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Research on the Multi-Objective Cooperative Competition Mechanism of Jinsha River Downstream Cascade Reservoirs during the Flood Season Based on Optimized NSGA-III

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Abstract: This paper analyzes the complex relationship among flood control, power generation and ecological maintenance for the four cascade reservoirs located on the lower reaches of the Jinsha River, China. A weighted flood control index is incorporated and a constraining method consisting of the combination of a constrained corridor and a penalty function is proposed. A comprehensive utilization model is established in this paper based on the objectives of flood prevention, power generation, and ecological maintenance of the downstream cascade reservoir group of the Jinsha River during flood season. In addition, based on the coalescent selection of reference points and vector angles, an optimized non-dominated sorting genetic algorithm (VA-NSGA-III) is proposed. The algorithm is applied to the constructed model to define the cooperative competition mechanisms among these three targets, resulting in a set of non-inferior scheduling schemes with more uniformity and better convergence acquired with VA-NSGA-III. The scheduling program shows that there is a non-linear competitive relationship between the power generation and ecological effects of the cascade reservoirs during flood season, and the competitiveness weakens as the power generation increases. Furthermore, when the flood control is at low risk, there exists a complex coupling relationship between competition and coordination of the flood control, power generation, and ecological maintenance. While the risk appears high, there is a competitive relationship between flood control and power generation, with flood control being in synergy with ecological maintenance.

Keywords: cascade reservoirs of Jinsha River; comprehensive utilization during flood season; cooperative competition; NSGA-III; vector angle

1. Introduction

Since the late 1990s, hydropower projects in China have developed rapidly, and a complex and large-scale network of cascade reservoirs has emerged throughout the country. Currently, hydropower development in China is transitioning from building reservoirs at a high rate, to the better operational management of existing reservoirs. Optimization of reservoir groups has become the primary focus to improve the operational efficiency of cascade reservoirs in drainage areas. Reservoir group scheduling is an optimal control problem for a multi-objective, dynamic, and complex nonlinear system with a large number of constraints. The current scheduling method is mainly divided into two types based on rule extraction and optimization.

Regarding the scheduling model based on rule extraction, fuzzy systems, neural networks, data mining, and other methods are mainly used to perform clustering analysis, nonlinear mapping relationship analysis, logical association analysis, and other operations using a large number of historical data, from which expert knowledge and experience is extracted, and a practical scheduling rule is then abstracted. Some representative studies including Bolouri-Yazdeli et al. [1] compared the real-time scheduling rules of reservoir groups such as standard operation strategies and nonlinear decision rules with the satisfaction degree of downstream demand as the index and concluded that the nonlinear decision rule is more suitable for the real-time scheduling of reservoir groups. Bruwier et al. [2] evaluated the operation regulation of two multi-purpose reservoirs in the Vesdre Basin and the Meuse Basin in Belgium by establishing a model chain of hydrological models, river hydraulic models, reservoir system models, and flood damage models. Zhang et al. [3] proposed adaptive scheduling rules considering historical runoff information and future forecast runoff information under climate change, which can reduce the uncertainty and increase the robustness, and facilitates the adaptive operation of reservoirs. According to the storage and discharge function of the system, Zeng et al. [4] derived the optimal conditions for the general operating rules of parallel reservoirs in the case of water supply based on a two-period model. Following this, a new set of scheduling rules was proposed for the reservoirs in Northeast China, which effectively improved the reliability of the water supply.

Risks are ubiquitous in nature, and as for the integral dispatching of reservoirs in flood season, there are multiple risk factors such as the uncertainties of the flooding process, the ecological load, the hydraulics model, and the engineering facilities. Therefore, the analysis of the cooperative competition mechanism between multiple objectives contributes to risk decision-making in actual scheduling. Pietrucha-Urbanik K. et al. [5] pointed out that the risk decision-making means a measure by which to assess a hazard or threat resulting either from probable events beyond our control or from the possible consequences of a decision. Wang et al. [6] proposed a calculation method combining the analytic hierarchy process (AHP) method and the entropy weight method. Zhou et al. [7] proposed a comprehensive flood control function considering the safety of the dam itself and the lower reaches. Wu et al. [8], Yan et al. [9], Chen et al. [10], Dun et al. [11] and other scholars made in-depth research on the decision risk brought by the uncertainty of flood forecasting. These studies have shown a certain positive significance for the actual dispatching, but they mainly concentrate on the uncertainty of the flooding process, with only one risk factor considered, and lack a description of the risks of the ecological maintenance and power generation objectives.

Currently, the optimization-based scheduling method is most commonly used, with both conventional optimization and heuristic optimization scheduling usually being applied. The main difference between these two is the logic of the algorithm that implements the optimization. Conventional optimization scheduling is based on the dynamic programming method (DP) and its improvement, the progressive optimality algorithm (POA), and on the large system decomposition coordination method. However, heuristic algorithms such as the genetic algorithm (GA), particle swarm optimization (PSO) and a variety of new swarm intelligence algorithms are commonly used tools for heuristic optimal scheduling. Although it may not guarantee the feasibility and optimality of the solution, the advantages of self-organization, self-adaptation, and self-learning can give a higher quality solution under the reasonable computing resource condition and provides a new idea for solving the reservoir group scheduling problem. In recent years, there have been some representative studies on both conventional and heuristic scheduling: Ostadrahimi et al. [12] introduced a multi-group mechanism into the particle swarm optimization algorithm, and a set of "parameterization-simulation-optimization" scheduling methods combined with the HEC-ResPRM simulation model, was proposed, which was later applied to the optimized dispatching of the Mica, Libby, and Grand Coulee reservoir system in the Columbia River Basin. Chang et al. [13] constructed an adaptive mutation operator and crossover operator model based on a genetic algorithm to study the conflict between flood control and power generation in cascade reservoirs. Aboutalebi et al. [14]

proposed a non-dominated sorting genetic algorithm (SVR-NSGAII) that combines support vector regression (SVR) and nonlinear programming to minimize the errors made by SVR in extracting optimized operational rules and the number of input variables which serve as predictors in the regression model, thus optimizing the reservoir generation process. Chen et al. [15] improved the initial population generation of the NSGA-III algorithm, introduced the ε-domination and archiving strategies, and studied the coordination problems between downstream flood control safety and reservoir flood control safety in the Three Gorges reservoir area. Lei et al. [16] improved stochastic dynamic programming (SDP) based on the Copula function and linear regression, and applied it to the case study of the Ertan Reservoir, effectively improving the efficiency of the reservoir's power generation.

Considering the difficulties with high-dimensionality, nonlinearity, coupling, and uncertainty, it is more arduous to achieve the comprehensive utilization of reservoir groups during the flood season than by using other common multi-objective utilization methods. Mu et al. [17] analyzed the complicated water quantity and hydraulic linkages of the Three Gorges-Gezhouba cascade during the flood season, and then with the discharge flow of the Three Gorges adopted as the control factor, three schemes for the cascade operation during flood season were formulated. Liu et al. [18], considering the spillway, studied the multi-objective dispatching of the Three Gorges during the flood season. Based on the POA, the most effective operational scheme for the spillway was determined in their research. The smooth support vector machine model was used to solve the reservoir operation process, and then the scheduling rules concerning the number and sequence of activation of spillways were extracted. Generally, the existing studies regarding the comprehensive utilization of cascade reservoirs during the flood season have taken into consideration comparatively fewer targets and fewer reservoirs, so the number of overall decision variables is low, and intelligent algorithms can thus exert their advantages. As with the existing intelligent algorithms used to achieve the optimal scheduling of a reservoir group, especially its comprehensive utilization during the flood season, on the one hand, a large number of infeasible solutions that violate the constraints will appear in the solution process, resulting in a low searching efficiency; on the other hand, the population of decision variables is too large, making it easy to fall into the "dimensional disaster", which makes it difficult for an algorithm to converge.

Through the analysis of the various objective tasks, respectively, flood control, power generation, and ecological maintenance, undertaken by considering cascade reservoirs at the lower reaches of the Jinsha River, a dispatching method capable of balancing the needs of the various missions to maximize the benefits are studied in this paper. Additionally, through the introduction of vector angle selection strategy and improvement of the two random selections of individuals in randomly selected clusters for parental propagation and niche retention in NSGA-III, an improved non-dominated sorting genetic algorithm based on the reference point and vector angle selection (VA-NSGA-III) is proposed. Based on the model results acquired with the VA-NSGA-II, the collaborative competition mechanisms are discussed in this paper for three objectives: power generation, flood control, and the ecological benefits of the reservoir group.

2. Multi-Objective Problem Formulation

2.1. Research Area Overview and System Generalization

The lower reaches of the Jinsha River are rich in water energy resources. Four large reservoirs from the Panzhihua to Pingshan section known as Wudongde, Baihetan, Xiluodu, and Xiangjiaba have been built or are currently under construction, which are of great importance to China's energy framework alongside the contribution to flood control of the Yangtze River. The basic parameters of these four reservoirs are shown in Table 1.

As to the main stream of the lower channel segments from the Wudongde to the Xiangjiaba section, the generalization of the system is made according to the following features: (1) reservoirs with eximious regulation performance; (2) the sections of the important hydrometric station are set as the flow control section; (3) the establishment of water intake and outfall nodes. Combined with the hydrological data, the downstream stem is divided into eight river sections, for a total of seven nodes, as shown in Figure 1.

Table 1. The engineering characteristics of the Jinsha River downstream cascade reservoirs.

Reservoir	Dead Water Level (m)	Flood Control Level (m)	Normal High Water Level (m)	Upper Water Level for Flood Control (m)	Flood Control Storage Capacity (× 10^9 m^3)	Regulated Storage Capacity (× 10^9 m^3)	Installed Capacity (MW)
Wudongde	945	952	975	975	24.4	30.2	10,200
Baihetan	765	785	825	825	75	104.36	16,000
Xiluodu	540	560	600	600	46.51	64.62	13,800
Xiangjiaba	370	370	380	380	9.03	9.03	6400

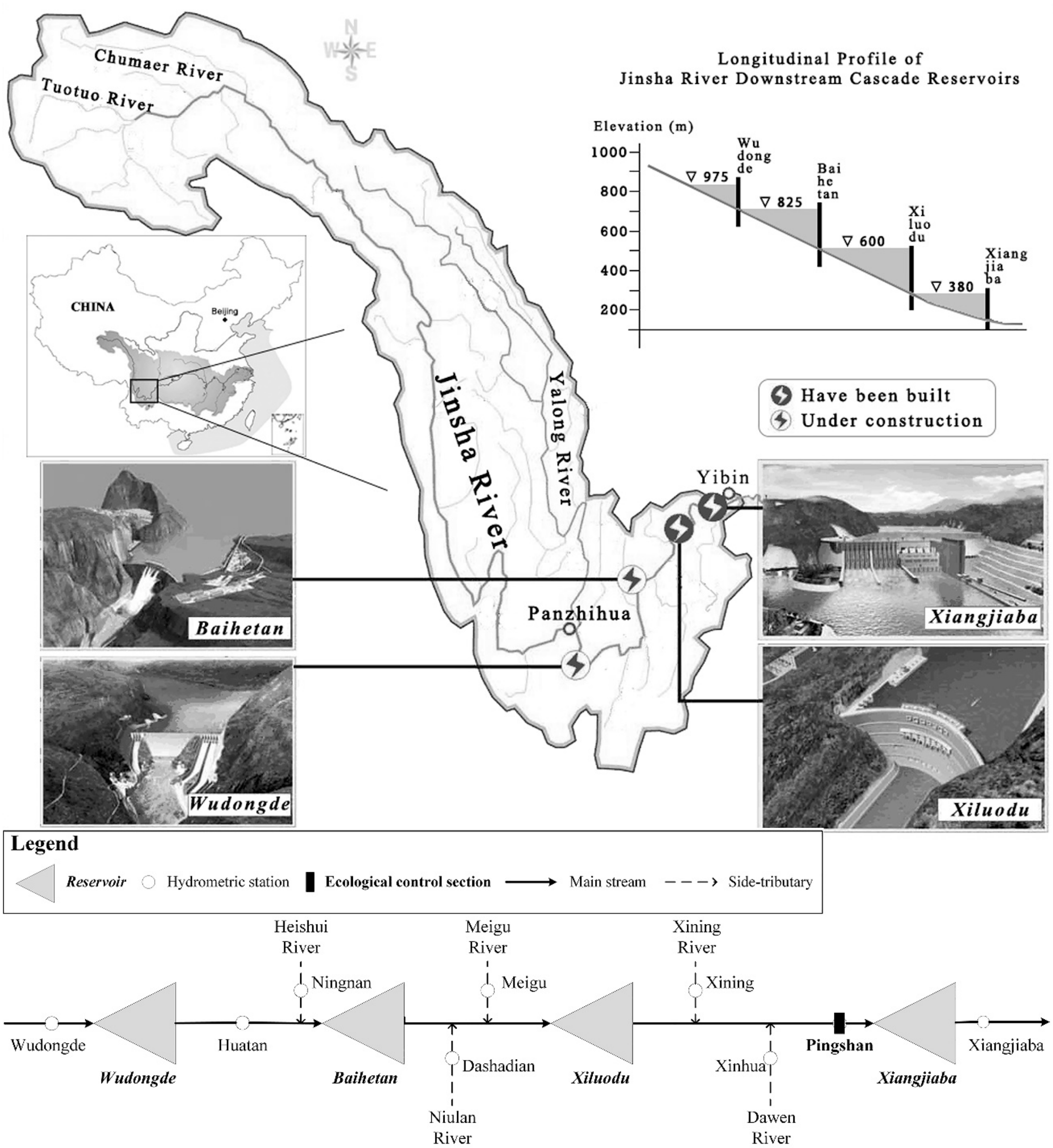


Figure 1. The schematic diagram of the Jinsha River downstream cascade reservoirs.

2.2. Multi-Objective Problem Identification

There is a complex cooperative competition relationship among the incommensurable objectives, respectively, power generation benefit, flood prevention mission, and maintenance of the river ecology of the reservoirs during flood season, which is the physical basis for the comprehensive utilization of cascade reservoirs.

The exploitation of power projects is in full swing for the reservoirs in the main stream of the lower reaches of the Jinsha River, with a total installed capacity of 46,400 MW, which occupies an important position in the Jinsha River Basin, even compared to the entire Yangtze River Basin, and plays an important role in the implementation of China's "West to East Power Transmission Project". With electrical capacity as the backbone of the national grid, it guarantees a high rate of power generation. Therefore, the maximum total energy generation is used as an objective in the course of the study in this paper.

Regarding the area between the Chuanjiang River and the Jinsha River, many major cities and towns, such as Yibin, Luzhou, and Chongqing, as well as extensive farmlands, are distributed on the first-level terraces of both banks and are vulnerable to flooding. In addition, the downstream cascade reservoirs of the Jinsha River must cooperate with the Three Gorges Dam to prevent floods in the middle and lower reaches of the Yangtze River and to reduce the probability of utilization of the flood detention areas. The general flood control requirements are to maintain downstream flood control safety and to ensure the safety of the reservoir itself. For the downstream flood control, the minimum largest discharge flow of the lowest-level reservoir of the cascade is always used as an objective; and for the reservoir safety, the minimum highest water level upstream of the dam is usually regarded as an objective.

To preserve the river's ecosystem, the amount of water in the channel and the upstream discharge flow must be controlled within a certain range. Otherwise, an excess or deficiency of water will have an adverse impact on the ecology of the river. Therefore, for the ecological goal, the minimum suitable ecological water deficit and overflow are used as the objective. According to the "Comprehensive Planning of the Yangtze River Basin", there is only one ecological control section—Pingshan Station—located downstream of Xiluodu in the lower reaches of the Jinsha River, and its suitable ecological flow rate is 1954 m^3/s during flood season.

As to a single reservoir, the competition between multiple targets during flood season is mainly reflected in the contradiction between power generation efficiency and flood control during the main flood period. When releasing water before the flood season, each reservoir strives to prolong its running time with high water levels, but this may cause artificial flooding owing to concentrated water discharge. When storing water at the end of the flood season, each reservoir makes efforts to fill up with water as soon as possible, but owing to the centralized water storage, new issues concerning flood protection, water supply, shipping, and ecology may emerge. Considering the ecological target to meet the water demand of the basin ecosystem, the discharge flow should be moderated to prevent large deviations from the appropriate ecological flow. However, to prevent flooding, the discharge flow is bound to increase during flood season. A high water head ensures the efficiency of power generation. However, the reduction of the discharge flow to maintain a high water head is in conflict with the suitable ecological flow. Thus, there is a complex cooperative competition relationship among the incommensurable objectives: power generation efficiency, flood prevention, and preservation of the river ecology.

In the case of multiple reservoirs, it is necessary to share the power generation efficiency implied by high water levels, leading to competition for limited water amounts and the time of water storing during storage periods at the same time. Meanwhile, the potential risk of flooding at the end of the season must be considered. The combined effect of the above factors significantly complicates the realization of optimal scheduling.

3. Multi-Objective Model

3.1. Objective Functions

According to the analysis in Section 2.2, the complex demands of power generation, flood control and river ecology in the lower reaches of Jinsha River during flood season can be generalized as follows:

(1) Power generation objective, the maximum total energy generation of the cascade reservoirs is defined by:

$$\max f_1 = \max E = \sum_{i=1}^{M} \sum_{t=1}^{T} N_{i,t} \times \Delta T \tag{1}$$

where E is the total generated energy of the cascade reservoirs, $N_{i,t}$ is the output of the i-th reservoir during the t-th period, M is the total number of cascade reservoirs, T is the total length of the period, and ΔT is the length of a certain interval.

(2) Flood control objective a, the minimum largest discharge flow is

$$\min f_{2a} = \min\left\{\max q_{i,t}\right\} \tag{2}$$

where $q_{i,t}$ represents the discharge flow of the i-th reservoir during the t-th period.

Flood control objective b, the minimum highest water level upstream of the dam is

$$\min f_{2b} = \min\left\{\max Z_{i,t}\right\} \tag{3}$$

where $Z_{i,t}$ represents the water level upstream of the dam of the i-th reservoir during the t-th period.

(3) Ecological objective, the minimum suitable ecological water deficit and overflow is

$$\min f_3 = \sum_{l=1}^{L} \sum_{t=1}^{T} |R_{l,t} - E_{l,t}^{app}| \tag{4}$$

where L is the total number of ecological control sections, $E_{l,t}^{app}$ is the suitable ecological flow of section l at time period t, and $R_{l,t}$ is the actual flow of section l at time period t.

3.2. Constraints

The optimal scheduling of the reservoir group should be carried out under certain restrictions, including the following constraints:

(1) Reservoirs water balance principle constraint:

On a daily timescale, the water balance equation of the reservoirs in unit time is

$$V_{i,t+1} = V_{i,t+1} + (I_{i,t} - Q_{i,t} - E_{i,t}) \times \Delta T \tag{5}$$

where $V_{i,t}$, $V_{i,t+1}$ represent the storage capacities (m^3) of the i-th reservoir respectively at the beginning and end of the t-th period (s); $I_{i,t}$, $Q_{i,t}$ respectively represent the average inflow and outflow (m^3/s) of the i-th reservoir during the t-th period; $E_{i,t}$ represents the flow loss (m^3/s) of the i-th reservoir in the t-th period; ΔT is the calculation period length (s).

(2) Reservoir discharge flow constraint:

$$q_{i,t}^{min} \leq q_{i,t} \leq q_{i,t}^{max} \tag{6}$$

where $q_{i,t}^{min}, q_{i,t}^{max}$ represent, respectively, the minimum and maximum allowed discharge flows (m^3/s) of the i-th reservoir in the t-th period (s).

(3) Reservoir operational water level constraint:

$$Z_{i,t}^{min} \leq Z_{i,t} \leq Z_{i,t}^{max} \tag{7}$$

where $Z_{i,t}^{min}, Z_{i,t}^{max}$ represent the lower and upper limit permissible water levels (m) upstream of the dam of the i-th reservoir in the t-th period (s), which are respectively set to the limited water level and the upper water level for flood control.

(4) Discharge flow amplitude constraint:

$$\left|q_{i,t+1} - q_{i,t}\right| \leq \Delta q_i \tag{8}$$

where Δq_i is the maximum allowable amplitude of the flow (m^3/s) of the i-th reservoir during the two periods before and after discharge.

(5) Output constraints:

The discharge flow turns the turbines and generates electricity under normal circumstances, and if it exceeds the maximum overcurrent capacity of the turbines, discarding of the surplus water will occur based on:

$$qE_{i,t} \leq qE_{i,t}^{max} \tag{9}$$

where $qE_{i,t}, E_{i,t}^{max}$ respectively represent the discharge flow rate (m^3/s) and the maximum overflow capacity (m^3/s) of the hydraulic generator units of the i-th reservoir at the t-th period (s).

3.3. Objectives and Constraints Processing

As to the flood control target, taking the strong competition between the two objectives into consideration, i.e., protection of the reservoir itself and maintaining downstream flood control safety, a solution appears to be complicated and intractable. Therefore, to reduce the target quantity and enhance the solution's efficiency, the balanced flood control index [7] is introduced to assess the flood control risk. Specifically, based on the division of tasks, the protection of the reservoir itself and maintaining downstream flood control safety, among the reservoirs, weights are introduced to improve the original formula, and then the dimensionless objective which called Weighted Flood Control Index (WFCI) is obtained.

$$\min f_2 = \min \sum_{i=1}^{n} \sum_{t=1}^{T} \left(\alpha \frac{Z_{i,t} - Z_{i,t}^{min}}{Z_{i,t}^{max} - Z_{i,t}^{min}} - \beta \frac{q_{i,t} - q_{i,t}^{min}}{q_{i,t}^{max} - q_{i,t}^{min}} \right)^2 \tag{10}$$

here, α is the weight of the water level upstream of the dam, β is the weight of the discharge flow; they are dimensionless, and their values are determined by the specific tasks undertaken by each reservoir. $Z_{i,t}, Z_{i,t}^{min}, Z_{i,t}^{max}$ are respectively the water level (m) upstream of the dam, and the maximum and minimum water level (m) limits of the i-th reservoir at the t-th period (s). $q_{i,t}, q_{i,t}^{min}, q_{i,t}^{max}$ are respectively the discharge flow (m^3/s), and the maximum and minimum outflow rate (m^3/s) limits of the i-th reservoir at the t-th period (s).

For the ecological target, in practical applications, it is easy to encounter jitter of the decision variable in the solution of the objective function in the form of an absolute value. Therefore, the square sum is utilized to eliminate the jitter to some extent as follows:

$$\min f_3 = \sum_{l=1}^{L} \sum_{t=1}^{T} \left(R_{l,t} - E_{l,t}^{app}\right)^2 \tag{11}$$

here, all variables have the same meaning as Equation (4), and the result is called the square sum of the ecological water deficit and overflow (SSEDO).

There is a flow-related influence relationship among the 'discharge flow constraint', 'operational water level constraint', and 'discharge flow amplitude constraint'. Therefore, it is difficult to satisfy all three constraints at the same time by using a sequential structure, resulting in a deformed solution. In this regard, some researchers introduced the penalty function method to help deal with these issues [19], but in the case of long series high-dimensional complex targets, the penalty function alone is insufficient to correct the search direction of the population in an intelligent algorithm, because the calculation iterations will be tremendously increased. Therefore, a constraining method combining a constrained corridor and a penalty function is proposed to deal with the constraints considered in this paper.

As for the 'discharge flow constraint' and 'operational water level constraint', they are considered to have a higher priority and are thus controlled by the constrained corridor method and given a corridor elastic boundary, while the 'discharge flow amplitude constraint' uses only the penalty function method, so the ultra-variable process is to be punished using the two constraining methods. The objective function is eventually reconstructed as follows:

$$g_N = f_N + \sum_{i=1}^{n} \sum_{t=1}^{T} G_{i,t} \tag{12}$$

$$G_{i,t} = \begin{cases} 0 & \Delta q_{i,t} \le \Delta q_i \\ \mu[\Delta q_{i,t} - \Delta q_i]^{\omega} & \Delta q_{i,t} > \Delta q_i \end{cases} \tag{13}$$

where g_N is the N-th objective function after processing and f_N is which before processing, corresponding to Equations (1), (10) and (11), $G_{i,t}$ is the calculated result (dimensionless) of the penalty function of the i-th reservoir at the t-th period (s), and μ and ω are the penalty factors, which are all positive constants and must be adjusted according to the actual conditions.

4. Optimized NSGA-III Algorithm (VA-NSGA-III)

Deb and Jain [20] proposed the NSGA-III algorithm, based on the well-known NSGA-II, with mphasis placed on changing the selection mechanism of NSGA-II. A set of reference points is defined in advance and points are updated adaptively on a standardized hyperplane. Thus, the performance can be defined by measuring the distance between individuals in the population and the reference point sets. Generally, to generate reference points, the method proposed by Das and Dennis [21] is applied to create some points on a hyperplane within a unit intercept (of $m-1$ dimension, where m is the target number).

Because the reference points are widely distributed on the hyperplane, and they have a close correlation with the population's individuals, the solution individuals can be widely distributed in the solution space as well, and the solution set obtained is globally optimal. Therefore, the reference-point-based selection strategy can ensure a diversity of solutions.

Compared with NSGA-II, NSGA-III has strong convergence capability for optimization when the number of targets exceeds three, owing to the main improvement based on the 'reference point', so NSGA-III has been widely used in the engineering field. However, in the field of multi-objective, long-series scheduling of reservoirs, it has shown some limitations and is rarely applied. Furthermore, with an increase in the number of targets, NSGA-III becomes much less capable of generating a sufficient momentum to bring evolutionary populations to the Pareto frontier, resulting in poor convergence performance. Despite these issues, there is still room for improving the algorithm. Therefore, an optimized algorithm on the basis of NSGA-III is proposed in this paper to solve the problem of comprehensive utilization of reservoirs during flood season.

Xiang et al. [22] applied the maximum-vector-angle-first strategy to improve the searching direction of the evolutionary population itself and proposed the VaEA algorithm. Fitness is measured by the vector angle between each pair of solutions.

For a standardized solution space, the minimum vector angle between each individual and the current solution is first calculated, and then based on the maximum-vector-angle-first principle, the largest angle is selected from all the minimum vector angles and the next generation is created, thus optimizing the search direction; individuals with a vector angle of 0 are considered to have been included in the search direction in advance.

As a simple example is shown in Figure 2, for the population Y, the vector angles between different pairs of individuals, respectively X_1 and Y_1, X_2 and Y_1, X_3 and Y_2 are minimum, and as for X_4, the vector angle is 0. Because X_2 has the comparatively maximum minimum vector angle, it is finally selected to enter the next generation of the population. X_4 is in the same known search direction.

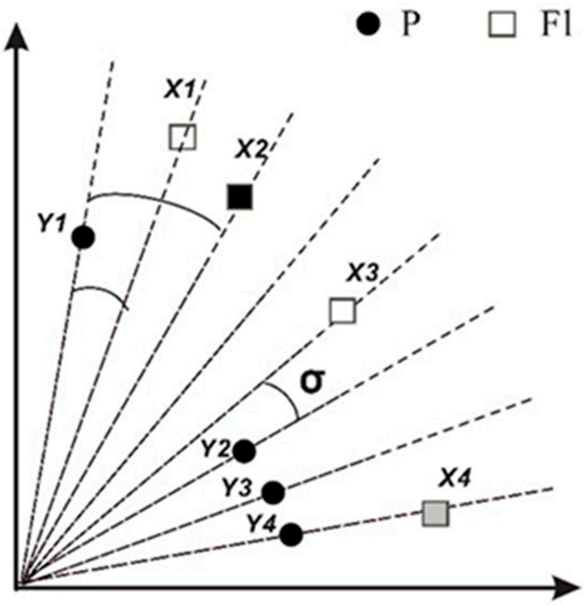


Figure 2. Vector Angle Selection Strategy.

Convergence and diversity are considered at the same time in the selection strategy based on the vector angle, and a good balance is achieved. The search direction can be determined quickly and the solution efficiency is vastly improved.

The original NSGA-III has two random selection processes, one is to randomly select the parent to reproduce; the other is that in the process of niche reservation when the niche number is greater than 0, the individuals that enter the next population will be randomly selected. Based on these two random selection processes, VaEA's vector-angle-based selection strategy is introduced, combined with the reference-point-based selection strategy to improve the selection process:

4.1. Step 1 Initialization

An initial population of size N is randomly generated and each individual $X_i(i = 1, 2, \ldots, N)$ in the population is a decision variable, with its initial value set to a random value of the discharge flow within an allowable band.

4.2. Step 2 Reproduction

Each individual is associated with a reference point and the mating parent is determined and selected through a 2-tournament in two phases: first, the reference point with a smaller number of niches is predominant; then, the shorter the Euclidean distance between the ideal point and the individual associated with the reference point selected previously is considered as the more favored. Offspring populations are generated based on the simulated binary crossover (SBX) and on polynomial mutations during reproduction.

4.3. Step 3 Normalization

VaEA's simple normalization method is applied. The ideal point and nadir point are determined by the minimum and maximum target values in the current population. The normalization goal of the j-th generation is calculated by

$$f'_j(X_i) = \frac{f_j(X_i) - Z_j^{min}}{Z_j^{max} - Z_j^{min}} (j = 1, 2, \cdots, M) \tag{14}$$

where Z_j^{min} is the value of the ideal point, Z_j^{max} is the value of the nadir point and M is the number of objectives.

4.4. Step 4 Non-Dominated Sorting

Through non-dominated sorting, the current population (P_t) can be combined with the newly generated offspring population(Q_t) to form a new population (R_t), and the 2N individuals in R_t are divided into different levels of non-dominated layers (F_1, F_2, ... , F_l). Starting from F_1, individuals are selected one layer at a time to enter the next new population, known as P_{t+1}, until the total number of selected individuals reaches or exceeds N for the first time. If the last selected individuals are at the layer F_l, individuals at the subsequent layers will all be discarded. The combination of the new population P_{t+1} and the last dominant layer F_l proceeds to the next step.

4.5. Step 5 Association

According to the description by Deb and Jain [14], a set of reference points is generated in the normalized target space, and for each individual, we calculate its distance to all reference lines. Then we select the reference line with the shortest vertical distance, and the individual will be associated with the reference point on the selected line.

4.6. Step 6 Niching

The purpose of the niche-preserving process is to retain individuals satisfying certain conditions in F_l for the next generation and to integrate them into the population P_{t+1} until the population number reaches N. I_j represents a set of individuals in F_l associated with reference point j. The operation process of NSGA-III is to select the reference point j* first, in each iteration, with the smallest number of niches. If the number of niches equals zero, an individual who has the minimum vertical distance from the reference line will be selected from I_{j^*} instead; if the number of niches is greater than 0, then an individual will be selected randomly from I_{j^*}. For the stochastic process of randomly selecting individuals to enter P_{t+1} when the number of niches is greater than 0, the vector angle selection strategy (shown in Fig.2) is adopted for optimization in VA-NSGA-III, and the individuals in F_l and those with the maximum minimum vector angles are added to P_{t+1}. The vector angle between X_i and X_j can be calculated by Equations (15)–(17):

$$angle\left(X_i, X_j\right) = arcos\left|\frac{F'(X_i)F'\left(X_j\right)}{norm(X_i)norm\left(X_j\right)}\right| \tag{15}$$

$$F'(X_i)F'\left(X_j\right) = \sum_{k=1}^{M} f'_k(X_i) f'_k\left(X_j\right) \tag{16}$$

$$norm(X_i) = \sqrt{\sum_{k=1}^{M} f'_k(X_i)^2} \tag{17}$$

The flow of the entire VA-NSGA-III algorithm is shown in Figure 3.

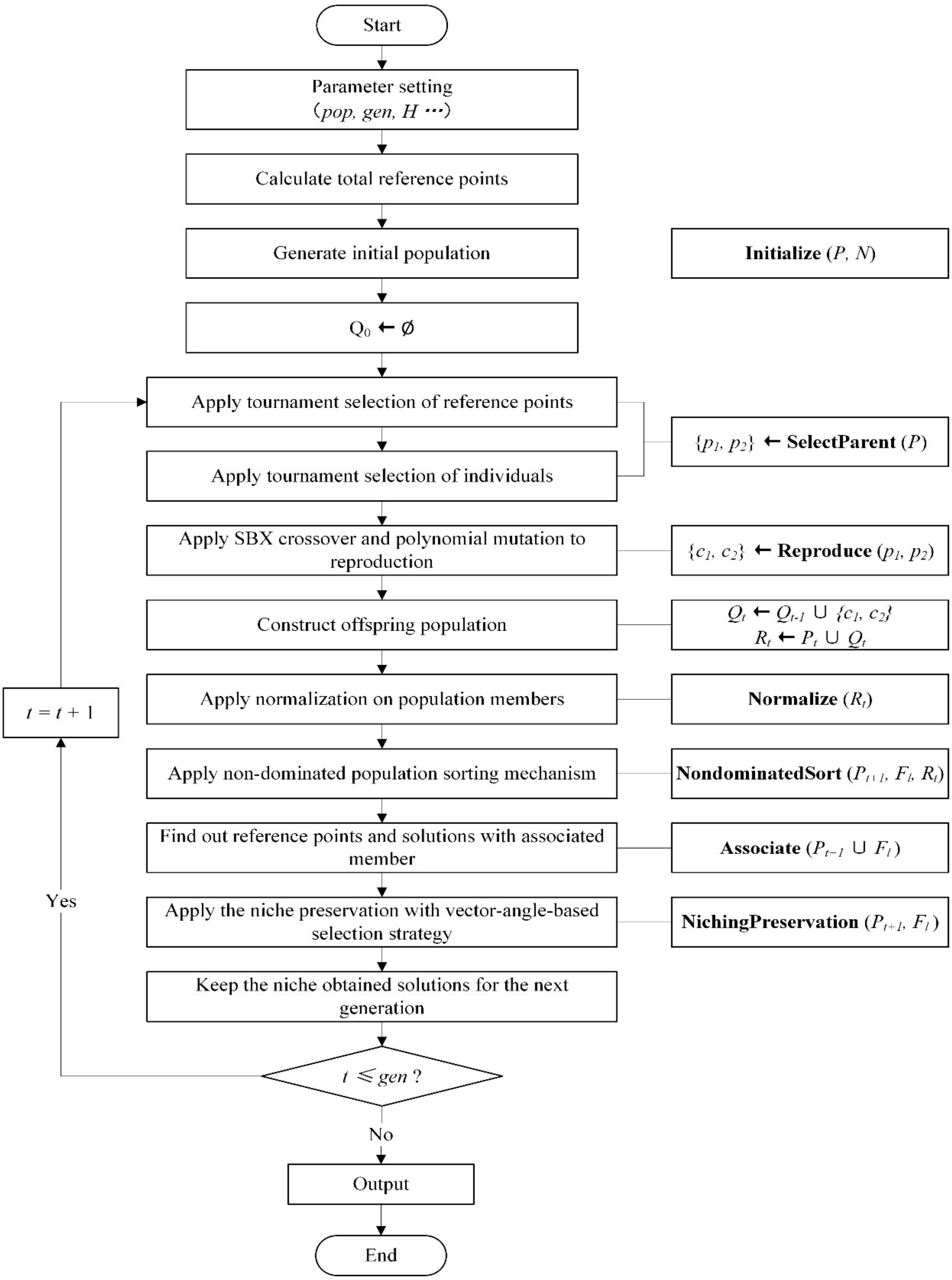


Figure 3. The flow chart of VA-NSGA-III.

5. Application and Discussion

5.1. Simulation Parameter Setting and Solving

VA-NSGA-III is applied to the multi-objective comprehensive utilization model of the Jinsha River downstream cascade reservoirs during the flood season. As described in Section 2, there are four reservoirs in the lower reaches of the Jinsha River, which undertake complicated tasks of power generation, flood control and river ecological maintenance in the flood season. According to the "Joint Operation Plan of Reservoirs in the Middle and Upper Reaches of the Yangtze River in 2017", the flood season in the lower reaches of the Jinsha River occurs from July 1 to September 10, for a total of 72 days. On a daily timescale, with discharge flows as decision variables, the number of decision variables reaches 288 for the four reservoirs as a whole. Under the premise of a daily timescale, the change of discharge flows caused by the operation of the gate and other types of equipment are averaged by the time interval. Therefore, as for the decision variables, the effects of the application of hydraulic structures such as gates, spillways and drainage outlets are not considered in more detail.

Comparatively large floods occurred in the flood season of 1981. No reservoirs had been built in the lower reaches of the Jinsha River at the time, and the measured runoff was close to the natural runoff. Therefore, the flood season sequence of 1981 is selected as the input, and the flood control level used is the original regulating method for the comprehensive utilization calculation of the cascade reservoirs during flood season in this paper.

With regard to the algorithm parameters, the crossover probability is initially set to 1.0, the SBX index to 30, the mutation probability to 1/288, the polynomial variation distribution index to 20, the population size to 120, and the number of engaged generations to 1000.

In terms of the model parameters, according to the "Joint Operation Plan", the flood control task of the Jinsha River downstream cascade reservoirs is to ensure the flood control safety of the dam first, and then to help relieve the downstream flood prevention pressure. Therefore, the target of the reservoir safety is more important, so the weight value of the water level upstream of each dam (α) is set to 0.8, and the discharge flow (β) is set to 0.2. Furthermore, the well-tried values of μ and ω in this study are respectively set to 4 and 1.3 to ensure the punishment effect of the penalty factor and to deter the penalty function value from being too large.

5.2. Simulation Results Comparison

To verify the effectiveness and superiority of VA-NSGA-III, the NSGA-III, VaEA, and VA-NSGA-III algorithms are used for the calculation process under the same conditions, and the results obtained by the three different algorithms are compared and analyzed. Figure 4 shows the Pareto frontiers and their projections on the XY, XZ, and YZ planes acquired for the three different algorithms. The X, Y, and Z axes respectively represent the SSEDO, the WFCI, and the power, all with penalty terms which are calculated by Equation (13).

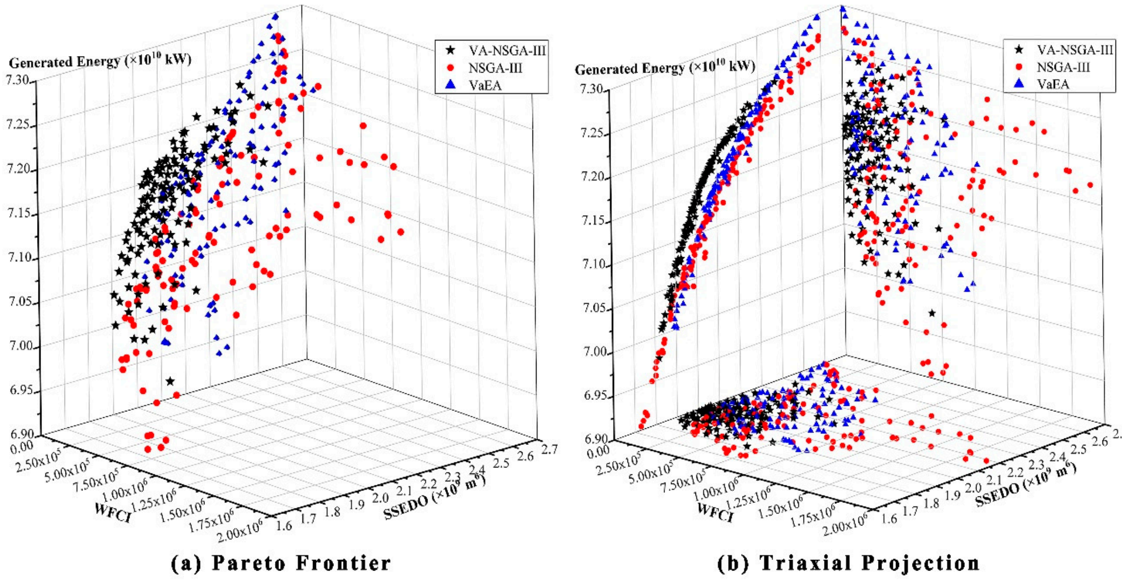


Figure 4. The Pareto frontier and tri-axial projections of the three algorithms.

Figure 4 indicates that under the same conditions, the Pareto frontier distribution obtained by the VA-NSGA-III algorithm is comparatively the most concentrated and uniform compared to NSGA-III and VaEA.

Boxplots are used to statistically analyze the objective function values with penalty terms of the Pareto frontier, as shown in Figure 5. Regarding the flood control target, first, the WFCIs of the three algorithms share the same lower boundary, whereas VA-NSGA-III has the lowest upper boundary. Second, in reference to the position of the upper and lower tail lines and the average points, the variance of the solution set of VA-NSGA-III is obviously the smallest. The variance represents the dispersion degree of the solutions' distribution of VA-NSGA-III, it proves to be the smallest. Third, regarding the top and bottom quartiles, VA-NSGA-III has the lowest box height and the data representing the solution have the least fluctuation as well. Fourth, the median of VA-NSGA-III is the smallest and is closest to the middle of the box shape and the average level of the calculated WFCI is the lowest. In addition, the distribution skewness of the characteristic solution is comparatively weak. Finally, although VA-NSGA-III has outlier values, it overmatches NSGA-III. The VaEA does not have outlier values, its tail line range exceeds the outlier value point. To conclude, VA-NSGA-III proves to be superior to NSGA-III and VaEA.

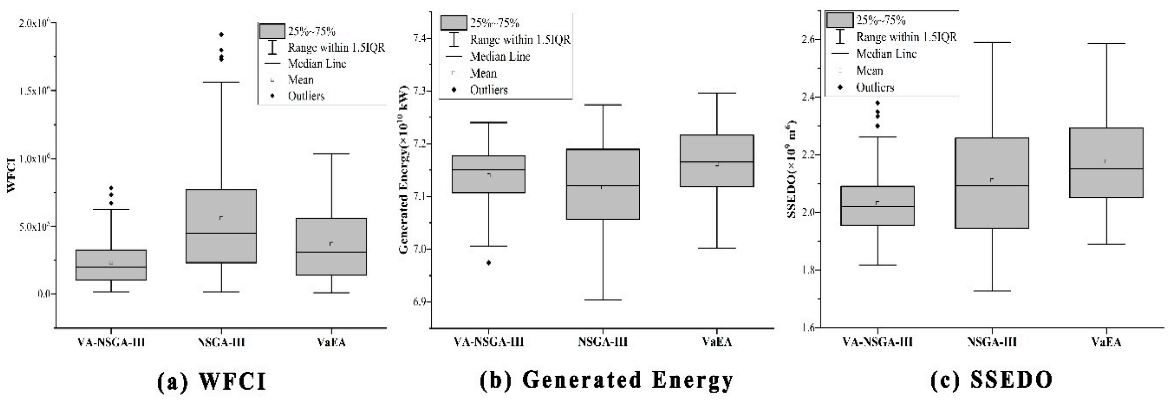


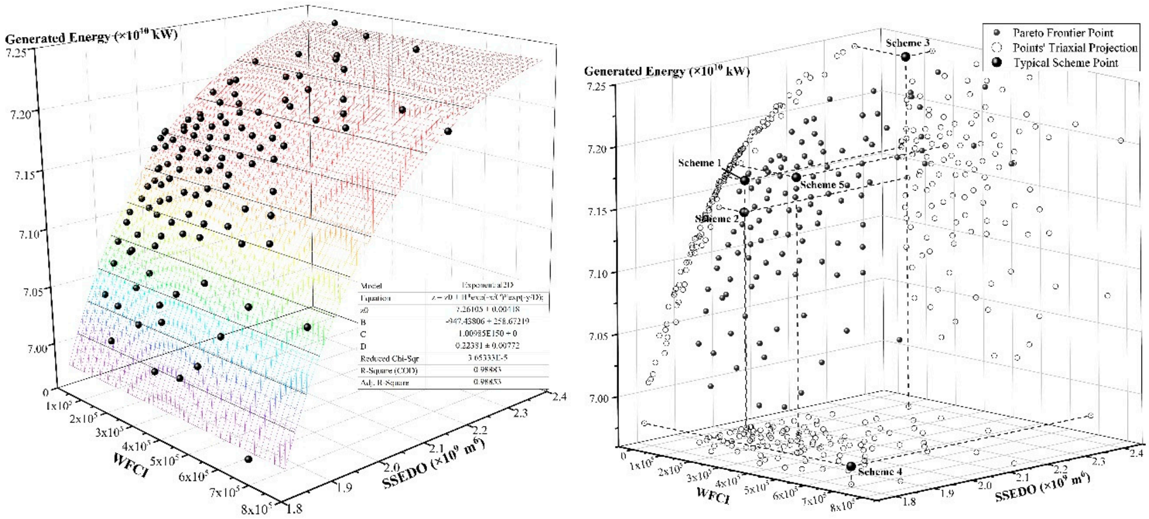
Figure 5. The box plot of each Pareto frontier target value of the three algorithms.

Similarly, for power generation and ecological objectives which are represented in Figure 5b,c respectively, VA-NSGA-III provides significant advantages in terms of the degree of dispersion, fluctuation, and skewness of the solution. Although there are some outlier points in the solution set of VA-NSGA-III, these outlier points scarcely deviate from the boundary and are still within the tail line range of the other two algorithms.

Therefore, from a statistical point of view, it can be considered that VA-NSGA-III performs better than both NSGA-III and VaEA when applied to the comprehensive utilization model of the downstream cascade reservoirs of the Jinsha River during flood season.

5.3. Simulation Results and Cooperative Competition Mechanism Analysis

The solution set obtained by VA-NSGA-III is analyzed independently. As shown in Figure 6a, the spatial distribution surface of the Pareto frontier is relatively smooth, and the internal distribution tends to be dense and uniform. Furthermore, none of the three targets gains absolute superiority, and in reference to the Pareto frontier tri-axial projection shown in Figure 6b, there is an apparent functional relationship between the power generation target and the ecological target under the influence of the three overall objectives (power generation, flood control, and ecological maintenance), whereas the relationships between the flood control target and the ecological target, as well as between the flood control target and the power generation target, are not very obvious.



(a) Fitting Surface of Pareto Frontier **(b) Pareto Frontier and the Typical Schemes**

Figure 6. The Pareto frontier of VA-NSGA-III.

To analyze in detail the relationships among the three objectives, from the perspective of the universality of the sample, the penalty function values of the solution sets are first calculated, and then they are subtracted from the original target values to obtain the true target values, from which five groups of non-inferior solutions are obtained for further analysis (Scheme 1–Scheme 5): the minimum penalty function value-oriented scheme (to best satisfy the constraints), the minimum WFCI-oriented scheme (with a bias toward the flood control), the maximum generated energy-oriented scheme (with a bias toward power generation), the minimum SSEDO-oriented scheme (with a bias toward ecological preservation), and the center of the intensive part of the solution sets-oriented scheme (equilibrium). In addition, the position of the selected scheme in the Pareto frontier is shown in Figure 6b, and the true target values of each scheme are shown in Table 2:

Table 2. The scheduling results of each typical scheme with VA-NSGA-III.

Scheme		1	2	3	4	5
Focus		Constraint	Flood Control	Power Generation	Ecological Maintenance	Equilibrium
Target value	WFCI	1354	1230	29,314	34,971	90,109
	Generated Energy ($\times 10^{10}$ kW)	7.158	7.134	7.240	6.974	7.166
	SSEDO ($\times 10^9$ m^6)	2.037	2.020	2.380	1.818	2.507

It can be inferred from Table 2 that, as the generated energy increases, the SSEDO generally presents an increasing trend. That is, as the power generation efficiency increases, the ecological benefit decreases, and the competition between the power generation and ecological targets is very obvious. According to the analysis, water quantity is abundant during flood season benefitting power generation, and the cascade reservoirs will always operate under high water heads, which leads to the increase of the flow amplitude, thus raising the ecological water deficit and overflow, and the ecological benefit tends to be low. These mechanisms explain why the power generation and ecological targets exhibit contradiction during flood season. Non-dimensional analysis of the SSEDO and generated energy is performed, calculated through the Levenberg–Marquardt iterative algorithm, and a nonlinear equation based on the natural base is eventually fitted (Figure 7). The results show that when the generated energy is relatively small, then as the power generation efficiency increases by 1%, the ecological benefit decreases by 1.46%. As the generated energy becomes larger, then as the power generation efficiency increases by 1%, the ecological benefit decreases by 0.06%. When the power generation efficiency increases further, the competition between the power generation and ecological targets will gradually decline.

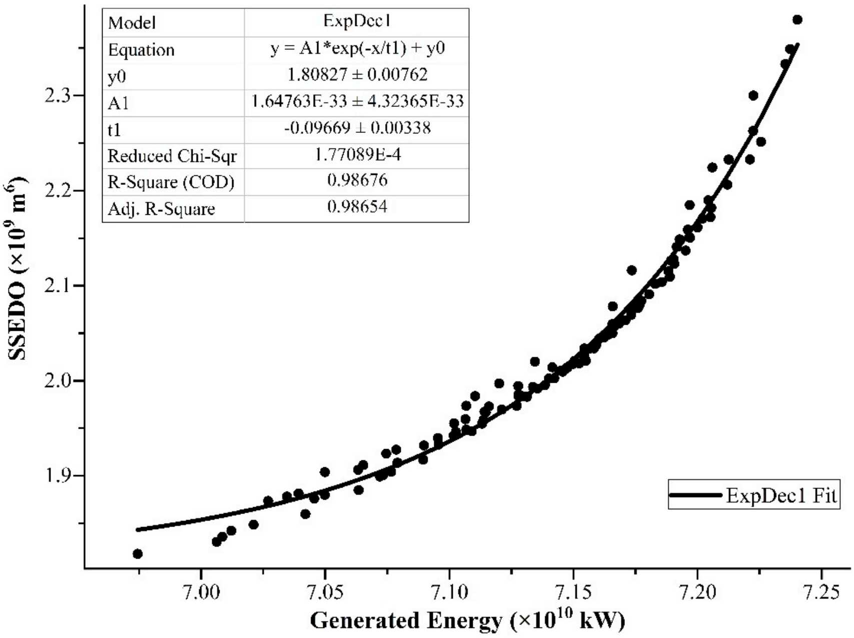


Figure 7. The non-dimensional analysis of the square sum of the ecological water deficit and overflow (SSEDO) and generated energy.

In terms of the relationship between flood control and power generation targets and that between flood control and ecological targets, the impact of the change of WFCI on power generation and ecological maintenance is not very large, and there is no obvious trend involving simultaneous increases or decreases (Figure 6). In order to analyze the two groups of complex relationships, we use the statistical analysis method to calculate the established model with the same parameters 5 times and plot the Pareto points obtained in the 5 times on the same graph. Their projection on the X-Y and X-Z planes is shown in Figure 8.

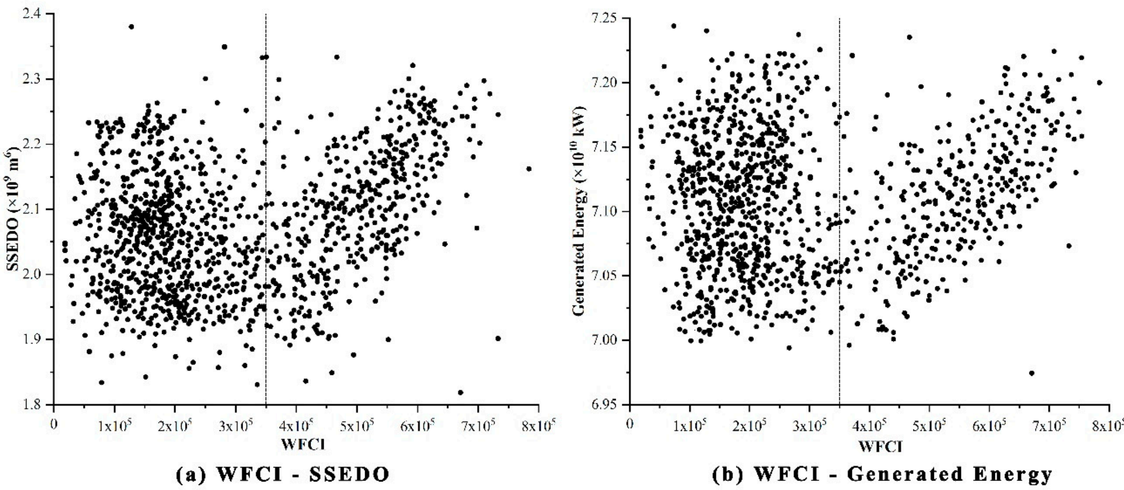


Figure 8. The biaxial projection graph of Pareto frontier sets.

It can be inferred from the total sample that when the WFCI is less than or equal to 350,000, the points within the solution spaces of the flood control and power generation targets and those between the flood control and ecological targets are relatively evenly dispersed, and there is no simple collaborative or competitive relationship between the flood control target or the power generation and ecological targets. According to the analysis, because the WFCI comprehensively examines the two objectives of dam protection and downstream safety, increasing and decreasing the discharge flow will increase its index value. Second, to increase the power generation efficiency, the cascade reservoirs should operate under high water heads, which impairs dam protection. However, if the benefits of power generation are completely abandoned, the discharge will increase, which can be highly unfavorable to the downstream safety condition. Therefore, both the increase and decrease of power generation efficiency within a certain range will lead to the reduction of flood control benefits, so the relationship between power generation and flood control is not unary. In addition, the ecological benefits are appraised by the ecological water deficit and overflow, and both the increase and decrease of the discharge will eliminate this difference if the appropriate ecological flow is achieved, thus its coupling with the flood control target involves a complicated relationship.

When the WFCI is greater than 350,000, as it increases, both the generated energy and SSEDO increase at the same time. There is a competitive relationship between flood control and power generation, and a synergistic relationship between flood control and ecological maintenance. According to the analysis, a large WFCI is generally induced by the excessive fluctuation of the discharge flow in accordance with the characteristics of the flood season. As the WFCI continues to increase, the amplitude of the discharge flow is bound to increase as well, leading to the loss of the ecological target and an increase of the power generation efficiency at the same time. The increased WFCI also represents an increase in the flood control risk. This case represents the accordant relationship between flood control and ecological maintenance, while that between flood prevention and power generation is competitive when the flood control target tends to be unfavorable.

Figure 6b also indicates that the true value of WFCI in Scheme 4, ranks fourth, which is lower than Scheme 5, while its value with the penalty function is considered to be much greater than those of other schemes. As such, the penalty function value of Scheme 4 is very large, and the scheme violates the constraints excessively compared with other schemes. This is because the ecological objective measures the violation of the appropriate ecological flow, meaning both excess and deficiency will produce positive values to Equation (11). Thus to minimize the SSEDO, it is necessary to adjust the flow rate that reaches the Pingshan section as close as possible to the appropriate ecological flow value. Once the flow in the channel is excessive, it is vital to reduce the discharge immediately. Similarly, when the flow in the channel is insufficient, it is necessary to increase the discharge to maintain the appropriate ecological flow. Therefore, under the scheme with a bias toward power generation, this sort of adjustment becomes the primary task, and inevitably, there will be a strenuous variability of the discharge flow, inducing a discharge amplitude that greatly violates the constraint.

Under the five typical schemes, the scheduling process of each reservoir is shown in Figure 9. It can be found that in Wudongde, the five schemes are not much different, because as the first reservoir of the cascade, the adjustment range is limited under the same inflow conditions. However, the slight differences in Wudongde's discharge are magnified in the following three reservoirs. The schemes for bias toward flood control and, to best satisfy constraints, are basically consistent, and through comparing the data in Table 2, the target values of the two schemes are also the closest, whereas the scheme bias toward power generation tends to have a relatively large variation, as does the scheme to utilize the stock water for power generation at the end of the flood season. In addition, the fluctuations of the schemes with a bias toward ecological preservation and maintaining equilibrium are more severe, which is consistent with the previous analysis.

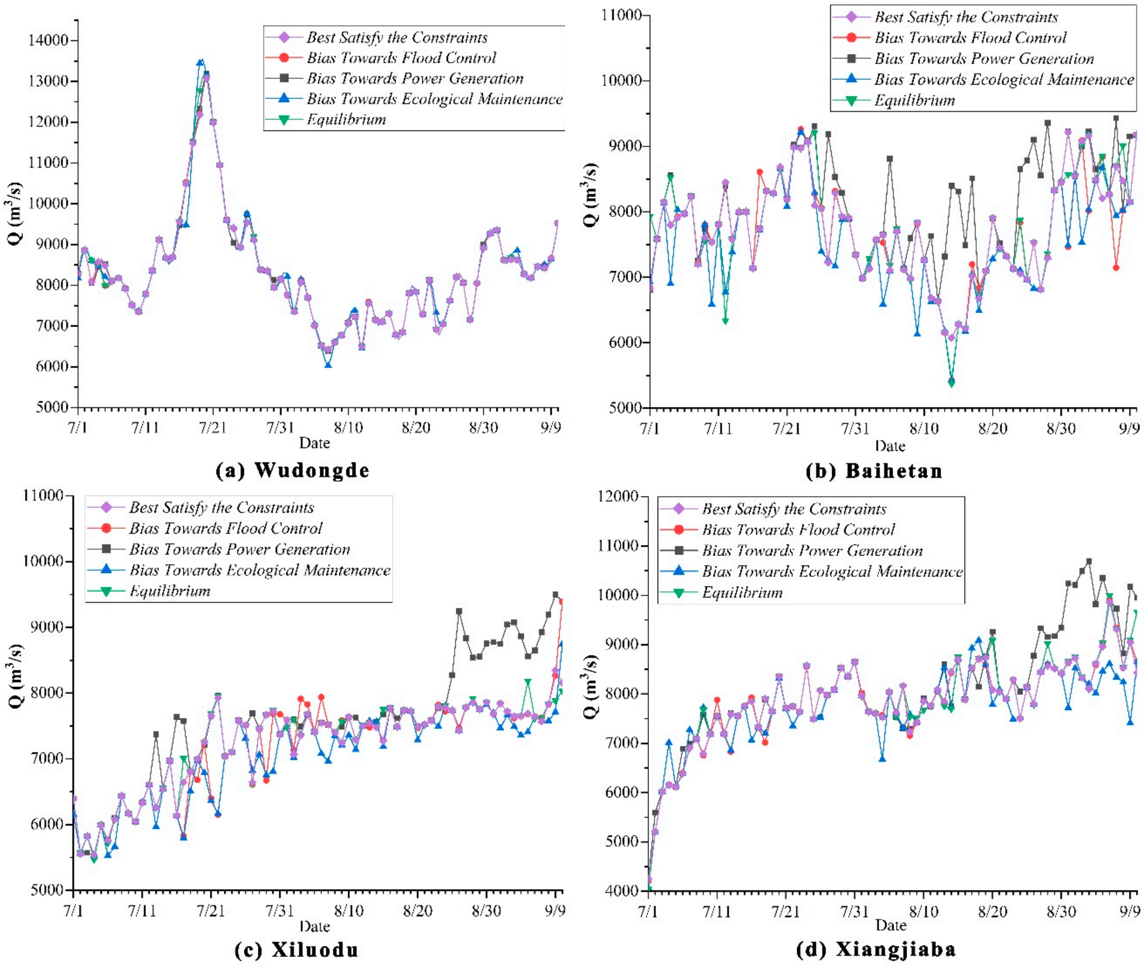


Figure 9. The cascade dispatching process downstream of the Jinsha River under the typical schemes.

Regarding the scheme that best satisfies the constraints, the constraint violation values should be the lowest, and the discharge amplitude constraint should be guaranteed to the greatest extent. The true values should suit the three objective functions: flood control, power generation, and ecological maintenance. In addition, under the premise of ensuring flood control safety, the power generation efficiency should be maximized. Based on these criteria, the scheme with a bias toward flood control is found to be a suboptimal alternative. However, the other three schemes, although superior in one single respect, sacrifice other goals to too great an extent as a whole. Figure 10 shows the scheduling results that best satisfy the constraints scheduling scheme for the comprehensive utilization of the Jinsha River downstream cascade reservoirs during flood season.

In 1981, the upstream natural water quantity was very large, whereas the downstream inflow generally decreased considerably after adjustment, and exhibited obvious peak-staggering, peak-clipping, and compensation adjustment effects. After adjustment, the water level of the reservoirs at the end of the flood season can generally be raised to normal high water levels. Therefore, under the premise of ensuring flood control safety, the benefits of the cascade reservoirs can be tremendously improved. It is of practical significance to enhance their capability to promote benefits and reduce the harmful effects.

In summary, the results show that in the integral dispatching of the Jinsha River reservoir group in the flood season, the two objectives of power generation and ecological maintenance are competing against each other. When the flood control risk is at a low level, the relationship between flood control, power generation and ecological maintenance are complex. When the flood control risk is at a high level, the flood control and power generation objectives are in a competitive relationship, and the relationship between the flood control and ecological maintenance objectives is synergistic, which will guide the actual dispatching of the Jinsha River cascade reservoirs. At the same time, the conclusion is also applicable to the watersheds with similar hydrological conditions to the Jinsha River, such as the Yalong River. The analysis shows that the conclusion is in line with the theoretical expectations and the scheduling practical experience, indicating the reliability of the research method. The multi-objective scheduling of any watershed's reservoir group is similar to the model established and studied on in this paper. Thus the research method proposed in this paper can be utilized as a reference for the optimal scheduling decision-making of any basin in any period of time. In addition, the optimized algorithm proposed in this paper has the advantages of high efficiency and reliability, and it can be applied to the multi-objective optimization projects such as the optimal allocation of water resources.

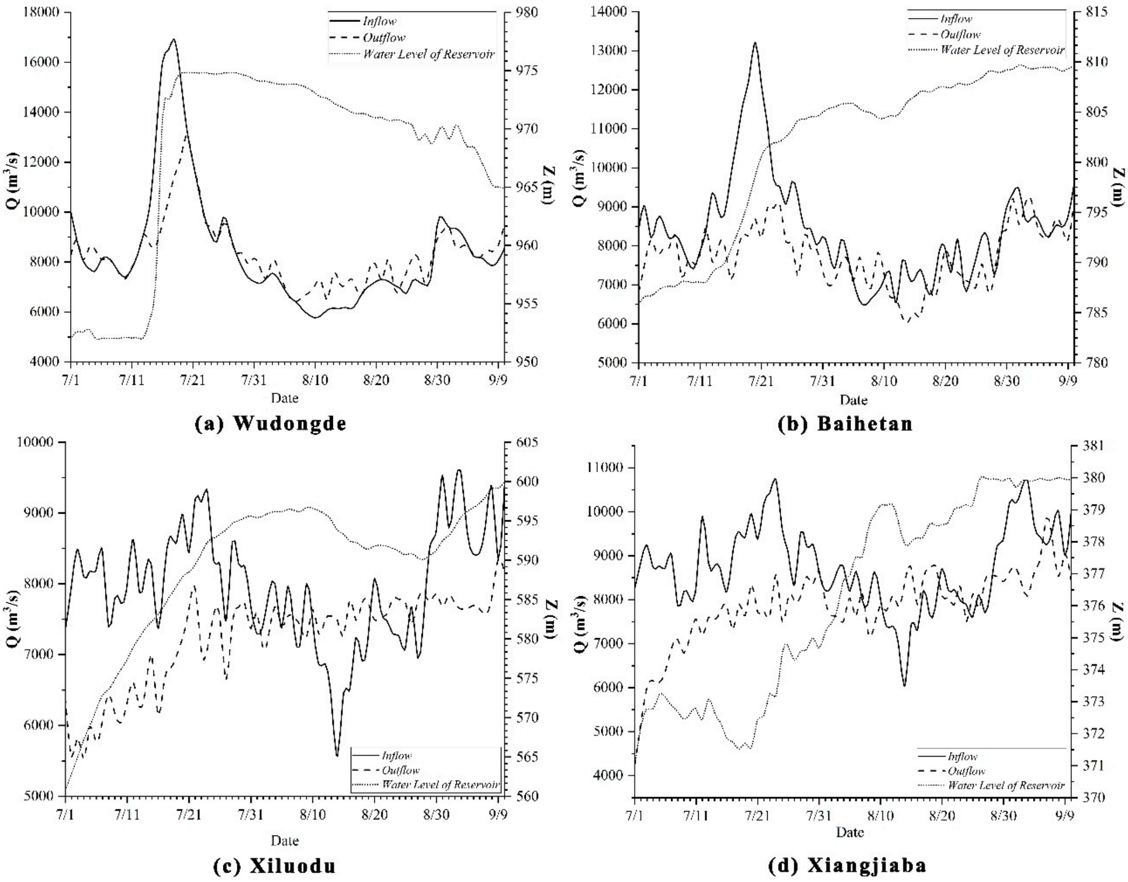


Figure 10. The cascade scheduling results under the optimal scheme to best satisfy the constraints.

Due to the restriction of data, only the daily average discharge flows are used in this paper as the decision variables for the dispatching simulation to study on the cooperative-competitive relationship among the multiple objectives, without the impact of the equipment used such as sluices and dams and the lagging effects of floods taken into account, and no refined dispatching is carried out. The ecological maintenance objective is only controlled by the suitable ecological flow, without considering more complex factors such as flow rate and water temperature. Further study is recommended.

6. Conclusions

The advantages of both NSGA-III and VaEA are drawn upon and exploited in this paper, and through the optimization of the two random selection processes of the original NSGA-III, an optimized algorithm named 'VA-NSGA-III' is proposed. By conducting two-tournament selection during the mating selection process based on the number of niches and the Euclidean distance to the ideal point, both the diversity and convergence of the breeding parent population are guaranteed; in the niching process, with the strategy based on coalescent selection of reference points and vector angles, the diversity of the acquired individuals, which are more reasonable than those obtained by random selection, can be satisfied, and their position of them can be easily defined.

To meet the demands of flood control, power generation, and ecological maintenance of the cascade reservoirs in the lower reaches of the Jinsha River, a comprehensive multi-objective optimization model is established in this paper, with the minimum WFCI, the largest generated energy, and the minimum SSEDO as its targets, and VA-NSGA-III is applied to its solution. The calculation results show that the dispersion degree, fluctuation degree, and skewness of the non-inferior solution sets obtained by VA-NSGA-III are significantly better than those of NSGA-III and VaEA, showing a good Pareto frontier distribution. According to the analytical results, there is a competitive relationship between the power generation and ecological effects of the cascade reservoirs during the flood season, and the competitiveness weakens as the power generation increases. Furthermore, when flood control is at low risk (WFCI ≤ 350,000), there will be a complex coupling relationship between competition and coordination of flood control, power generation, and ecological maintenance. When the flood risk is high (WFCI > 350,000), there will be a competitive relationship between flood control and power generation, with flood control being synergistic with ecological maintenance. The varying scheduling programs show that the operation process with a bias toward ecological maintenance fluctuates sharply with varied amplitude, whereas the one in favor of flood control is relatively stable for the cascade reservoirs in the Jinsha River during flood season.

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