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Multi-Objective Optimal Operation Decision for Parallel Reservoirs Based on NSGA-II-TOPSIS-GCA Algorithm: A Case Study in the Upper Reach of Hanjiang River

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Abstract: The parallel reservoirs in the upper reach of the Hanjiang River are key projects for watershed management, development, and protection. The optimal operation of parallel reservoirs is a multiple-stage, multiple-objective, and multiple-decision attributes complex decision problem. Taking Jiaoyan–Shimen parallel reservoirs as an example, a method of multi-objective optimal operation decision of parallel reservoirs (MOODPR) was proposed. The multi-objective optimal operation model (MOOM) was constructed. The new algorithm coupling NSGA-II, TOPSIS, and GCA was used to solve the MOODPR problem. The method of MOODPR was formed by coupling problem identification, model construction, an optimization solution, and scheme evaluation. The results show that (1) combining the Euclidean distance with the grey correlation degree to construct a new hybrid closeness degree makes the multi-attribute decision making method more scientific and feasible. (2) The NSGA-II-TOPSIS-GCA algorithm is applied to obtain decision schemes, which provide decision support for management. (3) It can be seen from the Pareto chart that for the Jiaoyan–Shimen parallel reservoirs, the comprehensive water supply was negatively related to ecology. (4) The comprehensive water supply and ecological AAPFD value in the extraordinarily dry year was 4.212×10^8 m^3 and 4.953. The number of maximum continuous water shortage periods was 4 and 6. The maximum ten-day water shortage was 4.46×10^7 m^3 and 2.3×10^6 m^3. The research results provide technical support and reference value to multi-objective optimal operation decisions for parallel reservoirs in the upper reach of the Hanjiang River.

Keywords: Jiaoyan–Shimen parallel reservoirs; multiple-objective optimization; multiple-attribute decision making; hybrid closeness degree; NSGA-II-TOPSIS-GCA

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1. Introduction

As a primary tributary of the Yangtze River, the Hanjiang River is the main water source for towns along the river. In recent years, the trend of population continuing to gather in regional central cities is more significant, which puts forward higher demand for water resource utilization and introduces challenges for ecological environment protection. At the same time, the runoff of the Hanjiang River has been decreasing in recent years [1], which further aggravates the water scarcity in large irrigation areas and ecological problems. The strong competitive situation among various users will show a normalized and long-term trend, which greatly restricts the ecological protection and sustainable development of watersheds and regions. How can we coordinate the relationship among various users? As the main force of water resources regulation, reservoirs should undertake the important mission of supporting social-economic development and ensuring river health. As important water source projects built and planned in the region, Jiaoyan–Shimen parallel reservoirs will jointly undertake the various tasks of water resource management on the north bank of the Hanjiang River. In recent years, the competition between multiple objectives of the reservoir has become increasingly fierce, and the difficulty of operation decisions has further increased. In order to alleviate the water resource competition among various objectives of the Hanjiang River Basin, improve the rationality of water resources utilization, and further strengthen the protection and restoration of the ecological environment, it is urgent that we explore the service potential of reservoir group and find a method for the multi-objective optimal operation decision of parallel reservoirs (MOODPR).

The multi-objective optimal operation decision (MOOD) of reservoir groups consists of three parts. The first part is the model construction. The second part is the optimization solution. The third part is the multi-attribute decision, that is, the scheme evaluation. For model construction, Lu et al. [2] established the multi-objective optimal operation model (MOOM) with the objectives of maximizing power generation and minimizing the ecological water shortage. Wang et al. [3] set up the MOOM based on the fast non-inferior sequencing genetic algorithm with objectives of minimum comprehensive water shortage, maximum power generation, and minimum ecological water shortage. Chen et al. [4] established the MOOM of the Ganjiang River reservoir group with objectives of maximum power generation, minimum total water supply shortage, and minimum flow deviation before and after operation. Jin et al. [5] established the MOOM to explore the relationship between power generation and water diversion of the Hanjiang-to-Weihe River Project in dry years. Reddy et al. [6] applied the genetic algorithm and particle swarm algorithm to the MOOD problem of the reservoir group and solved the contradiction between irrigation and power generation. Chang et al. [7] applied the NSGA-II to parallel reservoirs and constructed the MOOM with the objective of minimizing the water shortage index. Afshar et al. [8] proposed the hybrid automatic and coordinated search method and applied it to cascade reservoirs, which improved the operational efficiency of the cascade reservoirs. Babel et al. [9] established the MOOM with the goal of maximizing users' satisfaction and economic benefits.

For the optimization solution, there are two types of existing optimization algorithms. Among them, traditional optimization algorithms have strong local search ability, resulting in a local optimum, so their application scope is greatly limited, including linear programming [10–12], nonlinear programming [13–15], dynamic programming [16–21], etc. Intelligent optimization algorithms are constructed by intuition or experience, including the genetic algorithm [22–24], the ant colony algorithm [25–28], the artificial neural network algorithm [29,30], and some new algorithms, such as the artificial immune algorithm [31], the differential evolution algorithm [32], the whale optimization algorithm [33], etc. These methods have strong robustness and are suitable for solving reservoir operations. Due to the complexity of the MOODPR problem and the limitation of constraints, there is no universal solution algorithm.

The scheme evaluation is a decision-making problem. To coordinate the contradiction among objectives and obtain a relatively optimal and balanced operation scheme, decision makers need to conduct multi-attribute decision making, which is an optimal decision based on a limited number of alternatives. TOPSIS [34] compares the distance closeness to sort the schemes. The lack of consideration of the correlation among attribute indexes may lead to problems such as insignificant decision results and reverse order. The set pair analysis (SPA) [35] can judge the quality according to the identical–different–contrary relations between each scheme and the optimal scheme. However, the uncertainty of the difference coefficient of this method has decision risk to a certain extent. The fuzzy set pair analysis (FSPA) [36] is based on the idea of SPA, attaches importance to relativity and fuzziness in information processing, and describes the identical–different–contrary relations between evaluation samples and evaluation grades with the fuzzy connection number, which is an effective method to analyze uncertain multi-objective decision-making problems. The grey correlation analysis (GCA) [37–39] can judge the quality of the scheme from the geometric shape of alternative schemes and optimal schemes. This method ignores the correlation among attribute indexes, and there is information loss. The grey target model (GTM) [40,41] can judge the quality of the scheme from the distance between each scheme and the optimal scheme (target center). The method has a single target center, and there may be a problem that the decision result is not significant. The entropy weight method (EWM) [42] can judge the quality of the scheme from the balanced adjacent degree of each scheme and the optimal scheme, which makes up for the shortcomings of GCA to a certain extent. The above methods should be reasonably determined according to the specific decision information in practical applications.

It can be seen that the existing research has made continuous exploration and achieved meaningful results in optimization solutions and scheme evaluation of reservoir groups. However, the existing operation schemes are difficult to implement in practical applications and it is challenging to coordinate the relationship between the ecological objective and the profit objective. The main reasons are as follows: (1) The essence of optimal operation of a reservoir group is a multiple-stage, multiple-objective, and multiple-decision attributes complex decision problem. The ultimate goal is to provide a reasonable and feasible operation scheme for decision makers. (2) Most existing multi-attribute decision making methods have large information loss and insufficient data mining. The correlation among attribute indexes and index weights is not deeply discussed when selecting schemes, resulting in poor significance of decision results and an unreasonable ranking of schemes. (3) There is an urgent need for a rational and adaptable operation decision method for parallel reservoirs that can correlate multiple projects, multiple objectives, and multiple decision attributes with each other.

Therefore, this study adopted the idea of “problem identification-model construction-optimization solution-scheme evaluation” and proposed a multi-objective optimal operation decision method for parallel reservoir coupling modeling, optimization, and decision making. This method was applied to Jiaoyan–Shimen parallel reservoirs to verify its applicability and rationality.

The main research contents of each part of this study are as follows. Firstly, we identify the MOODPR problem existing in the study area, select typical years, and analyze water demand. Secondly, we establish the MOOM of parallel reservoirs. Thirdly, we introduce the NSGA-II-TOPSIS-GCA algorithm, provide the steps of NSGA-II-TOPSIS-GCA for solving the MOODPR problem, and select the attribute indexes. Fourthly, we apply the algorithm to solve the model, compare the non-inferior solution sets, and discuss the decision schemes. Finally, we summarize the full text, point out the shortcomings, and outline the prospects of future study.

2. Study Area

2.1. Projects Overview

Jiaoyan–Shimen parallel reservoirs in the upper reach of the Hanjiang River are selected as the research object, as shown in Figure 1. Shimen Reservoir (106°94′ E, 33°27′ N), located 1.8 km away from the exit of Baohe River Gorge, a tributary of the upper reach of Hanjiang River, is a large (II) type water conservancy project with comprehensive utilization of irrigation, urban-rural water supply, ecological improvement, and flood control. Jiaoyan Reservoir (107°3′ E, 34°22′ N), located in the Xushuihe River, a tributary of the upper reach of Hanjiang River, has the functions of irrigation, urban-rural water supply, ecological environment improvement, and power generation. Jiaoyan Reservoir is still in the early planning stage, which is the second largest reservoir to be built after Shimen Reservoir in Hanzhong. The water supply scope of the Jiaoyan Reservoir and Shimen Reservoir are independent and related to each other. In addition to their respective water supply objects, they will jointly supply water to the Shimen Irrigation Area and improve irrigation conditions. The joint operation of the Jiaoyan–Shimen parallel reservoirs will jointly provide water security for the Hanzhong Plain. Table 1 shows the parameters of the projects.

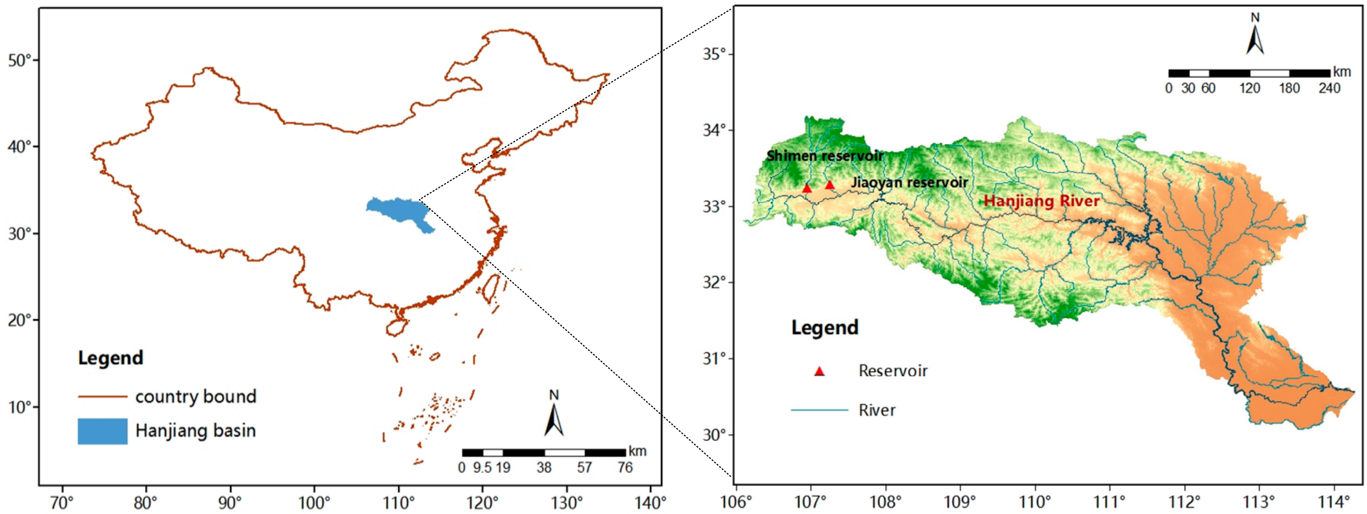


Figure 1. Location of Jiaoyan–Shimen parallel reservoirs.

Table 1. Main parameters of Jiaoyan–Shimen parallel reservoirs.

Parameter Category	Dead Water Level /m	Normal Water Level /m	Flood Control Level /m	Total Storage /10^8 m³	Utilizable Capacity /10^8 m³	Installed Capacity /MW	Maximum Flow through Water Turbine /(m³/s)	Minimum Flow through Water Turbine /(m³/s)
Jiaoyan reservoir	540	585	585	2.125	1.718	50	87.5	0
Shimen reservoir	595	618	615	0.607	0.524	37.5	67.5	27

2.2. Problem Identification

The Baohe River and the Xushuihe River both belong to the Yangtze River Basin. The water resources are abundant, but the annual runoff processes are uneven. The annual surface runoff is mainly concentrated in July to September. Due to insufficient storage capacity and the low utilization rate of water resources, Jiaoyan and Shimen reservoirs have the following water supply problems: (1) The urban–rural siphon effect causes the population to gather in the regional central cities. The increasing demand for water intensifies the competition between urban–rural water supply and other objectives. (2) There is a serious shortage of water inflow in dry years, which makes it difficult to meet the water demand of the irrigation area. (3) During the rush hour of water use, urban–rural irrigation water seriously occupies the ecological water of river channels. To coordinate the multi-objective competition relationship, improve the water supply guarantee degree in dry years, and protect the ecological environment, it is necessary to carry out the optimal operation of the Jiaoyan–Shimen parallel reservoirs.

2.3. Typical Years Selection and Water Demand Analysis

The section flows of Hedongdian and Shengxiancun hydrological stations were considered the inflow of Shimen and Jiaoyan reservoirs, respectively. The designed runoffs of Shimen reservoir under 25%, 50%, and 75% inflow frequencies were 1.36×10^9 m^3, 9.00×10^8 m^3, 6.65×10^8 m^3, and 4.41×10^8 m^3, respectively. The designed runoff of Jiaoyan reservoir under 25%, 50%, and 75% inflow frequencies were 1.21×10^9 m^3, 8.93×10^8 m^3, 7.00×10^8 m^3, and 4.94×10^8 m^3, respectively. Figure 2 shows the inflow processes of the Shimen and Jiaoyan reservoirs.

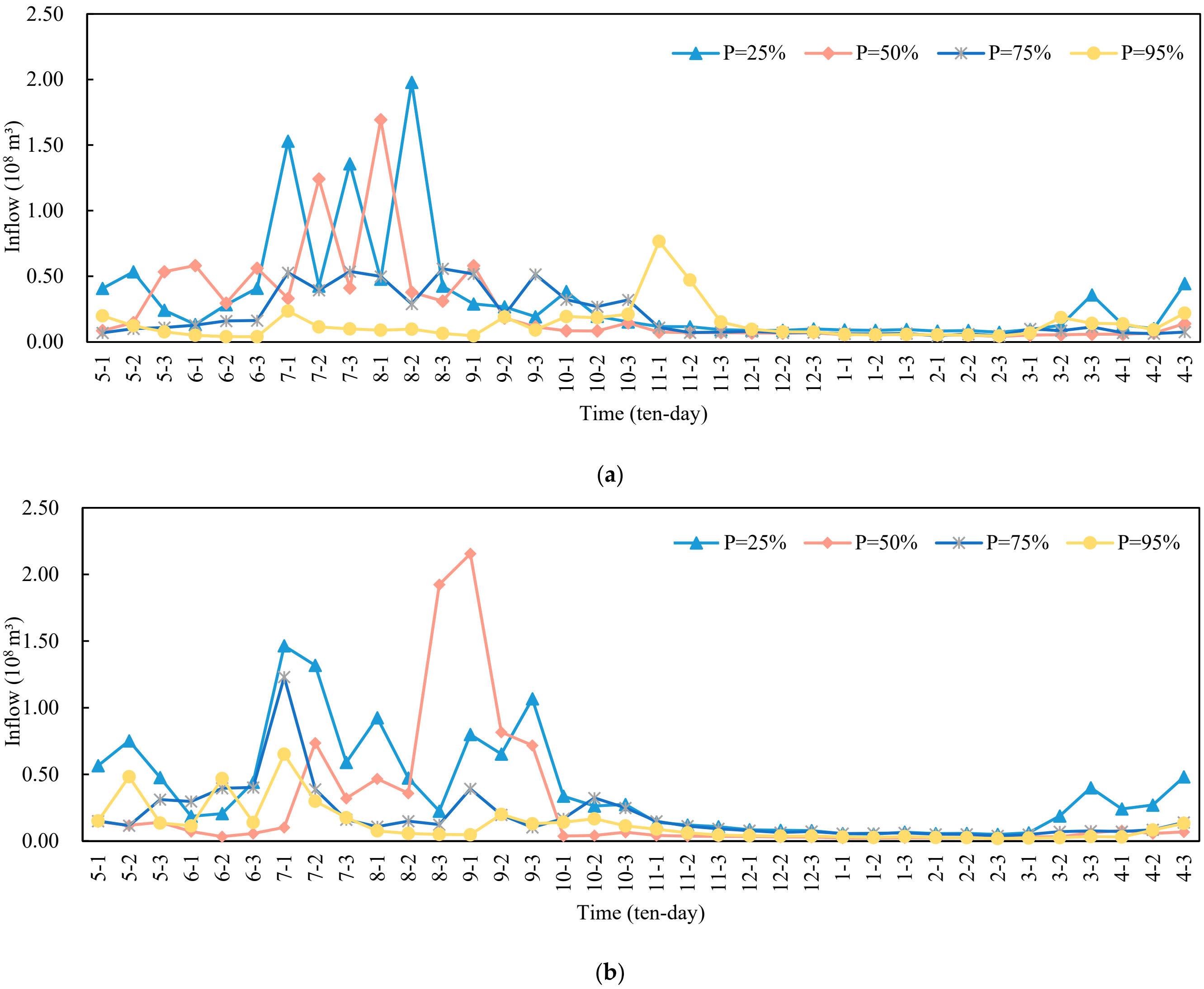


Figure 2. Inflow processes in different typical years: (**a**) Shimen reservoir; (**b**) Jiaoyan reservoir.

The water supply objective of the Jiaoyan–Shimen parallel reservoirs mainly included urban–rural water demand, irrigation, and ecology of the downstream river. Among them, the urban–rural water demand and ecology were the same under different inflow frequencies. The comprehensive water demand mainly included the urban–rural water demand and irrigation. The comprehensive water demand under 25%, 50%, and 75% inflow frequencies were 4.83×10^8 m^3, 5.07×10^8 m^3, and 6.73×10^8 m^3, respectively. The comprehensive water demand under a 95% inflow frequency was the same as that under a 75% inflow frequency. The ecological and comprehensive water demand processes are shown in Figures 3 and 4.

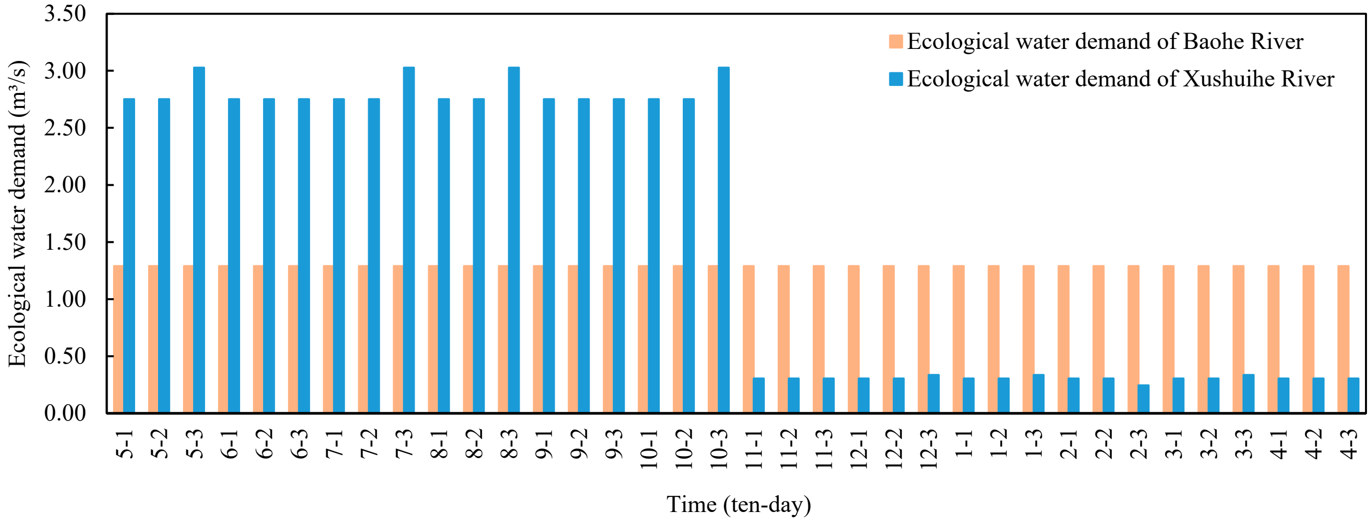


Figure 3. Ecological water demand processes.

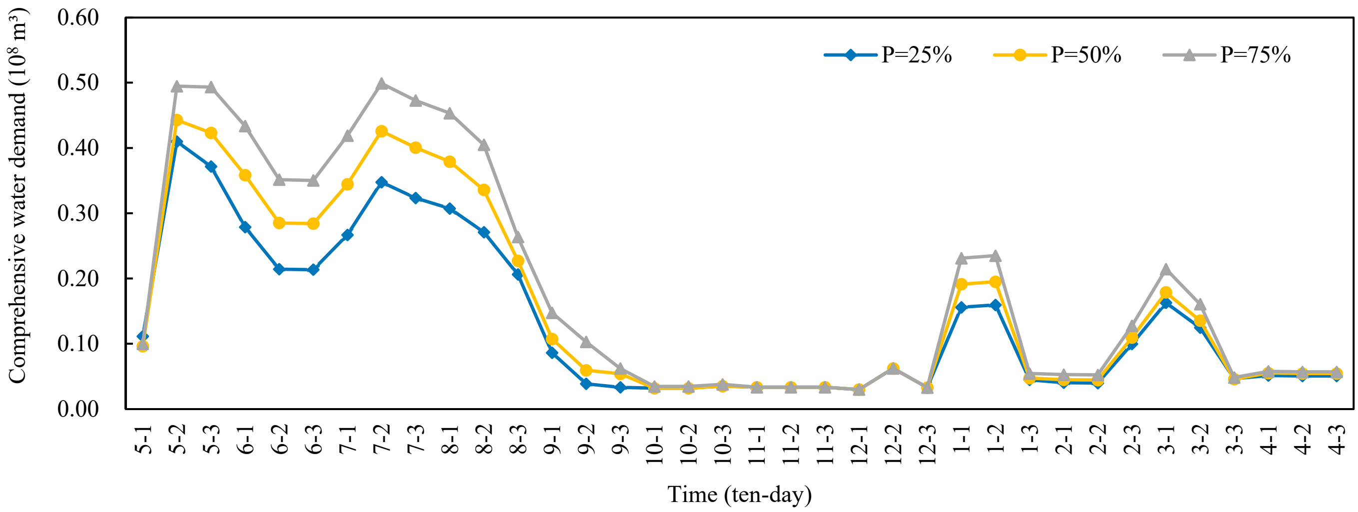


Figure 4. Comprehensive water demand processes.

3. Model Construction and Solving Algorithm

3.1. Model Construction

3.1.1. Objective Functions

The optimal operation for Jiaoyan–Shimen parallel reservoirs needs to consider urban–rural, irrigation, ecology, power generation, and so on. The power generation objective was completely obedient to urban–rural water, irrigation water, and ecological water of river channels. The flood control objective can be satisfied by limiting the water level. The comprehensive water use and ecological water use are the main objectives for the establishment of MOOM. Therefore, the objective functions of MOOM for Jiaoyan–Shimen parallel reservoirs are the maximum comprehensive water supply and the minimum amended annual proportion flow deviation (ecological AAPFD value) [43].

(1) Maximum comprehensive water supply.

$$f_1 = max \sum_{t=1}^{T} \sum_{p=1}^{P} q_z(p,t)\Delta t \tag{1}$$

where f_1 denotes the maximum comprehensive water supply; p denotes the index of reservoirs; t denotes the index of the operational period; Δt denotes the duration of the operational period; $q_z(p,t)$ denotes the comprehensive water supply flow for reservoir p during period t; P denotes the number of reservoirs; and T denotes the number of operational periods.

(2) Minimum ecological AAPFD value. The larger the ecological AAPFD value, the greater the influence of the reservoir on the downstream ecosystem, and vice versa.

$$AAPFD_p = min\left\{\sum_{t=1}^{T}\left(\frac{Q(p,t) - Q^n(p,t)}{\overline{Q}^n}\right)^2\right\}^{0.5} \tag{2}$$

$$f_2 = \max\{\mathrm{AAPFD}_1, \ldots, \mathrm{AAPFD}_p\} \tag{3}$$

where $AAPFD_p$ denotes the minimum ecological AAPFD value for reservoir p; $Q(p,t)$ denotes the outflow for reservoir p during period t; $Q^n(p,t)$ denotes the natural flow for reservoir p during period t; $\overline{Q}^n$ denotes the average natural flow for reservoir p during the operation period; and f_2 denotes the final ecological AAPFD value.

3.1.2. Constraints

(1) Water balance constraint:

$$V(p,t+1) = V(p,t) + (Q_{in}(p,t) - Q_{out}(p,t))\Delta t \tag{4}$$

where $V(p,t+1)$ denotes the final reservoir storage for reservoir p during period t; $V(p,t)$ denotes the initial reservoir storage for reservoir m during period t; $Q_{in}(p,t)$ denotes the inflow for reservoir p during period t; and $Q_{out}(p,t)$ denotes the outflow for reservoir p during period t.

(2) Water level constraint:

$$\mathrm{Z}_{min}(p,t) \leq \mathrm{Z}(p,t) \leq \mathrm{Z}_{max}(p,t) \tag{5}$$

where $\mathrm{Z}(p,t)$ denotes the water level for reservoir p during period t; $Z_{min}(p,t)$ and $Z_{max}(p,t)$ denote the lower and upper limits.

(3) Power output constraint:

$$N_{min}(p,t) \leq N(p,t) \leq N_{max}(p,t) \tag{6}$$

where $N(p,t)$ denotes the power output for reservoir p during period t; $N_{min}(p,t)$ and $N_{max}(p,t)$ denote the minimum and maximum power outputs.

(4) Constraint of flow through the water turbine:

$$Q^f_{min}(p,t) \leq Q^f(p,t) \leq Q^f_{max}(p,t) \tag{7}$$

where $Q^f(p,t)$ denotes the flow through the water turbine for reservoir p during period t; $Q^f_{min}(p,t)$ and $Q^f_{max}(p,t)$ denotes the minimum and maximum flow through the water turbine.

(5) All the variables mentioned above are non-negative.

3.2. Solving Algorithm

3.2.1. NSGA-II-TOPSIS-GCA

In this paper, the NSGA-II-TOPSIS-GCA algorithm was constructed to solve the MOODPR problem. The core of NSGA-II is to coordinate the relationship between objective functions, and the NSGA-II introduces the concepts of individual non-dominated sorting, individual crowding, and the parent elite retention strategy, which can adapt to multi-objective problem solving and improve search efficiency. The principle of TOPSIS is to compare the distance closeness degree of the scheme in the non-inferior solution set (alternative scheme set) so as to sort the schemes. However, TOPSIS ignores the correlation among attribute indexes. For this problem, a new hybrid closeness degree is constructed by combining the GCA with TOPSIS, which not only considers the distance closeness degree but also takes into account the correlation among attribute indexes and the implicit relationship among the data, which makes the decision schemes more reasonable and feasible.

The overall idea of the new algorithm is as follows: Firstly, we input the MOODPR problem, basic data, and parameters. Secondly, the MOOM is constructed, and the non-inferior solution set can be obtained by NSGA-II. Thirdly, we establish the decision matrix according to the appropriate attribute indexes, and the matrix is weighted and normalized. Then, the TOPSIS-GCA is used to sort all the schemes according to the hybrid closeness degree. Finally, the scheme that has the largest closeness degree is taken as the final decision scheme. Figure 5 shows the main flow diagram of the NSGA-II-TOPSIS-GCA algorithm.

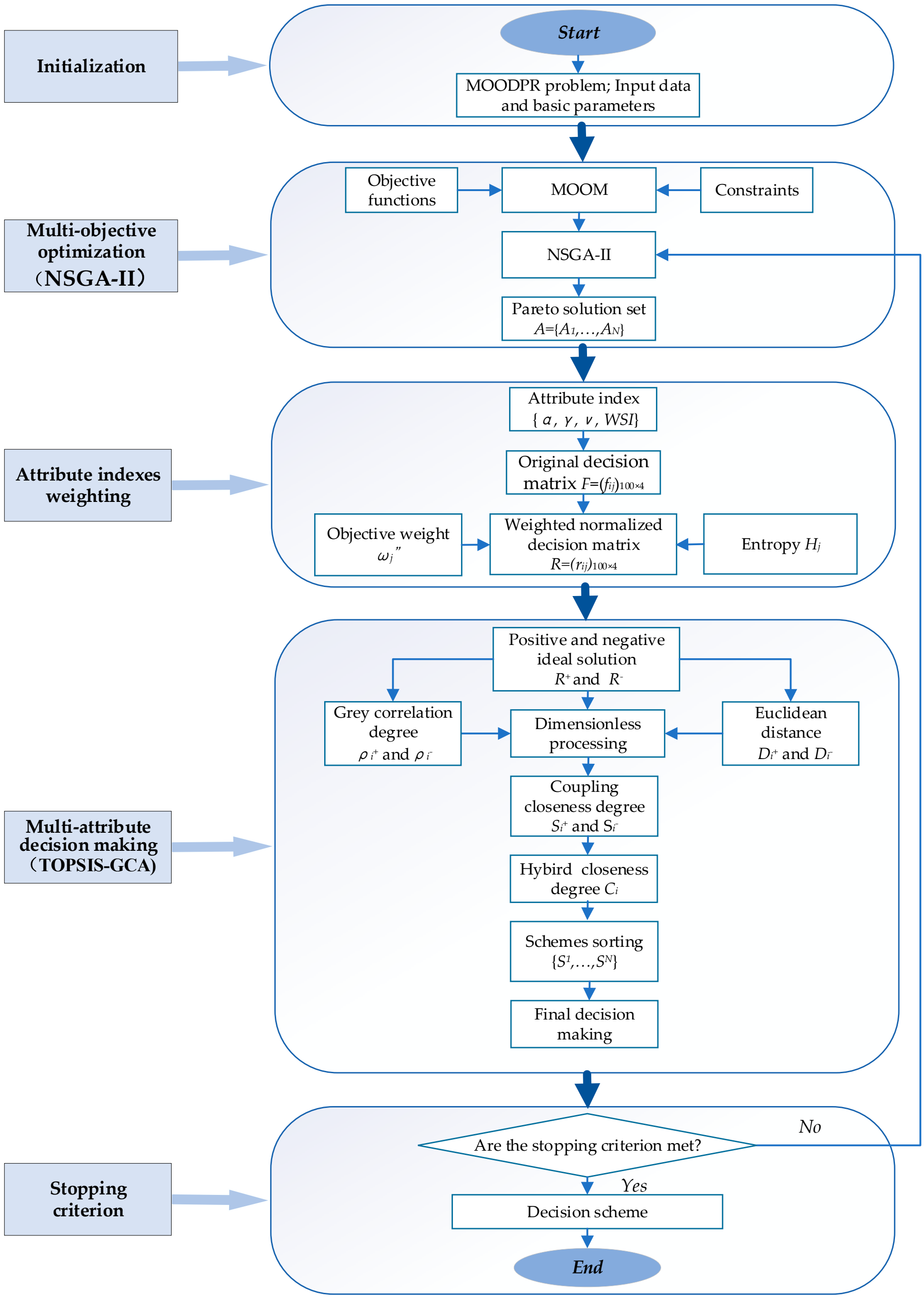


Figure 5. Flow diagram of NSGA-II-TOPSIS-GCA algorithm.

3.2.2. Application of NSGA-II-TOPSIS-GCA Algorithm for MOODPR Problem

The new algorithm was used to solve the MOODPR problem for Jiaoyan–Shimen parallel reservoirs. The parameters of the algorithm include the population size N, maximum iteration times $Maxgen$, crossover probability pc, mutation probability pm, crossover distribution index η_c, and mutation dispersion index η_m. The operation periods are 36 ten-day periods, and the water level represents the decision variable, which is generated randomly within its feasible ranges. The application of the algorithm includes initialization, multi-objective optimization, attribute index weighting, multi-attribute decision making, etc. The detailed steps are shown in Algorithm 1.

Algorithm 1: Detailed steps of NSGA-II-TOPSIS-GCA algorithm:

Input: The decision variables, objective functions, constraints, N, $Maxgen$, pc, pm, η_c, and η_m.
Output: $\{S^1, \cdots, S^N\}$ and $\{Z^1, \cdots, Z^T\}$.
Step 1: Initialization
1.1 N = 100, $Maxgen$ = 1500, pc = 0.9, pm = 0.08, η_c = 20, η_m = 20, Gen = 0 $\leftarrow$ Parameter setting.
1.2 $\{X^1, \cdots, X^N\} \leftarrow$ Initialization population P_0 randomly.
Step 2: Multi-objective optimization
2.1 MOOM construction.
2.2 Initialized population P_0 is non-dominated sorted, and individuals with better fitness are selected for genetic operation to generate the first-generation offspring population Q_0.
2.3 Gen = 2, $R_t = P_t \cup Q_t \leftarrow$ Merge offspring population and parent population.
2.4 $P_{t+1} = R_t[0:N] \leftarrow$ Individuals with better fitness are selected as the parent population.
2.5 Perform genetic operation to obtain new offspring population.
2.6 If $Gen = Maxgen$, non-inferior solution set $A = \{A_{1,}A_{2,} \cdots A_{100}\}$ is obtained, otherwise $Gen = 1 + Gen$, return to step 2.3.
Step 3: Attribute indexes weighting
3.1 $F = (f_{ij})_{100\times 4} (i = 1, 2, \ldots, 100; j = 1, 2, 3, 4) \leftarrow$ Select attribute indexes $\{\alpha, \gamma, \nu, MSI\}$, establish 4-dimensional original decision matrix.
3.2 $Z = (z_{ij})_{100\times 4} \leftarrow$ The 4-dimensional original decision matrix $F = (f_{ij})_{100\times 4}$ is normalized to obtain the 4-dimensional decision matrix.
3.3 Calculate the entropy H_j of attribute indexes:

$$H_j = -\frac{1}{lnm}\sum_{i=1}^{100} e_{ij} lne_{ij},\ e_{ij} = \frac{z_{ij}}{\sum_{i=1}^{100} z_{ij}}$$

3.4 Calculate the objective weight ω''_j of attribute indexes:

$$\omega''_j = \frac{1+e^{2(1-H_j)}}{\sum_{j=1}^{4}(1+e^{2(1-H_j)})}$$

3.5 Calculate the weighted normalized decision matrix $R = (r_{ij})_{100\times 4}$, where $r_{ij} = z_{ij} \times \omega''_j$.
Step 4: Multi-attribute decision making
4.1 Determine the positive ideal solution R^+ and negative ideal solution R^- of each scheme:

$$R^+ = \begin{cases} maxr_{ij}, j\ is\ a\ benefit\ attribute \\ minr_{ij}, j\ is\ a\ cost\ attribute \end{cases},$$

$$R^- = \begin{cases} maxr_{ij}, j\ is\ a\ cost\ attribute \\ minr_{ij}, j\ is\ a\ benefit\ attribute \end{cases}$$

4.2 Calculate the grey correlation degree ρ_i^+ and ρ_i^- of each scheme:

$$\rho_i = \frac{1}{4}\sum_{i=1}^{100}\rho_{ij}, \text{where } \rho_{ij} = \frac{(m+\zeta M)}{(\Delta_i(j)+\zeta M)}, \Delta_i(j) = |R(j) - r_{ij}|, m = min\{min\Delta_i(j)\}, M = max\{max\Delta_i(j)\}$$

4.3 Calculate Euclidean distance D_i^+ and D_i^- of each scheme:

$$D^+(R_i, R^+) = \sqrt{(R_i - R^+)^T(R_i - R^+)}, D^-(R_i, R^-) = \sqrt{(R_i - R^-)^T(R_i - R^-)}$$

4.4 Dimensionless processing for grey correlation degree and Euclidean distance determined in steps 4.2 and 4.3.
4.5 Construct the coupling closeness degree S_i^+ and S_i^-:

$$S_i^+ = \alpha D_i^- + \beta\rho_i^+, S_i^- = \alpha D_i^+ + \beta\rho_i^-$$

4.6 Calculate hybrid closeness degree C_i of each scheme:

$$C_i = \frac{S_i^+}{S_i^+ + S_i^-}$$

4.7 $\{S^1, \cdots, S^N\} \leftarrow$ Sort all the schemes according to the hybrid closeness degree, and the scheme which has the largest hybrid closeness degree is taken as the final decision scheme.
Step 5: Stop
If the stop requirement is met, stop; otherwise return to Step 2.

3.2.3. Attribute Indexes Selection

The attribute indexes are the standard to evaluate the quality of the schemes. In this paper, the 4-dimensional decision matrix is composed of the water supply reliability (α), water shortage depth (ν), water supply recoverability (γ), and water shortage index (WSI).

(1) Reliability (α) refers to the guaranteed degree of water supply. The calculation formula is as follows:

$$\alpha = \frac{\sum_{t=1}^{T} K_t}{T} \tag{8}$$

$$\begin{cases} K_t = 1, \sum\limits_{m=1}^{M} q_z(m,t) \geq Q_z(t) \\ K_t = 0, \sum\limits_{m=1}^{M} q_z(m,t) < Q_z(t) \end{cases} \tag{9}$$

where $Q_z(t)$ denotes the comprehensive water demand flow of parallel reservoirs during period t; K_t is used to determine whether the water supply satisfies the demand during period t.

(2) Recoverability (γ) refers to the probability that the water supply return to a normal state from an insufficient state ($q_z(m,t) < Q_z(t)$) during operation periods. The calculation formula is as follows:

$$\gamma = \frac{\sum_{t=1}^{T}(K_t = 1|K_t = 0)}{T - \sum_{t=1}^{T} K_t} \tag{10}$$

(3) Water shortage depth (ν) refers to the maximum ecological water shortage degree during operation periods. The ecological water shortage degree can be used to measure the severity of water shortage. The calculation formula is as follows:

$$\nu = \max\{DR_1, DR_2, ..., DR_t\}, \mathrm{DR}_t = 1 - \frac{\sum_{m=1}^{M} q_e(m.t)}{\sum_{m=1}^{M} Q_e(m.t)} \tag{11}$$

where DR_t denotes the degree of ecological water shortage during period t; $q_e(m,t)$ and $Q_e(m,t)$ denote the ecological water supply and demand flow for reservoir m during period t.

(4) The water shortage index (WSI) reflects the ecological loss degree of parallel reservoirs. The calculation formula is as follows:

$$\mathrm{WSI} = \frac{100}{T}\sum_{t=1}^{T} {DR_t}^2 \tag{12}$$

4. Results and Discussion

4.1. Model and Algorithm Application

The MOODPR proposed in this paper mainly includes four modules: problem identification, model construction, the optimization solution, and scheme evaluation. Figure 6 shows the application flowchart of the method:

1. Problem identification. The relevant data of the research area are systematically collected, the development status of the research area is analyzed, and the existing problems are identified.
2. Input parameters such as reservoirs and hydropower stations.
3. Model construction. The MOOM is constructed according to the objective functions and constraints.
4. Optimization solution. The non-inferior solution set is obtained.
5. Scheme evaluation. The appropriate attribute indexes are selected and the 4-dimensional decision matrix is established. The TOPSIS-GCA is adopted to optimize the non-inferior solution set, so as to obtain the decision schemes.
6. Output results, such as attribute indexes and decision schemes.

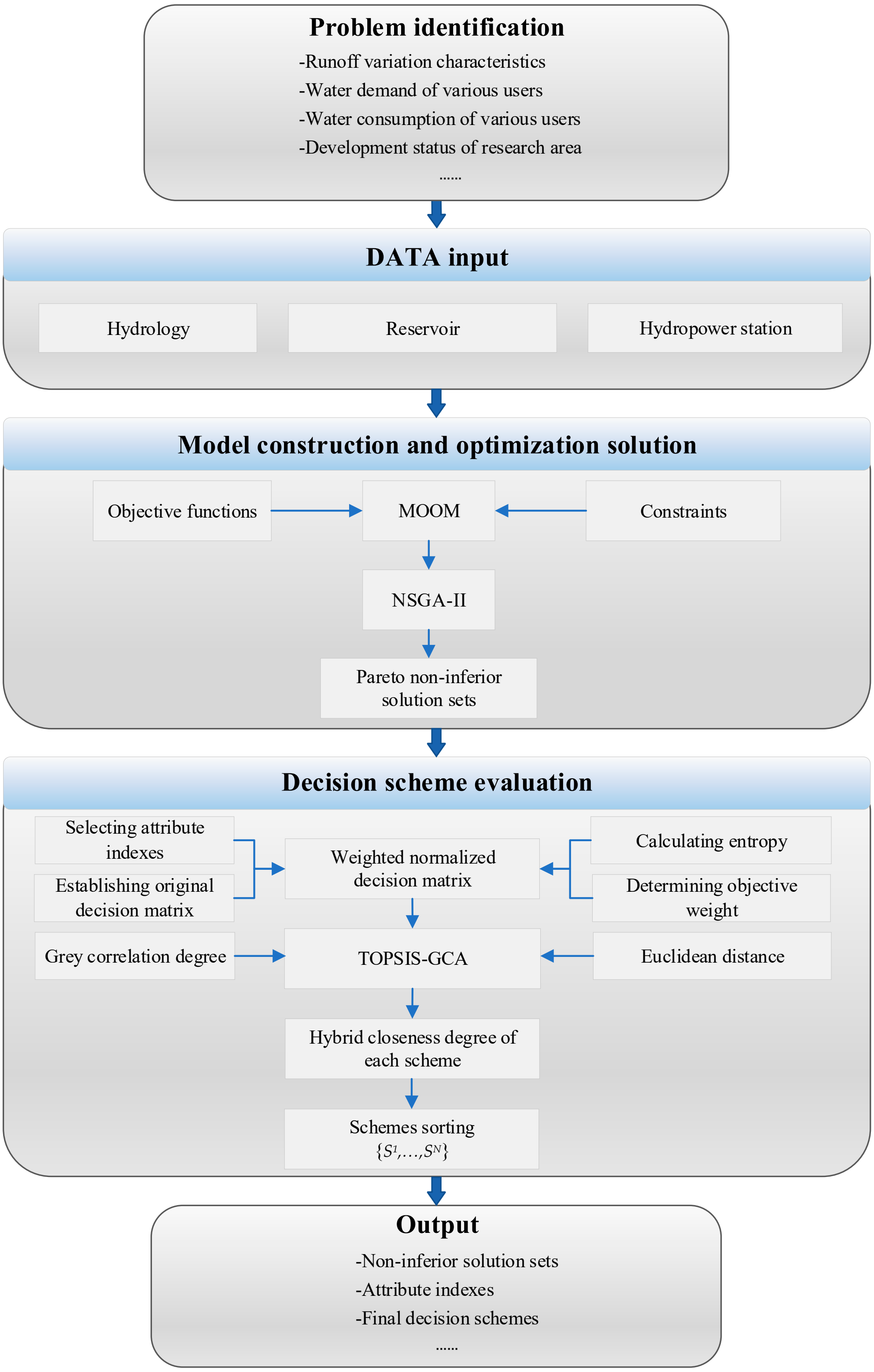


Figure 6. Application flowchart of the method.

4.2. Pareto Solution Set

Figure 7 shows the Pareto non-inferior solution sets of comprehensive water supply and ecological AAPFD value. The comprehensive water supply and ecological AAPFD value showed an obvious positive correlation. That is, comprehensive water supply was significantly negatively correlated with ecology, which further highlighted the competition and contradiction of the two objectives. With the continuous decrease in natural inflow, the increase in comprehensive water demand caused the comprehensive water supply to show an increasing trend, the ecological AAPFD value increased, and the ecological environment of river channels deteriorated. For example, the maximum comprehensive water supply and minimum ecological AAPFD value under a 25% inflow frequency were 4.63×10^8 m^3 and 1.974, respectively, while the corresponding values under a 75% inflow frequency were 5.73×10^8 m^3 and 4.553, respectively. The comprehensive water supply increased by 1.10×10^8 m^3 and the ecological AAPFD value increased by 2.579, indicating that the natural inflow had a remarkable influence on the reservoirs' benefits. Due to the decrease in natural inflow under a 95% inflow frequency, the comprehensive water supply and ecological AAPFD value were significantly affected. In addition, the amplification of water supply was less than that of ecology in all non-inferior solution sets, indicating that the ecology objective was more sensitive to the comprehensive water supply objective, which also required the decision makers to comprehensively weigh the pros and cons of the two in actual operation.

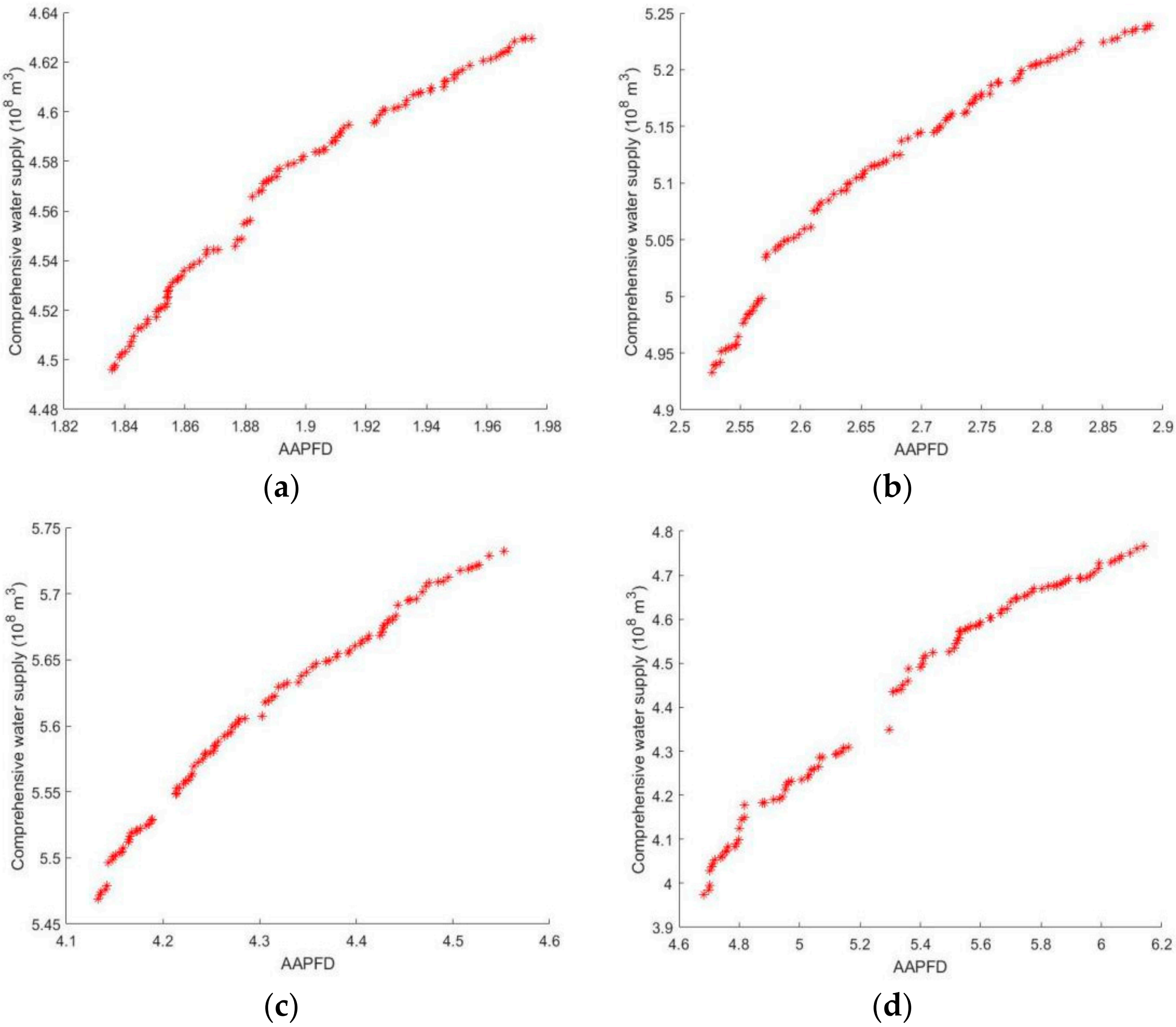


Figure 7. Pareto non-inferior solution sets: (**a**) P = 25%; (**b**) P = 50%; (**c**) P = 75%; (**d**) P = 95%.

4.3. Decision Making Results

The Pareto non-inferior solution sets of the above typical years were taken as the alternative scheme sets. The scheme sets under 25%, 50%, 75%, and 95% inflow frequencies were denoted as A, B, C, and D, respectively. By calculating the attribute indexes of each scheme, the 4-dimensional original decision matrix of each scheme set was constructed.

Table 2 shows the statistical results of attribute indexes for four scheme sets. Each scheme set had different 4-dimensional attribute indexes. In order to determine the decision schemes, it is necessary to use TOPSIS-GCA to evaluate the scheme sets.

Table 2. Statistical results of attribute indexes for four scheme sets.

Scheme Sets		**Attribute Indexes**			
		$\boldsymbol{\alpha}$	$\boldsymbol{\gamma}$	$\boldsymbol{\nu}$	***WSI***
A	Variation range Standard deviation	[0.750, 0.806] 0.0249	[0.556, 0.857] 0.133	[0.743, 0.843] 0.0279	[5.073, 11.603] 2.095
B	Variation range Standard deviation	[0.588, 0.689] 0.0161	[0.494, 0.667] 0.0486	[0.827, 0.892] 0.0166	[21.826, 29.463] 1.256
C	Variation range Standard deviation	[0.533, 0.639] 0.0170	[0.400, 0.538] 0.0509	[0.829, 0.990] 0.0407	[23.758, 30.795] 1.413
D	Variation range Standard deviation	[0.250, 0.528] 0.0912	[0.111, 0.389] 0.0594	[0.862, 0.995] 0.0335	[37.566, 57.470] 5.705

The 4-dimensional original decision matrix was normalized and the objective weights of 4-dimensional attribute indexes for the new 4-dimensional decision matrix in different typical years were calculated as follows:

Wet year: ω'' = (0.2493, 0.2503, 0.2493, 0.2511)

Normal year: ω'' = (0.2499, 0.2501, 0.2499, 0.2501)

Dry year: ω'' = (0.2499, 0.2502, 0.2499, 0.2500)

Extraordinary dry year: ω'' = (0.2505, 0.2507, 0.2493, 0.2495)

The decision matrix was weighted and normalized to determine the $R+$ and $R-$ for four scheme sets, as shown in Table 3.

Table 3. Positive and negative ideal solutions for four scheme sets.

Scheme Sets	**Positive Ideal Solutions**	**Negative Ideal Solutions**
A	$R+$ = (0.0262, 0.0326, 0.0233, 0.0157)	R^- = (0.0243, 0.0211, 0.0265, 0.0358)
B	$R+$ = (0.0272, 0.0294, 0.0240, 0.0210)	R^- = (0.0225, 0.0218, 0.0259, 0.0282)
C	$R+$ = (0.0264, 0.0285, 0.0227, 0.0215)	R^- = (0.0241, 0.0212, 0.0273, 0.0279)
D	$R+$ = (0.0320, 0.0378, 0.0222, 0.0192)	R^- = (0.0152, 0.0108, 0.0276, 0.0294)

Table 4 shows the hybrid closeness degree of schemes and their sorts. The scheme with the largest hybrid closeness degree was the optimal scheme, and the scheme with the smallest hybrid closeness degree was the worst scheme.

Table 5 shows the attribute indexes of final decision schemes for four scheme sets. The attribute indexes of different scheme sets varied greatly. The reliability α in the wet year was 0.806, indicating that there were 29 ten-day periods to meet the comprehensive water demand. The reliability α under 50%, 75%, and 95% inflow frequencies was 0.611, 0.556, and 0.467, which was 0.195, 0.250, and 0.339 lower than that of the 25% inflow frequency, indicating that only 22, 20, and 18 ten-day periods met the requirement of comprehensive water, and the other periods were affected. In comparison with the other inflow frequencies, under a 25% inflow frequency, the recoverability γ increased by 0.391 on average, the water shortage depth ν decreased by 0.187 on average, and the *WSI* decreased by 25.459 on average. On the whole, the attribute indexes in the wet year were better than those of other inflow frequencies.

Table 4. Hybrid closeness degree of schemes and their sorts for four scheme sets.

Scheme No.	A		B		C		D	
	Hybrid Closeness Degree	Scheme Sort	Hybrid Closeness Degree	Scheme Sort	Hybrid Closeness Degree	Scheme Sort	Hybrid Closeness Degree	Scheme Sort
1	0.6919	71	0.5632	99	0.5243	35	0.6796	31
2	0.6802	14	0.5563	94	0.5231	36	0.6794	97
3	0.6715	44	0.5538	95	0.5230	37	0.6751	1
4	0.6706	18	0.5481	80	0.5229	1	0.6699	95
5	0.6681	30	0.5476	81	0.5216	38	0.6599	14
6	0.6664	84	0.5467	100	0.5198	39	0.6589	54
7	0.6660	74	0.5462	96	0.5175	40	0.6589	61
8	0.6644	37	0.5461	82	0.5155	92	0.6587	43
9	0.6591	98	0.5435	83	0.5144	41	0.6559	87
10	0.6524	79	0.5419	84	0.5140	42	0.6552	75
11	0.6520	59	0.5408	7	0.5117	43	0.6272	71
12	0.6519	3	0.5404	97	0.5094	93	0.6248	93
13	0.6483	28	0.5390	8	0.5089	44	0.6230	70
…	…	…	…	…	…	…	…	…
99	0.3270	65	0.4657	64	0.3746	33	0.3139	52
100	0.3094	1	0.4647	1	0.3717	34	0.2878	55

Table 5. The attribute indexes of final decision schemes for four scheme sets.

Scheme Sets	Decision Scheme No.	α	γ	ν	*WSI*
A	71	0.806	0.857	0.748	5.073
B	99	0.611	0.663	0.880	20.963
C	35	0.556	0.429	0.938	30.610
D	31	0.498	0.305	0.987	40.024

4.4. Decision Schemes Analysis

Table 6 shows the objective values and characteristic indexes of the final decision schemes for four scheme sets. For the comprehensive water supply, from the wet year to the dry year, the comprehensive water supply gradually increased with the increase in the comprehensive water demand. It increased from 4.577×10^8 m^3 under a 25% inflow frequency to 5.563×10^8 m^3 under a 75% inflow frequency, with an increase of 22.1%. In the extraordinarily dry year, the comprehensive water supply was the smallest due to the least inflow. With the decrease in inflow of parallel reservoirs, the comprehensive water shortage gradually increased with the decrease in inflow, and the guaranteed rate in the flood season was obviously higher than that in the non-flood season. The water shortage depth increased from 5% in the wet year to 37% in the extraordinarily dry year, and the number of maximum continuous water shortage periods increased from one ten-day period in the wet year to four ten-day periods in the extraordinarily dry year.

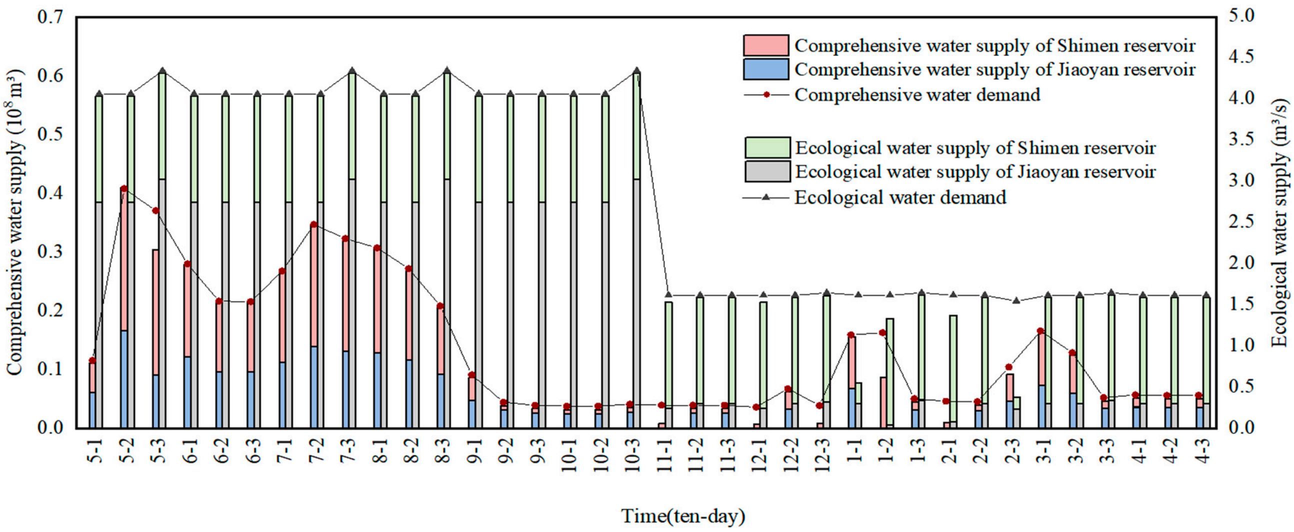
For the ecological water supply, with the decrease in the inflow of parallel reservoirs, the ecological water demand under different inflow frequencies remained unchanged, so the ecological water supply decreased from 9.06×10^7 m^3 under a 25% inflow frequency to 7.35×10^7 m^3 under a 95% inflow frequency, with a decrease of 18.9%. The ecological AAPFD value increased by 3.062. The guaranteed rate decreased from the wet year to the dry year, and the guaranteed rate in the flood season was obviously higher than that in the non-flood season. The ecological water shortage increased gradually from the wet year to the dry year. The water shortage depth increased from 3% to 21%, and the number of maximum continuous water shortage periods increased from two ten-day periods in the wet year to six ten-day periods in the extraordinarily dry year.

Table 6. Final decision schemes for four scheme sets.

Scheme Sets	Objectives	Water Demand	Water Supply	Guarantee Rate		Water Shortage	Water Shortage Depth	Number of Maximum Continuous Water Shortage Periods
				Flood Season	Non-Flood Season			
		/10^8 m³	/10^8 m³	/%	/%	/10^8 m³	/%	
A	Comprehensive water supply	4.828	4.577	94%	63%	0.251	5	1
	Ecology water supply	0.931	0.906 (1.891) [1]	100%	61%	0.025	3	2
B	Comprehensive water supply	5.702	4.996	89%	39%	0.706	12	3
	Ecology water supply	0.931	0.813 (2.565) [1]	89%	44%	0.118	13	4
C	Comprehensive water supply	6.726	5.563	78%	44%	1.163	17	3
	Ecology water supply	0.931	0.804 (4.230) [1]	67%	39%	0.127	14	4
D	Comprehensive water supply	6.726	4.212	61%	39%	2.514	37	4
	Ecology water supply	0.931	0.735 (4.953) [1]	50%	33%	0.196	21	6

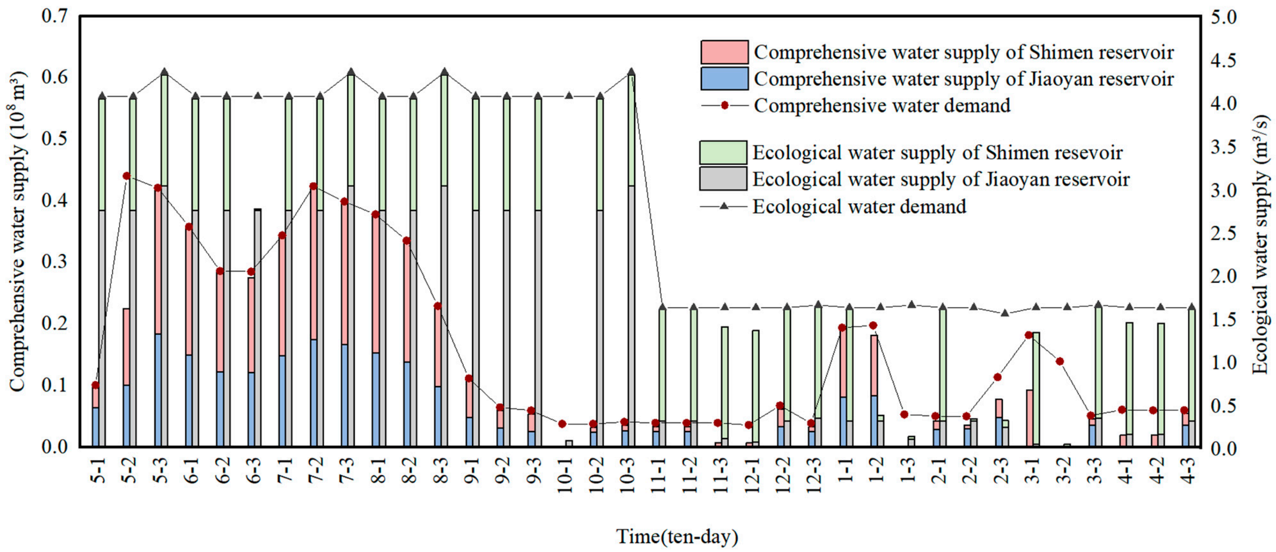
[1] The values in the brackets represent the ecological AAPFD values of different scheme sets.

In addition to the total amount of each objective, its time allocation process is also an important basis for objectively reflecting the water supply capacity and ecological protection. Figure 8 shows the ecological and comprehensive water supply processes in different typical years. The comprehensive water demand included urban–rural water and irrigation water. The urban–rural water process was relatively stable, while the irrigation water was relatively unstable, which was mainly affected by the irrigation system. Therefore, the peaks of the comprehensive water supply were consistent with the peaks of irrigation water, which were mainly concentrated in January, March, May, and July. Figure 9 shows the satisfaction degree of ecological water supply per ten-day period from May to April of the next year in different typical years. From the wet year to the extraordinarily dry year, the satisfaction degree of the ecological water supply gradually decreased, and the number of unsatisfactory periods increased significantly, which mainly occurred in the non-flood season.

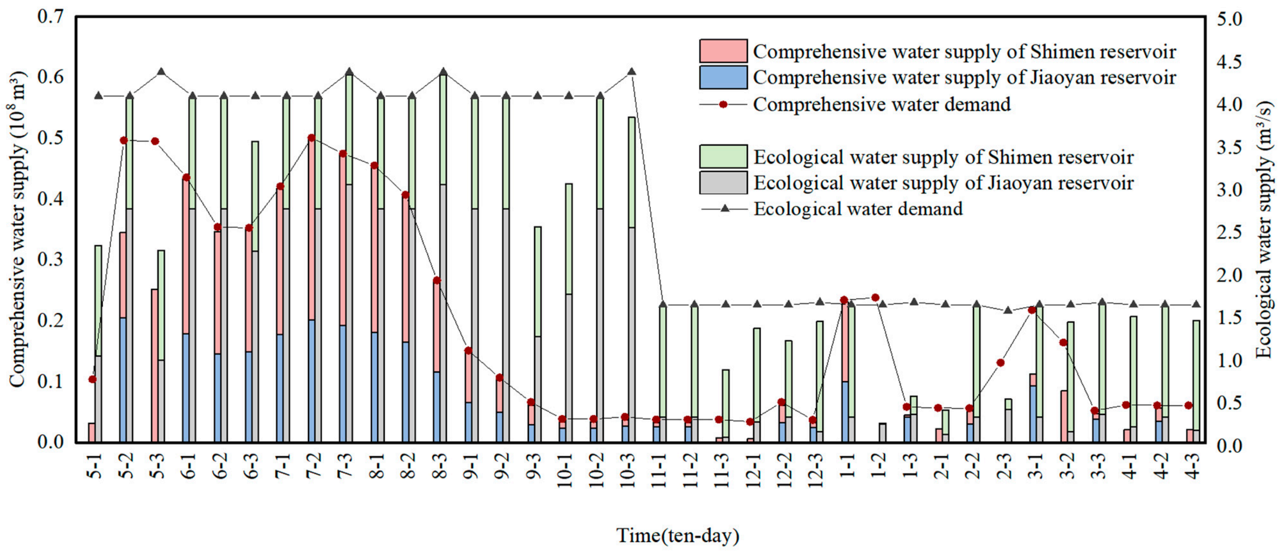


(a)

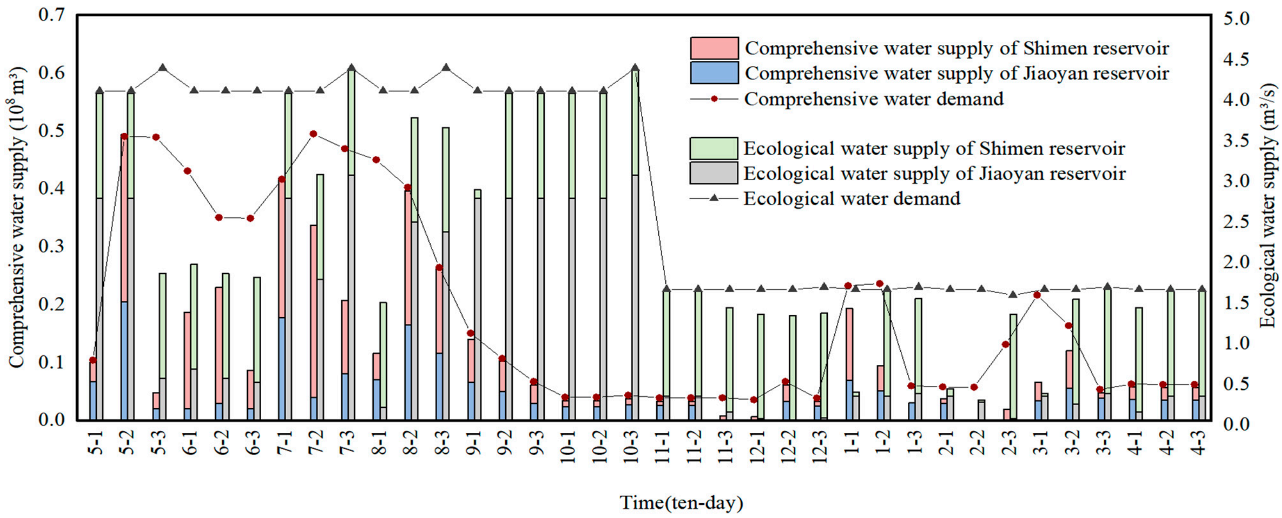
Figure 8. *Cont.*



(**b**)



(**c**)



(**d**)

Figure 8. Ecological and comprehensive water supply processes: (**a**) P = 25%; (**b**) P = 50%; (**c**) P = 75%; (**d**) P = 95%.

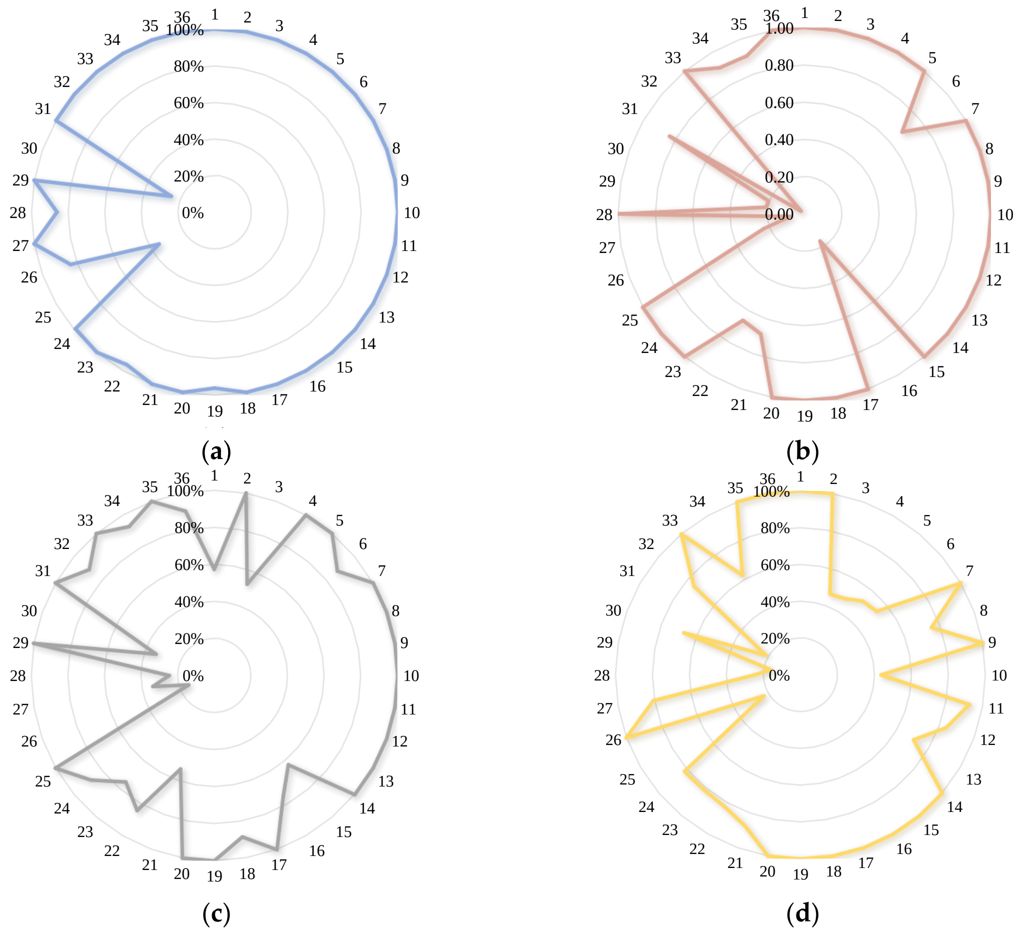


Figure 9. Satisfaction degree of ecological water supply per ten-day period from May to April of the next year: (**a**) P = 25%; (**b**) P = 50%; (**c**) P = 75%; (**d**) P = 95%.

In the wet year, there was more upstream inflow in the flood season, which could meet the comprehensive and ecological water demand at the same time. There was less upstream inflow in early November, early and late December, mid-January, and early and late February, and the optimal operation of parallel reservoirs could not satisfy the comprehensive and ecological water demand. Among them, in early November, early and late December, mid-January, and early February, the available water supply of Jiaoyan reservoir was limited, and Shimen reservoir undertook the main water supply task. Except for an individual ten-day period in the non-flood season, the ecological water demand could essentially be met. The maximum ten-day water shortage of comprehensive and ecological water demand was 7.2×10^6 m^3 and 1.0×10^6 m^3, respectively.

In the normal year, the upstream inflow was large in July, August, and September, which could meet the comprehensive and ecological water demand. The water shortage was mainly concentrated in mid-May, late June, late November, early December, mid-late January, February, early March, mid-March, early April, and mid-April. Among them, in late November, early December, early March, and early and mid-April, due to the limited water supply of Jiaoyan reservoir, Shimen reservoir was used to supplement the insufficient water supply. In the flood season, the satisfaction degree of the ecological water demand was 93.72% and the number of water shortage periods was two ten-day periods. In the non-flood season, the satisfaction degree was 70.86% and the number of water shortage periods was 10 ten-day periods. The maximum ten-day water shortage period of comprehensive and ecological water supply was 2.17×10^7 m^3 and 3.6×10^6 m^3, respectively.

In the dry year, the comprehensive water demand could be satisfied in July, August, September, and October, and the ecological water demand could be satisfied in July and

August. Due to the lack of upstream inflow, it is difficult to fully satisfy the water demand in other months. Among them, in early and late May, late November, early December, early February, mid-March, and early and late April, the inflow of Jiaoyan reservoir was low, and Shimen reservoir undertook the main water supply task. In the flood season, the satisfaction degree of the ecological water demand was 90.14%, and the number of water-shortage periods was 6. In the non-flood season, the satisfaction degree was 76.73%, and the number of water-shortage periods was 11 ten-day periods. The maximum ten-day water-shortage period of comprehensive and ecological water supply was 2.41×10^7 m^3 and 1.9×10^6 m^3, respectively.

In the extraordinarily dry year, due to the increase in upstream inflow in early and middle May, early July, late August, middle and late September, October, early and middle November, early and late March, and middle and late April, parallel reservoirs could meet the ecological and comprehensive water demand. In other periods, the ecological and comprehensive water supply were below the water demand line. In late November, early December, and late February, Shimen Reservoir undertook the main water supply task. In the flood season, the satisfaction degree of the ecological water demand was 81.48%, and the number of water-shortage periods was 9. In the non-flood season, the satisfaction degree was 72.44%, and the number of water-shortage periods was 12 ten-day periods. The maximum ten-day water-shortage period of comprehensive and ecological water supply was 4.46×10^7 m^3 and 2.3×10^6 m^3, respectively.

The new method proposed in this paper is applicable to the multi-objective optimal operation decision of a single reservoir and s reservoir group and has a certain universality. It should be noted that when constructing the model, the conflict degree among various objectives should be considered to avoid redundant objectives, resulting in a large number of false non-dominated solutions. In addition, when evaluating the schemes, it is necessary to consider the reservoir operation mode, operation objectives, attribute indexes, and decision-makers' preferences, and also take into account many objective factors such as actual water conditions and operating conditions.

By consulting relevant literature and similar studies, it was found that there are few studies on the multi-objective optimal operation decision of Jiaoyan–Shimen parallel reservoirs, and the application of TOPSIS-GCA in multi-attribute decision-making of reservoir operation is also rare. Reference [44] introduced the multi-attribute decision-making method based on GCA and TOPSIS to construct a multi-attribute risk decision-making model for flood control operations. Reference [45] adopted the NSGA-II-SEABODE algorithm to solve the multi-stakeholder coordinated operation model of the reservoir, and the relationship between irrigation benefit and ecological benefit was explored. Compared with previous studies, the NSGA-II-TOPSIS-GCA algorithm proposed in this paper can not only adapt to multi-objective problem solving and improve search efficiency but also consider the correlation among attribute indexes and the implicit relationship among the data, making the decision-making scheme more reasonable and feasible.

With the continuous advancement of ecological civilization construction, many comprehensive utilization reservoirs no longer simply pursue the maximization of economic benefits in actual operation. The benefit orientation focuses on ecological benefits and sometimes even sacrifices some economic benefits, which leads to the lack of enthusiasm of reservoir managers. In order to ensure the real implementation of the decision schemes, it is necessary for governments at all levels and water administrative departments to give full play to their social service and public management functions and to formulate and implement some practical and feasible security systems as soon as possible, such as clarifying the subjects of economic compensation, the standards of economic compensation, the sources of funds, the forms of compensation, and the corresponding accounting and supervision system. This will ensure the decision schemes are put into practice and produce benefits as soon as possible and play an active role in promoting the creation of a harmonious society of humans and water in the Hanjiang River Basin and ensuring the sustainable utilization of water resources.

5. Conclusions

The MOODPR is of great importance for the efficient utilization of hydropower resources, the protection of the ecological environment of river channels, and the improvement of the management level of parallel reservoirs. To solve the MOODPR problems, a new method of multi-objective optimal operation decision of parallel reservoirs was proposed. Taking Jiaoyan–Shimen parallel reservoirs as an example, the conclusions are as follows:

(1) Problem identification, model construction, optimization solution, and scheme evaluation are combined to build the MOOM and NSGA-II-TOPSIS-GCA algorithm. The decision schemes can be obtained from the alternative scheme sets, which can provide theoretical guidance for decision makers.

(2) By combining the Euclidean distance with the grey correlation degree, a new hybrid closeness degree considering the correlation among attribute indexes and the implicit relationship among the data is constructed, which makes the decision method more scientific and reasonable.

(3) Through the implementation of the new method of Jiaoyan–Shimen parallel reservoirs, this study explores the significant competition between the comprehensive water supply and ecology. The results provide scientific support for the planning, operation, and management of Jiaoyan–Shimen parallel reservoirs.

The multi-objective optimal operation of a reservoir group is a complicated dynamic decision-making process in essence, with dynamic changes among various water processes. The existing optimal operation of a reservoir group finds it difficult to cope with the complex and changeable operation environment and operation requirements, resulting in a large deviation between the operation effect and the expected effect. Most studies lack the compensation and economic incentive mechanism after operation, which affects the enthusiasm of various stakeholders. In addition, the multi-objective optimal operation of a reservoir group often pursues the optimal benefit of each objective such as the maximum water supply and the minimum ecological AAPFD value and pays insufficient attention to the key periods or key indicators of different objectives. We will consider the above problems in the follow-up study and constantly improve the theory and practice of the optimal operation of reservoir groups.

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