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Multi-Stakeholder Coordinated Operation of Reservoir Considering Irrigation and Ecology

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Abstract: In traditional ecological operation, it is difficult to coordinate the balance among the interests of stakeholders, and stakeholders find it difficult to accept the operation scheme. To address these problems, this study proposed a method of multi-stakeholder coordinated operation of reservoir (MSCOR). By comprehensively considering the interest demands of stakeholders, the multi-stakeholder interval coordination mechanism (MSICM) for reservoir operation was established. The multi-stakeholder coordinated operation model (MSCOM) was constructed. The multi-stakeholder solution algorithm based on the MSICM, the non-dominated sorting genetic algorithm II, and the approach of successive elimination of alternative schemes based on the *k*-order and *p*-degree of efficiency (MSIC-NSGA-II-SEABODE) were applied to solve the MSCOR problem. The coordination mechanism, model construction, multi-stakeholder optimization, and multi-attribute decision making were coupled to establish a multi-stakeholder coordinated operation method, comprising the whole process of mechanism–modeling–optimization–decision making. Taking Baojixia Reservoir as an example, the performance of the coordinated operation method was compared with that of the traditional optimal operation method, and the relationship between the irrigation benefits and ecological benefits of the reservoir was explored. The results show that: (1) On the premise of the same satisfaction degree of basic irrigation interests, the ecological AAPFD value of coordinated operation decreased by 0.184, 0.469, and 0.886 in a normal year, dry year, and extraordinary dry year, respectively. The effect of coordinated operation on balancing various stakeholders was more obvious with the decrease in water inflow. (2) The MSICM ensures that the multi-stakeholder operation of the reservoir conforms to the principles of comprehensiveness, balance, and sustainability. (3) The coordination scheme obtained by the MSIC-NSGA-II-SEABODE algorithm is more reasonable and feasible. The research results provide a new idea and method to address the MSCOR problem.

Keywords: reservoir operation; multi-stakeholder interval coordination (MSIC); multi-attribute decision making; MSIC-NSGA-II-SEABODE

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1. Introduction

As a result of the acceleration in ecological civilization and the construction of river basins, the objects of the construction and management of reservoirs are diversified, and involve many stakeholders. Water demand for economic development and steady operation of the ecological environment have become a pair of contradictions under the current situation of limited water resources [1]. For water-deficient watersheds and regions, water resource utilization needs to serve multiple stakeholders, including the eco-environment. This will affect the original pattern of interests, and lead to the normalization over a long period of a highly competitive situation among multiple stakeholders, which is difficult to alleviate in the short term. Although the existing reservoir operation methods take into account ecological protection in rivers, they often fail to balance the interests of all stakeholders [2,3]. Therefore, there is an urgent need to find a reasonable and applicable method for the multi-stakeholder coordinated operation of reservoir (MSCOR).

A reservoir's optimal operation considering the ecological flow is generated on the basis of traditional reservoir optimal operation. This research direction mainly focuses on two aspects: the determination of the ecological flow, and its implementation in the optimal operation model. At present, there are more than 200 methods for the determination of the ecological flow, which can be divided into four categories: hydrological methods based on historical runoff data [4–6]; hydraulic methods considering river section parameters (such as hydraulic radius, roughness, and hydraulic gradient) [7,8]; habitat simulation methods meeting the needs of representative species [9–11]; and holistic analysis methods considering the integrity of river and lake ecosystems [12,13]. Of these methods, no general method is applicable to all rivers. Different methods have different emphases, and the calculation results are quite different. Moreover, the natural–social uncertainties make it difficult to accurately quantify ecological flow and lead to poor adaptability of results.

On the basis of the traditional optimal model, the optimal operation model considering the ecological flow takes the ecological flow as a constraint or a new objective of the system. At present, the optimal operation models considering the ecological flow can be divided into three categories: the ecological flow constraint (EFC) model, the ecological flow objective (EFO) model, and the ecological value objective (EVO) model [3]. Of these, the EFC model takes the ecological flow as one of the constraints. According to different ecological flows, the EFC model can be further subdivided into the minimum ecological flow constraint (MEFC) model [14,15], the target species suitable ecological flow constraint (TSSEFC) model [16], and the integrated ecological flow constraint (IEFC) model [17]. The EFO model [3,18] takes the ecological flow as one of the objective functions; this model conforms to the essence of the multi-objective operation problem and is a new stage in the development of optimal operation models considering the ecological flow. However, the operation schemes obtained by these models often have a great impact on the social and economic benefits of reservoirs. Thus, the EVO model [19] was generated to study the optimal operation of reservoirs from the perspective of comprehensive river management and economy. The key to this model lies in the reasonable calculation of the ecosystem service function value. At present, many methods exist to estimate the ecological service function value. The results of different methods are quite different, and are closely related to national, and even provincial, conditions.

The above models need to be solved by optimization techniques. The optimization theories and methods can be divided into three categories: optimization methods based on mathematical theory, optimization methods based on evolutionary theory, and hybrid optimization methods [20]. The optimization methods based on mathematical theory include linear programming (LP) [21,22], nonlinear programming (NP) [23,24], dynamic programming (DP) [25–27], and large-scale system decomposition-coordination (LSSDC) [28]. The optimization methods based on evolutionary theory have developed rapidly in recent years, and include the non-dominated sorting genetic algorithm II (NSGA-II) [29–31], ant colony optimization (ACO) [32,33], the artificial bee colony algorithm (ABCA) [34], particle swarm optimization (PSO) [35–37], the artificial neural network (ANN) [38,39], and the simulated annealing algorithm (SAA) [40]. The hybrid optimization method is a calculation method obtained by coupling more than two optimization methods [41,42]. This approach represents a trend in the research on complex problems.

It can be seen that the models and solution algorithms of multi-objective optimal operation have emerged sequentially. However, it is difficult to implement the obtained operation schemes in practical application. The main reasons for this are: (1) The existing operation schemes often blindly pursue the maximization of benefits, while ignoring the principles of comprehensiveness, coordination, and sustainability. It is thus difficult for stakeholders to accept these schemes. (2) Most existing operation models are simply optimal operation models, resulting in unstable optimal solutions and poor operation schemes. (3) The fact that the essence of reservoir operation is a multi-objective, multi-stage, and multi-attribute decision-making problem is often ignored. (4) There is a lack of a rational and adaptable coordinated operation method that can relate stakeholders, the reservoir, the coordination mechanism, the operation model, and decision making with each other.

Therefore, the goal of this study was to examine the MSCOR problem and propose a method for the multi-stakeholder coordinated operation of reservoir. Firstly, the multi-stakeholder interval coordination mechanism (MSICM) for reservoir operation was established. Secondly, the multi-stakeholder coordinated operation model (MSCOM) was constructed. Then, the MSIC-NSGA-II-SEABODE algorithm was applied to solve the model. The coordination scheme obtained by the MSIC-NSGA-II-SEABODE algorithm can balance the interests of all stakeholders, and effectively guide decisions on actual reservoir operation. Finally, taking Baojixia Reservoir as an example, the multi-stakeholder coordinated operation was carried out, and the rationality and application value of the method was verified by comparison with the traditional optimal operation method.

2. Study Area

Baojixia Reservoir (107°3′ E, 34°22′ N), located in the upper reaches of the Wei River, is the only reservoir having a regulation capacity on the mainstream of the Wei River. The project location is shown in Figure 1. The controlled watershed area of the dam site is 30,661 km^2, and the height of the dam is 637.6 m. The dead water level of the reservoir is 626.0 m, the normal pool level is 636.0 m, the flood control level is 630.0 m, the total reservoir storage is 50 million m^3, and the effective storage capacity is 38 million m^3. Initially, the main water supply task of the project was irrigation, and the maximum water flow of the main canal was 52 m^3/s. In 2003, the Baojixia hydropower station was built behind the dam. The diversion of power generation water is consistent with the irrigation water diversion. The total installed capacity of the hydropower station is 8000 kW, the designed power generation is 41.5 million kW·h, and the maximum working head is 24 m. The hydropower station is composed of three generator sets. The flow passing through the hydraulic turbine of the two large sets is 20.8 m^3/s, and that of the small set is 10.4 m^3/s. The maximum and minimum flows passing through the hydraulic turbine are 52 and 5 m^3/s, respectively.

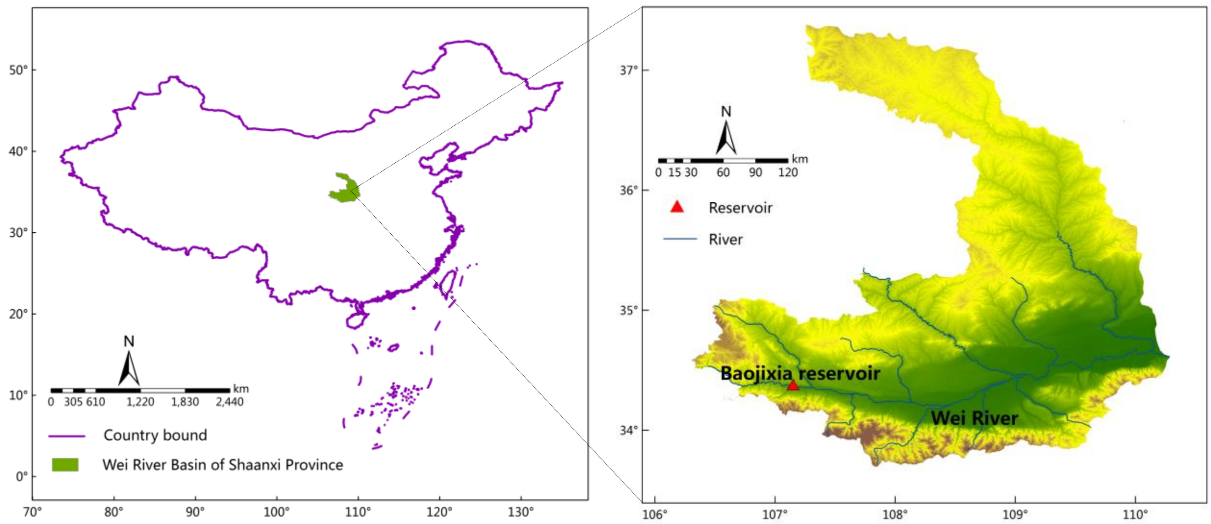


Figure 1. Location of the Baojixia Reservoir.

Baojixia Reservoir, as a key water conservancy project in Shaanxi Province, is of great significance to regional economic and social development. The reservoir effectively alleviates water shortages and helps promote the development of the agricultural economy in the irrigated area. However, it also leads to serious eco-environmental problems. A large amount of Wei River water is diverted into a channel for irrigation and power generation. The river water is affected for more than 70 km downstream of the point of extraction for irrigation, resulting in serious water shortages and eco-environmental deterioration in this section of the river in dry years [43,44]. The new round of Wei River regulation has further increased the eco-environmental water demand of the downstream section of the river. The operation of Baojixia Reservoir needs to consider the irrigation water, ecological water of the downstream section of the river, power generation water, and other stakeholders, and the conflicts regarding water use are thus more prominent. Therefore, in order to alleviate the shortage in the ecological flow and meet the water demands of various stakeholders, it is necessary to carry out research on the multi-stakeholder coordinated operation of Baojixia Reservoir.

3. Multi-Stakeholder Interval Coordination Mechanism

It is difficult in multi-stakeholder coordinated operation to meet the original engineering task and the new task of serving the ecology, coordinate the conflicts among the old and new stakeholders, and achieve a balance of interests. This paper proposes the multi-stakeholder interval coordination mechanism (MSICM) of reservoir operation, as shown in Figure 2. Firstly, water use characteristics of various stakeholders are analyzed to clarify the demands of stakeholders. Secondly, according to the relationship among water use, cost, and benefit, the water demand processes of various stakeholders are divided into the basic interval and the game interval. The basic interval is the basic water demand of stakeholders, which represents the basic benefits of stakeholders and should be met first. The game interval represents the water demand that can provide additional benefits to the stakeholders and should be an aim. Thirdly, on the premise of ensuring the basic water demand of all stakeholders, the game interval is regarded as the feasible region of ecological operation for each stakeholder. The alternative scheme set is obtained in the game interval. Finally, the coordination scheme is found in the scheme set. The specific implementation steps are as follows:

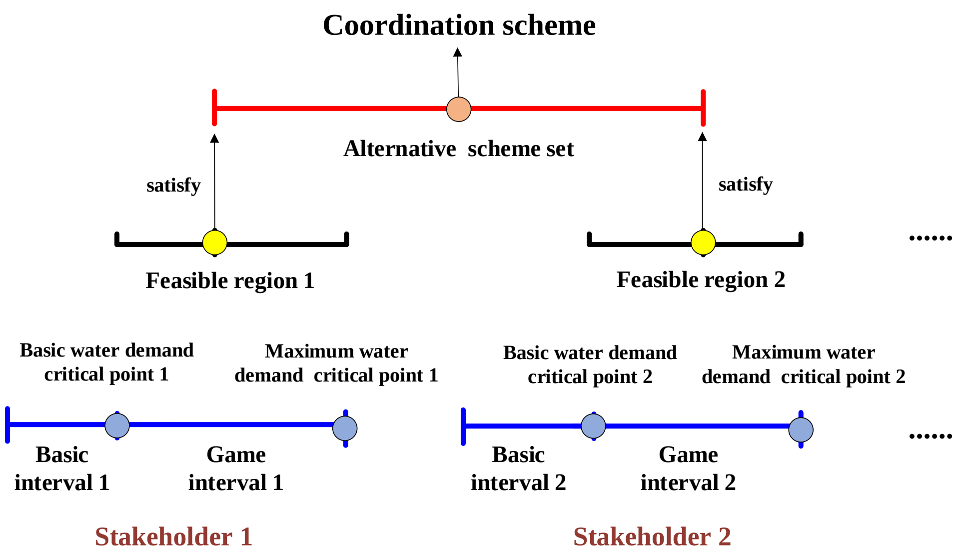


Figure 2. Sketch map of the multi-stakeholder interval coordination mechanism.

(1) Define the basic water demand critical point $Q^n_{min,\ t}$ and maximum water demand critical point $Q^n_{max,\ t}$ of each stakeholder, where $n = 1, 2, \ldots, m; t = 1, 2, \ldots T$, m represents the total number of stakeholders, T. represents the total number of operation periods. Determine the basic interval and the game interval of each multi-stakeholder as follows: $[0,\ Q^n_{min,\ t}]$ and $(Q^n_{min,\ t},\ Q^n_{max,\ t}]$. The sum of the basic intervals of all stakeholders is $[0,\ Q_{min,\ t}]$, where $Q_{min,\ t} = Q^1_{min,\ t} + Q^2_{min,\ t} + \ldots + Q^m_{min,\ t}$. The sum of the game intervals of all stakeholders is $(Q_{min,\ t},\ Q_{max,\ t}]$, where $Q_{max,\ t} = Q^1_{max,\ t} + Q^2_{max,\ t} + \ldots + Q^m_{max,\ t}$. It should be noted that when there is reuse of water among stakeholders, the largest value is taken when determining the boundary.

(2) Determine the water use priorities of all stakeholders in the basic interval and game interval, and compare the inflow of the reservoir I_t. with $Q_{min,\ t}$. and $Q_{max,\ t}$ in each period. If $0 \leq I_t \leq Q_{min,\ t}$, the water is supplied according to the water use priorities of stakeholders in the basic interval. If $Q_{min,\ t} < I_t \leq Q_{max,\ t}$, the water demand of each stakeholder in the basic interval is guaranteed first, then the alternative scheme set is obtained by constructing a model and optimization algorithm in the game interval. Finally, the best coordination scheme is selected in the scheme set.

In order to realize the above MSICM for reservoir operation, in this study, the MSCOM was constructed and the MSIC-NSGA-II-SEABODE algorithm was used to obtain the coordination scheme. The coordinated operation method was compared with the traditional optimal operation method to verify the scientific validity and feasibility of the proposed method.

4. Multi-Stakeholder Coordinated Operation Model and Solving Algorithm

4.1. Model Construction

4.1.1. Objective Functions

The coordinated operation of Baojixia Reservoir needs to consider multiple stakeholders, such as the irrigation water, ecological water of the downstream river, power generation water, and flood control. The flood control objective can be met by converting the upper limit of the flood control level into a constraint condition. Power generation water diversion is entirely consistent with irrigation water diversion and the ecological water of the downstream river. The irrigation water and ecological water are the two main stakeholders for which an MSCOM must be established. Therefore, in this paper, the maximum irrigation benefits and the minimum amended annual proportion flow deviation (ecological AAPFD value) were selected as the objective functions of multi-stakeholder coordinated operation for Baojixia Reservoir.

(1) Maximum irrigation benefits:

$$maxY = max\left[f(\sum_{t=1}^{T} W_t)\right],\ t = 1,\ 2,\ \cdots,\ T \tag{1}$$

where Y represents the total irrigation benefits during the operation periods; W_t is the irrigation water volume during each period; and $f(\sum_{t=1}^{T} W_t)$ is the relationship between irrigation water volume and irrigation benefit. According to the research results of the literature [45], without considering the total power of agricultural machinery, agricultural employees, and the amount of converted fertilizer application, the relationship between irrigation benefits and the irrigation water volume in Baojixia irrigation district is as follows:

$$f\left(\sum_{t=1}^{T} W_t\right) = 7.16 \times (\sum_{t=1}^{T} W_t)^{0.087} \tag{2}$$

(2) Maximum ecological benefits, that is, the minimum ecological AAPFD value. The ecological AAPFD value proposed by Ladson et al. [46] means that the smaller the ecological AAPFD value, the better the river eco-environment and the greater the ecological benefits. The calculation formula is as follows:

$$minR = min\left[\sum_{t=1}^{T}\left(\frac{Q_t - Q_t^n}{\overline{Q_t^n}}\right)^2\right]^{0.5},\ t = 1,\ 2,\ \cdots,\ T \tag{3}$$

where R is the minimum ecological AAPFD value; Q_t is the outflow of the reservoir after operation during each period; Q_t^n is the natural inflow during each period; and $\overline{Q_t^n}$ is the average of the natural inflow during the operation period.

4.1.2. Constraints

(1) Water balance constraint:

$$V_{t+1} = V_t + (I_t - Q_t)\Delta t \tag{4}$$

where V_{t+1} and V_t are the final and initial reservoir storage during each period Δt, respectively; I_t is the inflow of the reservoir during each period Δt; and Q_t is the outflow of the reservoir during each period Δt.

(2) Water level constraint:

$$Z_{t,\ min} \le Z_t \le Z_{t,\ max}. \tag{5}$$

where $Z_{t,\ min}$ and $Z_{t,\ max}$ are the lower and upper limits of water levels allowed to be stored during each period.

(3) Water diversion flow constraint:

$$0 \le Q_{I,\ t} \le Q_{I,\ max} \tag{6}$$

where $Q_{I,\ t}$ is the water diversion flow for irrigation during each period; and $Q_{I,\ max}$ is the maximum water diversion flow for irrigation.

(4) Power output constraint:

$$N_{min} \le N_t \le N_{max} \tag{7}$$

where N_t is the power output during each period; and N_{min} and N_{max} are the minimum and maximum power output during each period, respectively.

(5) Flow constraint passing through the hydro turbine:

$$Q^f_{min} \le Q^f_t \le Q^f_{max} \tag{8}$$

where Q^f_t is the flow passing through the hydro turbine during each period; and Q^f_{min} are the minimum and maximum flow passing through the hydraulic turbine, respectively.

(6) Water quantity constraint of the basic interval:

$$0 \le I_t \le Q_{min,\ t} \tag{9}$$

$$Q_{min,\ t} = Q^I_{min,\ t} + Q^E_{min,\ t} \tag{10}$$

where $Q^I_{min,\ t}$ and $Q^E_{min,\ t}$ are the basic irrigation water demand and the basic ecological water demand during each period, respectively; and $Q_{min,\ t}$ is the sum of $Q^I_{min,\ t}$ and $Q^E_{min,\ t}$.

(7) Water quantity constraint of the game interval:

$$Q_{min,\ t} < I_t \le Q_{max,\ t} \tag{11}$$

$$Q_{max,\ t} = Q^I_{max,\ t} + Q^E_{max,\ t} \tag{12}$$

where $Q^I_{max,\ t}$ and $Q^E_{max,\ t}$ are the maximum irrigation water demand and the maximum ecological water demand during each period, respectively; and $Q_{max,\ t}$ is the sum of $Q^I_{max,\ t}$ and $Q^E_{max,\ t}$.

(8) All variables above are positive.

4.2. Solving Algorithm

4.2.1. MSIC-NSGA-II-SEABODE

With the above model and constraints, the appropriate algorithm was applied to solve the MSCOR problem. In this study, the MSIC, NSGA-II, and SEABODE were coupled to establish an MSIC-NSGA-II-SEABODE algorithm for the MSCOR problem. The general idea of the algorithm is as follows: In the initialization stage, the data, parameters, and studied problem are input. According to the MSICM, the interest demands of all stakeholders are comprehensively considered and the interval boundaries of each stakeholder are determined so as to obtain the basic interval and the game interval. The MSCOM is constructed, and the NSGA-II is used to obtain the Pareto solution set (or alternative scheme set) in the game interval. Then, the approach of SEABODE is used to sort, eliminate, and select the alternative scheme set. The stopping criterion is finally satisfied and the coordination scheme is obtained. The specific processes are shown in Figure 3.

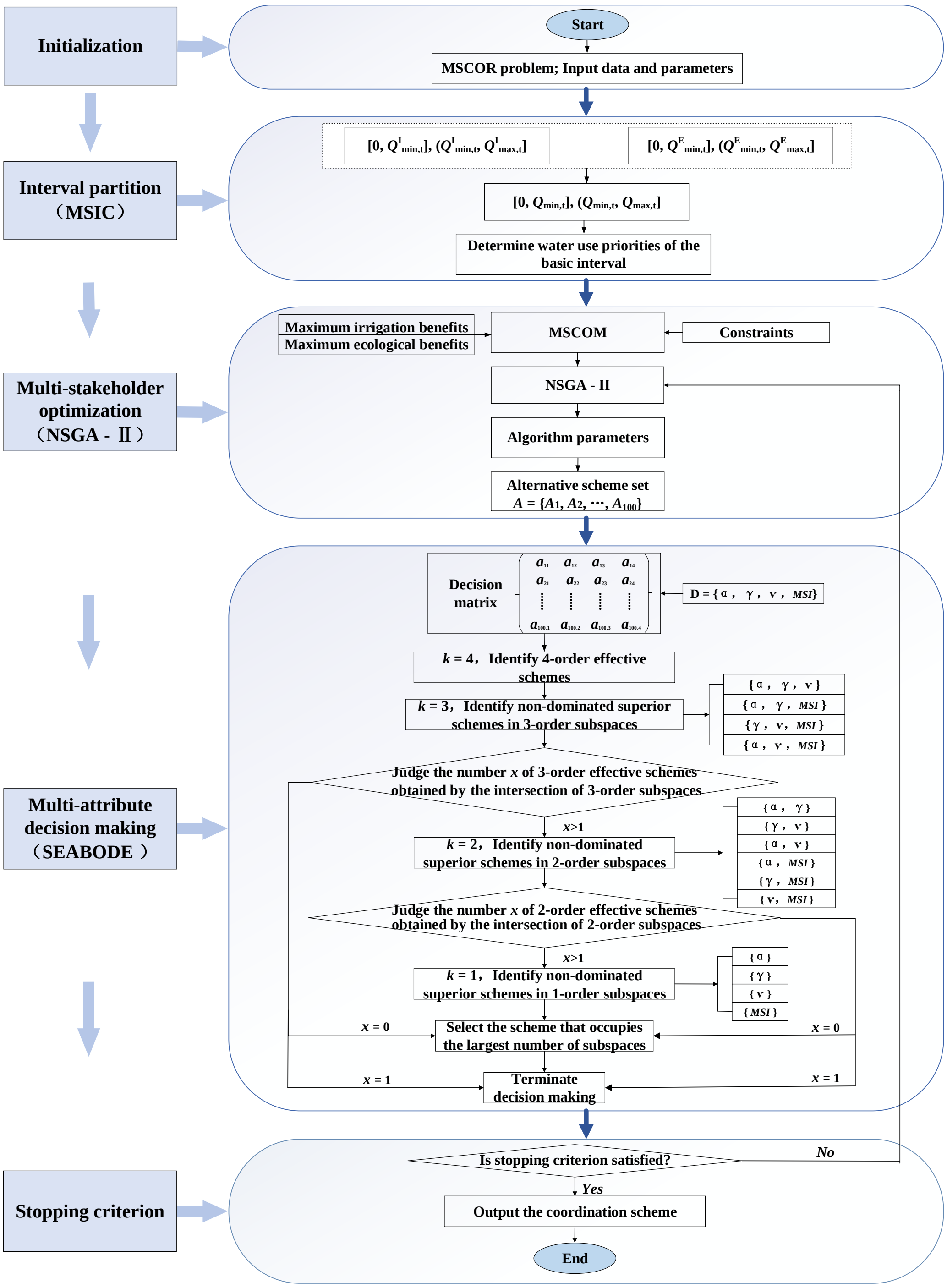


Figure 3. Simplified flow chart of MSIC-NSGA-II-SEABODE algorithm.

4.2.2. Application of MSIC-NSGA-II-SEABODE for the MSCOR Problem

The MSIC-NSGA-II-SEABODE algorithm was applied to the MSCOR problem of Baojixia Reservoir, and the established functions and constraints of the MSCOR problem were added into the algorithm. The coordinated operation calculation was carried out for a normal year, dry year, and extraordinary dry year. The basic parameters of the algorithm were set as follows: the population size is N; the maximum number of iterations, $Maxgen$, is 1000; the crossover probability is pc; the mutation probability is pm; the crossover distribution index is η_c; the mutation distribution index is η_m; and 36 ten-day operation periods are used. Taking water levels as the decision variables, N individuals are randomly generated within the feasible ranges of water levels (upper and lower limits of water levels). A series of steps, mainly including interval partition, multi-stakeholder optimization, and multi-attribute decision making, is repeated, until the stopping criterion is satisfied. The specific steps are shown in Algorithm 1.

Algorithm 1: MSIC-NSGA-II-SEABODE

Input: The MSCOR problem, constraints, decision variables (water levels), population size N, maximum iteration times $Maxgen$, crossover probability pc, mutation probability pm, cross distribution index η_c, mutation distribution index η_m.
Output: $\{X^1, \cdots, X^N\}$ and $\{S^1, \cdots, S^N\}$ ← Final water levels and decision-making scheme.
Step 1: Initialization
1.1 Set parameters: N = 100, $Maxgen$ = 1000, pc = 0.9, pm = 0.08, η_c = 20, η_m = 20, Gen = 0;
1.2 $\{X^1, \cdots, X^N\}$ ← Initialization population randomly;
Step 2: Interval partition (MSIC)
2.1 Analyze the water use characteristics of stakeholders and clarify the demands of stakeholders;
2.2 $[0,\ Q^I{}_{min,\ t}]$ and $\left(Q^I{}_{min,\ t},\ Q^I{}_{max,\ t}\right]$ ← Determine basic interval and game interval of irrigation water demand;
2.3 $[0,\ Q^E{}_{min,\ t}.]$ and $\left(Q^E{}_{min,\ t},\ Q^E{}_{max,\ t}\right]$ ← Determine basic interval and game interval of ecological water demand;
2.4 $[0, Q_{min,\ t}]$ and $\left(Q_{min,\ t},\ Q_{max,\ t}\right]$ ← $Q_{max,\ t} = Q^I_{max,\ t} + Q^E_{max,\ t}$ and $Q_{min,\ t} = Q^I_{min,\ t} + Q^E_{min,\ t}$;
2.5 Priorities of water use in basic interval: Ecology → Irrigation;
Step 3: Multi-stakeholder optimization (NSGA-II)
3.1 Construct the MSCOM according to objective functions and constraints;
3.2 If $0 \le I_t \le Q_{min,\ t}$, water is supplied according to the water use priorities of basic interval;
else if $Q_{min,\ t} < I_t \le Q_{max,\ t}$, water demand of each stakeholder in basic interval is guaranteed first, then the alternative scheme set $A = \{A_{1,} A_{2,} \cdots A_{100}\}$ is obtained by NSGA-II;
Step 4: Multi-attribute decision making (SEABODE)
4.1 $D = \{\alpha,\ \gamma,\ \nu,\ MSI\}$ ← Establish decision-making space with 4-dimensional attributes;
4.2 k = 4, identify 4-order effective schemes;
4.3 k = k−1, identify non-dominated superior schemes in (k−1)-order subspaces; then identify the number x of (k−1)-order effective schemes obtained by the intersection of (k−1)-order subspaces;
4.4 If x > 1, go to Step 3.3;
else if x = 1, the scheme is directly output as the final decision-making scheme $\{S^1, \cdots, S^N\}$;
else x = 0, then the scheme that occupies the largest number of subspaces is selected.
4.5 Terminate decision making.
Step 5: Stopping criteria
If the stopping criterion is satisfied, stop; else go to Step 3.

4.2.3. Evaluation Indexes Selection

In this study, the reliability, recoverability, water shortage depth, and water shortage index were selected to construct the decision-making space with 4-dimensional attributes for the evaluation of reservoir operation schemes. The SEABODE method was used to evaluate 100 schemes of the Pareto solution sets in different typical years, and the coordination scheme was obtained. The calculation method of each index is as follows:

(1) Reliability (α). This index represents the ratio of the number of periods meeting the basic demand of irrigation water to the total number of periods during the reservoir

operation period, reflecting the guaranteed degree of irrigation water. The calculation formula is as follows:

$$\alpha = \frac{\sum_{t=1}^{r} K_t}{T} \quad (13)$$

where K_t is the discriminant coefficient of whether the outflow of the reservoir meets the basic demand of irrigation water during each period. When $Q_t \geq Q^I_{min,\ t}$, $K_t = 1$; otherwise, $K_t = 0$.

(2) Recoverability (γ). This index indicates the average probability of the reservoir recovering from the failure state ($Q_t < Q^I_{min,\ t}$) to the normal state during the reservoir operation period. The calculation formula is as follows:

$$\gamma = \frac{\sum_{t=1}^{T} (K_{t+1} = 1 | K_t = 0)}{T - \sum_{t=1}^{T} K_{t+1}} \quad (14)$$

(3) Water shortage depth (ν). This index represents the maximum of the ecological relative water shortage degree in a single period during the reservoir operation period. The calculation formula is as follows:

$$\nu = \max(DR_1,\ DR_2,\ \cdots,\ DR_t),\ DR_t = 1 - \frac{Q^E_{s,\ t}}{Q^E_{max,\ t}} \quad (15)$$

where DR_t is the ecological relative water shortage degree during each period.

(4) Water shortage index (WSI). The index indicates the degree of loss of reservoir ecological benefit. The calculation formula is as follows:

$$WSI = \frac{100}{T} \sum_{t=1}^{T} {DR_t}^2 \quad (16)$$

Among the above four indicators, reliability (α) and recoverability (γ) are maximization-type indexes: the larger the value, the better; water shortage depth (ν) and water shortage index (WSI) are minimization type indexes: the smaller the value, the better.

5. Results and Discussion

5.1. Model and Algorithm Application

A total time span of 36 ten-day periods was selected. The operation period was from Jul. to Jun. the following year. The inflow data were selected as a normal year (50% inflow frequency), dry year (75% inflow frequency), and extraordinary dry year (90% inflow frequency).

The application processes of the model and algorithm are shown in Figure 4. The basic parameters of the reservoir, hydropower station, and inflow data are input. In the study, the coordinated operation method proposed in this paper was compared with the traditional optimal operation method. The former uses a multi-stakeholder coordinated operation model, whereas the latter uses a multi-stakeholder optimal operation model, both of which have the same objective functions, namely, to maximize irrigation benefits and ecological benefits. The traditional optimal operation method does not consider the interval coordination, and does not need to divide the water demand processes of the stakeholders into the basic interval and the game interval. Therefore, it is not affected by the interval boundary constraints. The traditional optimal operation uses the NSGA-II-SEABODE algorithm to solve the optimal operation model to obtain the optimization scheme, and the coordinated operation method uses the MSIC-NSGA-II-SEABODE algorithm to solve the coordinated operation model to obtain the coordination scheme. The algorithm parameters are set; in this study, the two algorithms used the same parameters. Among these, the population size, N, is 100; the maximum number of iterations, $Maxgen$, is 1000; the crossover probability, pc, is 0.9; the mutation probability, pm, is 0.08; the crossover distribution index, η_c, is 20; and the mutation distribution index, η_m, is 20. Both algorithms contain 37 decision variables, namely, the 37 water level values of the reservoir, for the 36 time periods. Then, the final results are obtained until the stop condition is reached. The results of the coordinated operation method were compared with the results of the traditional optimal operation method. The results include the Pareto solution sets, the variable values, the evaluation indexes, and the comparison results.

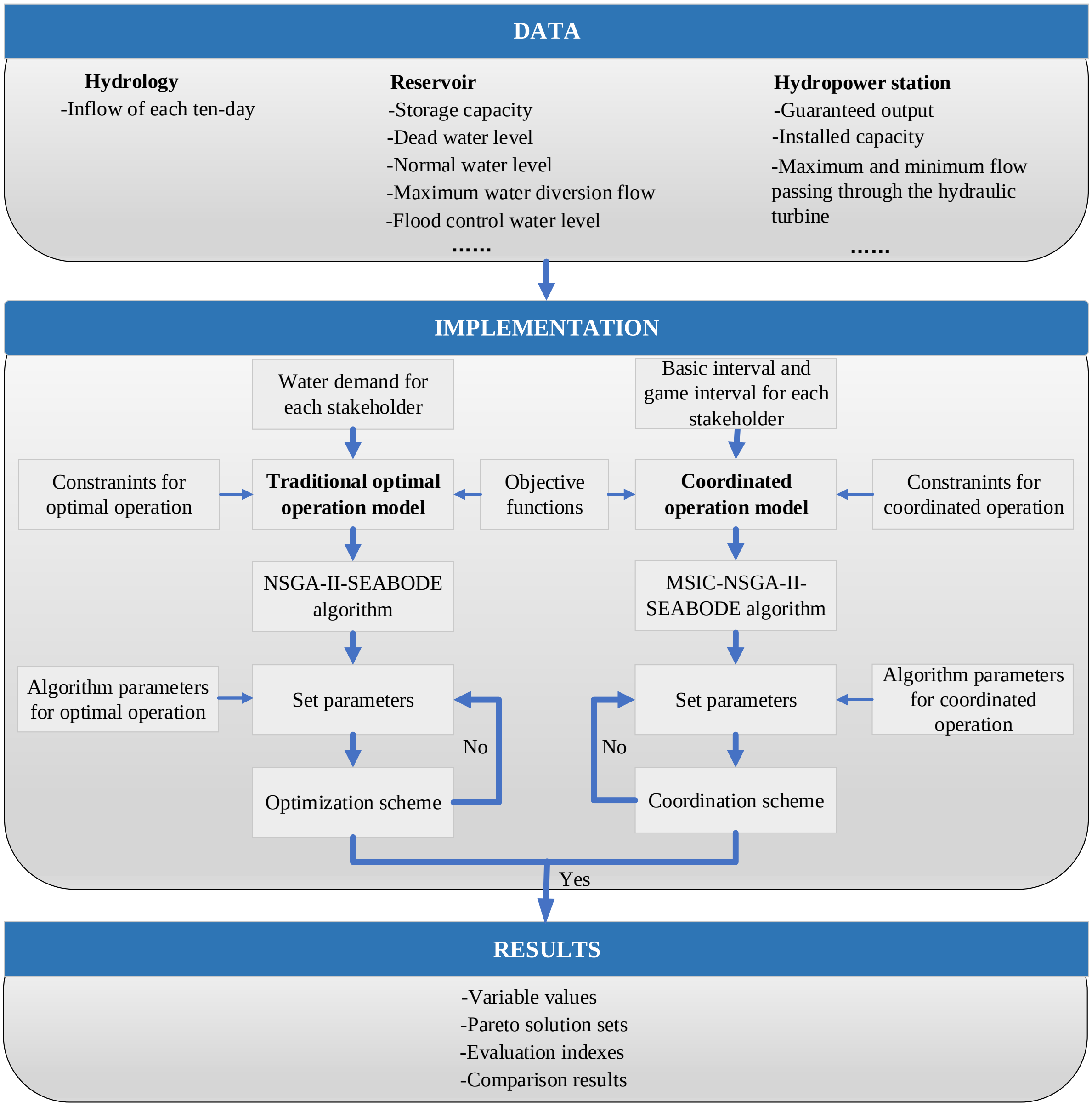


Figure 4. Application processes of models and algorithms.

5.2. Interval Partition of Multi-Stakeholder

According to the literature [43], the interval boundaries of water demand of Baojixia irrigation district and the ecological water demand of the downstream Linjiacun Section were determined. The basic and maximum irrigation water demand processes for Baojixia irrigation district in 2020 are shown in Figure 5, corresponding to the upper limit of the basic interval and the upper limit of the game interval, respectively. The basic irrigation water demand in a normal year, dry year, and extraordinary dry year was 1.798×10^8, 2.675×10^8, and 3.129×10^8 m^3, respectively. The maximum irrigation water demand was 4.137×10^8, 7.806×10^8, and 9.547×10^8 m^3, respectively. In this study, the ecological water demand mainly considered the ecological base flow. Table 1 shows the basic and maximum ecological base flow of Linjiacun Section, corresponding to the upper limit of the basic interval and the upper limit of the game interval, respectively. The power generation water diversion of Baojixia hydropower station was completely consistent with the irrigation water diversion and the ecological water use of the downstream river.

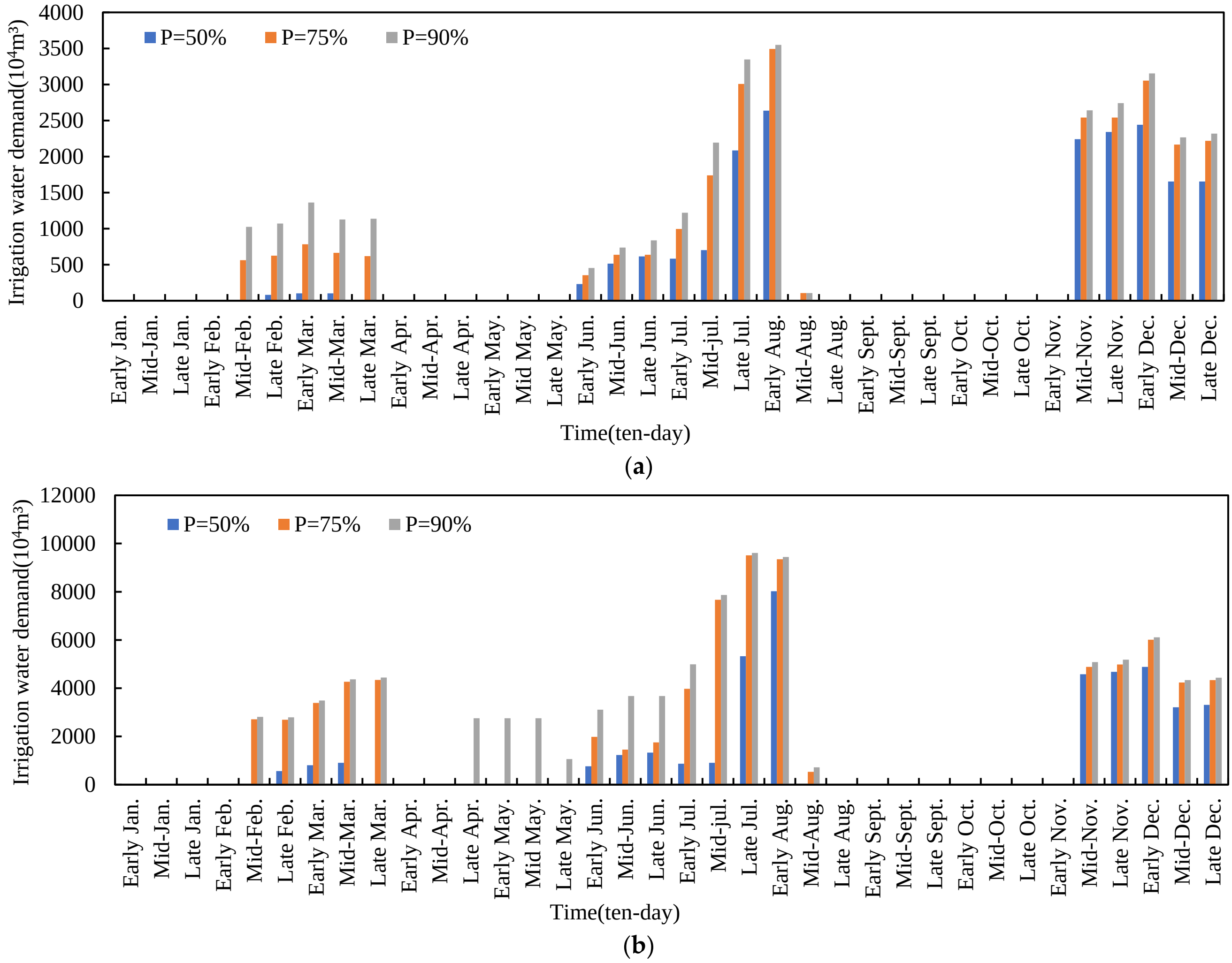


Figure 5. Irrigation water demand processes for different typical years: (**a**) basic irrigation water demand; (**b**) maximum irrigation water demand.

Table 1. Basic and maximum ecological base flow of Linjiacun Section (m^3/s).

Ecological Base Flow	Months											
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Basic ecological base flow	2.24	2.39	3.27	4.38	5.57	5.63	9.99	10.45	11.88	9.11	4.79	2.70
Maximum ecological base flow	8.28	8.72	11	13.74	20.99	21.85	41.48	39.15	37.87	35.16	15.59	8.84

5.3. Model Solving

In this section, the coordinated operation method is taken as an example and the solution processes of the coordination scheme are presented. The Pareto solution set of irrigation benefits and the ecological AAPFD value for different typical years were obtained by the MSIC-NSGA-II-SEABODE algorithm, as shown in Figure 6. It can be seen that there was a significant positive correlation between irrigation benefits and the ecological AAPFD value. Conversely, the smaller the ecological AAPFD value, the greater the ecological benefit; that is, there was a significant negative correlation between irrigation benefits and ecological benefits, which further illustrates the conflict between the two objectives. In addition, with the increase in natural inflow, the irrigation benefits and ecological benefits also increased. For example, the maximum irrigation benefits and minimum ecological AAPFD value in an extraordinary dry year were CNY 7.831 × 10^8 and 1.512, respectively, whereas the corresponding values in a normal year were CNY 7.957 × 10^8 and 0.800, respectively. The irrigation benefits increased by CNY 0.126 × 10^8 and the ecological AAPFD value decreased by 0.712, indicating that the amount of natural inflow had a significant impact on the benefits of the reservoir. In the Pareto solution set of three typical years, the range of the ecological AAPFD value was greater than that of the irrigation benefit, indicating that the ecological objective was very sensitive to the irrigation objective. As a result, the staff are required to comprehensively consider and weigh the advantages and disadvantages of the two during actual operation, so as to achieve the balance between irrigation benefits and ecological benefits.

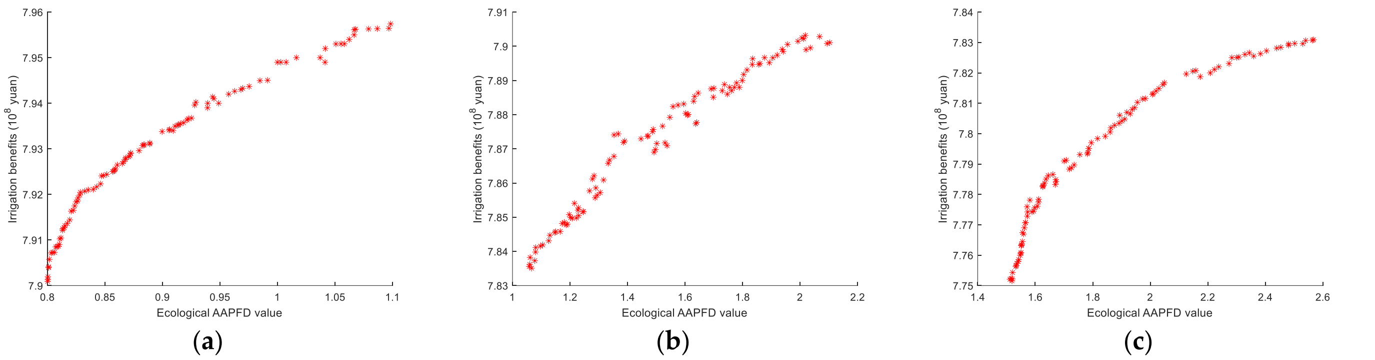


Figure 6. Pareto solution sets for different typical years: (**a**) normal year; (**b**) dry year; (**c**) extraordinary dry year.

The Pareto solution sets obtained in different typical years were used as the alternative scheme sets of multi-attribute decision making, in which the scheme set in a normal year was recorded as A = $\{A_1, A_2, \cdots, A_{100}\}$, the scheme set in a dry year was recorded as B = $\{B_1, B_2, \cdots, B_{100}\}$, and the scheme set in an extraordinary dry year was recorded as C = $\{C_1, C_2, \cdots, C_{100}\}$. The decision matrixes of scheme sets in different typical years were constructed. Table 2 shows the statistical results of four-dimensional evaluation indexes for different scheme sets. It can be seen that there were differences in the four-dimensional evaluation indexes of scheme sets in different typical years. Therefore, the approach of SEABODE was used to sort, select, and eliminate each scheme set to determine the final coordination scheme.

Table 2. Statistical results of 4-dimensional evaluation indexes for different scheme sets.

Scheme Sets		α	γ	ν	*WSI*
A	Variation range	[0.888, 0.996]	[0.250, 0.429]	[0.395, 0.741]	[9.917, 11.195]
	Standard deviation	0.016	0.088	0.146	0.253
B	Variation range	[0.617, 0.772]	[0.151, 0.398]	[0.667, 0.998]	[27.205, 33.788]
	Standard deviation	0.037	0.107	0.165	1.518
C	Variation range	[0.614, 0.695]	[0.167, 0.286]	[0.767, 0.999]	[38.652, 44.668]
	Standard deviation	0.039	0.035	0.108	1.324

The number of 4-order effective schemes, non-dominated superior schemes in 3-order subspaces, and 3-order effective schemes of each scheme set is shown in Table 3. When k = 4, the number of 4-order effective schemes for different typical years is 34, 8, and 6, as achieved by sorting the schemes of scheme set A, B, and C in the first round. This reduced the preferred range of schemes by 66%, 92%, and 94% respectively, and greatly reduced the number of alternative schemes. When k = 3, the 4-order effective scheme set was sorted in the second round; that is, the non-dominated superior schemes in 3-order subspaces were obtained from the 4-order effective scheme sets. Then, the number of 3-order effective schemes obtained by the intersection of 3-order subspaces was 25, 2, and 2, respectively. At this time, the third-round sorting of the 3-order effective scheme sets of the scheme sets A, B, and C was also needed.

Table 3. Number of 4-order and 3-order effective schemes for different scheme sets.

Scheme Sets	{1-2-3-4}	{1-2-3}	{1-2-4}	{1-3-4}	{2-3-4}	Number of 3-Order Effective Schemes
A	34	30	28	29	30	25
B	8	6	5	7	4	2
C	6	3	5	4	2	2

Note: 1—a, 2—γ, 3—ν, 4—MSI

Table 4 shows that that the final coordination schemes after the third round of sorting in a normal year (corresponding to scheme set A), dry year (corresponding to scheme set B), and extraordinary dry year (corresponding to scheme set C) were A_{70}, B_{16}, and C_{11}, respectively. It can be seen that the evaluation indexes varied greatly in different typical years. With the decrease in natural inflow, the reliability α and recoverability γ decreased, and water shortage depth ν and water shortage index MSI increased. The reliability α in a normal year was 0.996, which meant that the demand for irrigation water could be met in 36 ten-day periods of the year. However, the reliability α in a dry year and extraordinary dry year were 0.722 and 0.694, and were reduced by 0.274 and 0.302, respectively, compared with a normal year, which meant that the demand for irrigation water could only be met for 25 to 26 ten-day periods of the year, and the irrigation water in other periods was affected to varying degrees. Recoverability γ in a normal year increased by an average of 0.164 compared with that in a dry year and an extraordinary dry year. The water shortage depth ν in a normal year decreased by an average of 0.312 compared with that in a dry year and an extraordinary dry year. The water shortage index MSI in a normal year decreased by an average of 23.252 compared with that in a dry year and an extremely dry year. On the whole, the evaluation indexes of coordinated operation results in a normal year were better than those in dry and extraordinary dry years.

Table 4. Coordination schemes for different typical years.

Typical Years	Scheme Number	Evaluation Indexes			
		α	γ	ν	MSI
Normal year	A_{70}	0.996	0.413	0.427	10.013
Dry year	B_{16}	0.722	0.331	0.697	27.205
Extraordinary dry year	C_{11}	0.694	0.167	0.781	39.324

5.4. Comparative Analysis

In order to verify the effectiveness of the method described in this paper, the final decision-making schemes obtained by the coordinated operation method and traditional optimal operation method of Baojixia Reservoir were compared and analyzed. Table 5 shows the results of traditional optimal operation and coordinated operation for different typical years. It can be seen that the irrigation benefits and ecological benefits decreased with the decrease in natural inflow under the two operation methods. There was obvious conflict between irrigation benefits and ecological benefits. The irrigation benefits of traditional optimal operation were greater than those of coordinated operation, with an increase of CNY 0.031×10^8, CNY 0.052×10^8, and CNY 0.105×10^8 in a normal year, dry year, and extraordinary dry year, respectively. However, the ecological AAPFD value of coordinated operation was less than that of traditional optimal operation, with a decrease of 0.184, 0.469, and 0.886 in a normal year, dry year, and extraordinary dry year, respectively. That is, the river eco-environment of coordinated operation was better than that of traditional optimal operation. Moreover, with the decrease in natural inflow, the difference between the two was larger; that is, the effect of coordinated operation on balancing various stakeholders was more obvious.

Table 5. Results of traditional optimal operation and coordinated operation for different typical years.

Methods	Normal Year		Dry Year		Extraordinary Dry Year	
	Irrigation Benefits /(CNY 10^8)	Ecological AAPFD Value	Irrigation Benefits /(CNY 10^8)	Ecological AAPFD Value	Irrigation Benefits /(CNY 10^8)	Ecological AAPFD Value
Traditional optimal operation	7.95	1.147	7.906	1.642	7.857	2.405
Coordinated operation	7.919	0.963	7.854	1.173	7.752	1.519

Figure 7 shows the irrigation and ecological water supply processes of two operation methods in a normal year. It can be seen from Figure 7a that the satisfaction degree of irrigation water demand of the two operation methods was basically the same. Both methods could meet the basic irrigation water demand in all periods. The maximum irrigation water demand could be met by both methods, except in Jun., late Jul., early Aug., mid-late Nov., and Dec. It can be seen from Figure 7b that the coordinated operation performed better in terms of the satisfaction degree of the ecological base flow. The coordinated operation could meet the basic ecological base flow in all periods, whereas the traditional optimal operation failed to meet the demand in eight ten-day periods, mainly during the non-flood season. The coordinated operation failed to meet the maximum ecological base flow in nine ten-day periods, whereas the traditional optimal operation failed to meet the demand in 13 ten-day periods, both of which mainly occurred during the non-flood season.

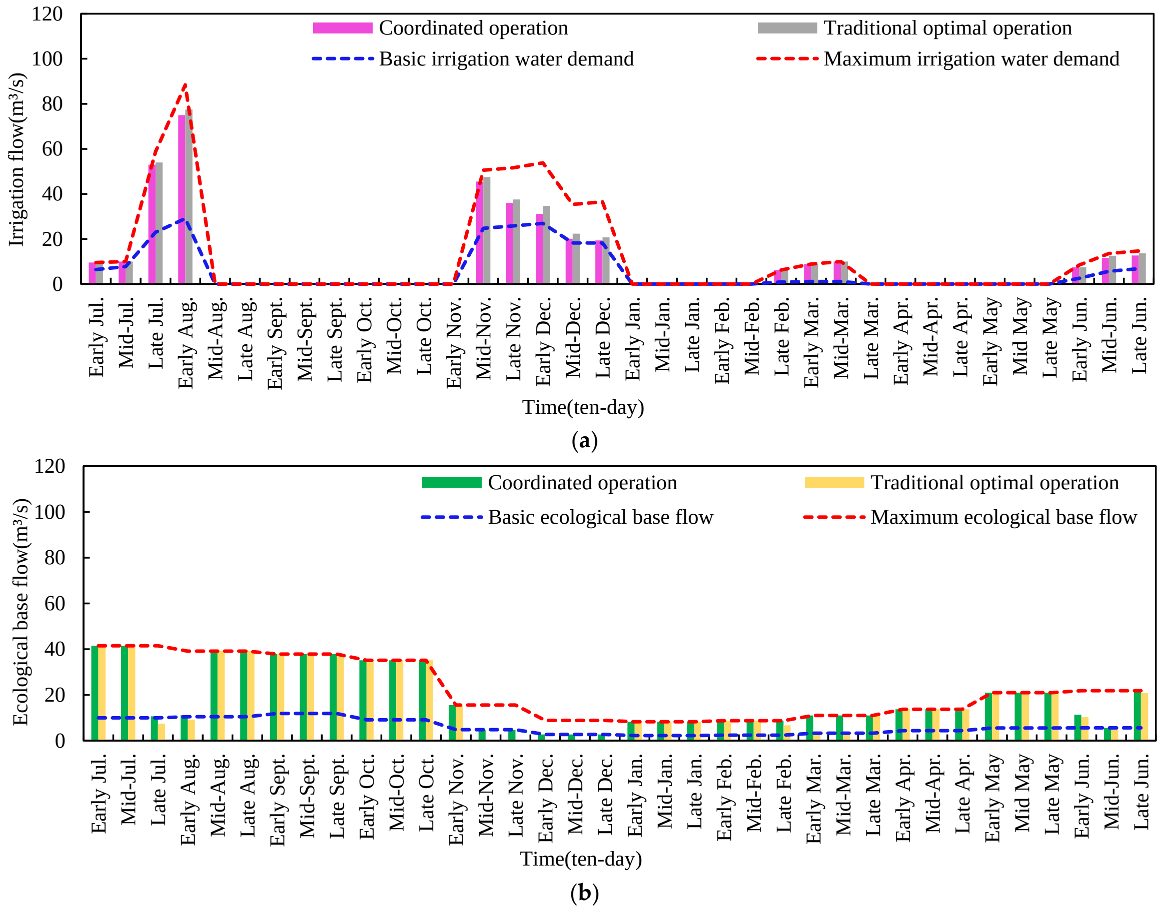


Figure 7. Irrigation and ecological water supply processes of two operation methods in a normal year: (**a**) irrigation; (**b**) ecology.

Figure 8 shows the irrigation and ecological water supply processes of two operation methods in a dry year. It can be seen from Figure 8a that the satisfaction degree of basic irrigation water demand of the two operation methods was basically the same, and the satisfaction degree of maximum irrigation water demand of the traditional optimal operation was slightly better. The basic irrigation water demand could be met by both methods, except in mid-late Feb., Mar., mid-late Nov., and Dec. of the non-flood season. The coordinated operation failed to meet the maximum irrigation water demand in 18 ten-day periods, whereas the traditional optimal operation failed to meet the demand in 16 ten-day periods, both of which mainly occurred in the non-flood season. It can be seen from Figure 8b that the satisfaction degree of the ecological base flow of the coordinated operation was better. The coordinated operation could meet the basic ecological base flow in all periods, whereas the traditional optimal operation failed to meet the demand in 15 ten-day periods, mainly in the non-flood season. The coordinated operation failed to meet the maximum ecological base flow in 18 ten-day periods, whereas the traditional optimal operation failed to meet the demand in 22 ten-day periods, both of which mainly occurred in the non-flood season.

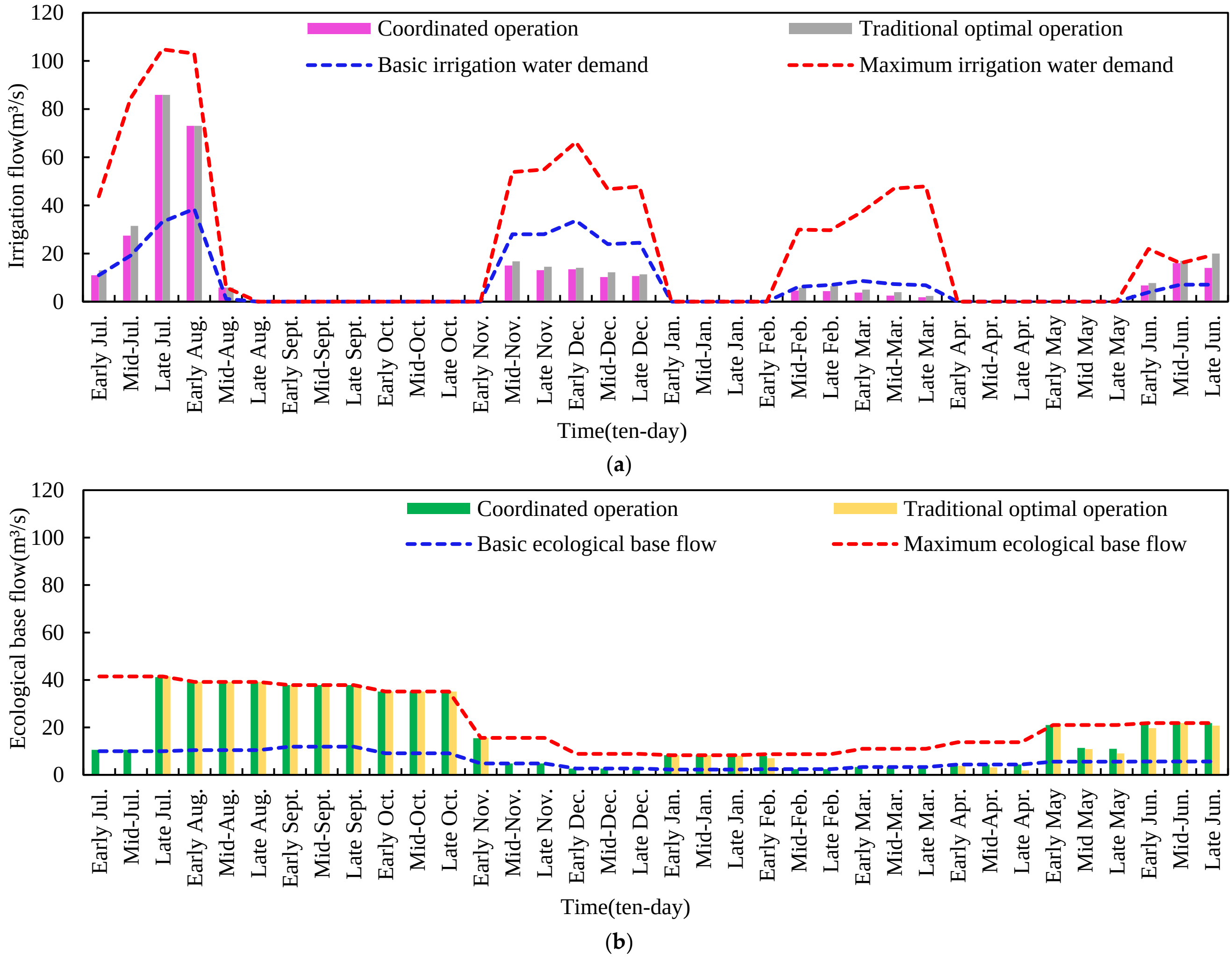
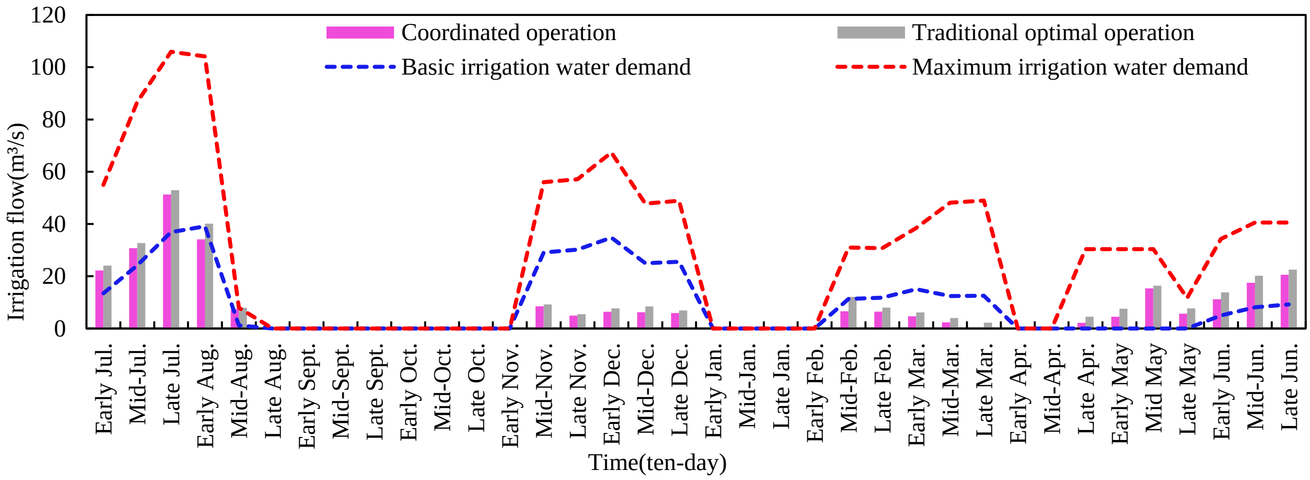
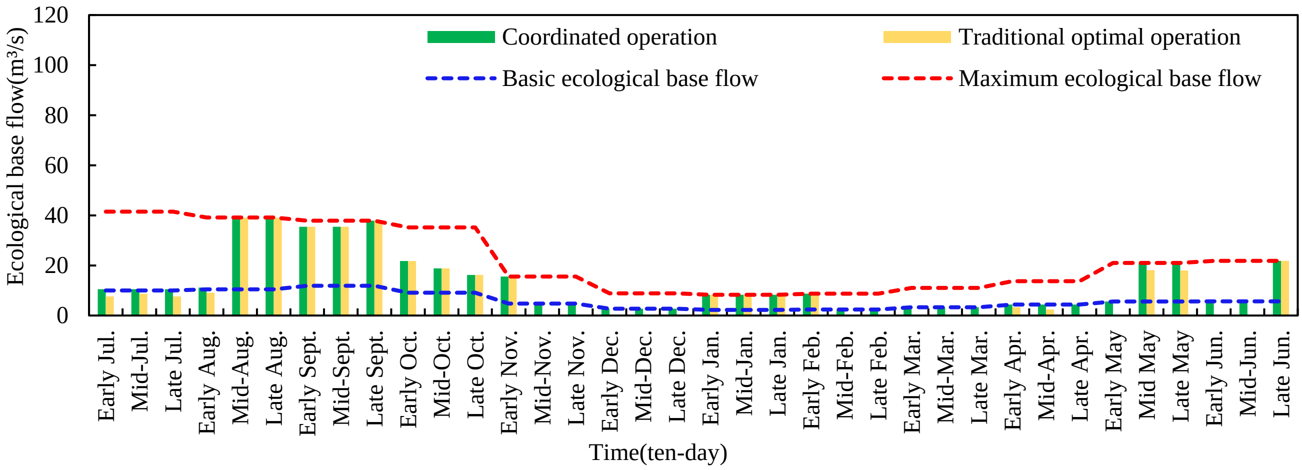


Figure 8. Irrigation and ecological water supply processes of two operation methods in a dry year: (**a**) irrigation; (**b**) ecology.

Figure 9 shows the irrigation and ecological water supply processes of two operation methods in an extraordinary dry year. In extraordinary dry years, due to the water shortage in the upper reaches of the Wei River, both stakeholders were affected. It can be seen from Figure 9a that the satisfaction degree of irrigation water demand in traditional optimal operation was slightly dominant. The coordinated operation failed to meet the basic irrigation water demand in 11 ten-day periods, whereas the traditional optimal operation failed to meet the demand in nine ten-day periods, both of which mainly occurred in the non-flood season. The coordinated operation failed to meet the maximum irrigation water demand in 22 ten-day periods, whereas the traditional optimal operation failed to meet the demand in 21 ten-day periods. The unsatisfied periods existed in both the flood season and the non-flood season. It can be seen from Figure 9b that the satisfaction degree of the ecological base flow of the coordinated operation had obvious advantages. The coordinated operation could meet the basic ecological base flow in all periods, whereas the traditional optimal operation failed to meet the demand in 20 ten-day periods, mainly concentrated in the non-flood season. The coordinated operation failed to meet the maximum ecological base flow in 25 ten-day periods, whereas the traditional optimal operation failed to meet the demand in 27 ten-day periods. The unsatisfied periods existed in both the flood season and the non-flood season.



(**a**)



(**b**)

Figure 9. Irrigation and ecological water supply processes of two operation methods in an extraordinary dry year: (**a**) irrigation; (**b**) ecology.

To summarize, for irrigation, the satisfaction degree of irrigation water demand of traditional optimal operation in different typical years was slightly dominant, but the basic irrigation water demand satisfaction degree of the two operation methods was basically the same. For ecology, the coordinated operation could meet the basic ecological water demand in each typical year, whereas the traditional optimal operation could not fully meet the demand.

In previous research, some studies did not consider the ecological water demand of the downstream river of Baojixia Reservoir [47,48]. Some studies carried out research on the optimal operation of Baojixia Reservoir with the maximum irrigation water supply (or minimum irrigation water shortage) as the objective and the ecological water demand as the constraint condition [49,50]. Another study [51] established a multi-objective optimal operation model for Baojixia Reservoir with the objectives of maximizing irrigation benefits and ecological benefits. Compared with the optimization scheme of the ecological flow-constrained optimal operation model, the irrigation benefits increased by 0.91% and 0.82% in a normal year and dry year, respectively, and decreased by 1.59% in an extraordinary dry year. The ecological AAPFD value decreased by 0.176 and 0.163 in a normal year and dry year, respectively, and increased by 0.325 in an extraordinary dry year. It can be seen that both irrigation and ecological benefits were improved in a normal year and dry year, whereas both were worse in an extraordinary dry year. In this study, we established the MSCOM for Baojixia Reservoir based on the MSICM. Compared with the optimization scheme of the traditional optimal operation model without considering the MSICM, the ecological AAPFD value decreased by 0.184, 0.469, and 0.886 in a normal year, dry year, and extraordinary dry year under the premise that the satisfaction degree of basic irrigation benefits was basically the same. It can be seen that, compared with the previous study [51], the multi-stakeholder coordinated operation of Baojixia Reservoir can effectively coordinate the balance of interests between irrigation and ecology. With the decrease in incoming water, the effect of coordinated operation on balancing the interests of various stakeholders was more obvious, which confirmed the rationality and feasibility of the method proposed in this paper.

6. Conclusions

Noteworthy problems exist in traditional ecological operation, including difficulty in coordinating a balance among interests of stakeholders and the poor operation scheme. This paper proposed a method of multi-stakeholder coordinated operation of reservoir. Taking Baojixia Reservoir as an example, the coordinated operation method was compared with the traditional optimal operation method. The following conclusions were obtained:

(1) The MSICM divides the water demand processes of the stakeholders into the basic interval and the game interval. The basic interval is used to protect the basic water demand of the stakeholders, which must be met first. The game interval can enable the stakeholders to obtain more benefits, which should be attempted. The MSICM is in line with the comprehensive, balanced, and sustainable principles.

(2) The coordination mechanism, model construction, multi-stakeholder optimization, and multi-attribute decision making are coupled in the construction of the MSCOM and solution algorithm. The coordination scheme can be selected from the feasible scheme set and provide a decision-making basis for managers.

(3) There is a competitive relationship between irrigation benefits and ecological benefits of Baojixia Reservoir. Compared with the traditional optimal operation method, it was found that the coordinated operation method can not only meet the basic irrigation benefits, but also take the basic ecological benefits into account, so that the interests of various stakeholders can be implemented in coordination.

Although some achievements were made in this study, due to the complexity of MSCOR problems, there are still many shortcomings, which should be further explored. The objects of the construction and management of reservoirs are diversified, involving many stakeholders. We will thus conduct interval partitioning for the water demand processes of different stakeholders, such as industry and households. Under limited water resources and the water source project scale, we will carry out research on multi-stakeholder coordinated operation of the reservoir group, so as to take full advantage of the ecological service potential of the reservoir group; the core of this is to build a multi-stakeholder interval coordination mechanism of the reservoir group. Furthermore, we will establish a multi-stakeholder coordination operation model of the reservoir group. The feasible scheme set will be obtained using the solution algorithm with high computational efficiency, and the coordination scheme will be selected by the multi-attribute decision-making method having strong optimization ability.

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References

1. Xu, Z.X.; Wu, W.; Yu, S.Y. Ecological baseflow: Progress and challenge. *J. Hydroelectr. Eng.* **2016**, *35*, 1–11.
2. Chen, Y.Y.; Mei, Y.D.; Cai, H.; Xu, X.F. Multi-objective optimal operation of key reservoirs in Ganjiang River oriented to power generation, water supply and ecology. *J. Hydraul. Eng.* **2018**, *49*, 628–638.
3. Ai, Y.D.; Ma, Z.Z.; Xie, X.M.; Huang, T.; Cheng, H.G. Optimization of ecological reservoir operation rules for a northern river in China: Balancing ecological and socio-economic water use. *Ecol. Indic.* **2022**, *138*, 108822. [CrossRef]
4. Tian, X.J.; Zhao, G.J.; Mu, X.M.; Zhang, P.F.; Tian, P.; Gao, P.; Sun, W.Y. Hydrologic alteration and possible underlying causes in the Wuding River. *Sci. Total Environ.* **2019**, *639*, 133556. [CrossRef] [PubMed]
5. Wang, M.J.; Du, Z.P.; Duan, Z.Z.; Yan, C.A.; Gao, W.; Liu, C.E. Estimating the eco-environmental water demand of a river and lake coupled ecosystem: A case study of Lake Dianchi Basin. *Acta Ecol. Sin.* **2021**, *41*, 1341–1348.
6. Karimi, S.; Salarijazi, M.; Ghorbani, K.; Heydari, M. Comparative assessment of environmental flow using hydrological methods of low flow indexes, Smakhtin, Tennant and flow duration curve. *Acta Geophys.* **2021**, *69*, 285–293. [CrossRef]
7. Sedighkia, M.; Datta, B.; Abdoli, A. Design of optimal environmental flow regime at downstream of reservoirs using wetted perimeter-optimization method. *J. Hydro-Environ. Res.* **2021**, *39*, 1–14. [CrossRef]
8. Prakasam, C.; Saravanan, R.; Varinder, S.K. Evaluation of environmental flow requirement using wetted perimeter method and GIS application for impact assessment. *Ecol. Indic.* **2021**, *121*, 107019. [CrossRef]
9. Fu, Y.C.; Leng, J.W.; Zhao, J.Y.; Na, Y.; Zou, Y.P.; Yu, B.J.; Fu, G.S.; Wu, W.Q. Quantitative calculation and optimized applications of ecological flow based on nature-based solutions. *J. Hydrol.* **2021**, *598*, 126261. [CrossRef]
10. Wang, R.L.; Huang, J.H.; Ge, L. Study on ecological flow in the lower Yellow River based on hydrological ecological response relationship of carp habitat in the Yellow River. *J. Hydraul. Eng.* **2020**, *51*, 1175–1187.
11. Wang, H.; Wang, H.; Hao, Z.C.; Wang, X.; Liu, M.; Wang, Y.L. Multi-objective assessment of the ecological flow requirement in the upper Yangtze national nature reserve in China using PHABSIM. *Water* **2018**, *10*, 326. [CrossRef]
12. Zhang, P.; Li, K.F.; Wu, Y.L.; Liu, Q.Y.; Zhao, P.X.; Li, Y. Analysis and restoration of an ecological flow regime during the *Coreius guichenoti* spawning period. *Ecol. Eng.* **2018**, *123*, 74–85. [CrossRef]
13. Li, Y. Research on Ecological Flow of Fish Spawning in Dam-Building River: Case Study on Jinpin Dahe Bay. Ph.D. Thesis, China Institute of Water Resources and Hydropower Research, Beijing, China, 2019.
14. Gao, X.S.; Liu, S.F.; Guan, S.; Chen, J.C.; Feng, P. Comprehensive reservoir operation based on ecological runoff assurance: Scheduling and application. *J. Yangtze River Sci. Res. Inst.* **2021**, *38*, 19–24.
15. Ren, K.; Liu, D.F.; Huang, Q.; Meng, X.M. Reservoir ecological operation based on stochastic flow duration curves. *J. Hydroelectr. Eng.* **2017**, *36*, 32–41.
16. Dai, L.Q.; Dai, H.C.; Li, W.; Tang, Z.Y.; Ren, Y.F.; Chang, M.Q. Optimal operation of cascade hydropower plants considering spawning of four major Chinese carps. *J. Hydroelectr. Eng.* **2022**, *41*, 21–30.
17. Xu, S.Q.; Su, X.; Xing, Z.X.; Wang, L.L.; Lu, H.J. Reservoir ecological operation model under condition of non-sufficient ecological constraints. *Trans. Chin. Soc. Agric. Mach.* **2017**, *48*, 190–197.
18. Zhang, H.; Chang, J.; Gao, C.; Wu, H.; Wang, Y.; Lei, K.; Zhang, L. Cascade hydropower plants operation considering comprehensive ecological water demands. *Energy Convers. Manag.* **2019**, *180*, 119–133. [CrossRef]
19. Zhang, D.Q.; Shen, C.Y.; Yu, G.R.; Zou, J. Optimal operation of reservoir ecological value based on the ecological service effect of instream flow. *Wuhan Univ. Eng. J. Wuhan Univ.* **2020**, *53*, 101–109 and 116.

20. Zhao, M.L. Study on Multi-Objective Optimal Operation of Cascade Hydropower Stations in the Main Stream of Heihe River. Ph.D. Thesis, Xi'an University of Technology, Xi'an, China, 2019.
21. Chen, C.; Kang, C.X.; Wang, J.W. Stochastic linear programming for reservoir operation with constraints on reliability and vulnerability. *Water* **2018**, *10*, 175. [CrossRef]
22. Yue, W.C.; Yu, S.J.; Xu, M.; Rong, Q.Q.; Xu, C.; Su, M.R. A Copula-based interval linear programming model for water resources allocation under uncertainty. *J. Environ. Manag.* **2022**, *317*, 115318. [CrossRef]
23. Yin, D.Q.; Li, X.; Wang, F.; Liu, Y.; Croke, B.F.W.; Jakeman, A.J. Water-energy-ecosystem nexus modeling using multi-objective, non-linear programming in a regulated river: Exploring tradeoffs among environmental flows, cascades small hydropower, and inter-basin water diversion projects. *J. Environ. Manag.* **2022**, *308*, 114582. [CrossRef] [PubMed]
24. Hermida, G.; Castronuovo, E.D. On the hydropower short-term scheduling of large basins, considering nonlinear programming, stochastic inflows and heavy ecological restrictions. *Int. J. Electr. Power* **2018**, *97*, 408–417. [CrossRef]
25. Yves, M.; Gendreau, M.; Emiel, G. Benefit of PARMA modeling for long-term hydroelectric scheduling using stochastic dual dynamic programming. *J. Water Resour. Plan. Manag.* **2021**, *147*, 05021002. [CrossRef]
26. Rani, D.; Mourato, S.; Moreira, M. A Generalized Dynamic Programming Modelling Approach for Integrated Reservoir Operation. *Water Resour. Manag.* **2020**, *34*, 1335–1351. [CrossRef]
27. Wu, X.Y.; Cheng, C.T.; Lund, J.R.; Niu, W.J.; Miao, S. Stochastic dynamic programming for hydropower reservoir operations with multiple local optima. *J. Hydrol.* **2018**, *564*, 712–722. [CrossRef]
28. Pan, Z.H.; Chen, L.H.; Teng, X. Research on joint flood control operation rule of parallel reservoir group based on aggregation–decomposition method. *J. Hydrol.* **2020**, *590*, 125479. [CrossRef]
29. Chen, J.; Zhong, P.A.; Liu, W.; Wan, X.Y.; Yeh, W.G.A. Multi-objective risk management model for real-time flood control optimal operation of a parallel reservoir system. *J. Hydrol.* **2020**, *590*, 125264. [CrossRef]
30. Thomas, T.; Ghosh, N.C.; Sudheer, K.P. Optimal reservoir operation–A climate change adaptation strategy for Narmada basin in central India. *J. Hydrol.* **2021**, *598*, 126238. [CrossRef]
31. Seetharam, K.V. Three level rule curve for optimum operation of a multipurpose reservoir using genetic algorithms. *Water Resour. Manag.* **2021**, *35*, 353–368. [CrossRef]
32. Sharifazari, S.; Sadat-Noori, M.; Rahimi, H.; Khojasteh, D.; Clamore, W. Optimal reservoir operation using Nash bargaining solution and evolutionary algorithms. *Water Sci. Eng.* **2021**, *14*, 260–268. [CrossRef]
33. Asvini, M.S.; Amudha, T. Design and development of bio-inspired framework for reservoir operation optimization. *Adv. Water Resour.* **2017**, *110*, 193–202. [CrossRef]
34. Yu, Y.C.; Liu, Z.; Dong, P.; Lei, X.H.; You, F.H.; Yang, Z. Research on reverse order impoundment mode of cascade reservoir flood control system: Case study on upper reaches of Yangtze River. *J. Hydrol.* **2022**, *605*, 127348. [CrossRef]
35. Dobson, B.; Wagener, T.; Pianosi, F. An argument-driven classification and comparison of reservoir operation optimization methods. *Adv. Water Resour.* **2019**, *128*, 74–86. [CrossRef]
36. Feng, Z.K.; Niu, W.J.; Zhang, R.; Wang, S.; Cheng, C.T. Operation rule derivation of hydropower reservoir by k-means clustering method and extreme learning machine based on particle swarm optimization. *J. Hydrol.* **2019**, *576*, 229–238. [CrossRef]
37. Diao, Y.F.; Ma, H.R.; Wang, H.; Wang, J.N.; Li, S.X.; Li, X.Y.; Pan, J.Y.; Qiu, Q.T. Optimal flood-control operation of cascade reservoirs using an improved particle swarm optimization algorithm. *Water* **2022**, *14*, 1239. [CrossRef]
38. Zhang, D.; Liu, J.Q.; Peng, Q.D.; Wang, D.S.; Yang, T.T.; Sorooshian, S.; Liu, X.F.; Zhuang, J.B. Modeling and simulating of reservoir operation using the artificial neural network, support vector regression, deep learning algorithm. *J. Hydrol.* **2018**, *565*, 720–736. [CrossRef]
39. Xu, G.; Shu, Y.L.; Ren, Y.F.; Wu, B.Q. Real-time flood control operation model of Three Gorges Reservoir based on deep learning. *J. Hydroelectr. Eng.* **2022**, *41*, 60–69.
40. Azizipour, M.; Sattari, A.; Afshar, M.H.; Goharian, E.; Solis, S.S. Optimal hydropower operation of multi-reservoir systems: Hybrid cellular automata-simulated annealing approach. *J. Hydroinf.* **2020**, *22*, 1236–1257. [CrossRef]
41. Rani, D.; Srivastava, D.K. Optimal operation of Mula reservoir with combined use of dynamic programming and genetic algorithm. *Sustain. Water Resour. Manag.* **2016**, *2*, 1–12. [CrossRef]
42. He, S.K.; Guo, S.L.; Yin, J.B.; Liao, Z.; Li, H.; Liu, Z.J. A novel impoundment framework for a mega reservoir system in the upper Yangtze River basin. *Appl. Energy* **2022**, *305*, 117792. [CrossRef]
43. Wei, N. Research on Ecological Operation of Hydraulic Engineering Based on Complex Water Resources System. Ph.D. Thesis, China Institute of Water Resources and Hydropower Research, Beijing, China, 2015.
44. Lin, Q.C.; Li, H.E. Influence and guarantee on ecological base flow of Weihe River from Baojixia water diversion. *J. Arid Land Resour. Environ.* **2010**, *24*, 114–119.
45. Gao, Z.Y.; Li, H.A.; Zhang, Q. C-D function ridge regression analysis of agricultural water supply benefit in Baojixia Irrigation Area. *Agric. Res. Arid Areas* **2018**, *36*, 33–40.
46. Ladson, A.R.; White, L.J. *An Index of Stream Condition: Reference Manual*, 2nd ed.; Department of Natural Resources and Environment: East Melbourne, Australia, 1999; pp. 15–27.
47. Chen, H.R. Study on joint operation of sluice dam of Baoji reaches. *Shaanxi Water Resour.* **2021**, *8*, 86–90.
48. Wang, Y. Analysis on flood control operation scheme of Linjiacun Reservoir in Baojixia Irrigation District. *Shaanxi Water Resour.* **2021**, *12*, 71–73.

49. Liu, J.M.; Liu, F.; Zhang, L.J. Study on optimal dispatch of water resources in Baoji irrigation areas. *Agric. Res. Arid Areas* **2004**, *22*, 86–90.
50. Liu, F. Study on Optimal Dispatch for Baojixia Irrigation Area and Headwaters Engineering Management Strategy Research in Western Region of Guanzhong. Master's Thesis, Northwest Sci-Tech University of Agriculture and Forestry, Xi'an, China, 2004.
51. Liu, Y. Research on Operation of Baojixia Reservoir in Weihe for Ecological Flow Guarantee. Master's Thesis, Xi'an University of Technology, Xi'an, China, 2020.