficient of water price; E_2 is the elastic coefficient of evaporation; and E_3 is the elastic coefficient of rainfall. In the above planning, it is difficult to determine whether W_{ci}^{+} should correspond to f^{+}, and W_{ci}^{-} should correspond to f^{-} (decision W_{ci}^{+} will generate large economic benefits, but brings with it a lot of risk; W_{ci}^{-} corresponds to a small economic benefit, but brings little risk).

Solving steps:

$$W_{ci}^{\pm} = W_{ci}^{-} + \Delta W_{ci} y_i,\ \Delta W_c = W_{ci}^{+} - W_{ci}^{-},\ 0 \leq y_i \leq 1.$$

This corresponds to f^{+}:

$$\text{Max}\, f^{+} = \sum_{i}^{m} (M_{ic}^{+} - P_{0i}^{-}) \cdot (W_{ci}^{-} + \Delta W_{ci} y_i) - \sum_{i=1}^{m} M_{ic}^{-} \cdot Y_{ci}^{-} + \sum_{i=1}^{m} (M_{ia}^{+} - P_{0a}^{-}) \cdot W_{ai}^{+} - \sum_{i=1}^{m} (M_{ia}^{-} - P_{1a}^{+}) \cdot Y_{ai}^{-} \tag{4}$$

Subject to

$$P_{0a}^{-} = (qc^{-}/KR^{E_2}Z^{E_3})^{\frac{1}{E_1}}$$

$$\sum_{j=1}^{4} H_j^{+} X_j^{+} \leq qc^{+}$$

$$P_{1j}^{+} < P_{0j}^{-} < P_{\max}$$

$$\sum_{i=1}^{12} \Delta W_{ci} - Y_{ci}^{-} \leq qc^{+} - \sum_{i=1}^{12} W_{ci}^{-}$$

$$W_{ci}^{-} + \Delta W_{ci} y_i + W_{ai}^{+} \leq qc^{+} - W_{li}^{+} - W_{di}^{+}$$

$$W_{i\ \max} \geq W_{ci}^{-} + \Delta W_{ci} y_i \geq Y_{ci}^{-} \geq 0$$

Solve for this linear program to find f^{+}, y_i and Y_{ci}^{-}. y_i is substituted:

$$\text{Max}\, f^{-} = \sum_{i}^{m} (M_{ic}^{-} - P_{0i}^{+}) \cdot (W_{ci}^{-} + \Delta W_{ci} y_i) - \sum_{i=1}^{m} M_{ic}^{+} \cdot Y_{ci}^{+} + \sum_{i=1}^{m} (M_{ia}^{-} - P_{0a}^{+}) \cdot W_{ai}^{-} - \sum_{i=1}^{m} (M_{ia}^{+} - P_{1a}^{-}) \cdot Y_{ai}^{+} \tag{5}$$

Subject to

$$P_{0a}^{+} = (qc^{+}/KR^{E_2}Z^{E_3})^{\frac{1}{E_1}}$$

$$\sum_{j=1}^{4} H_j^{-} X_j^{-} \leq qc^{-}$$

$$P_{1j}^{-} < P_{0j}^{+} < P_{\max}$$

$$\sum_{i=1}^{12} \Delta W_{ci} - Y_{ci}^{+} \leq qc^{-} - \sum_{i=1}^{12} W_{ci}^{-}$$

$$W_{ci}^{-} + \Delta W_{ci} y_i + W_{ai}^{-} \leq qc^{-} - W_{li}^{-} - W_{di}^{-}$$

$$W_{ci}^{-} + \Delta W_{ci} y_i \geq Y_{ci}^{+} \geq 0$$

$$Y_{ci}^{+} \geq Y_{ci}^{-}$$

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Determine the optimal solution and the optimal value:

$$f^{\pm} = [f^{-}, f^{+}]$$

$$Y_{ci}^{\pm} = [Y_{ci}^{-}, Y_{ci}^{+}]$$

2.3. Research area overview

The Shaying River is the largest tributary on the left bank of the middle reaches of the Huai River. It covers an area of 36,651 km^2 and a total length of 561 km (Zuo *et al.* 2016). Within the basin, there are three types of terrain: mountainous, hilly and plain. The mountain area stretches to more than 9,070 km^2, distributed in the northwest of the basin, the hills stretch to more than 5,370 km^2, sandwiched between the mountain and the plain transition zone, and the plain area exends to 22,201 km^2, distributed in the southeast. From the perspective of the shape of the river, the shape of the tributaries of the Shaying River has changed greatly, and the main stream is stable and relatively wide. As the largest tributary of the Huai River, the water resources of the Shaying River are very unevenly distributed during the year. Due to the lack of a scientific management mechanism, the ecological flow plan that has been formulated cannot be implemented. The flow of multiple sections of the Shaying River is zero and will even last for a whole year. In the long run, the gradual transformation of river-type water ecosystems to lake type is not conducive to the sustainable and healthy development of river species. Figure 2 shows the geographic location of the study area.

There are three ecological water supply projects in the Shaying River Basin to replenish water for the river. (i) Water storage project: Located in Taihe County, Fuyang City, Genglou Gate is the largest ship lock and control gate hub on the Shaying River. The control area above the Genglou Gate is 29,290 km^2, the normal storage level is 32 m, the normal storage capacity is 15.3×10^6 m^3 and the effective storage capacity above the Genglou Hub is 43.6×10^6 m^3. (ii) Reclaimed water reuse project: There are two sewage treatment plants near Genglou Gate, both of which are located in the economic development zone. The total incoming sewage volume of the two sewage treatment plants is 0.12×10^6 m^3/d. In the planning year, the sewage outflow rate of the Taihe County sewage treatment plant is 0.8, and the outflow rate of the reclaimed water plant is generally 0.6–0.8, so the outflow rate of the reclaimed water plant is $[57.6, 76.8] \times 10^3$ m^3/d. (iii) Water transfer project: The water supply project of the Shaying River Basin is the water diversion project from the Yangtze River to the Huaihe River. The water available for the project in this study area is $[188, 228] \times 10^6$ m^3/a.

2.4. Application model setting

Water is replenished for ecologically water-scarce rivers through engineering or non-engineering measures to prevent the destruction of the river ecological structure and function and gradually restore the self-regulation ability of the ecosystem

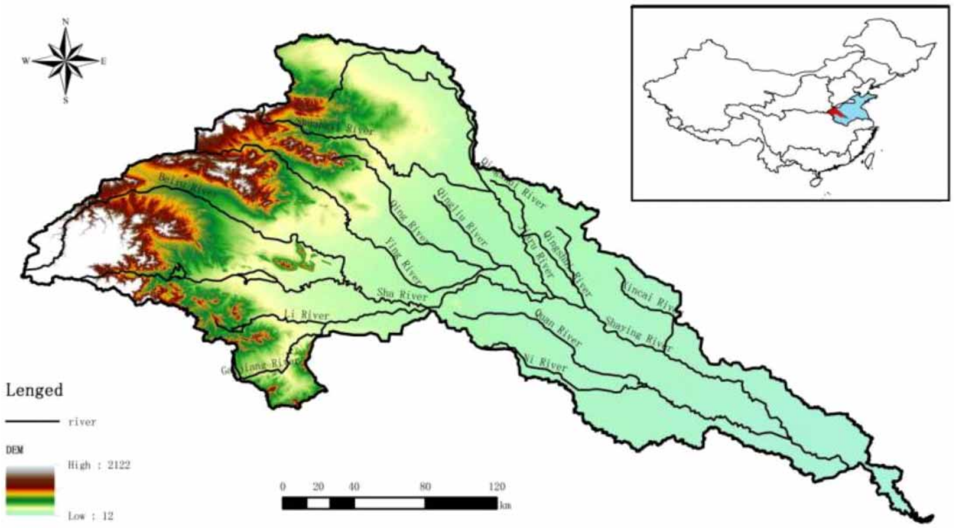

Figure 2 | Study area.

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(Qing *et al.* 2015). Thus, the following water environment replenishment plan is established:

$$\text{Max}\, f^{\pm} = \sum_{i=1}^{m} (M_{ic}^{\pm} - P_{0i}^{\pm}) \cdot W_{ci}^{\pm} - \sum_{i=1}^{m} M_{ic}^{\pm} \cdot Y_{ci}^{\pm} + \sum_{i=1}^{m} (M_{ia}^{\pm} - P_{0a}^{\pm}) \cdot W_{ai}^{\pm} - \sum_{i=1}^{m} (M_{ia}^{\pm} - P_{1a}^{\pm}) \cdot Y_{ai}^{\pm} + \sum_{i=1}^{m} P_{2k}^{\pm} W_{pi}^{\pm} - \sum_{i=1}^{m} P_{0i}^{\pm} W_{pi}^{\pm} \quad (6)$$

Subject to

$$P_{0a}^{\pm} = (qc^{\pm}/KR^{E_2}Z^{E_3})^{\frac{1}{E_1}}$$

$$\sum_{j=1}^{4} H_j^{\pm} X_j^{\pm} \leq qc^{\pm}$$

$$P_{1j}^{\pm} \leq P_{0j}^{\pm} \leq P_{j\ \max}$$

$$\sum_{i=1}^{12} W_{ci}^{\pm} - \sum_{i=1}^{12} Y_{ci}^{\pm} \leq qc^{\pm}$$

$$W_{ci}^{\pm} + W_{ai}^{\pm} \leq qc^{\pm} - W_{li}^{\pm} - W_{di}^{\pm}$$

$$qc^{\pm} \leq Q^{\pm}$$

$$W_{i\ \max} \geq W_{ci}^{\pm} \geq Y_{ci}^{\pm} \geq 0$$

where $P_{2k}^{\pm}$ is the unit water revenue; $W_{pi}^{\pm}$ is the expected replenishment amount of the water conservancy project. The Shaying River is supplemented by three water source projects during the dry season and the benefit generated by anticipated hydration is $\sum_{i=1}^{m} P_{2k}^{\pm} W_{pi}^{\pm}$; the cost of replenishing water from the water source project is $\sum_{i=1}^{m} P_{0i}^{\pm} W_{pi}^{\pm}$.

2.5. Model data

2.5.1. Improved Tennant method

This study combines the hydrology method and habitat simulation method to produce an improved Tennant method to calculate the recommended value of environmental flow and compares it with the implementation plan for the pilot work of environmental flow (water level) in the Huaihe River Basin (Ceola *et al.* 2018; Tsai *et al.* 2016). The results are summarized in Table 1.

Due to its speed and economic characteristics, the Tennant method is often the preferred method for large-scale water resource development planning. The minimum ecological discharge value calculated by using the improved Tennant method accounts for 8% of the multi-year average discharge, which can meet the needs of aquatic organisms. The calculation result of the combination of the improved Tennant method and the habitat simulation method was used as the recommended value of the minimum environmental flow, and the ecological environment of the river can reach a 'good' state in the evaluation standard of the Tennant method. In general, the recommended value of environmental flow in this article can meet the basic protection requirements for aquatic organisms.

In view of the special hydrological situation of the Shaying River, the traditional Tennant method was improved, the original water period and proportion were adjusted and the defect that is not applicable to seasonal rivers was removed. Based on the relevant fish habitat information obtained from the survey, a flow-effective habitat area relationship curve was constructed to obtain the environmental flow required for the fish spawning period.

2.5.2. Expected water allocation data

Policy setting: In 2016, farmland irrigation water consumption in Anhui Province was 15.89 billion m^3, and in 2017, farmland irrigation water consumption was 14.93 billion m^3 (Tsai *et al.* 2016; Ministry of Water Resources of China, Anhui 2016). A policy plan was set up for reducing agricultural water consumption based on a 1% reduction in total agricultural water consumption each year. Therefore, the total agricultural water consumption in the Shaying River Basin of Anhui Province would have reduced by 3% in 2020, and the total agricultural water consumption in the river basin will be reduced by 2025. By 2030,

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Table 1 | Recommended value of environmental flow (m^3/s)

Month	Multi-year average	Status quo	Improved Tennant method	Habitat simulation method	Recommended value	Remarks
Jan	43.2	5.5	4.8		4.8	Dry season
Feb	36.8	5.5	4.8		4.8	
Mar	48.3	5.5	4.8		4.8	
Apr	71.2	5.8	8.4	33.0	33.0	Fish spawning period
May	73.2	5.8	8.4	33.0	33.0	
Jun	83.1	16.7	14.8	33.0	33.0	
Jul	281.5	16.7	14.8	33.0	33.0	
Aug	295.3	16.7	14.8		14.8	Wet season
Sept	198.9	16.7	14.8		14.8	
Oct	124.3	5.5	8.4		8.4	Normal period
Nov	83.6	5.5	8.4		8.4	
Dec	63.0	5.5	4.8		4.8	Dry season

the total agricultural water consumption in the basin will be reduced by 13%, and by 2035, the total agricultural water consumption will be reduced by 18%. Table 2 shows the expected environmental flow allocation.

Table 3 shows that water used in the section from the Jieshou Hydrological Station to Genglou Gate is mainly agricultural irrigation water, accounting for about 79% of the total water consumption.

After water is drawn by various sectors, the river flow cannot satisfy the environmental flow in most months. Therefore, it is necessary to recharge the river from the water source project. The environmental water shortage of the basin is shown in Table 4.

2.5.3. Economic data

The parameters for the modeling formulation are calculated based on government reports and statistical yearbook (Ministry of Water Resources of China, Anhui 2017). Table 5 shows economic data such as net benefit/loss from unit environmental flow, which are estimated by regional statistical yearbooks from the water input–output table.

There have been many quantitative studies on the economic affordability of farmers. In China, the water fee should account for 10–20% of the net income, and it is reasonable to account for 5–15% of the total output value (Ministry of Water Resources of China, Fuyang 2017). Therefore, $P_{\max}$ is 0.12 yuan/m^3. The added value of the agricultural industry in 2017 was 5.1 billion yuan. The agricultural economic data loss is shown in Table 6.

2.5.4. Water source project cost coefficient

The water supply cost coefficient of the water source project is different (Development Research Center of Ministry of Water Resources 2010). The water source cost coefficient is shown in Table 7. (1) The cost coefficient of water conservancy project is the sum of water resource fee, sewage treatment fee and water delivery cost; (2) the reclaimed water cost coefficient is generally based on the sum of investment, construction and operating expenditures of sewage treatment facilities; (3) the cost coefficient of water storage projects such as reservoirs, sluices and dams is the sum of operation and maintenance and water delivery costs.

3. RESULTS

3.1. Environmental flow allocation

Under the scenario of water supply for projects without water sources, the system's revenue added value (adjustment of water-use structure in the basin) is as follows: 3% scenario: $[170.76, 231.64] \times 10^6$ yuan; 8% scenario: $[432.02, 510.65] \times 10^6$ yuan; 13% scenario: $[766.61, 885.22] \times 10^6$ yuan; 18% scenario: $[1057.56, 1207.54] \times 10^6$ yuan. Under the water supply scenario of the water source project, the system revenue added value is as follows: 3% scenario: $[8475.70, 9077.76] \times 10^6$ yuan; 8% scenario: $[8585.55, 9201.47] \times 10^6$ yuan; 13% scenario: $[8701.35, 9377.69] \times 10^6$ yuan; 18% scenario: $[8797.49, 9372.98] \times 10^6$

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Table 2 | Expected environmental water demand target (10^6 m^3)

	Total control policy scenario			
Month	**3%**	**8%**	**13%**	**18%**
Jan	[12.86, 13.25]	[12.86, 13.63]	[12.86, 14.02]	[12.86, 14.40]
Feb	[11.61, 12.00]	[11.61, 12.42]	[11.61, 13.12]	[11.61, 13.70]
Mar	[12.86, 13.25]	[12.86, 13.50]	[12.86, 14.15]	[12.86, 14.53]
Apr	[85.54, 86.40]	[85.54, 87.25]	[85.54, 88.11]	[85.54, 88.96]
May	[88.39, 89.27]	[88.39, 89.27]	[88.39, 89.27]	[88.39, 90.16]
Jun	[85.54, 86.40]	[85.54, 87.25]	[85.54, 88.11]	[85.54, 88.11]
Jul	[88.39, 89.27]	[88.39, 90.16]	[88.39, 91.04]	[88.39, 91.04]
Aug	[39.64, 40.83]	[39.64, 41.62]	[39.64, 43.21]	[39.64, 44.00]
Sept	[38.36, 39.51]	[38.36, 39.90]	[38.36, 40.66]	[38.36, 41.43]
Oct	[22.50, 22.95]	[22.50, 23.18]	[22.50, 23.63]	[22.50, 23.85]
Nov	[21.77, 22.21]	[21.77, 22.86]	[21.77, 23.51]	[21.77, 23.95]
Dec	[12.86, 13.12]	[12.86, 13.25]	[12.86, 13.63]	[12.86, 14.02]

Table 3 | Expected agricultural water demand target (10^6 m^3)

	Total control policy scenario			
Month	**3%**	**8%**	**13%**	**18%**
Jan	[7.30, 7.40]	[6.75, 7.15]	[6.50, 6.68]	[6.10, 6.32]
Feb	[9.85, 10.05]	[9.35, 9.60]	[8.80, 9.12]	[8.30, 8.55]
Mar	[7.70, 7.82]	[7.30, 7.43]	[6.80, 7.12]	[6.40, 6.72]
Apr	[14.80, 15.20]	[14.00, 14.60]	[13.38, 13.50]	[12.58, 12.77]
May	[4.90, 5.00]	[4.70, 4.77]	[4.50, 4.54]	[4.14, 4.20]
Jun	[12.29, 12.50]	[11.65, 11.90]	[10.95, 11.45]	[10.30, 10.70]
Jul	[12.62, 12.80]	[11.90, 12.30]	[11.20, 11.71]	[10.65, 10.88]
Aug	[20.65, 22.00]	[19.50, 22.50]	[18.50, 21.50]	[17.50, 19.00]
Sept	[13.85, , 15.00]	[13.20, 14.50]	[12.65, 13.20]	[12.00, 12.35]
Oct	[5.75, 5.85]	[5.45, 5.57]	[5.00, 5.30]	[4.85, 4.92]
Nov	[10.46, 10.80]	[9.9, 10.25]	[9.40, 9.70]	[8.82, 9.15]
Dec	[4.6, 4.65]	[4.37, 4.40]	[4.16, 4.18]	[3.85, 3.90]

Table 4 | Expected water replenishment (10^6 m^3)

	Total control policy scenario			
Month	**3%**	**8%**	**13%**	**18%**
Feb	[14.63, 14.70]	[14.19, 14.24]	[13.51, 13.66]	[12.99, 13.15]
Apr	[35.89, 36.00]	[35.18, 35.31]	[34.34, 34.44]	[33.49, 33.67]
Jun	[6.44, 6.47]	[5.87, 5.90]	[5.01, 5.18]	[4.37, 4.54]
Aug	[47.18, 47.45]	[46.17, 46.49]	[44.88,45.26]	[43.89, 44.18]
Sept	[31.58, 31.97]	[31.02, 31.32]	[30.27, 30.48]	[29.57,29.74]
Oct	[28.39, 28.47]	[28.11, 28.20]	[27.58, 27.86]	[27.35, 27.57]
Nov	[10.71, 10.82]	[10.22, 10.34]	[9.56, 9.71]	[8.98, 9.17]

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Table 5 | Ecological economic data (yuan/m^3)

Month	Unit ecological water benefit	Unit ecological water shortage
Jan	[97.01, 99.01]	[101.07, 103.07]
Feb	[107.46, 109.67]	[111.95, 114.17]
Mar	[97.01, 99.01]	[101.07, 103.07]
Apr	[14.53, 14.83]	[15.19, 15.50]
May	[14.06, 14.35]	[14.70, 15.00]
Jun	[14.53, 14.83]	[15.19, 15.50]
Jul	[14.06, 14.35]	[14.70, 15.00]
Aug	[31.44, 32.08]	[32.79, 33.44]
Sept	[32.48, 33.15]	[33.88, 34.55]
Oct	[55.42, 56.56]	[57.77, 58.91]
Nov	[57.28, 58.46]	[59.70, 60.89]
Dec	[97.01, 99.01]	[101.07, 103.07]

Table 6 | Agricultural economic data

	Total control policy scenario			
Month	3%	8%	13%	18%
Unit agricultural water benefit (yuan/m^3)				
Jan	[55.86, 57.01]	[58.90, 60.11]	[62.28, 63.57]	[66.08, 67.44]
Feb	[41.36, 42.22]	[43.61, 44.51]	[46.12, 47.07]	[48.93, 49.94]
Mar	[52.93, 54.02]	[55.81, 56.96]	[59.02, 60.23]	[62.62, 63.91]
Apr	[27.50, 28.07]	[29.00, 29.59]	[30.66, 31.30]	[32.53, 33.20]
May	[81.36, 83.04]	[85.78, 87.55]	[90.71, 92.58]	[96.24, 98.22]
Jun	[33.30, 33.99]	[35.11, 35.83]	[37.13, 37.89]	[39.39, 40.20]
Jul	[32.43, 33.10]	[34.20, 34.90]	[36.16, 36.91]	[38.37, 39.16]
Aug	[19.58, 19.98]	[20.64, 21.07]	[21.83, 22.28]	[23.16, 23.64]
Sept	[28.77, 29.37]	[30.34, 30.96]	[32.08, 32.74]	[34.04, 34.74]
Oct	[69.50, 70.93]	[73.28, 74.79]	[77.49, 79.08]	[82.21, 83.91]
Nov	[38.79, 39.59]	[40.90, 41.74]	[43.25, 44.14]	[45.88, 46.83]
Dec	[88.48, 90.31]	[93.29, 95.21]	[98.65, 100.69]	[104.67, 106.83]
Unit agricultural water shortage (yuan/m^3)				
Jan	[58.17, 59.32]	[61.33, 62.54]	[64.85, 66.14]	[68.81, 70.17]
Feb	[43.07, 43.92]	[45.41, 46.31]	[48.02, 48.97]	[50.95, 51.96]
Mar	[55.12, 56.21]	[58.11, 59.27]	[61.45, 62.67]	[65.20, 66.49]
Apr	[28.64, 29.20]	[30.20, 30.79]	[31.93, 32.56]	[33.88, 34.55]
May	[84.71, 86.39]	[89.32, 91.09]	[94.45, 96.32]	[100.21, 102.20]
Jun	[34.67, 35.36]	[36.56, 37.28]	[38.66, 39.43]	[41.02, 41.83]
Jul	[33.77, 34.44]	[35.61, 36.31]	[37.66, 38.40]	[39.95, 40.74]
Aug	[20.39, 20.79]	[21.50, 21.92]	[22.73, 23.18]	[24.12, 24.60]
Sept	[29.96, 30.55]	[31.59, 32.22]	[33.41, 34.07]	[35.44, 36.15]
Oct	[72.37, 73.80]	[76.30, 77.81]	[80.69, 82.28]	[85.61, 87.30]
Nov	[40.39, 41.19]	[42.59, 43.43]	[45.03, 45.93]	[47.78, 48.73]
Dec	[92.13, 93.96]	[97.14, 99.06]	[102.72, 104.76]	[108.99, 111.15]

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Table 7 | Water source project cost coefficient (yuan/m^3)

Water source project	Genglou Gate Water Storage Project	Water diversion project from Yangtze River to Huaihe River	Water reuse project
Cost coefficient	[0.6, 0.8]	[3.5, 4.0]	[1.0, 1.3]

yuan. Agricultural water reduction is used to allocate environmental flow. For example, when total agricultural water consumption reduced by 3%, the added environmental flow accounted for 0.73–0.98%. The results are given in Table 8.

It can be seen from Figure 3 that in the months with low flow, the added value of ecological flow is low. At the same time, agricultural water demand in these months is also at a relatively low level; during the flood season and the peak period of agricultural water consumption, some of the months overlap. Due to the relatively high inflow of water and the huge amount of agricultural water use, there is a greater reduction in this amount, which makes ecological water use more supplemented. The increase in ecological water consumption in August is the annual peak. From the perspective of the whole year and different policy scenarios, the ecological water added value in different months will not change much in different years in the future. However, since agricultural water use will be in a downward adjustment state in the future, ecological water consumption will also be continuously replenished.

It can be seen from Figure 4 that the ecological water demand varies greatly in different months, and – there are roughly three situations: From January to March is the dry season of the river. Generally, the flow rate is at the lowest value of the year. At this time, the ecological water demand of the river basin is also roughly the lowest value of the year. From April to July, when the current flow level is at the annual peak, and fish in the river are in the spawning period, the corresponding ecological water demand is the annual peak of the river. After August, the river flow decreases year by year, and the environmental water demand in the river channel also decreases month by month.

It can be seen from Figure 5 that in the months with high flow, the proportion of ecological water demand increases, and the same is true in months with high agricultural water consumption. Looking at it from another perspective, the months when the newly increased proportion of ecologically available water is high are the months when the ecological water efficiency is high. At the same time, the unit agricultural water-use efficiency in these months is low, which leads to higher reductions in agricultural water use, and ecological water replenishment is at a high level.

Figure 6 shows a comparison between the recommended and the actual environmental flow. It can be seen that environmental flow cannot be guaranteed in some months, and, therefore, water source engineering supplementary measures are required.

Table 8 | Optimized water targets under scenario (10^6 m^3)

	Total control policy scenario			
Month	3%	8%	13%	18%
Jan	[13.08, 13.52]	[13.42, 14.40]	[13.85, 15.14]	[14.23, 15.94]
Feb	[11.91, 12.37]	[12.37, 13.23]	[12.95, 14.61]	[13.46, 15.72]
Mar	[13.09, 13.54]	[13.45, 14.14]	[13.91, 15.38]	[14.31, 16.18]
Apr	[85.99, 86.96]	[86.68, 88.52]	[87.55, 90.22]	[88.32, 91.92]
May	[88.54, 89.50]	[88.77, 89.70]	[89.07, 90.01]	[89.31, 91.27]
Jun	[85.91, 86.80]	[86.48, 88.22]	[87.20, 89.94]	[87.84, 90.58]
Jul	[88.77, 89.68]	[89.35, 91.21]	[90.10, 92.96]	[90.75, 93.57]
Aug	[40.27, 41.73]	[41.23, 43.53]	[42.46, 46.41]	[43.54, 48.19]
Sept	[38.79, 40.33]	[39.44, 41.28]	[40.28, 42.79]	[41.02, 44.26]
Oct	[22.68, 23.21]	[22.95, 23.72]	[23.30, 24.71]	[23.58, 25.15]
Nov	[22.09, 22.64]	[22.57, 23.78]	[23.20, 25.09]	[23.74, 26.11]
Dec	[13.00, 13.29]	[13.21, 13.62]	[13.49, 14.29]	[13.72, 15.13]

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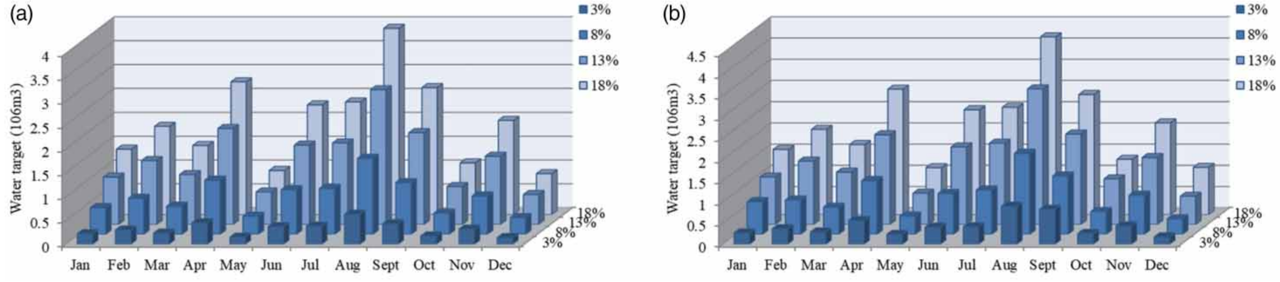

Figure 3 | Environmental flow increase targets. (a) Lower bound. (b) Upper bound.

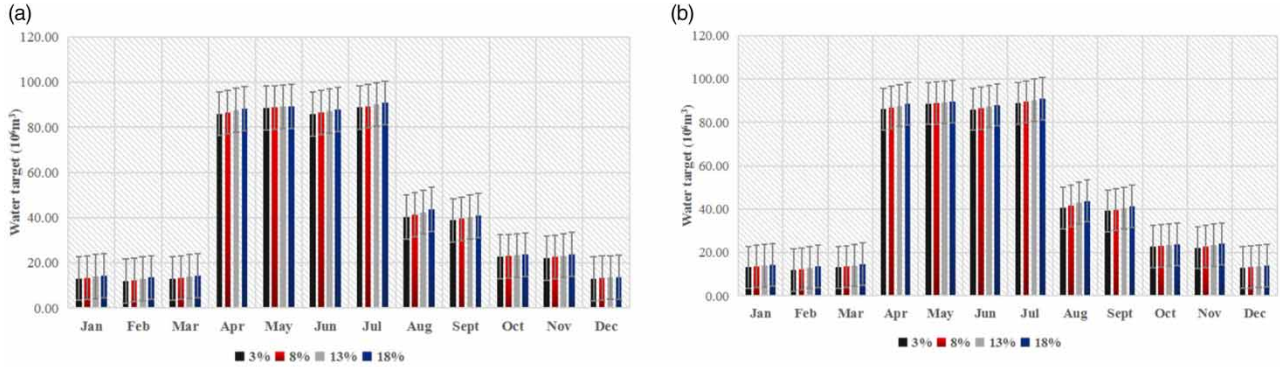

Figure 4 | Optimized water targets under scenario. (a) Lower bound. (b) Upper bound.

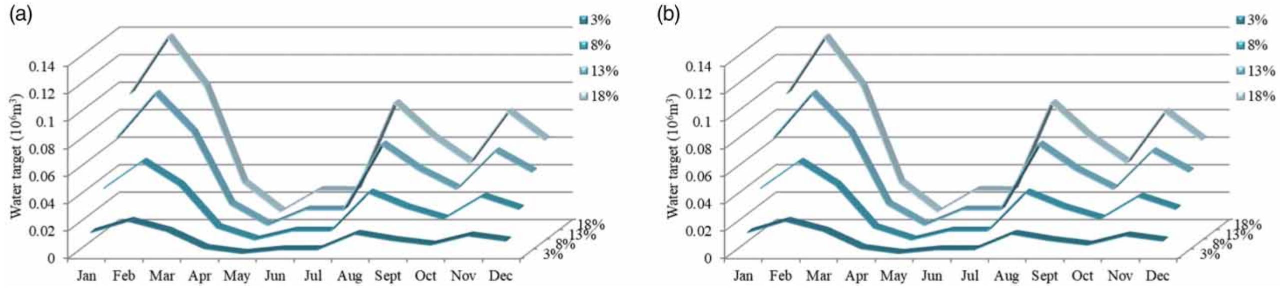

Figure 5 | Environmental flow growth rate. (a) Lower bound. (b) Upper bound.

3.2. Water replenishment plan

Table 9 shows the ecological water shortage in the Shaying River Basin. There are three water source projects in the basin, Genglou Gate Water Storage Project, Water reuse project and Water diversion project from Yangtze River to Huaihe River. In accordance with the principle of low to high unilateral water prices, priority shall be given to the use of the Genglou Gate water storage project for ecological water supply to the river. It can be seen that the ecological water shortage in the study area is the greatest in April and August. In February, the low water supply of Genglou Gate is due to the low level of water shortage. The water storage capacity of Genglou Gate is much larger than the water shortage downstream, while the smaller water supply of Genglou Gate in the remaining months is due to the control section located in the main urban area, which leads to social water squeezing ecological water supply. The upstream water storage capacity of Gengloumen is insufficient, and the ecological water shortage cannot be guaranteed.

The non-optimal dispatching plan of Genglou Gate alone cannot guarantee the environmental flow of the river in August–November, and the recommended environmental flow of this article can be reached in other months. According to the principle of maximizing economic benefits, when the Genglou Gate cannot meet the water replenishment demand of the Shaying River Basin, the reclaimed water reuse project is given priority to replenish water in the study area, and the maximum

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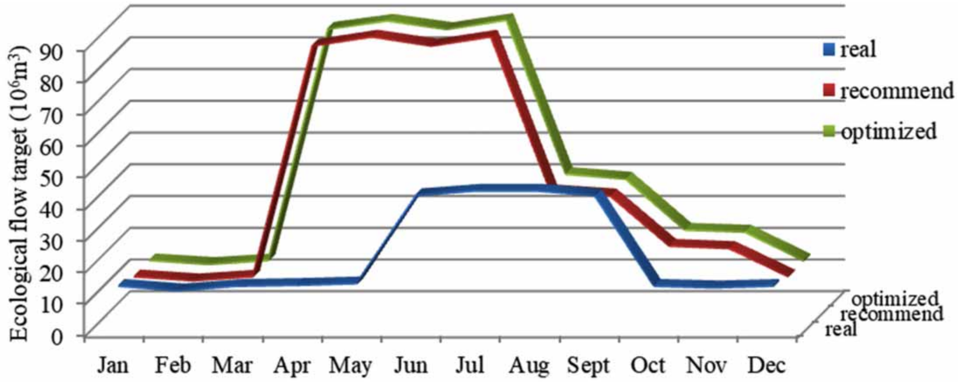

Figure 6 | Environmental flow lower bound.

Table 9 | Water supply project

Genglou gate (10^6 m^3)

	Total control policy scenario			
Month	**3%**	**8%**	**13%**	**18%**
Feb	[14.63, 14.70]	[14.19, 14.24]	[13.51, 13.66]	[12.99, 13.15]
Apr	[35.89, 36.00]	[35.18, 35.31]	[34.34, 34.44]	[33.49, 33.67]
Jun	[6.44, 6.47]	[5.87, 5.90]	[5.01, 5.18]	[4.37, 4.54]
Aug	[32.89, 37.44]	[32.89, 37.44]	[32.89, 37.44]	[32.89, 37.44]
Sept	[4.38, 7.54]	[4.38, 7.54]	[4.38, 7.54]	[4.38, 7.54]
Oct	[0, 0]	[0,0]	[0,0]	[0, 0]
Nov	[9.43, 11.83]	[9.43, 11.83]	[9.43, 11.83]	[8.98, 9.17]
Water reuse project (10^6 m^3)				
Aug	[1.79, 2.38]	[1.79, 2.38]	[1.79, 2.38]	[1.79, 2.38]
Sept	[1.79, 2.38]	[1.79, 2.38]	[1.79, 2.38]	[1.79, 2.38]
Oct	[1.79, 2.38]	[1.79, 2.38]	[1.79, 2.38]	[1.79, 2.38]
Nov	[1.28, 1.39]	[0.79, 0.91]	[0.13, 0.28]	0
Water diversion project from Yangtze River to Huaihe River (10^6 m^3)				
Aug	[12.50, 12.77]	[11.49, 11.81]	[10.20, 10.58]	[9.21, 9.50]
Sept	[25.41, 25.80]	[24.85, 25.15]	[24.10, 24.31]	[23.40, 23.57]
Oct	[26.60, 26.68]	[26.32, 26.41]	[25.79, 26.07]	[25.56, 25.78]

monthly water production of the reclaimed water treatment plant is used to recover the ecological water shortage in the study area make up. For the ecological water shortage in August, September and October, the water diversion project from the Yangtze River to the Huaihe River is used to supplement water in the study area.

It can be seen from Table 9 that the study area has the largest ecological water shortage in the three months of August, September and October, and it is necessary to transfer water from other river basins across river basins. When the total agricultural water consumption in this area is reduced year by year, it can be seen that the ecological water shortage is gradually replenishing, and the benefits of the entire watershed water system will also increase.

4. DISCUSSION

Two-stage planning is often used in water resource management. Zeng developed a two-stage CP with a Hurwicz criterion (TCP-CH) approach for water resource management and planning under uncertainty (Zeng *et al.* 2014a). It can check for

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system failure risk based on different risk preferences of decision makers. However, too many subjective factors will lead to nonlinear problems in the system that cannot be reasonably solved. The ITS-SPM can simultaneously deal with the nonlinear problems with the goal of maximizing system revenue, which is mainly characterized by planning numerous nonlinear influencing factors into a fuzzy interval form. This makes the system goal a globally optimal one. The incorporation of IPP into a TSP framework by Li *et al.* can reflect not only the uncertainties expressed as probability distributions but also interval numbers (Zeng *et al.* 2014b; Li *et al.* 2019). However, the economic data of uncertainties in the model do not necessitate the adoption of a reasonable evaluation method. The ITS-SPM expresses uncertain ecological water-use benefits as fuzzy shadow prices, reflects the interplay between social water-use benefits and ecological water-use benefits and makes the best trade-off between water shortage losses and water supplement benefits. At the same time, this model can also deal with the uncertainties of the data source and unified planning into an interval form, which allows the overall benefit analysis of the system to run and produce an efficient distribution method.

The application of the ITS-SPM in the Shaying River Basin can effectively solve the problem of the lack of ecological water in the area and replenish the water ecology of the basin through continuous optimization of social water. It is worth mentioning that Tennant (1976) developed a hydrology method for the calculation of ecological flow (Tennant 1976). However, it cannot measure the response of fish to the changes in flow and lacks biological confirmation. It is a relatively rough method. (a) This study uses the improved Tennant method combined with the Habitat Simulation Method, and in this way, the minimum guaranteed environmental flow value of the Shaying River Basin can be obtained more accurately. (b) The study area lacked serious ecological flow from August to November, and the main reason for this was the sudden drop in incoming flow; (c) the Shaying River Basin added the highest ecological water consumption from April to July. This was mainly due to the huge amount of agricultural water used in the current month and high wastage. Therefore, the largest reduction in agricultural water use in such months is in the model; (d) in the same period from April to July, even though it was the most newly added ecological water use, its newly increased proportion was the lowest. The main reason is that the current month is in the fish spawning period, and the required flow in the river is the annual peak. Even if the incoming flow level is relatively high, the ecological water resources are still in a state of lack; the three water source project water replenishment schemes given above give priority to the principle of optimal economic benefits, and the Shaying River is refilled according to the maximum water available from the water source project. Therefore, adjusting the social water-use structure in the basin and saving water is still the key.

A water resource planning model is mainly used to remove the uncertain factors prevailing in the system. The ITS-SPM removes the uncertainties of environmental flow demand and economic data to a certain extent, but there is still room for improvement. In this study, the evaluation of social and economic benefits without the considered benefits of domestic water and industrial water, and the future planning of both were not considered. At the same time, the water-use unit was refined in the interval two-stage planning model to make it evolve into a multi-stage planning model. Refined water resource management will also be the development direction of future water resource planning.

5. CONCLUSION

In this study, an inexact two-stage environmental flow allocation model (ITS) is developed that combines TSP and the SPM. Then, IPP is used to remove uncertainties. Finally, an optimal allocation plan for the environmental flow of the Shaying River Basin is obtained. The main research contents and environmental flow planning recommendations are as follows:

5.1. Main research contents

This study mainly considers various uncertainties factors in the water resource planning system. A water resource value system (SPM, DWPM) is established for removing the uncertainties in economic data and ecological water value that cannot be reasonably estimated. For removing the uncertainties in water demand and incoming flow, an empirical decision on the recommended value of ecological flow is made based on the combination of an improved Tennant method and the Habitat Simulation method, and the empirical decision is optimized by the interval two-stage planning method. Its ultimate goal is to control the total amount of water use and optimize the system benefits. The lack of environmental flow has been supplemented by the adjustment of the agricultural water structure in the basin. Meanwhile, the adjustment of the water structure has increased the benefits of the system: 3% scenario: $[170.76, 231.64] \times 10^6$ yuan; 8% scenario: $[432.02, 510.65] \times 10^6$ yuan; 13% scenario: $[766.61, 885.22] \times 10^6$ yuan; 18% scenario: $[1057.56, 1207.54] \times 10^6$ yuan. Under the water supply scenario of the water source project, the system revenue added value is: 3% scenario: $[8475.70, 9077.76] \times 10^6$ yuan; 8% scenario:

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[8585.55, 9201.47] × 10^6 yuan; 13% scenario: [8701.35, 9377.69] × 10^6 yuan; 18% scenario: [8797.49, 9372.98] × 10^6 yuan. Then planning is done for three aspects: (a) adjusting the social–ecological water-use structure in the basin. This study mainly considers the adjustment and reduction of agricultural water use to supplement the ecological water shortage; (b) replenishing the ecological water shortage in the basin through water source projects; (c) Taking water replenishment measures for cross-basin water source projects. The consideration of these three aspects helped to successfully achieve the future environmental flow planning target and water transfer plan of the river basin.

5.2. Environmental flow planning recommendations

Environmental flow management is essentially a problem of interest adjustment. It is not only a trade-off between social and ecological economic benefits, but also an adjustment of the interest pattern generated by the distribution of water resources among river basins, different regions within a river basin, and different industries. The protection of environmental flow has gradually become an important prerequisite for the social economic development of various regions, and the planning of environmental flow has also become an important link in the water resource planning system. According to the practical application of the ITS-SPM developed by this study in the Shaying River Basin, the following suggestions are made for the environmental flow planning of the basin: (i) The protection of the environmental flow of the river basin depends not only on whether the regional ecological water shortage is huge, but also on whether the reduction of social water use will cause more losses. For example, when the environmental flow increases by more than 20% in 2035, more penalties will be imposed on the regional economy. (ii) The estimation of the recommended value of environmental flow in different basins should also be combined with the characteristics of the basin itself. During this study, a lot of fish was discovered in the Shaying River Basin. Therefore, a combination of an improved Tennant method and the Habitat Simulation method is used to infer recommended value. (iii) This study deals with the reduction of social water consumption, focusing on the reduction of agricultural water, which has high water wastage and low unit water output value. The reduction process does not adopt a one-size-fits-all model but combines the reduction of water resources to improve and repair local farmland water conservancy projects. At the same time, the government formulates relevant water-saving bonus measures to make up for the cost of water saving in the irrigation area. (iv) The Shaying River Basin lacks environmental flow in the months of February, April, July, August, September, October and November. In this study, three water source water replenishment projects are used as water replenishment projects. Considering the cost and water supply, the Genglou Gate Water Storage Project, the Reclaimed Water Reuse Project and the River Diversion Project to the Huaihe River Basin have the lowest water replenishment costs.

5.3. Research prospect

It should be noted that uncertainty exists in the acquisition of input data, especially the source and statistical methods. In this study, an interval programming was used to generate interval parameters to simplify such uncertainty caused by nonlinearity. However, on the issue of actual water resource planning, the water resource system was affected by multiple factors. IP considers extreme and average values too subjectively and lacks predictive properties for future planning. Therefore, integrating large-scale hydrological prediction models into the water resource system can reduce the impact of a large number of hydrological uncertainties on the planning results.

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AUTHOR CONTRIBUTIONS

The main text was written by S.Y. W.H. was in charge of polishing the English. L.X.W. was responsible for preparing the basic data. Conceptualization, S.Y.; Data curation, S.Y. Formal analysis, S.Y. Funding acquisition, W.H; Investigation, S.Y.; Methodology, S.Y.; Project administration, L.X.W.; Software, S.Y.; Validation, L.X.W.; Writing – original draft, S.Y.; Writing – review and editing, Z.W.W. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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