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Collaborative Ecological Flow Decision Making under the Bengbu Sluice Based on Ecological-Economic Objectives

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Abstract: The construction of dams destroys the integrity of a watershed system and the continuity of natural water flow, creating a watershed with segmented and fragmented rivers. This, in turn, affects and even destroys the health and stability of the watershed ecosystem. This study selected the downstream area of Bengbu Sluice in the Huai River Basin of China as the study area. To address the increasingly prominent ecosystem degradation in the Huai River Basin, ecological flow thresholds were determined using habitat simulation and hydrological approaches for mutual validation. A multi-objective synergistic decision model incorporating ecological and socioeconomic objectives was developed to coordinate the economic and ecological water use conflicts in the study area. The optimal coordinated solution for the ecological flow of important biological habitats in the basin was determined with the multi-objective synergistic method. The results demonstrated that a coordinated solution could guarantee the ecological and economic water demands of the basin. The findings of this study can be used as a reference for scientific guidelines on future ecological operations in dam-controlled rivers.

Keywords: ecological flow; habitat simulation; multi-objective decision making; ecological operation

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1. Introduction

China has the highest number of dams in the world. Dams are utilized for water storage and regulation [1,2], and people use them to control the water volume of rivers and regulate water resources according to socioeconomic needs.

The construction of dams alters the natural state of a river, leading it to become segmented or fractured, which threatens its integrity and consistency. Downstream runoff and the quantity of accessible water are considerably decreased, which affects the economic growth of downstream regions. A substantial quantity of silt accumulates in reservoir regions and reduces the flood storage capacity and river flow, thereby decreasing the self-purification ability of the water body relative to its natural condition [3]. Thus, fish migratory pathways are obstructed, and fish habitats are in peril [4]. Owing to the dams operation method, substantial amounts of sewage are discharged during the flood season, causing downstream water contamination. Therefore, the study of the ecological flow of rivers is of considerable theoretical significance and practical value for protecting river morphology and restoring integrity, continuity, and diversity of its species.

The calculation methods for ecological flow can broadly be grouped into the four categories: hydrological, hydraulic, habitat simulation, and holistic methods [5]. Hydraulic methods require measured data and cannot reflect seasonal variations in flow characteristics [6]. Holistic methods require the involvement of diverse disciplines and a series of long-term information. Thus, the employment of holistic models is costly and requires complicated computational procedures [7]. Hydrological methods are the only approaches that employ natural hydrological rhythms as a foundation for computing ecological flow and offering clear benefits when mimicking hydrological rhythms [8]. Habitat simulation methods assist in forecasting flow impacts on habitats. The key to these approaches is to combine hydrodynamic models with habitat preferences for the quantitative simulation of flow–habitat relationships. Habitat simulation methods combine hydrological characteristics, physical parameters of rivers, and habitat requirements of indicator species for ecological flow. Currently, the most commonly utilized models are the physical habitat simulation system model (PHABSIM) [9,10] and the two-dimensional (2D) river habitat model (River 2D) [11]. In this study, a comparative flow preference technique was developed to determine ecological flows by comparing the hydrological and habitat simulation methods. This new approach combines the benefits of both methods, considering the ecological integrity and increasing the link between runoff and river representative species while maintaining the operational benefits of the hydrological method.

The multiple services provided by dams have resulted in significant ecological and socioeconomic water disputes, making dam operation extremely complex. When the ecological environment of rivers is fiercely maintained, it has become one of the primary responsibilities of dam dispatching to fulfill the water requirements of ecological safety by reserving as much water as feasible while satisfying social and commercial water usage. Habitat simulation and hydrological approaches estimate ecological flow only from the standpoint of sustaining the steady growth of river ecosystems. However, they do not guarantee the sensible allocation of water resources. Since the 1950s, research on the best use of water resources has emerged. Most early studies utilized a system analysis strategy that primarily focused on the optimal operation of reservoirs [12]. Since the notion of water resources and the growing human consciousness of ecological preservation have grown, researchers have begun to concentrate on ecological flow and established multi-objective theories [13]. Various analytical methods, including system analysis, quadratic programming [14], and linear programming have been utilized to resolve multi-objective decision problems. Zomorodian et al. [15] employed system dynamics and game theory to alleviate local water problems by resolving ecological water demand and commercial water usage. Atef et al. [16] optimized economic and ecological benefits and used game theory to resolve water allocation. To reconcile the conflict between ecological and economic water use, it is essential to ensure the ecological river flow and function of river ecosystems and to provide a certain amount of water for social and economic water consumption to maintain sustainable economic development [17–19]. Recent studies have indicated that the best distribution of water resources must consider ecological and socioeconomic river usage. However, the water allocation of dam-controlled rivers has rarely been directly studied. Researchers have concentrated on discovering coordination techniques and have studied a larger number of water-quantity-based conflicts than flow-based conflicts, which may result in coordination outcomes that do not satisfy the optimal use of water resources. Water ecology quality is correlated with the flow process [19], which is one of the objectives of water resources allocation [17]. Owing to seasonal variations in the biological flow process of dam-controlled rivers, the coordination of water quantity conflicts alone cannot ensure the aquatic creatures' habitat conditions. Seasonal fluctuations in the ecological flow process of dam-controlled rivers serve as the basis for ecological dam operation. To fill this literature gap, a multi-objective collaborative decision-making model was developed for optimal water resources allocation in dam-controlled rivers, considering the changing pattern of ecological flow over time.

The Huai River is one of the seven largest rivers in eastern China. Numerous dams in the Huai River Basin play a crucial role in ensuring the availability of water for domestic, industrial, and other economic purposes in every river segment. However, the construction of dams damages the integrity of the basin water system and the continuity of natural water flow, resulting in basin fragmentation, which in turn impacts and even destroys its ecology. The Bengbu Sluice is a large water conservation hub project on the Huai River and has caused numerous downstream ecological issues. This study aimed to develop a method to tackle the growing issue of ecosystem degradation in the Huai River Basin, which is controlled by multiple dams. The Bengbu Sluice underneath was set as the study area to compute the ecological flow using habitat simulation and hydrological methods for mutual validation. On this basis, a multi-objective collaborative ecological and socioeconomic decision-making model was developed to coordinate the economic and ecological water use conflicts in the study area. This was resolved utilizing the multi-objective collaborative approach to determine the best coordinated solution for ecological flow in important biological habitats in the dam-controlled river for guaranteeing the ecological and economic water needs of the basin. The results of this study are expected to enhance operational capacity and support the harmonious development of the social, economic, and ecological environments in dam-controlled rivers.

2. Materials and Methods

2.1. Habitat Simulation Method

The habitat simulation method comprises the following three steps:

(1) Selection of indicator fish and mapping of habitat suitability curves for fish. The habitat suitability index (HSI) was associated with habitat parameters, including water depth, flow rate, water temperature, and substrate, of a typical fish species in the study area. An HSI value of 1 indicated that the fish species was suitable for survival, whereas a value of 0 indicated that the fish species was unsuitable for survival.

(2) Hydrodynamic model. Water depth and flow velocity distributions of the studied river sections were simulated using the MIKE21 model. For more details about the model, please refer to [20].

(3) Habitat simulation. The habitat simulation method emphasizes estimating the weighted usable area (WUA) of a habitat. The equation of WUA is expressed as follows [21]:

$$WUA = \sum A_i * F[f(V_i), f(D_i), f(C_i), f(T_i)]/L \quad (1)$$

where A_i is the area of unit i; $F[]$ is the composite suitability index, such as HSI; $f(V_i)$ is the flow suitability index of unit i; $f(D_i)$ is the depth suitability index of unit i; $f(C_i)$ is the channel substrate suitability index of unit i; $f(T_i)$ is the temperature suitability index of unit i; and L is the river section length.

The multiplication method was employed to determine the integrated suitability index:

$$HSI = f(V) \cdot f(D) \cdot f(C) \cdot f(T) \quad (2)$$

For computational convenience, this study assumed that the substrate condition of the study area was good. The comprehensive suitability index classes were classified as listed in Table 1.

Table 1. Habitat suitability index classification criteria.

Level	Value	Evaluation	Significance
I	0–0.25	Unsuitable	Habitat ecology was damaged and unsuitable for habitat
II	0.25–0.50	Less suitable	Habitat was usually destroyed and unable to maintain essential functions post-disturbance
III	0.50–0.75	Suitable	Habitat ecological functions were relatively well developed and could be restored post-disturbance
IV	0.75–1.00	Optimal	The habitat ecological function was perfect and had strong restoration ability

As depicted in Table 1, an HSI above 0.5 indicates that the region is suitable for habitat. The initial inflection and maximum points on this curve correspond to the horizontal coordinates of the minimum and optimal ecological flows, respectively.

2.2. Hydrological Method

In this study, the ecological flow threshold for each month was determined by combining the improved Tennant, monthly frequency calculation, and monthly minimum calculation methods with the habitat simulation method.

(1) Improved Tennant method. The minimal, optimal, and maximal ecological flows for each month were determined to be 10%, 60%, and 200% of the average monthly flow over several years, respectively.
(2) Improved monthly frequency calculation method. With the improved Tennant method as a reference, the guaranteed rates for the three periods of abundance, flatness, and depletion were computed using a trial-and-error approach to obtain the guaranteed rates that best fit the study area and determine the optimal ecological flow in this area. The maximum and minimum ecological flows in the study area were determined using the same algorithm.
(3) Improved monthly minimum method. To protect the safety of aquatic ecosystems, the sub-minimum and sub-maximum monthly runoff values were selected as the minimum and maximum ecological flows, respectively.

The results of the improved Tennant, improved monthly frequency calculation, improved monthly minimum, and habitat simulation methods were compared, and 200% and 10% of the average monthly flow specified in the improved Tennant method were used to correct the maximum and minimum ecological flow results.

2.3. Multi-Objective Collaborative Decision Model

The multi-objective collaborative decision model for ecological flow control transforms a multi-objective decision problem into a single-objective optimization problem by computing the system coordination degree to determine the best coordinated solution for ecological flow to maximize the economic and ecological demands and the benefits of water.

An eco-economic system includes ecological and economic objectives. The multi-objective problem is formulated as follows:

$$Opt[f_1(x), \ldots, f_k(x)]^T \tag{3}$$

where x is the decision variable, such as ecological flow; $f(x) = [f_1(x), \ldots, f_k(x)]^T \in R^k$ is an objective function of k; and Opt indicates the synergy of economic and ecological goals and that of goals and ecological flows.

2.3.1. Computation of the Synergy Contribution Function

The ecological flow synergistic contribution function x is $s_i(x)$, and the formula is as follows:

(1) $f_i(x)$ is the objective function for which a high index value is preferable;

$$s_i(x) = \begin{cases} 1 & (f_i(x) > f_i{}^H) \\ [f_i(x) - f_i{}^L] / (f_i{}^H - f_i{}^L) & (f_i{}^L \leq f_i(x) \leq f_i{}^H) \\ 0 & (f_i(x) < f_i{}^L) \end{cases} \tag{4}$$

where $f_i{}^L$ is the tolerance limit, which is the minimum target value acceptable to the decision maker; $f_i{}^H$ is the ideal value, which t is the maximum value; and $0 \leq s_i(x) \leq 1$.

(2) $f_i(x)$ is the objective function for which a small value of the index is preferable;

$$s_i(x) = \begin{cases} 0 & (f_i(x) > f_i{}^H) \\ [f_i{}^H - f_i(x)] / (f_i{}^H - f_i{}^L) & (f_i{}^L \leq f_i(x) \leq f_i{}^H) \\ 1 & (f_i(x) < f_i{}^L) \end{cases} \tag{5}$$

where ${f_i}^H$ is the tolerance limit, which is the maximum target value acceptable to the decision maker; and ${f_i}^L$ is the ideal value, which is the minimum value.

2.3.2. Computation of the Synergistic Contribution Replacement Rate

To obtain information on the replacement rate between the ecological and economic objective functions, the synergistic contribution replacement rate ($r_{i,j}(x)$) was computed as follows:

$$r_{i,j}(x) = \lim_{\Delta x \to 0} \frac{s_i(x + \Delta x) - s_i(x)}{s_j(x + \Delta x) - s_j(x)} \tag{6}$$

2.3.3. Computation of the System Coordination Degree Function

The multi-objective problem of ecological flow control is converted into a multi-objective synergistic decision model based on the synergistic contribution degree function, formulated as:

$$\max[s_1(x), \ldots, s_k(x)] \tag{7}$$

The system coordination degree function ($s(x)$) of the model is calculated as:

$$s(x) = 1 - \left\{ \sum_{i=1}^{k} \alpha_i [1 - s_i(x)]^q \right\}^{\frac{1}{q}} \tag{8}$$

where α_i is the weight of each sub-objective.

The computed value of $s(x)$ approached 1, indicating a great degree of system coordination. The optimal coordination solution was the ecological flow with the highest degree of system coordination. The biased water supply scheme [22] was utilized as the weighting index, and the weighting ratio between ecological and economic indices was set as 3:7.

2.3.4. Computation of Ecological Objectives

Ecological water scarcity and abundance were selected as the objective functions of the ecological target. When the ecological flow of the river reached the optimal ecological flow value, the objective function was optimal. The objective function is calculated as follows:

$$f = (Q_t - Q_{eco-best})^2 \tag{9}$$

where Q_t is the ecological flow that the river can provide at time t, and $Q_{eco-best}$ is the optimal river ecological flow at time t.

2.3.5. Computation of Economic Objectives

The economic benefits of a basin are represented in the water supply benefits of diverse sectors of the national economy that utilize water. The economic benefits of different types of water use are computed based on the generated water supply benefits, and the expression is as follows:

$$B_{li}(W_i) = f_{li}(W_i) \tag{10}$$

where B_{li} is the water supply efficiency of the ith water sector in the lth interval, and W_i is the water consumption of the ith sector.

The efficiency and volume of the watershed water supply are favourably connected. Based on this, the regional water supply was selected as the economic objective of the model. The computed maximum regional water supply within the flow interval was deemed the optimum value, whereas the minimum regional water supply was deemed the tolerance limit.

2.4. Study Area

The Huai River in eastern China is 1000 km long, with an average slope of 0.2 m/km and a drainage area of 190,000 km^2 (Figure 1). Several tributaries exist in the Huai

River Basin. The Huai River Basin includes well-developed tributaries, with as many as 15 first-class tributaries having a drainage area greater than 2000 km^2 and 21 with a drainage area greater than 1000 km^2. Being the climatic dividing line between the southern and northern areas of China, the Huai River possesses both southern and northern climatic characteristics. The region north of the Huai River is warm temperate, whereas that south of the Huai River is northern subtropical. The middle and lower portions of the Huai River are low-lying and have an insufficient water flow. Precipitation in the basin is concentrated and heavy from June to July. The maximum annual precipitation is 4.3 times higher than the minimum annual precipitation. Consequently, the Huai River Basin experienced frequent flooding. The Huai River Basin has aggressively supported the development of water conservation projects to alleviate the drought catastrophe and enhance the water supply of the Huai River on both sides of the river. There are more than 11,000 dams in this basin. Therefore, the Huai River is highly controlled by dams. After many phases of development and strengthening, the Bengbu Sluice is the first and largest sectional sluice in the Huai River Basin. The sluice is situated in the middle of the Huai River.

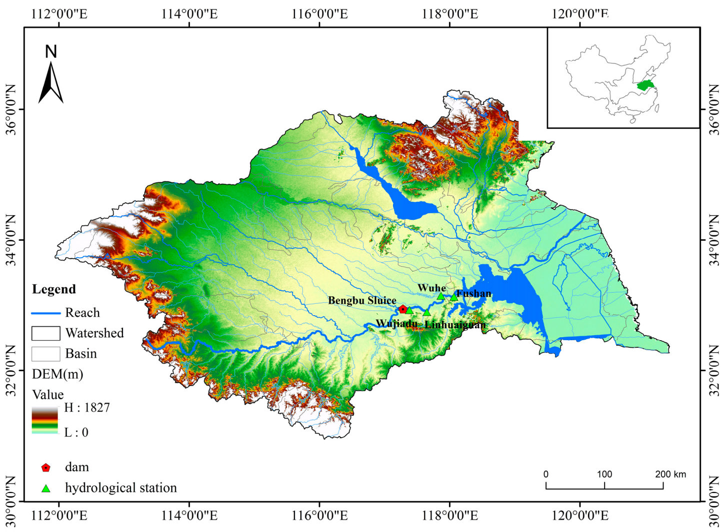


Figure 1. Geographical location of the Huai River.

A recent study [23] has shown that the Huai River Basin lacks valuable species. *Parabramis pekinensis* has economic value, lays eggs that drift and wander downstream to develop, is sensitive to changes in water level, and has high spawning habitat requirements. Thus, *Parabramis pekinensis* was selected as a representative species for this computation.

The *Parabramis pekinensis* spawning site is located between the mouths of Mohekou and Wuhe under the Bengbu Sluice. This delicate, 93 km long section of the river was considered the study area. Currently, there are four stations, namely Wujiadu, Linhuaiguan, Wuhe, and Fushan, along the study area segment. The Wujiadu hydrological station is located at 32°56′ N and 117°23′ E and is the control station of the Huai River. Linhuaiguan, Wuhe, and Fushan water level stations are located at 32°54′ N and 117°39′ E, 33°09′ N and 117°52′ E, and 33°08′ N and 118°04′ E, respectively. The MIKE21 hydrodynamic model was utilized for computations. The duration of the simulation period was from 00:00 on 1 January 2017, to 24:00 on 31 December 2017. The measured daily flow data from Wujiadu station for the entire year of 2017 were used as the flow boundary for computing the upstream of the river section, and the measured daily water level data from Fushan station for a full year in 2017 were selected as the water level boundary downstream. Topographic data were obtained from actual measured sections spaced 500 m apart. The model employed unstructured triangular grids to divide the study area into 4423 meshes with 2825 nodes (Figure 2). For rate determination, 2017 daily water measurements from the Linhuaiguan and Wuhe water level stations in the study area were selected, and the results are depicted in Figure 3 and Table 2. The model was rate-determined, the correlation coefficients of both stations were greater than 0.99, the Nash efficiency coefficient was close to 1, and mean relative errors were close to 0. The simulation accuracy of the model satisfied these requirements.

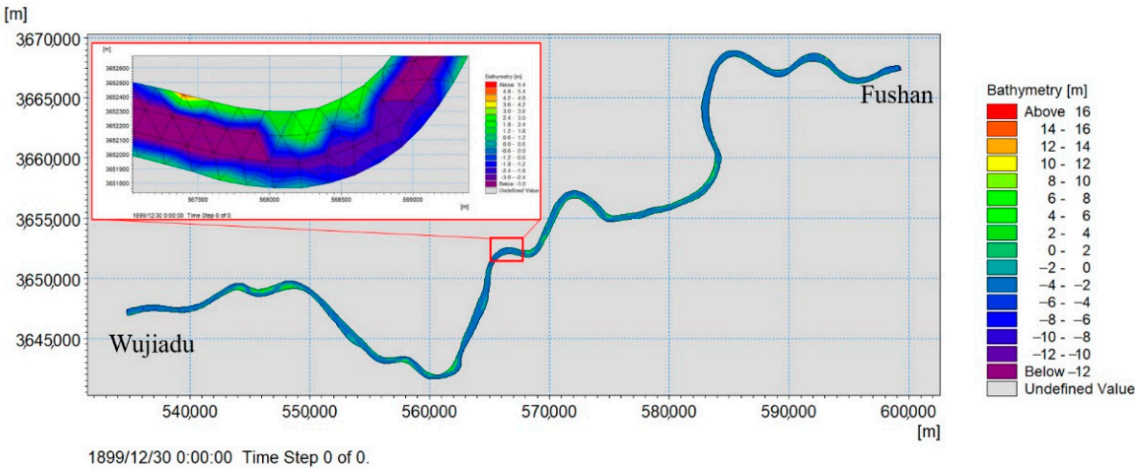
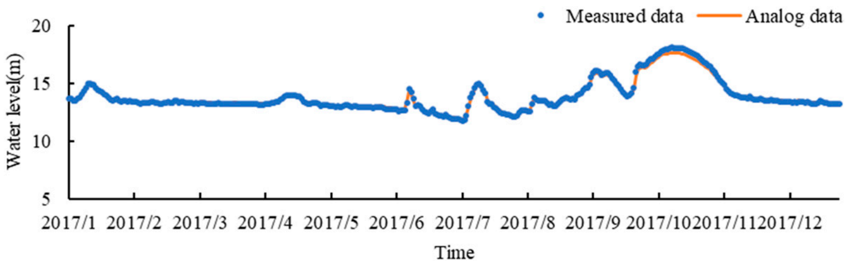
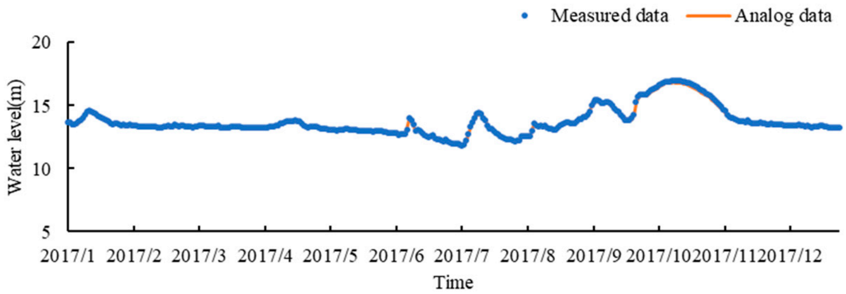


Figure 2. Mesh diagram of the study area.



(**a**)



(**b**)

Figure 3. Comparison of water level at the two stations: (**a**) Linhuaiguan; (**b**)Wuhe.

Table 2. Calculation of the error rating factor.

Station	CC [1]	NSE [2]	MRE [3]
Linhuaiguan	0.999	0.991	1.303‰
Wuhe	0.999	0.996	2.824‰

Note(s): [1] CC means correlation coefficients; [2] NSE means Nash efficiency; [3] MRE means mean relative errors.

Parabramis pekinensis spawning period was from April to June; the feeding period was from July to November, and the overwintering period was from December to March. The spawning period water temperature (20 °C–25 °C) and the feeding period water temperature (15 °C–30 °C) in the study area fell within the optimum range of spawning period water temperature (20 °C–27 °C) and feeding period water temperature (15 °C–30 °C) for *Parabramis pekinensis*. The *Parabramis pekinensis* suitability curve was constructed based on current research results on habitat suitability indicators [23].

3. Results and Discussion

3.1. Computation Results of Habitat Simulation Method

According to the runoff process of *Parabramis pekinensis* during spawning, feeding, and overwintering periods, flow field simulations under a flow series of 0–5000 m^3/s in the spawning period, 0–7000 m^3/s in the feeding period, and 0–1500 m^3/s in the overwintering periods were conducted based on the habitat model, followed by habitat suitability simulation under the flow series (Figure 4).

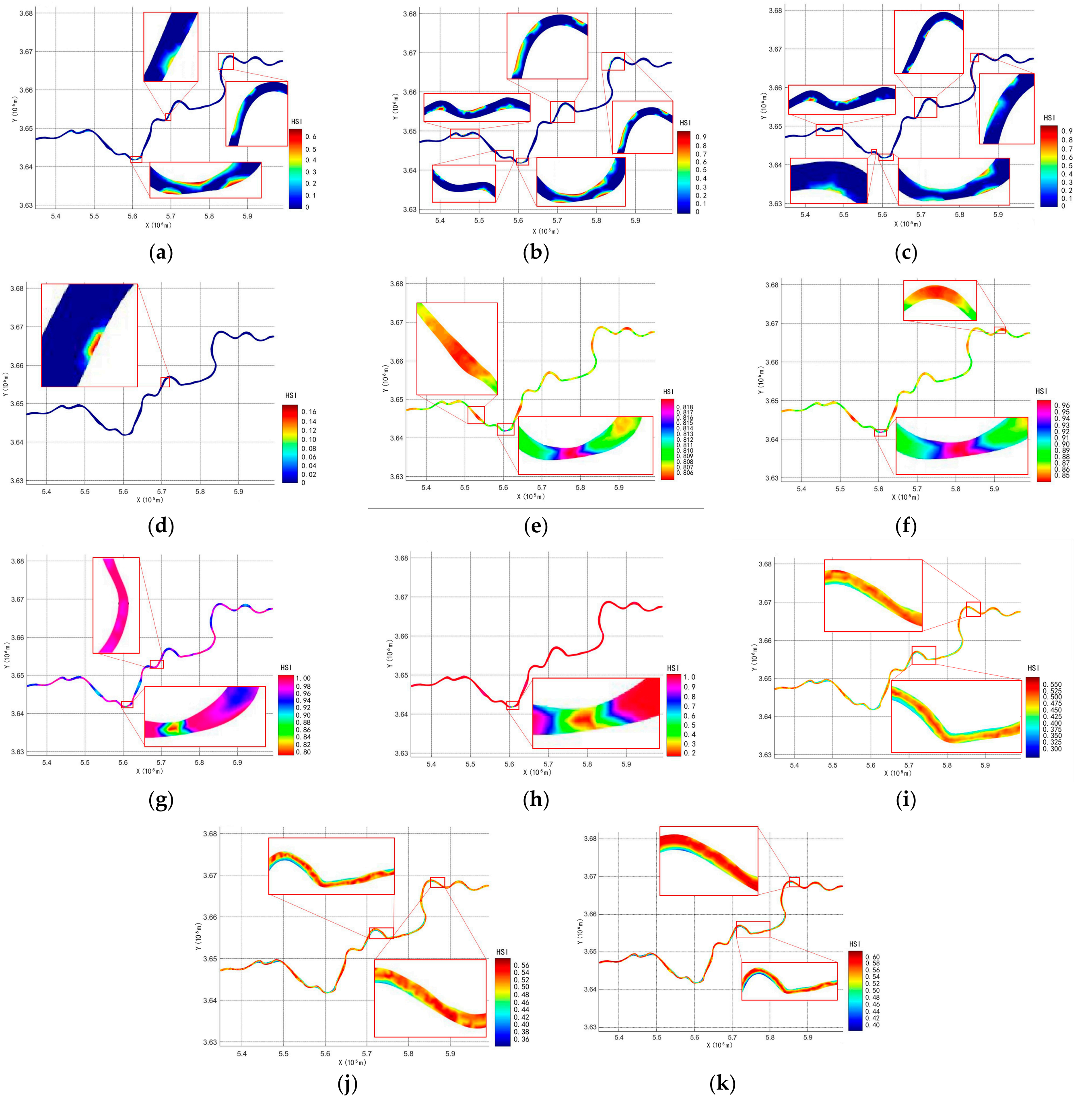


Figure 4. Distribution of *Parabramis pekinensis* HSI in different periods: (**a**) spawning (100 m^3/s); (**b**) spawning (500 m^3/s); (**c**) spawning (1000 m^3/s); (**d**) spawning (3000 m^3/s); (**e**) feeding (100 m^3/s); (**f**) feeding (1000 m^3/s); (**g**) feeding (3000 m^3/s); (**h**) feeding (5000 m^3/s); (**i**) overwintering (100 m^3/s); (**j**) overwintering (500 m^3/s); (**k**) overwintering (1000 m^3/s).

Figure 4a–d show that the HSI values of shallow water areas adjacent to the banks and bends of the river were greater than 0.5. These sections of the river meet the requirements of *Parabramis pekinensis* for flow velocity and depth during the spawning period. Therefore, they were suitable spawning sites for the fish. Considering that spawning grounds require high water depths and flow velocities, there were few appropriate waters for *Parabramis pekinensis* in the study area. When the flow rate increased from 100 to 500 m^3/s, the spawning region increased in size, the number of spawning places increased, and the maximum HSI value increased from 0.6 to 0.9. When the flow rate was increased by 3000 m^3/s, the highest HSI value was only 0.16, indicating that the study area was unsuitable for *Parabramis pekinensis* spawning at this flow rate and that increasing the flow rate was ineffective. There was no reason to further increase the flow rate.

Figure 4e–h depict that during the feeding period, *Parabramis pekinensis* had low flow requirements for flow velocity and water depth, and the HSI values in most areas exceeded 0.5. With the increase in simulated flow, the overall integrated suitability index of the study area increased. When the flow rate reached 3000 m^3/s, the Linhuaiguan section HSI value decreased to 0.8 because the flow velocity in this area exceeded the optimal flow velocity range during the predation period. However, the HSI value of other areas increased. *Parabramis pekinensis* feeds on a vast variety of species and may consume aquatic plants, including *Potamogeton distinctus*, *Vallisneria natans*, and *Hydrilla verticillata*, as well as terrestrial plants and plant detritus on the river bottom, which are widely dispersed in shallow and deep waters along the bank. Thus, *Parabramis pekinensis*′ habitat during the feeding period was vastly distributed and suitable for this section of the river.

Figure 4i–k depict that with an increase in flow, the HSI value gradually increased, and the majority of waterways in the study area were deemed suitable for overwintering. The habitat location in this river section did not change significantly, and the habitat was connected and distributed in deep water. According to *Parabramis pekinensis*′ habitat, they opt to overwinter in depth throughout the winter, and the simulation results were consistent with this behavior.

The habitat availability area was computed based on HSI, and the flow-habitat availability area relationship curves were plotted for the spawning, feeding, and overwintering periods (Figure 5).

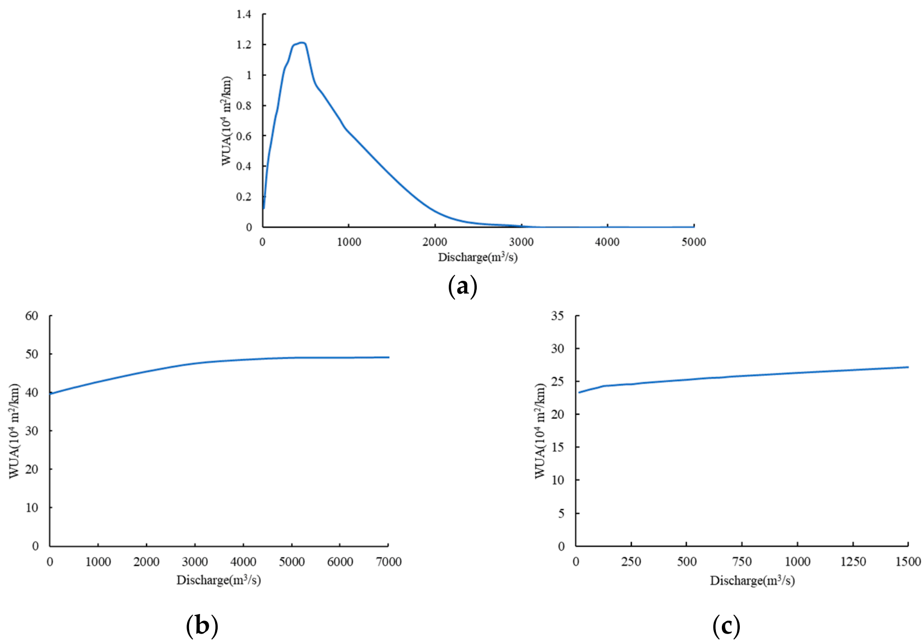


Figure 5. Variation of WUA with the discharge flow: (**a**) spawning period; (**b**) feeding period; (**c**) overwintering period.

Figure 5a depicts that in low flow conditions WUA increased with flow during the spawning period. The first obvious inflection point emerged when the discharge flow reached 150 m^3/s, which was the minimum ecological flow. The WUA was the largest when the flow value continued to increase to 450 m^3/s, and this flow value was the optimal ecological flow for the spawning period. As the flow increased, WUA decreased, and the optimal habitat requirements for fish spawning were not met at higher flows.

Figure 5b depicts that WUA was not zero when the flow was low because *Parabramis pekinensis* has a low requirement for water depth during the feeding period. The suitability index was one when the water depth exceeded 1.2 m. Thus, fish habitat requirements were met despite a low flow rate. As the discharge flow increased, the flow velocity, water depth, and WUA increased. The Huai River, which is regulated by multiple dams, has small fluctuations in water levels and can maintain a certain water level even when the flow is very small. Thus, the studied river section could meet the habitat requirements of *Parabramis pekinensis* when the flow is low.

Figure 5c depicts that WUA was not sensitive to flow changes during the overwintering period. Except for a few carnivorous species, most fish migrate to deep locations in the winter [24]. Parabramis pekinensis picked a deep-water river bottom to overwinter and the water level was the most important consideration for selecting a fish overwintering site. Thus, water depth had the most significant influence on *Parabramis pekinensis* habitat distribution. Most of the overwintering period falls within the dry period of the Huai River, which has a low water level. As a multi-dam-controlled river, the Huai River has small fluctuations in water level and small changes in water depth. Thus, the change in WUA was not obvious.

According to the computation results of the habitat simulation method, *Parabramis pekinensis* had minimal habitat requirements during the feeding period, and habitat indicators were insensitive to variations in flow. Therefore, it was challenging to employ a habitat simulation method to determine the ecological flow. The habitat of the indicated fish was predominantly influenced by water depth during the overwintering period. Considering that the Huai River has been regulated by dams, the water level has not changed significantly, and neither has the WUA. Thus, it was challenging to deduce the ecological flow in the study area using the habitat simulation method during the overwintering period.

3.2. Comparison of Computation Results of Habitat Simulation and Hydrological Methods and Selection of Optimal Solution

According to the habitat simulation, improved monthly frequency calculation and improved monthly minimum methods were used to compute the ecological flow with the improved Tennant method for correction. The results for the minimum, suitable, and maximum ecological flows are depicted in Figure 6.

Figure 6a depicts that, except for January, February, April, and December, the results of the improved monthly minimum method were all less than those of the improved Tennant method and at very low levels for riverine ecosystems. The minimum ecological flow determined by the improved monthly frequency calculation and habitat simulation methods were both greater than the results of the improved Tennant method from April to June, with the habitat simulation method ranking well above unsatisfactory results. Therefore, the minimum ecological flow from April to June was computed using the habitat simulation method, and the ecological flow for the remaining months was computed using the improved monthly frequency calculation method.

Figure 6b depicts that the results of the habitat simulation method from April to June were the highest among the three methods and superior to those of the improved monthly frequency calculation method. The results of the improved Tennant method were slightly higher for computing suitable ecological flow in October and November. To maintain habitat health, the results of the improved Tennant method were utilized to compute the suitable ecological flow in October and November. The results for the remaining months demonstrated that the improved monthly frequency calculation method provided better results.

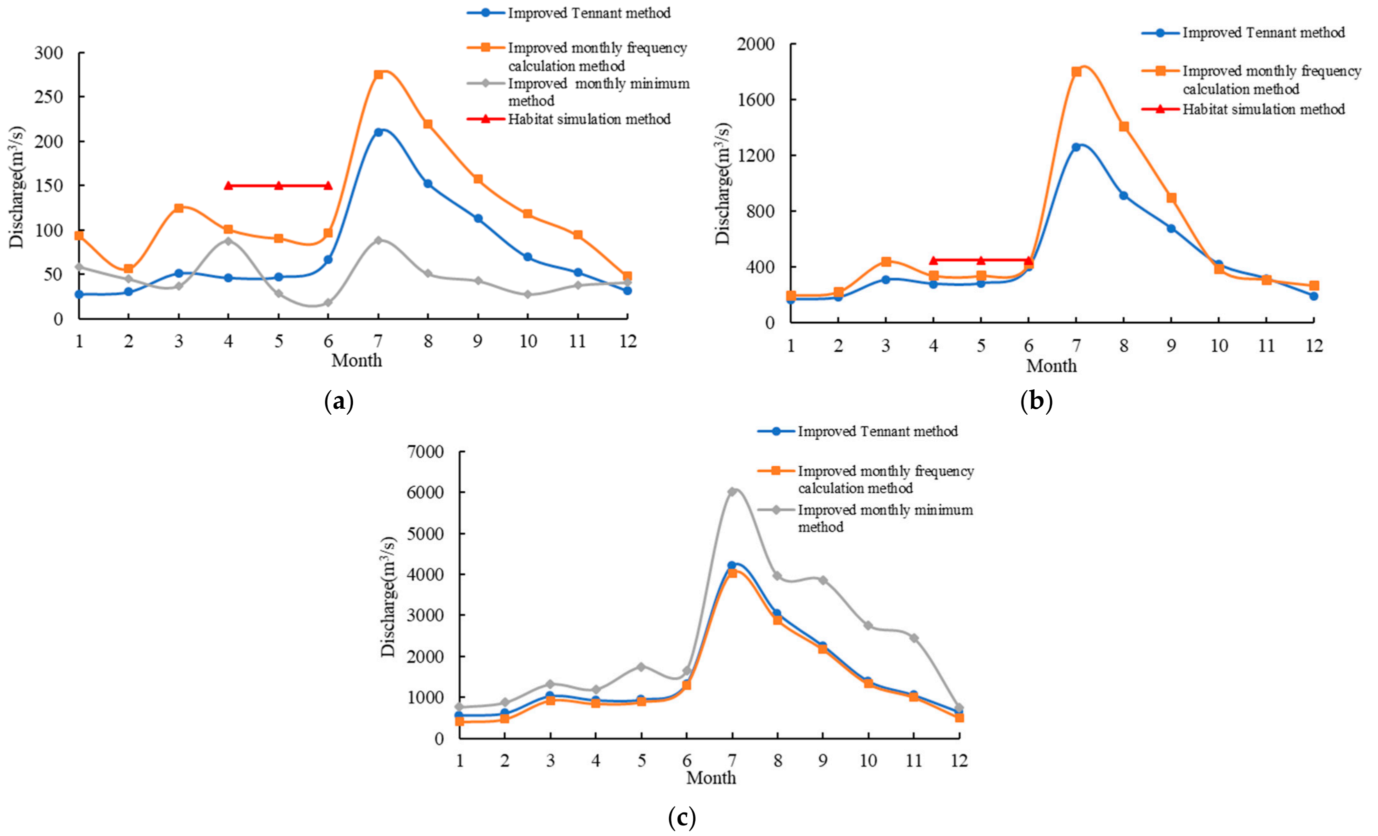


Figure 6. Results of multiple methods for computing ecological flows: (**a**) minimum ecological flow; (**b**) suitable ecological flow; (**c**) maximum ecological flow.

Figure 6c depicts that the computation result of the improved monthly minimum method exceeded the 200% cut-off value provided by the improved Tennant method, which exceeded the tolerance capacity of the species. In extreme situations, this might lead to extinction. Therefore, the maximum ecological flow was determined by modifying the monthly frequency calculation method.

The results for the minimum, suitable, and maximum ecological flows for each month are depicted in Figure 7.

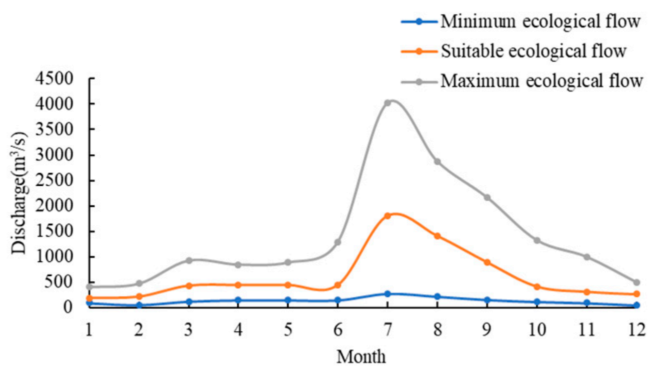


Figure 7. Results of minimum, suitable, and maximum ecological flows for each month.

3.3. Multi-Objective Analysis of Ecological Flow Control Based on Synergy Theory

In the case of theoretical limits, the total runoff is certain. However, the ecological water availability of the river fluctuates between zero and the total runoff. For simplicity, this study divided the total water resources into two parts, ecological and economic, and did not consider their mutual transformation. After deducting the whole runoff from the ecological water usage, the leftover runoff could be utilized for economic water use. Each discrete ecological flow had a corresponding economic water use, which served as the basis for computing the economic objective function values under diverse ecological flows. The maximum system coordination for each month and the corresponding ecological flows are depicted in Figure 8.

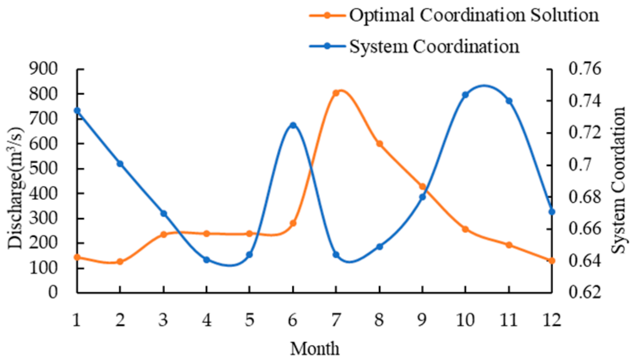


Figure 8. Maximum system coordination and optimal coordination solution by month.

A comparison of the optimal ecological flow and coordinated solution demonstrated that the optimal coordinated solution was less than the optimal ecological flow. This indicated that the difference between the optimal ecological flow and the coordinated solution could be used as economic water under the premise of safeguarding the ecological demand of the river to alleviate the conflict between the two interests of economy and ecology.

3.4. Evaluation of Ecological Operation

Currently, the *Implementation Plan for Ecological Flow (Water Level) Pilot Work in the Huai River Basin* (hereinafter referred to as the *Plan*) has been implemented in the mainstream of the Huai River as a reference for operation in the basin. The ecological flows for the Wujiadu portion throughout the months of October to March, April, May, and June to September were set at 48.35, 172.78, 188.81, and 96.2 m^3/s, respectively, in the *Plan*. The comparison of the best coordinated solution of ecological flow with the results of the *Plan* demonstrated that the optimum coordination solution of ecological flow was greater than the developed value of ecological flow. This indicates that the demand for fish habitats and ecological needs could be met. To further compare the two scenarios, the habitat simulation method was used to compute the area of fish habitat available in both scenarios (Figure 9).

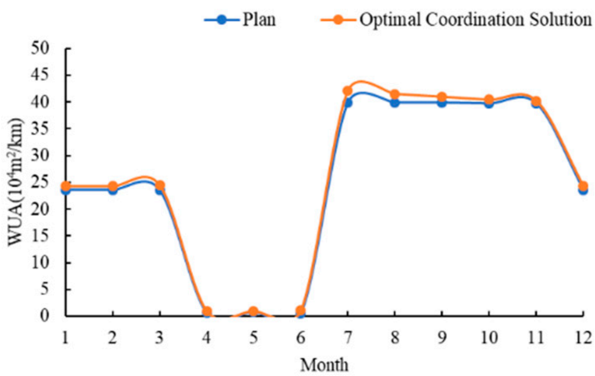


Figure 9. Habitat usable area (WUA) for both scenarios.

Figure 9 depicts that the amount of available habitat determined by the optimal coordination solution proposed in this study was larger and more suitable for fish habitat than the area computed by the ecological flow in the existing scheme. When the flow rate increased, the water level increased, causing the flow velocity to increase accordingly. The optimal coordination solution for the spawning period corresponded to a higher flow velocity and water depth, which were more suitable for fish spawning. Spawning of fish, including *Parabramis pekinensis* and tetra, requires the stimulation of flowing water, and a slow flow rate causes wandering eggs to drop to the bottom, reducing their survival chances. According to the measured data, the flow in the study area was large during the feeding period, and the actual operation should be conducted to ensure the fish feeding behavior by releasing a moderate amount of flow in response to the incoming water upstream. The ecological flow scheme determined in this study during the overwintering period had an improved even distribution of monthly flow values, which reflected the storage function of the Bengbu Sluice and could guarantee fish habitat during the overwintering period.

The construction of the Bengbu Sluice has altered the hydrological and sediment transport patterns of the downstream river and modified the water temperature, water quality, and other features, resulting in an ecological discontinuity. The natural discharge pattern is disrupted, and the native ecosystem has been damaged, which in turn impacts the food chain and population density of river creatures. The Bengbu Sluice has not yet adopted a precise ecological operation management policy. Therefore, the following management policies are offered based on the current Bengbu Sluice conditions:

(1) Optimized scheduling to achieve an ecological flow rate guarantee. According to the incoming water from upstream, the river channel storage capacity, and the future weather conditions predicted by relevant software, the opening and closing of the barrage gates should be optimized to ensure downstream biological flow.
(2) Implementation of a policy for monitoring and early warning. By monitoring the flow in the Wujiadu section, the ecological health of the river may be maintained when the flow value exceeds 120% of the downstream ecological flow value. When the observed flow value is less than the predetermined ecological flow value with a continuous downward trend, an early warning is required to enhance the downstream flow. When the flow in the monitoring section exceeds the established ecological flow value and does not decrease within three days, the alert can be discontinued.
(3) Development of non-engineering measures. (i) Optimize the discharge process and regulate water consumption by collecting data on precipitation, flow rates, and water consumption to optimize the discharge process and water allocation. (ii) Develop a water withdrawal restriction plan to regulate upstream water consumption when downstream water volume exceeds the maximum warning. (iii) Establish an emergency response system when faced with unforeseen water conditions or an abnormally dry year. A plan for emergency upstream and downstream dispatching should be developed and implemented.

4. Conclusions

In this study, a multi-objective collaborative decision model for ecological flow control was developed to compute the optimal coordinated solution for ecological flow to alleviate the contradiction between ecological and socioeconomic water use in the river under the influence of dams. The ecological flow threshold of the river downstream of the dam was computed from an ecological perspective, utilizing the habitat simulation method. During feeding and overwintering periods, the water level influenced the habitat requirements of the target fish more than the flow velocity when the flow velocity requirements were low. The Huai River has little fluctuation in water level during the year due to the regulation of dams. Therefore, habitat changes are not obvious. Consequently, hydrological and habitat simulation methods were utilized to compare and correct the ecological flow computation. In this study, we introduced synergy theory and developed a multi-objective synergy decision model for ecological flow control to compute the optimal coordination solution for ecological flow. All the results demonstrated that the optimal coordinated solution of ecological flow was able to guarantee the ecological water demand of the downstream area of the Huai River and accomplish the ecological operational objective. This study has provided deeper insights into the ecological operation of Bengbu Sluice. However, there are potential limitations. One concern regarding the observations is that the suitability curves were based on academic research and professional opinions, and they did not include information from locally measured biological samples. The values obtained in this study were probably conservative, as the ecological flow thresholds established by the habitat simulation method were sensitive to suitability curve changes. The other concern is that the choice of ecological and economic water usage indicators for rivers and the distribution of water are still being researched for the multi-objective decision-making approach to ecological flows presented in this study. Regarding the future research directions, the following two aspects should be particularly worthy of consideration: field research and the selection of indicators. Indicator fish suitability curves were determined using field tests. During the creation of the collaborative decision-making model, the water demand of the downstream Huai River receiving area and the adoption of more rational ecological and economic water consumption indicators should be considered.

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