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Evaluation of Economic and Ecological Benefits of Reservoir Ecological Releases Based on Reservoir Optimization Operation

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Abstract

To maximize the benefits of power generation and water supply of the reservoir under the premise of ensuring ecological flow as much as possible, it is necessary to formulate a highly operational release scheme in the actual production scheduling process. To mitigate the ecological impacts of reservoir operations, enhanced environmental flow releases are required; however, this results in diminished reservoir economic outputs. Therefore, in order to determine the government subsidy standards for ecological regulation of reservoirs and improve the enthusiasm of water conservancy departments for ecological regulation, it is necessary to conduct comprehensive analysis and research on the benefits of ecological regulation. According to the ecological releases of the reservoir, the reservoir operation scheme is formulated, and the comprehensive benefits of the reservoir operation are analyzed and studied to determine the optimal operation scheme. Based on the monthly inflow runoff of the Baishi Reservoir to the Daling River from 1956 to 2011, constrained by the ecological base flow specified by the government, and combined with the water supply and power generation functions of the reservoir, an optimal operation model of the Baishi Reservoir based on ecological release is constructed. The water supply, power generation, and ecological benefits of the reservoir discharge are comprehensively analyzed and calculated to analyze and study the loss of economic benefits caused by the reservoir discharge and the ecological benefits that can be obtained from the ecological discharge. Based on the comprehensive evaluation of multiple indicators, the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) fuzzy comprehensive evaluation method is used to select the optimal scheduling scheme. The optimal scheduling plan for a reservoir is closely related to its characteristic water level. In order to improve the efficiency of reservoir scheduling, monthly control of reservoir discharge can be implemented. The guarantee rate of urban domestic water supply and ecological water use can be increased as much as possible, while the guarantee rate of agricultural water use can be appropriately reduced to obtain the optimal comprehensive benefits. The outflow considering ecological release is 6.5–7 m^3/s from June to April and 1 m^3/s in May. The outflow without considering ecological release is 4 m^3/s from June to April and 1 m^3/s in May. This study has certain guiding significance and value for the formulation of an ecological operation scheme for reservoirs and the analysis of benefits.

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Keywords: ecological release of reservoir; multi-objective optimal scheduling; ecological benefit assessment

1. Introduction

The construction and operation of water conservancy projects have destroyed the connectivity of rivers, changed the hydrological situation of downstream rivers, and caused frequent river ecological problems [1,2]. The traditional operation mode takes the maximization of economic benefits as the core, which cannot meet the engineering needs of river ecological environment protection and restoration [3,4]. Therefore, reservoir ecological operation must be implemented. Reservoir ecological operation can alleviate the negative impact of the reservoir operation on the river ecosystem by taking into account the operation goal of river ecological protection when achieving the goals of reservoir flood control and benefit. The ecological flow can be regarded as an ecological target that can transform the flow process into an indicator that affects the habitat of target species. The ecological target is the amount of unsatisfied ecological water demand caused by the reservoir discharge flow. After the government has stipulated the relevant ecological base flow, the reservoir management department needs to determine the release plan of the reservoir from the perspective of economic, ecological, and other benefits, and there is a lack of relevant research. The reservoir ecological optimal operation model can be classified into three types: the ecological flow constraint model, ecological flow target model, and ecological value target model [5]. The ecological flow constraint model is established using ecological flow as the constraint for the discharge flow of the model. The ecological flow target model is a model established based on the ecological flow guarantee rate to achieve a certain target. The ecological value target model is constructed with the goal of maximizing downstream ecological dispatch benefits. Zhu [6] used the Tennant method to calculate the minimum ecological flow of the two control sections of Zhongmawan and Luohe in Shahe and established the ecological water operation model of the Shahe Reservoir group. Zhao [7] used the ecological flow group method to analyze the composition of ecological and hydrological events in the spawning process of the four big fish, proposed a suitable flow process to meet the spawning demand, and established the Three Gorges cascade ecological scheduling model as a constraint. Xu [8] took the Three Gorges cascade as the research object; established an operation model aimed at maximizing the power generation benefit of cascade hydropower stations by integrating the downstream river ecological base flow, ecological water demand for biological resource protection, and ecological flow in the dry season; and analyzed the impact of meeting different ecological flow processes on power generation benefit. Wu [9] took Wanjiazhai and Longkou Cascade Reservoirs in the upper reaches of the Yellow River as the research object, took the sum of water shortage that does not meet the minimum ecological water demand as the ecological goal, and established a multi-objective optimal operation model with the maximum cascade power generation, the minimum ecological water shortage, and the maximum water supply benefit. In order to evaluate the effectiveness of the Three Gorges Reservoir's drought-limited water level regulation, based on historical operating data, Yan [10] comprehensively considered the Three Gorges Reservoir's flood control, power generation, water resources, ecology, and shipping regulation objectives and constructed a Three Gorges daily regulation model. The research on multi-objective comprehensive scheduling model is still a key objective in the case of extremely dry water inflow. In response to the decline of fish resources, future research should increase theoretical methods and applied technologies in watershed ecological regulation, develop comprehensive ecological refinement ecological regulation

plans, and establish a reservoir ecological regulation effect evaluation system with different improvement goals [11].

The ecological flow can be regarded as an ecological target, which can transform the flow process into an indicator that affects the habitat of target species. The ecological target is the amount of unsatisfied ecological water demand caused by the reservoir discharge flow. After the government has stipulated the relevant ecological base flow, the reservoir management department needs to determine the release plan of the reservoir from the perspective of economic, ecological, and other benefits, and there is a lack of relevant research. Liu [12] improved a comprehensive fuzzy evaluation method, which has a good effect on multi-objective decision-making regarding ecological factors of built reservoirs. Guan [13] constructed the assessment system of ecological benefits for the development of the Three Gorges Reservoir Area in Chongqing, considering societal, economic, and environmental characteristics. At present, there are some studies on the evaluation and analysis of the ecological operation benefits of reservoirs, but further in-depth research is needed on their methods and indicator systems.

Scientifically and quantitatively evaluating the effectiveness of ecological regulation measures and their comprehensive impact on downstream ecosystems is not only a core issue in sustainable water resource utilization but is also a cutting-edge topic in river ecology and environmental management. Assessment and evaluation are important links in achieving overall coordination of water resources, water environment, and water ecology. It is necessary to consider the differences in natural resource endowments and economic development levels in the watershed region to ensure the fairness and rationality of assessment and evaluation. Therefore, the construction of scientific and reasonable evaluation techniques is of great significance and value for the long-term protection of the ecological environment of the water and the continuous promotion of an ecological civilization construction process [14].

Hydrological methods include the early Tennant method, which provides the percentage of annual flow required to maintain rivers of different health levels based on historical experience [15]. The more mainstream method is the Range of Variable Approach (RVA) method, which comprehensively quantifies the changes in flow before and after reservoir operation in terms of magnitude, time, frequency, duration, and rate of change using 32 indicators of hydrologic alteration (IHAs). It is widely used to evaluate the ecological impact of reservoirs [16]. Mao et al. [17] quantitatively evaluated the moderate changes in downstream hydrological conditions caused by the operation of the Ankang Reservoir using the RVA method. This method can quickly calculate the degree of change in hydrological conditions, but ignores the complex mechanism between hydrology and ecological response.

The representative method of hydraulic modeling is the Physical Habitat Simulation System (PHABSIM) [15], which simulates the water depth and flow velocity under the different flow rates using one-dimensional or two-dimensional hydraulic models and calculates the Weighted Available Area (WUA) based on the habitat preference curve of the target species in order to recommend suitable ecological flow rates. The advantage is that it establishes a direct connection between flow and habitat, but the disadvantage is that it requires high data and technical requirements.

The representative method of holistic approach is Building Block Methodology (BBM), which decomposes the flow process required to maintain the river health into several "building blocks", such as low flow, secondary flood, and flood, and jointly determines the flow parameters of each module using a multidisciplinary expert team [18]. The Hydrological Change Ecological Limitation Framework (ELOHA) is a regional assessment framework aimed at providing universal guidance for watershed water resource management by establishing a "flow ecology" response relationship within the region, rather

than conducting independent and expensive research on each river [16]. The advantage lies in the comprehensive and systematic evaluation system, which can better reflect the complexity of the ecosystem. The disadvantages are high cost, long cycle, and strong dependence on experts, with a certain degree of subjectivity.

Advanced model-based methods include ecosystem dynamic models, such as the stochastic dynamic system model constructed by Wang et al. [19], to evaluate the impact of scheduling schemes on the stability of downstream aquatic communities. Multi-objective optimization and game models apply genetic algorithms to seek Pareto optimal solutions for ecological and economic benefits [20] or introduce game theory to analyze conflicts and cooperation among different stakeholders [21]. Machine learning models use AI technologies such as neural networks to predict hydrological and ecological parameters and simulate complex response relationships. Quantitative impact assessment models, such as the Rainfall Reservoir Composite Index (RRCI) proposed by Xiong [22], couple the combined effects of reservoir scheduling and upstream rainfall to more accurately evaluate the impact of reservoirs on downstream flood frequency. The advantage is that it can handle high-dimensional and nonlinear relationships and perform multi-scenario optimization. The disadvantage lies in the high technical threshold, strict requirements for data quality, and the existence of "black box" problems in some models (such as machine learning). Hu [23] proposed four methods, including AHP, TOPSIS, Fuzzy AHP, and Fuzzy TOPSIS, to evaluate the optimal operational schemes. The results showed that TOPSIS and AHP were more suitable with the larger fluctuations.

The indicators for evaluating the effectiveness of ecological regulation include flow regulation degree, ecological flow, changes in fish population, water quality indicators (such as dissolved oxygen, nitrogen, and phosphorus concentrations), etc. Building a multi-index evaluation method based on relevant evaluation indicators has become a breakthrough in multi-index research. Lin [24] established a fish spawning habitat quality assessment model by coupling a two-dimensional hydrodynamic water temperature mathematical model and suitability curves of four important habitat factors for fish spawning (water level variation, water depth, flow velocity, and water temperature), achieving a refined simulation of the spatiotemporal distribution of the comprehensive suitability index (HSI) for fish spawning. Wang [25] used the fuzzy comprehensive evaluation method to construct a habitat suitability evaluation model for fish spawning grounds based on the ecological hydraulic index system (flow velocity, water temperature, daily water level rise rate, and rise duration) for drift-spawning fish. The model analyzed the habitat suitability of spawning grounds in the study area before and after the water storage operation of Xiangjiaba and Xiluodu, as well as during the ecological scheduling period. Zhang [26] constructed an evaluation system for the ecological regulation effect of reservoirs, which includes a target layer, a criterion layer, six primary indicators, and 10 secondary indicators. It proposed calculation methods and scoring criteria for each indicator and used the Analytic Hierarchy Process to calculate the weight coefficients of each indicator based on their relative importance in order to evaluate the ecological regulation effect of drifting egg fish in the Three Gorges Reservoir. Dai [27] proposed an improved hydrological change evaluation method based on the traditional RVA method and analyzed the hydrological changes at each station before and after the operation of the reservoir during the same period, taking the Yichang Datong section of the Yangtze River as a typical research area. Based on the aforementioned research, it can be seen that the evaluation of ecological effects focuses primarily on assessing hydrological conditions and fish spawning outcomes, but lacks measurements and evaluation of ecological, economic, and social benefits. The aforementioned studies often utilize a single method to evaluate the effectiveness of ecological scheduling, which lacks sufficient credibility.

The evaluation of the ecological release effect of reservoirs should be developed from a single objective and static threshold to achieve a multi-objective balance. The evaluation indicators have expanded from a single hydrological indicator to a comprehensive indicator system covering hydrology, biology, physical habitat, and water quality, as well as socio-economic factors, making the evaluation more comprehensive. Based on this research approach, this article constructs an ecological benefit assessment model for multi-objective comprehensive evaluation.

In this paper, the ecological discharge regulation of the Baishi Reservoir and the ecological regulation benefits of the Daling River downstream of the Baishi Reservoir are studied as research objects. According to the minimum ecological base flow specified by the government, the reservoir ecological operation model is built based on the maximum water supply and power generation, and the corresponding release process of different schemes is determined. Based on the analysis, calculation, and comprehensive evaluation of the benefits of the reservoir ecological release, the optimal reservoir release strategy is determined. It is of great significance and value to comprehensively understand the value of rivers, formulate plans for the healthy development and scientific management of river basin ecosystems, and achieve a win-win situation of ecological and economic benefits of rivers. A flowchart of the entire text is presented in Figure 1 to facilitate readers' understanding of the basic ideas and methods used in the article.

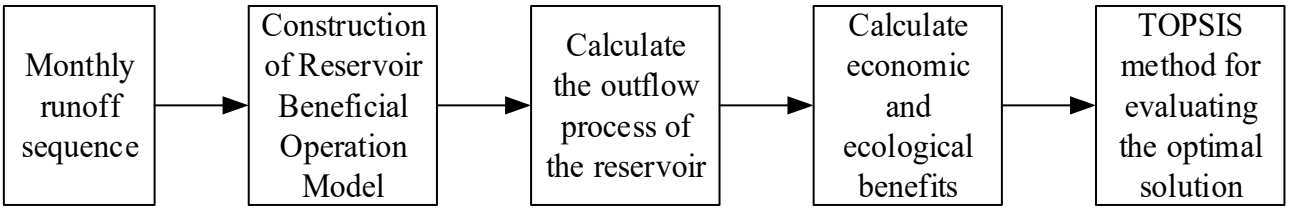


Figure 1. Flowchart of article ideas.

2. Model

2.1. Ecological Optimal Operation of Reservoir

To meet urban, rural, irrigation, ecological, and other comprehensive water demands, an optimal operation model is established with the objective of minimizing water shortage of the reservoir water supply. The objective function is as follows:

2.1.1. Objective Function

Based on the analysis of the objective function, the minimum water deficit and maximum power generation are considered, including the ecological water supply component. When constructing the model, a weighted approach is adopted to establish the comprehensive scheduling objective, and an equal weight method is used to construct the model. Using the long-term runoff series as model inputs, calculate the water deficit and power generation for each year based on a single objective function, and determine the maximum values of water deficit and power generation.

(1) Minimum water shortage

$$\min f = \sum_{j=1}^{T} \sum_{i=1}^{n} (Q_{ijS} - Q_{ijD}) \quad (1)$$

In the above formula, T is number of scheduling periods, n is water supply category, Q_{ijS} is water supply of reservoir (10,000 t), and Q_{ijD} is water demand of water users (10,000 t).

(2) Maximum generating capacity of the power station

$$\max f_1 = \sum_{t=1}^{T} KH_tQ_t\Delta t = \max \sum_{t=1}^{T} N_t\Delta t \quad (2)$$

$$N_t = KQ_tH_t \quad (3)$$

In the above formula, N_t is power station output during period t, kW; K is the comprehensive output coefficient of the hydropower station; Q_t and H_t are the quotative discharge and head of power generation, respectively, in t period, m^3/s, m; and Δt is period length, h.

(3) Comprehensive objective

$$\min F = \alpha \frac{f}{f_{\max}} - \beta \frac{f_1}{f_{1\max}} \quad (4)$$

In the above formula, F represents the comprehensive objective; α, β represents the weights, which the values are 0.5; $f_{\max}$ represents the maximum water deficit; and $f_{1\max}$ represents the maximum power generation capacity.

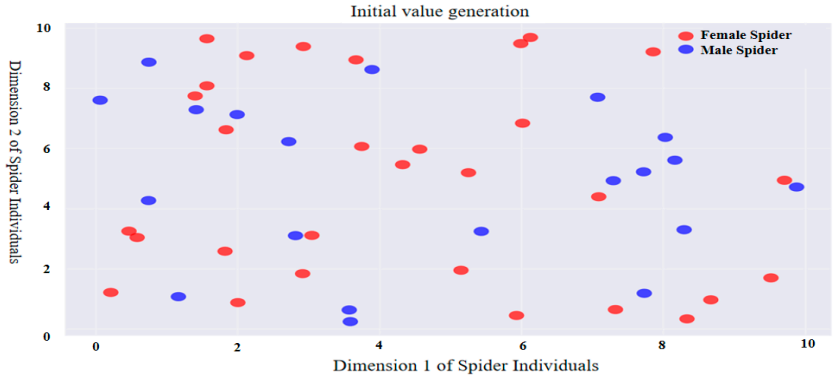
2.1.2. Constraint Condition

The reservoir operation shall meet the corresponding conditions, including water balance constraint (the change in reservoir storage capacity is equal to the inflow minus the outflow), water level constraint (the reservoir water level is higher than the dead water level but lower than the normal water level), water level amplitude constraint (the fluctuation range of the water level is within the safe range of the dam), flow constraint (the discharge is greater than or equal to 0 and less than or equal to the maximum discharge capacity), water level constraints at the beginning and end of the operation period (the water level of the reservoir at the beginning and end of the period is the normal pool level), and ecological constraint (the reservoir discharge is greater than or equal to the minimum value of ecological flow). Regarding the ecological water demand of rivers, the discharge flow of the reservoir is required to meet the appropriate ecological flow as much as possible, and the minimum ecological flow must be guaranteed in case of failure to meet the appropriate ecological flow in extremely dry years.

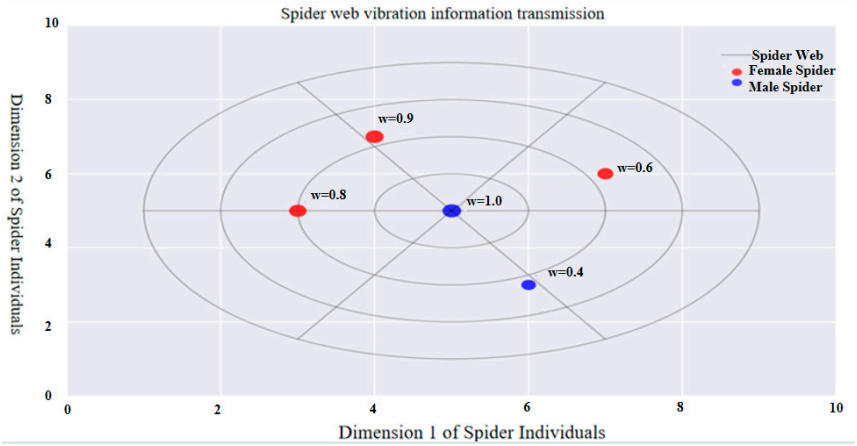
2.1.3. Model Solving

The Social Spider Optimization Algorithm (SSO) is a new random global optimization technology proposed by Cuevas et al. [28]. Taking the water level of the reservoir as an individual spider, the initial value is generated in a random way, the fitness value is calculated using the objective function, and the offspring are generated by simulating the behavior of male and female spiders in space. The offspring are optimized and iterated continuously until the termination conditions are met.

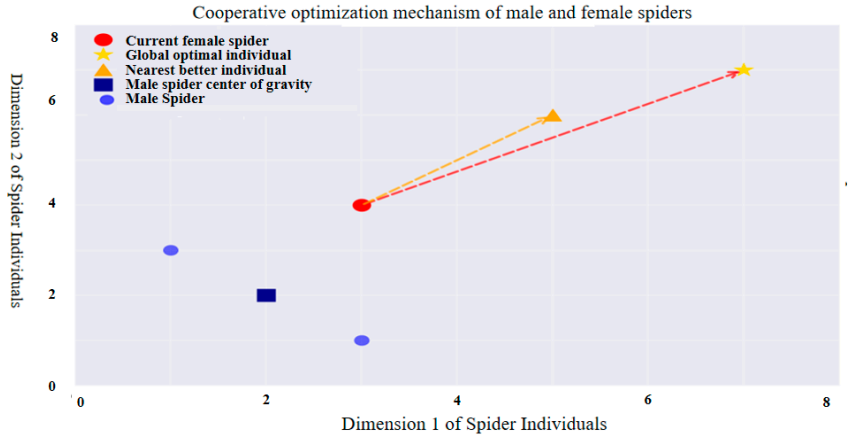
Each spider represents a complete scheduling plan, with the water level sequence of the reservoir at each time period serving as the decision variable, and the goal of reservoir optimization serving as the fitness function. Due to the fact that the dimensions of individual particles are related to the time period of reservoir operation, it is convenient to draw and can only display two-dimensional graphics. Therefore, Figure 2a–c are plotted in a two-dimensional manner.



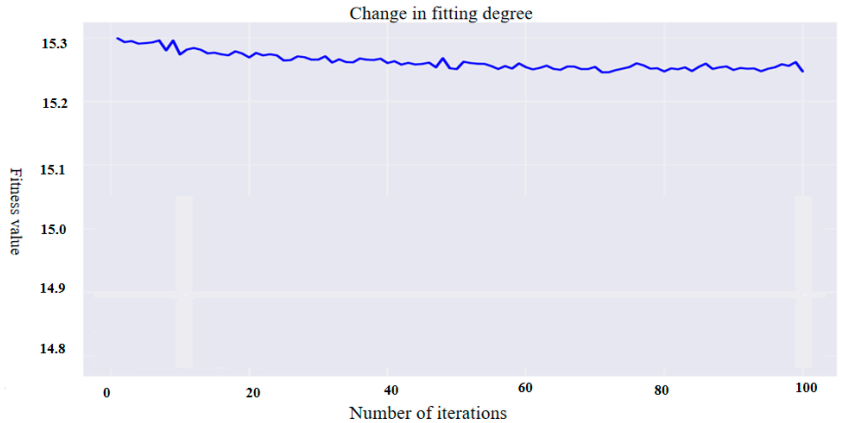
(**a**) Initial value generation of male and female spider individuals



(**b**) Male and female spiders transmit information through the vibration of their spider webs



(**c**) Mechanism of coevolution between male and female spiders



(**d**) The fitness value changes with the number of experiments

Figure 2. Optimization principle diagram of the optimization algorithm.

(1) Calculation of initial individuals and fitness

The optimization algorithm takes the water level process of the reservoir during the scheduling time as individual particles. First, the population is initialized, with the highest value of the reservoir water level as the upper limit and the lowest value of the reservoir water level as the lower limit. The initial value is generated using a random value method. The algorithm divides search individuals into two categories based on gender. Female spiders account for 65–90% of the total and responsible for the main exploration tasks. Male spiders account for 10–35% of the total, assisting in the optimization process. Calculate the corresponding fitness value based on indicators such as power generation and water supply, and calculate the weight of each spider based on the fitness value. The weight of each spider represents its ability to solve problems.

(2) Spider web vibration information transmission

The information transmission between spiders is achieved through network vibration, and the vibration intensity is related to the sender's weight and distance. The algorithm focuses on three special vibration relationships: the vibration of the nearest optimal individual, the vibration of the globally optimal individual, and the vibration of the nearest female individual.

(3) Cooperative optimization mechanism of male and female spiders

The cooperative mechanism of female spiders is noted when they decide to adopt attraction or repulsion behavior based on random probability. The collaborative mechanism of male spiders is noted when male spiders adopt different strategies based on their own weights. Male spiders with lower weights move towards the center of gravity of the group, while male spiders with higher weights move towards the nearest female spider. A mating selection mechanism is noted when dominant male spiders mate with nearby female spiders within a mating radius, and the probability of generating new individuals is based on parental weights, using roulette wheel to select the optimal individual.

(4) Adaptation update changes

The evolved individual can calculate its fitness value, and the change in fitness value and the number of optimizations are used as termination criteria to check whether the algorithm meets the stopping condition.

To understand the detailed process of using this algorithm for optimizing the operation of reservoirs, please read reference [29].

2.2. Benefits of Ecological Release from Reservoirs

2.2.1. Functional Division of Ecological Water Demand [30,31]

The water demand of the river ecological environment is divided into non-consumptive water demand and consumptive water demand. Consumptive water demand includes evaporation and leakage water demand. Non-consumptive water demand includes water demand for basic ecological environment of rivers, water demand for maintaining self-purification capacity of water bodies, and water demand for sediment transport. The principle of accumulation is adopted for consumptive water demand, and the maximum of the three items is taken for non-consumptive water demand. Then, the final result is the sum of the two items.

2.2.2. Economic Benefit Calculation

(1) Water supply benefit

Rivers provide domestic water, agricultural irrigation water, industrial water, and urban ecological water for human beings. The evaluation of water supply function value uses the market value method, and the calculation formula is expressed as follows [28]:

$$W_w = M_w \cdot P_w \quad (5)$$

In the above formula, W_w is water supply benefit, CNY; M_w is water supply, m^3; and P_w is the price of water, CNY/m^3.

(2) Water supply assurance rate

For the proportion of the number of months that the water supply is satisfied to the total number of months, the calculation formula is expressed as follows [29]:

$$B_w = T_s / T_t \quad (6)$$

In the above formula, B_w is the assurance rate of water supply, T_s is the number of months when the water supply is satisfied, and T_t is the total months of water supply.

(3) Power generation benefit

The market value method is adopted for the functional value of hydropower generation, and the calculation formula is expressed as follows [30]:

$$W_e = M_e \cdot P_e \quad (7)$$

In the above formula, W_e is the value of power generation function, CNY; M_e is the annual power generation of the power station, kW·h; and P_e is the price of electricity, CNY/kW·h.

2.2.3. Ecological Benefit Calculation

(1) Benefits of sediment transport function

River sediment transport refers to the role of river water in transporting sediment, scouring sediment on the riverbed, and dredging the river channel. The sediment transport function provides conditions for further flood discharge and drainage. The value calculation formula of sediment transport function is expressed as follows [32]:

$$W_s = V_s \cdot P_s \quad (8)$$

In the above formula, W_s is the sediment transport value of the river, CNY; V_s is the annual average sediment discharge of river flow, m^3; and P_s is the cost of manual river cleaning, CNY/m^3. Only under the condition of meeting the water demand for sediment transport can the river achieve a balance between erosion and deposition and ensure that the sediment accumulated in the river channel is fully transported away [33–35].

(2) Erosion control function benefit [36]

Erosion control functions include estuarine sediment land building function, riparian wetland function to control soil nutrient loss, and functions to prevent wind wave erosion of river banks. Here, only estuarine sediment land building function is evaluated. Assuming that all sediment transported by rivers has land building function at the estuary, the calculation formula of land building area is expressed as follows:

$$S_m = M \div W \div T_b \quad (9)$$

In the above formula, S_m is the land forming area, m^2; M is the amount of land forming sediment, m^3; W is the average soil capacity, t/m^3; and T_b is the average thickness of soil topsoil, m.

The ecological economic value of this function can be estimated by the opportunity cost method, and the calculation formula is expressed as follows:

$$W_{\mathrm{m}} = S_{\mathrm{m}} \cdot P_{\mathrm{m}} \tag{10}$$

In the above formula, W_m is the land making value, CNY. In addition, P_m is the income per unit land area, CNY/m^2.

(3) Purification function benefit [37]

The river ecosystem can purify pollutants brought into the river by runoff through a series of physical and biochemical reactions, such as dilution, adsorption, filtration, diffusion, oxidation, and reduction, and can play a role in purifying water quality. The replacement cost method is adopted. According to the amount of sewage purified by the river each year, the cost of purifying the same amount of sewage by artificial sewage plants is assumed to be the value of river purification function. The calculation formula is expressed as follows:

$$W_{\mathrm{d}} = V_{\mathrm{d}} \cdot P_{\mathrm{d}} \tag{11}$$

In the above formula, W_d is the river purification value, CNY; V_d is the annual purified sewage volume of the river (t); and P_d is the cost per ton of sewage purified by the sewage treatment plant (CNY/t).

(4) Habitat function benefits

The riparian zone, river water body, river bottom silt, and other diverse environments in the river ecosystem provide different habitats for aquatic and terrestrial organisms. They are places where various wild animals and plants inhabit, multiply, migrate, and overwinter. It cannot be ignored that they play an important role in maintaining biodiversity. At present, there is no effective and feasible evaluation method for the value of habitat. Through analysis and adoption of the research results of Costanza et al. [38], the annual ecological benefit of habitat service function is 439 USD/hm^2, equivalent to 2803.8 CNY/hm^2 (equivalent to 638.68 CNY at 100 USD). The calculation formula is expressed as follows:

$$W_{\mathrm{h}} = S_{\mathrm{h}} \cdot P_{\mathrm{h}} \tag{12}$$

In the above formula, W_h is the value of river habitat, CNY; S_h is the drainage area, hm^2; and P_h is the annual ecological benefit of the river habitat, CNY/hm^2.

2.3. Comprehensive Evaluation Model of Ecological Operation Benefits

Comprehensive evaluation refers to the process of judging the observation results by comparing multiple indicators of a complex system with certain standards and endowing such results with certain significance and value. Yoon [39] put forward the TOPSIS method, which uses two benchmarks: close to the positive ideal solution and far from the negative ideal solution as the objective function. The TOPSIS method has the advantages of no special requirements for data as well as flexibility, simplicity, and wide application. Guo [40] and Qian [41] established a weighted TOPSIS comprehensive evaluation model on the basis of using the grey correlation degree to determine the index weight, combining TOPSIS method, and the evaluation effect was good.

The brief calculation steps are as follows. The number of evaluation objects and evaluation indicators are set as n and m, respectively, and the original data form is presented in Table 1.

Table 1. Index form of the evaluation object.

Evaluation Object	Index 1	Index 2	...	Index m
1	x_{11}	x_{12}	...	x_{1m}
2	x_{21}	x_{22}	...	x_{2m}
...	...	...	...	...
n	x_{n1}	x_{n2}	...	x_{nm}

The indicator attribute assimilation process can transform all low excellent indicators and neutral indicators into high excellent indicators as follows:

$$x_{ij}^{'} = \begin{cases} x_{ij} & \text{high excellent indicators} \\ 1/x_{ij} & \text{low excellent indicators} \\ M/\left(M+\left|x_{ij}-M\right|\right) & \text{neutral indicators} \end{cases} \tag{13}$$

In the above formula, x_{ij} is indicator, $x_{ij}^{'}$ is high excellent indicator, and M is the mean value of indicator.

(1) Dimensionless processing

$$x_{ij}^{*} = \begin{cases} \dfrac{x_{ij}}{\sqrt{\sum\limits_{i=1} x_{ij}^{2}}}, \text{original high excellent indicators} \\ \dfrac{x_{ij}^{'}}{\sqrt{\sum\limits_{i=1}^{n}\left(x_{ij}^{'}\right)^{2}}}, \text{original low excellent and neutral indicators} \end{cases} \tag{14}$$

In the above formula, x_{ij}^{*} is dimensionless indicator.

(2) Determine objective weight

$$\overline{x_j} = \frac{1}{m}\sum_{i=1}^{m} x_{ij}^{*}, s_j = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}\left(x_{ij}^{*}-\overline{x_j}\right)^{2}}, \omega_j = s_j/|\overline{x_j}|, (j = 1, 2, \ldots n) \tag{15}$$

In the above formula, $\overline{x}_j$ is the average value of index in column j, s_j is the standard deviation of index in column j, and ω_j is the weight of index in column j.

Determine the weight of each index $\omega_1, \omega_2, \ldots, \omega_n$ and construct a diagonal matrix ω with them as the main diagonal elements. Then, the following is performed:

$$\omega = \begin{bmatrix} \omega_1, 0, ..., 0 \\ 0, \omega_2, ..., 0 \\ ..... \\ 0, 0, ..., \omega_n \end{bmatrix} \tag{16}$$

(3) Construct weighting coefficient matrix

The weighting coefficient matrix is expressed as follows:

$$Z = x_{ij}^{*} \cdot \omega = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{bmatrix} \tag{17}$$

(4) Determine the best scheme and the worst scheme

Composition of the maximum value in each column of the optimal scheme:

$$z^{+} = \{\max z_{i1}, \max z_{i2}, \ldots, \max z_{in}\} \tag{18}$$

Composition of the minimum value in each column of the worst case scheme:

$$z^{-} = \{\min z_{i1}, \min z_{i2}, \ldots, \min z_{in}\} \tag{19}$$

(5) The positive and negative ideal solutions are normalized, separately, to determine the weight value of each evaluation index

Calculation of weight of positive ideal solution:

$$z_{j}^{+} = \max z_{j} / \sum z^{+}, \tag{20}$$

The weight vector of the evaluation index calculated using the positive ideal solution is obtained as follows:

$$z^{+} = \left(z_{1}^{+}, z_{2}^{+}, \ldots, z_{n}^{+}\right) \tag{21}$$

Calculation of weight of negative ideal solution:

$$z_{j}^{-} = \min z_{j} / \sum z^{-}, \tag{22}$$

The weight vector of each evaluation index obtained using the negative ideal solution is obtained as follows:

$$z^{-} = \left(z_{1}^{-}, z_{2}^{-}, \ldots, z_{n}^{-}\right) \tag{23}$$

(6) Fuzzy Comprehensive Evaluation Model with TOPSIS Weighting

The evaluation matrix Y of each evaluation index is obtained by transposing and normalizing the $Z = x_{ij}^{*} \cdot \omega = \begin{bmatrix} z_{11}, z_{12}, \ldots\ldots, z_{1n} \\ z_{21}, z_{22}, \ldots., z_{2n} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ z_{m1}, z_{m2}, \ldots, z_{mn} \end{bmatrix}$:

$$Y = \begin{bmatrix} y_{11}, y_{12}, \ldots\ldots, y_{1m} \\ y_{21}, y_{22}, \ldots., y_{2m} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ y_{n1}, y_{n2}, \ldots, y_{mn} \end{bmatrix} \tag{24}$$

Then, the comprehensive evaluation vectors determined by the positive and negative ideal solutions are expressed as follows:

$$u^{+} = z^{+}Y, u^{-} = z^{-}Y \tag{25}$$

Normalize the comprehensive evaluation vector to obtain the membership degree of each vector combination. Based on the maximum membership degree principle, the comprehensive rankings of the evaluated objects are obtained.

3. Introduction to the Study Area

The Daling River basin is in the east–west direction, with geographic coordinates of 118°53′−121°52′ E and 40°28′−42°38′ N. The location map of Baishi Reservoir is presented in Figure 3. The main stream of Daling River is 435 km long, with a drainage area of 23,837 km^2. Daling River is a large river flowing into the sea along the western Bohai Sea in the northeast. The Baishi Reservoir is located in the main stream of the Daling River, a sandy river in the west near Shangyuan Township, Beipiao City, Liaoning Province. It is the most critical control reservoir in the Daling River basin. It is located at the junction of Chaoyang, Fuxin, and Jinzhou, 46 km from Beipiao City and 45 km from Yixian County. It is a key project of water resources development in Liaoning Province during the "Ninth Five Year Plan" period, and a large I type water conservancy project focusing on flood control, irrigation, and water supply that gives consideration to power generation, fish farming, and other comprehensive utilization. The project was started in 1995. The sluice was lowered and impounded after the flood in 1999, and the project was completed after the flood in 2000.

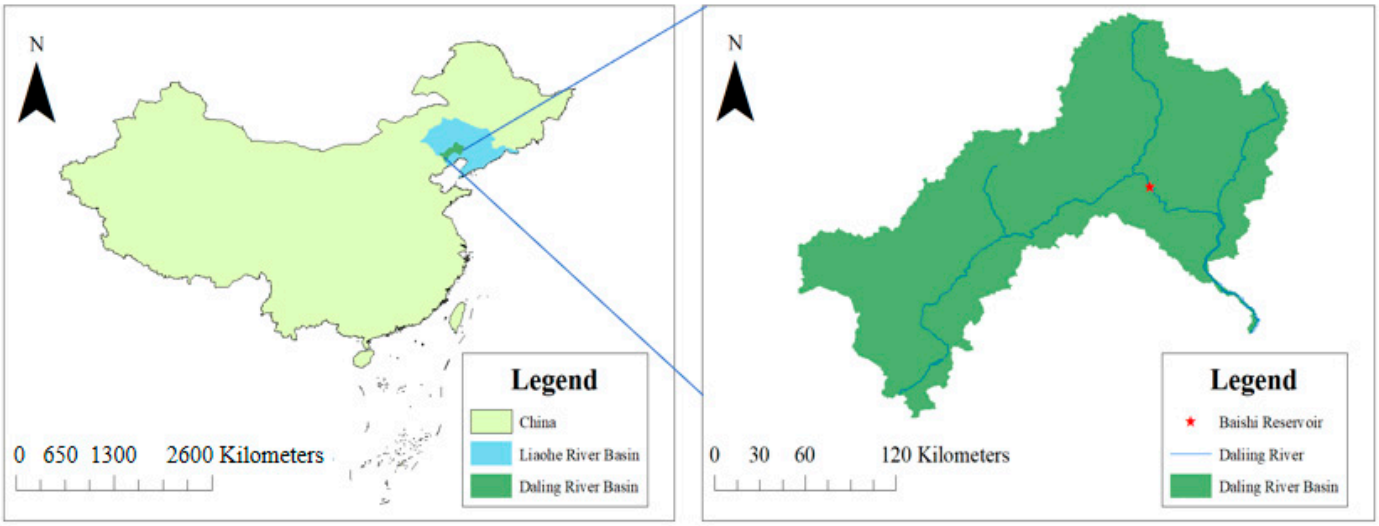


Figure 3. Location map of the Baishi Reservoir.

4. Ecological Operation Scheme

4.1. Operation Mode of Reservoir

4.1.1. Characteristic Water Level

Affected by the delayed relocation of Jinlingsi Railway Bridge immigrants in the reservoir area, the Baishi Reservoir has been operating at a low water level. The normal pool level is 120 m, and the elevation of the water intake leading from Baishi to Beipiao City is limited. When the reservoir water level is lower than 115 m, it will directly affect the urban domestic water supply of Beipiao City. Therefore, the water level cannot be lowered to the dead water level of 108 m. Under the current situation, the lower limit of the water level for water utilization is 115 m, and the flood control limit water level is 118 m.

4.1.2. Water Supply Characteristics

(1) Water intake leading from Baishi to the Fuxin City (WILBF)

The designed annual water intake is 60.23 million t (165,000 t/d), and the actual water intake in May is 7000 t/d, which is located in Liuhuang Village, Shangyuan Town, Beipiao City. The water is taken by pipeline.

(2) Water intake leading from Baishi to the Beipiao City (WILBB)

The designed annual water intake is 19.71 million t (50,000 t/d), and the actual water intake in May is 12,000 t/d, which is located in the central village of Xiafu Township, Beipiao City. The water is taken by pipeline.

(3) Water intake leading from Baishi to the industrial park of Beipiao City (WILBIPB)

The designed annual water intake is 14.6 million t (40,000 t/d), and the actual water intake in May is 3000 t/d, which is located in the sewage treatment center of Liangshuihe Township, Beipiao City, and the way is pipeline water intake.

(4) Yixian County Water source (YCWS)

The designed annual water intake is 9.13 million t (25,000 t/d), and the actual water intake in May is 29,000 t/d, which is located in Houwuliying and Balibao villages, Chengguan Township, Yixian County. The water is taken by river.

(5) Linghe Water Source (LWS)

The designed annual water intake is 18.25 million t (50,000 t/d), and the actual water intake in May is 10,000 t/d, which is located on the left bank of Daling River in Jiudaoling Township, Yixian County. The water is taken by river channel.

(6) Linghai Irrigation Area Water Source (LIAWS)

The licensed annual water intake is 30 million m^3. The annual water intake in 2020 is 42.77 million m^3, which is located on the right bank of Daling River in Daling River Street, Linghai City, and the water is taken by river channel.

(7) Dongguo Reed Farm Water Source (DRFWS)

The permitted annual water intake is 40 million m^3. The annual water intake in 2020 is 26.58 million m^3, which is located on the left bank of Daling River in Antun Township, Linghai City, and on the left bank of Daling River in Dongguo Street, Panshan County.

(8) Ecological release

Ensure the downstream discharge ecological flow of 3.97 m^3/s of the Baishi Reservoir.

4.2. Reservoir Operation Scheme

According to the analysis of the inflow runoff of the Baishi Reservoir from 1956 to 2011, the flood season of Baishi Reservoir is from June to September. The highest water level of the reservoir is 118 m, and the non-flood season is from October to May of the next year. The highest water level of the reservoir is analyzed in two situations. First, because of the delayed relocation of Jinlingsi Railway Bridge immigrants in the reservoir area, the Baishi Reservoir has been operating at a low water level, with a normal pool level of 120 m. Second, when the normal pool level of the reservoir returns to normal, it is 127 m.

The dead water level of the reservoir is analyzed in two cases. It can be seen that the dead water level is 115 m when the White Water Diversion Project works and 108 m when the LXB water supply project works.

The Baishi Reservoir starts from 118 m. The operation of the 56-year inflow runoff series is optimized with the above model, so as to obtain the average water level in each month and the minimum water shortage over many years, providing support for reservoir operation.

Based on the above analysis, the release scheme analysis of Baishi Reservoir is divided into the following schemes:

Scheme 1: The normal pool level is 120 m, dead water level is 115 m, and flood limit water level is 118 m.

Scheme 2: The normal pool level is 120 m, dead water level is 108 m, and flood limit water level is 118 m.

Scheme 3: The normal pool level is 127 m, dead water level is 115 m, and flood limit water level is 118 m.

Scheme 4: The normal pool level is 127 m, the dead water level is 108 m, and the flood limit water level is 118 m.

4.3. Benefit Evaluation

4.3.1. Economic Benefit

(1) Water supply benefit

The average price of water for urban use in Liaoning Province is 3.76 CNY/m^3, and the price of water for agricultural irrigation is 0.04 CNY/m^3. The price of water supply from Bai to Fu, from Bai to the north, from Bai to the park, and from Yixian County to Linghe River is 3.76 CNY/m^3 for urban water and 0.04 CNY/m^3 for agricultural irrigation in the Linghai Irrigation Area and Dongguo Reed Farm.

The multi-year average of monthly water supply of each water user can be calculated, and the water supply assurance rate and annual water shortage can be calculated. The higher the water supply assurance rate is, the smaller the annual water shortage, and the better the economic benefits.

(2) Power generation benefit

By looking up the statistical yearbook of Liaoning Province, it is determined that the electricity price of Liaoning Province is 0.38 CNY/kW h.

4.3.2. Ecological Benefit

The ecological environment water demand of Daling River is analyzed and calculated based on the 34-year monthly runoff data from 1968 to 2001 of four hydrological stations, namely Shangwopu, Chaoyang, Yixian and Linghai, as shown in Table 2 [32]. As required by the Ministry of Water Resources, the ecological flow under the Daling River dam is 3.97 m^3/s, and the water volume is 125.2 million m^3, which is close to the ecological base flow. If the ecological flow or water volume is small, it cannot fully meet the function of ecological water consumption. Then, the function of ecological flow will be reduced using the method of water volume reduction with the same ratio, and the reduction ratio is 0.28. If the ecological flow decreases, the reduction ratio will change accordingly.

Table 2. Water demand for the ecological environment of the Daling River.

Ecological Water Demand Type of the River Channel	10^8 m^3
Ecological environment base flow	1.65
Water demand for maintaining self-purification capacity of water body	3.51
Water demand for sediment transport	4.49
Consumable water demand	0.02
Ecological water demand	4.51

(1) Benefits of sediment transport function

Only when the water demand for sediment transport is met can the river reach the balance of erosion and deposition and can the sediment deposited in the river channel be fully transported away. The multi-year average sediment transport volume of the studied river reach is 24,668,200 t, and the sediment transport water demand is 449 million m^3/a.

Only when this water volume is met, the sediment transport volume can reach 24,668,200 t. If the sediment transport water demand is less than 449 million m^3/a, it will be scaled according to the same multiple of ecological water volume. Generally, the cost of manual river cleaning is 4.3 CNY/t.

(2) Erosion control function benefit

The amount of land-making sediment is calculated based on the same ratio of ecological release water volume. The average unit weight of soil is 1.28 t/m^3, and the average thickness of topsoil is 0.5 m. In 2009, the land income per unit area of the Daling River basin was 27,360 CNY/hm^2. As noted in the statistical yearbook, the GDP in 2009 was 1528.87 billion CNY, and the GDP in 2011 was 2340.92 billion CNY. Based on this, the land income per unit area was scaled by the same ratio. Therefore, the land income per unit area of this study is determined to be 41,892 CNY/hm^2.

(3) Purification function benefit

According to the data of the Comprehensive Management Plan of Water Resources in the Daling River Basin of Chaoyang City, the annual sewage discharge in the Daling River Basin is 194 million tons, and the unit cost price of wastewater treatment in the Daling River Basin in 2009 was 0.5 CNY/t. The statistical yearbook shows that the GDP in 2009 was 1528.87 billion CNY, and the GDP in 2017 was 2340.92 billion CNY. Based on this, the unit cost price of wastewater treatment was scaled by the same ratio. The unit cost price of wastewater treatment is 0.9 CNY/t.

(4) Habitat function benefits

Based on the land area formed by erosion controlled by reservoir ecological regulation, combined with the annual ecological benefit of the habitat of 2803.8 CNY/hm^2, the functional benefit of the habitat is calculated.

5. Results

5.1. Release Scheme

5.1.1. Scheme Type

In combination with the above four schemes, the above model is used for water supply operation of Baishi Reservoir, which is divided into two cases, namely, considering ecological release and not considering ecological release. The 56-year release process is obtained, and the maximum, minimum, and average values of the release are statistically analyzed, so as to serve as the release limit and reference value of the corresponding scheme, as shown in Tables 3 and 4. By conducting reservoir optimization dispatch calculations using the inflow from 1968 to 2001 as the reservoir's inflow and calculating the average outflow for each corresponding month of each year, we can obtain the corresponding results. If the flow rate is less than 3.97 m^3/s, it indicates that the inflow during that month is relatively low and the reservoir level is lower. The calculation results of the scheme represent the multi-year average results.

Table 3. Schemes 1–4 of the release process (considering ecological release).

Flow (m^3/s)	Scheme 1			Scheme 2			Scheme 3			Scheme 4		
	1	2	3	1	2	3	1	2	3	1	2	3
June	6.16	7.06	7.04	7.06	7.06	7.06	4.78	7.06	7.02	7.06	7.06	7.06
July	7.12	7.29	7.29	7.29	7.29	7.29	7.27	7.29	7.29	7.29	7.29	7.29
August	4.77	7.29	7.24	7.27	7.29	7.29	7.06	7.29	7.28	7.27	7.29	7.29
September	5.97	7.06	7.02	6.65	7.06	7.05	3.62	7.06	6.97	0.32	7.06	6.92

Table 3. *Cont.*

Flow (m^3/s)	Scheme 1			Scheme 2			Scheme 3			Scheme 4		
	1	2	3	1	2	3	1	2	3	1	2	3
October	4.99	7.29	7.13	7.17	7.29	7.29	4.35	7.29	7.08	5.68	7.29	7.25
November	4.37	7.06	6.91	6.33	7.06	7.02	2.11	7.06	6.82	6.08	7.06	7.02
December	0.03	7.29	6.79	1.37	7.29	7.08	3.32	7.29	6.96	5.13	7.29	7.19
January	0.05	7.29	5.97	2.36	7.29	7.08	0.00	7.29	5.98	0.13	7.29	6.98
February	0.97	6.59	5.71	2.47	6.59	6.38	0.57	6.59	5.85	2.07	6.59	6.17
March	0.07	7.29	6.04	2.00	7.29	6.84	0.02	7.29	6.30	3.21	7.29	6.80
April	3.16	7.06	6.56	4.90	7.06	6.88	2.36	7.06	6.48	0.05	7.06	6.53
May	0.01	7.29	1.72	0.00	7.29	1.09	0.01	7.29	1.98	0.00	7.29	1.34

1-Minimum value, 2-maximum value, 3-average value.

Table 4. Schemes 1–4 of the release process (without considering ecological release).

Flow (m^3/s)	Scheme 1			Scheme 2			Scheme 3			Scheme 4		
	1	2	3	1	2	3	1	2	3	1	2	3
June	1.77	3.09	3.06	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09
July	3.13	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19
August	2.34	3.19	3.18	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19
September	3.08	3.09	3.09	0.15	3.09	2.98	0.14	3.09	2.94	0.14	3.09	3.03
October	1.00	3.19	3.15	3.19	3.19	3.19	2.47	3.19	3.17	3.19	3.19	3.19
November	2.48	3.09	3.07	3.09	3.09	3.09	0.16	3.09	2.98	3.05	3.09	3.09
December	1.36	3.19	3.09	2.28	3.19	3.17	0.06	3.19	2.97	2.82	3.19	3.18
January	1.60	3.19	3.11	0.02	3.19	3.13	2.06	3.19	3.11	3.14	3.19	3.19
February	1.46	2.88	2.80	0.03	2.88	2.71	0.05	2.88	2.74	0.00	2.88	2.77
March	0.02	3.19	3.00	2.35	3.19	3.18	2.10	3.19	3.15	3.19	3.19	3.19
April	0.93	3.09	2.96	1.62	3.09	3.06	0.05	3.09	2.89	0.26	3.09	3.03
May	0.00	3.19	1.03	0.00	3.19	0.89	0.00	3.19	1.07	0.00	3.19	0.55

1-Minimum value, 2-maximum value, 3-average value.

5.1.2. Scheme Analysis

It can be seen from the analysis in Tables 3 and 4 that the maximum and minimum values of the discharge in the flood season of each scheme are not much different. However, the difference is large in non-flood season, indicating that the inflow size and water level in the non-flood season affect the discharge. At the end of the operation period, the discharge capacity of the reservoir is small, which makes the water shortage in this period large. According to the analysis of Schemes 1–4, the adjustment of the normal pool level has little impact on the release scheme, but the greater impact is the height of the dead water level, which indicates that the reservoir is difficult to fill due to the small inflow and large water supply volume of the reservoir. The water supply capacity of the reservoir can be improved by adjusting the dead water level during the operation of the reservoir.

5.2. Benefit Evaluation Results

(1) Statistics of water supply results

Statistical analysis is made on the multi-year average water supply of the release results of the above four schemes, namely, the WILBF, WILBB, WILBIPB, YCWS, LWS, LIAWS, DRFWS, and the ecological water supply (EWS), and the multi-year average water shortage of the corresponding months is calculated. See Table 5 for the results.

Table 5. Average annual water supply results of different water users (10^4 m^3).

Scheme	Statistics	WILBF	WILBB	WILBIPB	YCWS	LWS	LIAWS	DRFWS	EWS	Total Water Shortage
Scheme 1 CER	Guarantee rate (%)	80.91	80.91	80.91	80.91	76.36	76.36	68.48	80.91	
	Total water shortage	521.13	303.77	126.21	79.38	291.41	478.78	774.06	1082.58	3510.74
Scheme 1 WCER	Guarantee rate (%)	86.06	86.06	86.06	86.06	84.09	84.09	80.15	0.00	
	Total water shortage	270.58	227.84	65.47	41.42	130.49	214.23	348.84	0.00	1152.57
Scheme 2 CER	Guarantee rate (%)	83.03	83.03	83.03	83.03	81.67	81.67	76.82	83.03	
	Total water shortage	357.35	196.27	23.61	0	102.86	221.40	403.36	831.67	2629.34
Scheme 2 WCER	Guarantee rate (%)	85.45	85.45	85.45	85.45	84.85	84.85	84.09	0.00	
	Total water shortage	307.63	239.07	74.46	47.04	131.42	215.76	305.48	0.00	1174.56
Scheme 3 CER	Guarantee rate (%)	81.21	81.21	81.21	81.21	76.82	76.82	68.48	81.21	
	Total water shortage	395.87	209.21	34.32	0	202.91	382.76	683.15	909.80	3291.10
Scheme 3 WCER	Guarantee rate (%)	85.30	85.30	85.30	85.30	83.94	83.94	80.00	0.00	
	Total water shortage	285.80	232.46	69.16	43.73	144.25	236.84	373.34	0	1239.27
Scheme 4 CER	Guarantee rate (%)	83.33	83.33	83.33	83.33	80.45	80.45	75.45	83.33	
	Total water shortage	448.26	281.68	108.55	68.34	206.63	339.40	536.55	931.09	2773.91
Scheme 4 WCER	Guarantee rate (%)	84.70	84.70	84.70	84.70	84.24	84.24	83.03	0	
	Total water shortage	337.00	247.97	81.58	51.49	140.39	230.49	322.01	0	1264.62

CER-Considering ecological release, WCER-without considering ecological release.

(2) Water supply benefit statistics

Based on the consideration and non-consideration of ecological release, the power generation, water supply, and ecological benefits of ecological release in the four schemes are analyzed and calculated, as shown in Table 6.

Table 6. Multi-year average value of ecological and economic benefits of reservoir discharge (10^8 CNY).

Classification	Scheme	Urban Water Supply	Agricultural Water-Supply	Electricity Generation	Sediment Transport	Erosion Control	Purification Function	Habitat Function	Total
CER	1	4.09	0.02	0.03	0.27	2×10^{-4}	0.44	4.02	8.87
	2	4.18	0.02	0.02	0.27	2×10^{-4}	0.45	4.08	9.02
	3	4.12	0.02	0.03	0.27	2×10^{-4}	0.45	4.05	8.94
	4	4.17	0.02	0.02	0.27	2×10^{-4}	0.45	4.07	9.00
WCER	1	4.31	0.03	0.01	0.00	0.00	0.00	0.00	4.35
	2	4.28	0.03	0.01	0.00	0.00	0.00	0.00	4.32
	3	4.29	0.03	0.01	0.00	0.00	0.00	0.00	4.33
	4	4.26	0.03	0.01	0.00	0.00	0.00	0.00	4.30

CER-Considering ecological release, WCER-without considering ecological release.

(3) Evaluation of water supply scheme

The assurance rate and water shortage of four water supply schemes considering ecological release and not considering ecological release, including WILBF, WILBB, WILBIPB, YCWS, LWS, LIAWS, DRFWS, EWS, economic benefits of urban water supply, agricultural water supply, power generation, sand transport, erosion control, purification function, and habitat function, are evaluated. See Table 7 for the sequence of ecological releasing schemes considered and not considered. The smaller the water deficit index is, the better it is; the larger the other indexes are, the better it is.

Table 7. Scheme sorting results.

Category	Scheme 1	Scheme 2	Scheme 3	Scheme 4
CER	4	1	2	3
WCER	1	2	3	4

CER-Considering ecological release, WCER-without considering ecological release.

Considering the ecological and economic benefits of ecological release, Scheme 2 is the best, and Scheme 1 is the worst. Without considering the economic benefits of ecological release, the best one is Scheme 1, and the worst one is Scheme 4.

6. Analysis and Discussion

6.1. Release Process

From the analysis of Tables 4 and 5, it can be seen that the maximum outflow values of the four schemes are equal when considering ecological release and not considering ecological release, indicating that there is an upper limit boundary for water supply, irrigation, and downstream ecological water demand in the Daling River. This provides important discharge basis for reservoir operation. The analysis shows that, considering ecological release and not considering ecological release, the release of the reservoir is relatively small at the end of the dispatch period, and even zero values may occur. In actual scheduling, if the goal is to ensure that the reservoir has enough water to discharge, it is important to focus on the discharge demand at the end of the scheduling period. At the same time, it also indicates that when the discharge of the reservoir is 0 at the end of the scheduling period. This is to ensure the optimal efficiency of the reservoir's annual scheduling.

6.2. Water Supply Results

(1) The water supply results of Schemes 1–4 are shown in Table 5. It can be seen from the analysis that with the increase of normal pool level, the water supply assurance rate for each water user will increase slightly, and the water supply assurance rate can be significantly improved by reducing the dead water level. The water supply capacity of the reservoir is strong in flood season, and the water shortage of water users is small. The water supply capacity is weak in non-flood season, and the water shortage of water users is large. The assurance rates of WILBF, WILBB, WILBIPB, and YCWS are higher than that of LWS and LIAWS. DRFWS has the lowest assurance rate of water supply. It can be seen that the smaller the water demand is, the easier it is to meet it. In contrast, the larger the water demand is, the larger the water shortage is.

(2) If ecological release is not considered, the analysis shows that the monthly release capacity is similar to the change trend of the considered release. The difference is that the water supply assurance rate considering ecological release is lower than that without ecological release. This shows that ecological release will reduce water supply and the water supply assurance rate in urban, rural, and irrigation areas.

(3) Under the condition that the annual water shortage is the minimum and the water level is the maximum, when the dead water level is reduced to 108 m, the monthly water supply can be significantly increased without considering the ecological release conditions, but the improvement of the assurance rate for different water users is limited.

(4) Due to the large discharge after considering ecological discharge, the power generation is greater than that without considering ecological discharge. At the same time, the higher the normal pool level and dead water level of the reservoir, the greater the power generation of the reservoir.

6.3. Water Supply Benefit

(1) The analysis of the scheme considering ecological release shows that the ecological benefits are greater than the sum of urban water supply, agricultural water supply and power generation benefits, indicating that ecological release can create huge ecological benefits. According to the analysis of the economic benefits of the reservoir

discharge, the urban water supply of the reservoir creates the greatest benefits. The urban water supply benefits of Schemes 1–4 are 409 million CNY, 418 million CNY, 412 million CNY, and 417 million CNY, respectively. The benefits of agricultural water supply and power generation are close. The agricultural water supply benefits of Schemes 1–4 are all 2 million CNY, and the power generation benefits of Schemes 1–4 are 3 million CNY, 2 million CNY, 3 million CNY, and 2 million CNY, respectively. The benefit of power generation is slightly greater than that of agricultural water supply. According to the analysis of the ecological release benefit of the reservoir, the habitat benefit of the ecological release of the reservoir is the largest, and the power generation benefit of Schemes 1–4 is 402 million CNY, 408 million CNY, 405 million CNY, and 407 million CNY, respectively. This is followed by the purification function benefit and the sediment transport function benefit, and the erosion control function benefit is the smallest. Among the comprehensive benefits of reservoir discharge, the proportion of Schemes 1–4 is 53.36%, 53.20%, 53.36%, and 53.25%, respectively, which shows that the ecological benefits account for a large proportion in the comprehensive benefits of considering ecology.

(2) The analysis of the scheme without considering the ecological release shows that the ecological benefit cannot be accurately estimated without considering the ecological release, and the amount of power generation and water supply discharged from the reservoir can also serve as the function of ecological flow. However, it will be taken away in Yixian County, Linghai, and other places, making it difficult to accurately estimate the ecological benefit. In this study, it will be set as 0. According to the analysis of economic benefits, the reservoir has the greatest benefit for urban water supply. The urban water supply benefits of Schemes 1–4 are 431 million CNY, 428 million CNY, 429 million CNY, and 426 million CNY, respectively. This is followed by the agricultural water supply benefits. The agricultural water supply benefits of Schemes 1–4 are all 3 million CNY, and the power generation benefits of Schemes 1–4 are all 1 million CNY. Because of the small discharge flow, the power generation benefits are small. This result is also similar to the function orientation of the Baishi Reservoir, with water supply as the main and power generation as the auxiliary.

(3) The analysis of the schemes considering ecological release and not considering ecological release shows that after considering ecological release, the benefits of urban water supply and agricultural water supply of the reservoir are reduced. The urban water supply benefits of Schemes 1–4 are decreased by 22 million CNY, 10.47 million CNY, 17.3 million CNY and 9.6 million CNY respectively. The agricultural water supply benefits of Schemes 1–4 are decreased by 0.3 million CNY, 0.1 million CNY, 0.24 million CNY, and 0.01 million CNY, respectively. The power generation benefits are increased significantly. The added value of power generation benefits in Schemes 1–4 is 1.3 million CNY, 0.96 million CNY, 1.38 million CNY, and 1 million CNY, respectively, but it is still difficult to make up for the economic losses caused by water supply. The total decrease of economic benefits in Schemes 1–4 is 21 million CNY, 9.6 million CNY, 16 million CNY, and 8.7 million CNY, respectively. However, the ecological benefits created by ecological release are greater than the economic benefits of water supply and release of the reservoir itself. After considering ecological release in Schemes 1–4, the added value of comprehensive benefits is 452 million CNY, 470 million CNY, 461 million CNY, and 471 million CNY, respectively, indicating that ecological release is of great significance and value to the downstream of the Baishi Reservoir. This creates huge comprehensive ecological benefits with small loss of direct economic benefits.

According to other studies [32], considering ecological flow can ensure the sustainable development of river ecological environment and the effective functioning of river ecosystem services. Although the benefits may decrease, considering ecological flow is indispensable and imperative. This is consistent with the research presented in this article, indicating that the conclusions drawn are correct.

6.4. Assessment of Water Supply Scheme

Considering the operation scheme of ecological release, the best are Schemes 2 and 3, and the worse are Schemes 1 and 4. The reason why Scheme 1 is worse is that the dead water level is high, and there is excess water stored in the reservoir that cannot play a role. The reason why Scheme 4 is poor is that the normal pool level is high. At the end of the operation period, more water is required to be stored in the reservoir to raise the water level. The benefit is poor during the period when there is less water. Considering the operation scheme of ecological release, the benefits include ecological benefits and economic benefits. Increasing a certain amount of difference between the normal water storage and dead water level can effectively tap the ecological water supply benefits of the reservoir, and exceeding a certain limit will reduce the comprehensive benefits of reservoir operation.

Without considering the regulation scheme of ecological release, the best are Schemes 1 and 2, and the worst are Schemes 3 and 4. The reason why Schemes 3 and 4 are worse is that they are used to raise the water level in reservoirs that need more water at the end of the regulation period, and the benefit is poor in the period of less water. The operation scheme of ecological release is not considered, and the benefits are only the economic benefits of water supply and power generation. The main function of the Baishi Reservoir is water supply. Power generation is a secondary function, and the unit benefit of water supply is less than that of power generation. Therefore, lowering the dead water level will lower the water level, thereby reducing the power generation benefits.

7. Conclusions

Four release schemes were developed based on the ecological regulation model of the Baishi Reservoir that maximize comprehensive benefits. The release process of the reservoir is analyzed and calculated using an intelligent optimization algorithm, so as to further refine the release countermeasures of the reservoir. The economic and ecological benefits of the reservoir release are analyzed and calculated. The comprehensive evaluation method is used to evaluate the optimal operation with schemes considering ecological release and not considering ecological release. This study investigates the synergistic coupling relationship between reservoir scheduling strategies and benefits, providing new ideas and research methods for flood control, water supply, and ecological scheduling of other reservoirs. The benefit calculation model and scheme evaluation model constructed in this study can be promoted and applied in other reservoirs.

(1) For the optimal scheduling scheme considering ecological release, the normal pool level is 120 m, dead water level is 108 m, and flood limit level is 118 m. For June to December, January, March and April, the flow is 7 m^3/s. From February to April, the flow is 6.5 m^3/s. In May, the flow is 1 m^3/s. For the optimal operation scheme without considering ecological release, the normal pool level is 120 m, dead water level is 115 m, and flood limit level is 118 m. From April to May of the next year, the flow will be 4 m^3/s and 1 m^3/s.

(2) Considering the ecological release, the economic benefits of the Baishi Reservoir will be reduced correspondingly, but it can form huge ecological benefits. In order to achieve the optimal ecological and economic benefits of the Baishi Reservoir, the

ecological release can be controlled on a monthly basis during the ecological release process to achieve the overall optimal benefits.

(3) In the process of reservoir discharge, the demand for urban water supply shall be met as much as possible. The assurance rate of agricultural water supply can be appropriately reduced, and the assurance rate of ecological discharge shall be improved as much as possible on the basis of ensuring water use. For reservoirs with high ecological release assurance rates, financial subsidies can be appropriately increased to compensate for the economic losses caused by ecological release.

(4) This article aims to study the ecological release strategies of reservoirs and analyze the benefits of ecological regulation. Based on the construction of a reservoir ecological regulation model, the ecological and economic benefits of reservoir release are calculated, and a multi-index evaluation technique is used to select the optimal solution. This technological system provides quantitative support for the formulation of ecological release strategies for reservoirs, clarifies the benefits of ecological release from reservoirs, and offers subsidies and support for the country's ecological regulation.

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