Article

Modeling and Solving of Joint Flood Control Operation of Large-Scale Reservoirs: A Case Study in the Middle and Upper Yangtze River in China

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Abstract: Flood disasters are the most frequent and most severe natural disasters in most countries around the world. Reservoir flood operation is an important method to reduce flood losses. When there are multiple reservoirs and flood control points in the basin, it is difficult to use reservoirs separately to fully realize their flood control potential. However, the multi-reservoir joint flood control operation is a multi-objective, multi-constrained, multi-dimensional, nonlinear, and strong-transition feature decision-making problem, and these characteristics make modeling and solving very difficult. Therefore, a large-scale reservoirs flood control operation modeling method is innovatively proposed, and Dynamic Programming (DP) combined with the Progressive Optimality Algorithm (POA) and Particle Swarm Optimization (PSO) methods, DP-POA-PSO, are designed to efficiently solve the optimal operation model. The middle and upper Yangtze River was chosen as a case study. Six key reservoirs in the basin were considered, including Xiluodu (XLD), Xiangjiaba (XJB), Pubugou (PBG), Tingzikou (TZK), Goupitan (GPT), and Three Gorges (TG). Studies have shown that DP-POA-PSO can effectively solve the optimal operation model. Compared with the current operation method, the joint flood control optimal operation makes the flood control point reach the flood control standard, moreover, in the event of the flood with a return period of 1000 years, Jingjiang, the most critical flood control point of the Yangtze River, does not require flood diversion, and the volume of flood diversion in Chenglingji is also greatly reduced.

Keywords: optimal flood control operation; large-scale reservoirs; DP-POA-PSO; the Yangtze River Basin

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1. Introduction

Since ancient times, flood disasters have been the most frequent natural disasters, with the most severe losses, the most affected people, and the most extensive impacts faced by humans. In order to avoid or reduce flood disasters, people have built a large number of flood control projects such as dikes, reservoirs, flood storage and detention areas, among which reservoirs are a very important part [1–3]. Generally, the purpose of reservoir operation includes flood control, water supply, hydropower generation, shipping, ecology, tourism, fishery, etc., among which flood control is the most important function of most reservoirs [4,5]. The purpose of flood control is to minimize the flood disaster loss of flood control points protected by the reservoir under the premise of ensuring the safety of the dam itself. The key variables to control the operation of the reservoir are the remaining flood control capacity of the reservoir and the forecasted flood inflow [6]. Some studies have established a multi-reservoir joint flood control operation method with the minimum flood disaster loss as the objective function [7]. At present, most of the research on multi-reservoir flood control operation focuses on minimizing the maximum releases

of downstream flood control points, while making the highest operating water level of the dam itself the lowest, so that the operation can minimize potential flood control risks, such as in the research done by Li et al. [8], Lee et al. [9], and Chou [10]. Another aspect of multi-reservoir joint flood control operation focuses on balancing the contradiction between flood control and other objectives, such as hydropower generation and water supply. Guo et al. [11], Reddy et al. [5] and Chang et al. [12] proposed the multi-objective optimal operation of reservoirs. Reddy et al. [13], Shuo et al. [14] and Chen et al. [15] proposed the dynamic flood limit water level method, which appropriately raises the flood limit water level of the reservoir without increasing the risk of flood control to balance the conflict between flood control and conservation.

With the development of society, a large number of reservoirs are put into operation. Usually, a flood control system contains multiple reservoirs and flood control points. For the example shown in Figure 1, the flood control system consists of three reservoirs and four points. Point 1 is protected by reservoir A. Point 2 is protected by reservoir B, point 3 is protected by reservoirs A and B, and point 4 is protected by reservoirs A, B, and C. The flood control requirements of various control points are contradictory. For example, increasing the flood control standard of point 1 will reduce the flood control standard of point 4. The question is how to operate the reservoir to minimize the overall flood loss of the system, while balancing the flood control requirements of points and reservoirs?

Figure 1. Diagram of reservoirs and flood control points.

If the reservoirs are operated alone, it is difficult to realize the flood control potential of the reservoirs due to the lack of cooperation between the reservoirs [16–18]. Therefore, it is necessary to establish a joint flood control operation method for reservoirs [19]. However, the multi-reservoir joint flood control operation is a multi-objective, multi-constrained, multi-dimensional, nonlinear [20], and strongly coupled decision-making problem. These characteristics cause modeling and solving are very difficult [7]. Zhou et al. [21,22] proposed a virtual reservoir method, which simplified multiple reservoirs into one virtual reservoir for decision-making. Although the decision-making dimension is reduced, the hydraulic connection between reservoirs cannot be considered, which cannot be ignored, especially in a large basin. He et al. [8] designed a flood control operation method which is based on equal water storage, and successfully applied to flood control in the middle and upper Yangtze River. But this method does not attain the optimal allocation of reservoir flood control storage capacity. Due to this defect, the flood control effect of the reservoir has not reached the ideal goal. Therefore, this paper proposes an optimal flood control operation model with multiple reservoirs and multiple flood control points considering hydraulic connections.

Over the years, many optimization algorithms have been put into application for the solution of the reservoir optimal operation model. These applied algorithms are

divided into traditional optimization algorithms and artificial intelligence algorithms. Traditional optimization algorithms include Dynamic Programming (DP) [23,24], Progressive Optimality Algorithm (POA) [25–27], Linear Programming (LP) [28], Nonlinear Programming (NLP) [29], artificial intelligence algorithms include Particle Swarm Optimization (PSO) [30–32], Genetic Algorithm (GA) [33–35], and Differential Evolution Algorithm (DE) [12,36,37], Non-dominated Sorting Genetic Algorithm III (NSGA-III) [1,38], etc. When the number of reservoirs and flood control points is small, these algorithms can achieve an efficient solution to the model, but as the scale grows, the model goals, constraints, and dimensions increase exponentially, and it is difficult to solve the model directly using these algorithms. For example, when the number of reservoirs is large, DP suffers from the “dimensional disaster” [39], POA is greatly affected by the initial solution and easily falls into the local optimal solution [40], PSO locally converges quickly and leads to premature convergence [41], and LP is difficult to solve strong nonlinear problems through linear fitting [42]. For the DP algorithm, it can obtain the global optimal solution but has the “dimensional disaster”, the POA algorithm has a small amount of calculation but is easy to fall into the local optimal solution, and the PSO search ability is strong but the convergence is difficult when the dimensionality is large. Based on the advantages and disadvantages of each algorithm, this paper proposes an algorithm that combines DP, POA, and PSO to solve a large-scale reservoirs joint flood control optimal operation model. This algorithm reduces the scale of DP calculation and avoids the “dimensional disaster”. At the same time, it combines POA and PSO to improve the global search capability while avoiding falling into the local optimal solution.

The purpose of this research is to establish a flood control operation model for a flood control system composed of multiple reservoirs and flood control points, considering the flood routing, to minimize the system flood loss and balance the flood control requirements of each point and reservoir. A combination optimization algorithm is proposed to complete the efficient solution of the model, and the flood control system composed of six reservoirs and eight control points in the middle and upper reaches of the Yangtze River is taken as a case study.

2. Reservoirs Joint Flood Control Optimal Operation Model

The primary objective of reservoirs joint flood control operation is to minimize the total flood loss and risk of the system during the entire flood season while subjecting to several equality and inequality constraints. The objective function and constraints are described as follows.

2.1. Objective Function

Usually, reservoir joint flood control optimal operation has the following objectives:

- (1) Minimize the amount of flood diversion at the flood control point, this objective is to reduce the flood disaster loss of flood control points;
- (2) The minimum sum of squares of flow at the flood control point. This objective is to reduce the pressure of flood control points, which is used in the situation where the flood control point does not require flood diversion;
- (3) The highest operating water level of the reservoir is the lowest. This objective is to reduce the flood control risk of the reservoir itself;
- (4) The sum of squares of the inflow of the reservoir is the smallest. This objective is to avoid drastic changes in the inflow of the downstream reservoir caused by the operation of the upstream reservoir.
- (5) The sum of the square of the outflow of the reservoir is the smallest. This objective is to avoid drastic changes in the outflow flow of the reservoir from affecting power generation, water supply, etc.

In this model, the above five objectives are combined to be one objective by using the weight method, the final objective function is shown as follows:

$$\min F = \min \left\{ \sum_{n=1}^N \left(a_n \frac{Z_n^{up} - Z_n^{min}}{ZZ_n - Z_n^{min}} + \sum_{t=1}^T \frac{b_n Q_{n,t,in}^2 + c_n Q_{n,t,out}^2}{Q_{n,max}^2} \right) + \sum_{m=1}^M \left(\sum_{t=1}^T d_m \frac{Q_{m,t}^2}{Q_{m,max}^2} + e_m \frac{\sum_{t=1}^T Q_{m,t,E} \Delta t}{\sum_{t=1}^T Q_{m,t,E}^k \Delta t} \right) \right\} \quad (1)$$

where N is the total number of reservoirs; Z_n^{max} is the maximum allowable operating water level of the n -th reservoir; Z_n^{min} is the minimum allowable operating water level of the n -th reservoir; Z_n^{up} is the highest operating water level of the n -th reservoir; T is the total number of operation periods; $Q_{n,t,in}$ is the inflow of the n -th reservoir during the t -th period; $Q_{n,t,out}$ is the outflow of the n -th reservoir during the t -th period; $Q_{n,max}$ is the maximum inflow of the n -th reservoir when reservoirs are not in operation; M is the total number of flood control points; $Q_{m,t}$ is the inflow of the m -th point during the t -th period; $Q_{m,max}$ is the maximum inflow of the m -th point when reservoirs are not in operation; $Q_{m,t,E}$ is the flood diversion flow of the m -th point during the t -th period, which is equal to zero when the flow is less than the safe flow of the point; $Q_{m,t,E}^k$ is the flood diversion flow of the m -th point during the t -th period when reservoirs are not in operation; Δt is the length of operation period, which usually depends on the available data for operation; a_n , b_n , and c_n is the weight of the highest operating water level, the square sum of inflow and square the sum of outflow of the n -th reservoir, respectively; d_m and e_m is the weight of the square sum of flow and the square sum of flood diversion flow of the m -th point, respectively. The weight value is determined according to the importance of the objective and the requirements of the project, it is given in advance based on the experience of the decision maker, and the weight is appropriately modified according to the operation result until a satisfactory result is achieved. Generally, engineers give multiple sets of weights and their corresponding operation results based on experience, and then the decision maker selects a set of better weight values from them. When the decision maker is dissatisfied with all the operation results, the weights are appropriately modified after consultation with the engineer. A satisfactory operation result needs to meet the requirements of all reservoirs and flood control points as much as possible. When the requirements of all reservoirs and flood control points cannot be guaranteed at the same time, the weight should be adjusted to meet the requirements of high-level reservoirs and flood control points first.

2.2. Constraints

In the process of flood control operation, various complex equality and inequality constraints, such as water balance, water level, output, and hydraulic connection, should be considered for restricting objective optimization. The constraints of the model are described as follows:

(1) Water balance constraint:

$$V_{n,t} = V_{n,t-1} + (Q_{n,t,in} - Q_{n,t,out}) \Delta t \quad (2)$$

where $V_{n,t}$ is the reservoir storage of the n -th reservoir at the end of the t -th period.

(2) Water level constraint:

$$Z_n^{min} \leq Z_{n,t} \leq Z_n^{max} \quad (3)$$

$$|Z_{n,t} - Z_{n,t-1}| \leq \Delta Z_n \quad (4)$$

where $Z_{n,t}$ is the water level of the n -th reservoir at the end of the t -th period; $Z_{i,t}^{min}$ and $Z_{i,t}^{max}$ are the maximum and minimum allowable operating water level; ΔZ_n is the maximum amplitude of water level variation.

(3) Reservoir discharge constraint:

$$Q_n^{min} \leq Q_{n,t,out} \leq Q_n^{max}(Z_{n,t}) \quad (5)$$

$$|Q_{n,t,out} - Q_{n,t-1,out}| \leq \Delta Q_{n,out} \quad (6)$$

where Q_n^{min} is the minimum discharge of the n -th reservoir; $Q_n^{max}(Z_{n,t})$ is the maximum discharge ability of the n -th reservoir at t -th period. The maximum discharge ability is related to the water level; $\Delta Q_{n,out}$ is the maximum amplitude of discharge of the n -th reservoir.

(4) Constraint of discharge for downstream flood control points:

$$Q_{m,t} = \sum_h^H Q'_{h,m,t} + \Delta q_{m,t} \leq Q_m^{max} \quad (7)$$

where $Q_{m,t}$ is the flow of the m -th point at the t -th period; H is the number of reservoirs upstream of the m -th point; $Q'_{h,m,t}$ is the discharge of the h -th reservoir considering the flood routing at the m -th point at the t -th period; $\Delta q_{m,t}$ is the inflow in the interval zone between the reservoirs upstream and the m -th point; and Q_m^{max} is the allowed maximum discharge for the m -th point. This constraint is often used to turn the objective of non-critical points into constraints to reduce the difficulty of solving the model.

(5) Constraint of flood routing:

$$O_t = C_0 I_t + C_1 I_{t-1} + C_2 O_{t-1} \quad (8)$$

$$\left. \begin{aligned} C_0 &= \frac{0.5\Delta t - Kx}{K - Kx + 0.5\Delta t} \\ C_1 &= \frac{0.5\Delta t + Kx}{K - Kx + 0.5\Delta t} \\ C_2 &= \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t} \end{aligned} \right\} \quad (9)$$

$$C_0 + C_1 + C_2 = 1$$

The Muskingum method [43,44] is the most commonly used method of river channel flood routing and is applied to this model. Where O_t and I_t are the outflow and inflow of the river channel in t -th period, respectively; O_{t-1} and I_{t-1} are the outflow and inflow of the river channel in $t-1$ -th period, respectively; K is the storage time constant for the river channel, which has a value reasonably close to the flow travel time within the river channel; and x is a weighting factor varying between 0 and 0.5; C_0 , C_1 , and C_2 are coefficients that are functions of K , x , and Δt .

2.3. Optimization Algorithm

For the solution of the joint flood control optimal operation model of multi-reservoir, considering the influence of “curse of dimensionality”, flood routing, calculation efficiency, initial solution, and convergence, etc., a strategy combining DP, POA, and PSO is proposed. First, DP is used to calculate the reservoir one by one to obtain the initial solution. Second, considering the influence of flood routing, POA is used to optimize the initial solution. Third, from the beginning to the end, PSO is used to optimize the operation process for several consecutive periods in turn. The skeleton of this algorithm is shown in Figure 2. The equations for DP, POA, and PSO methods are given as follows.

Figure 2. The skeleton of the DP-POA-PSO (Dynamic Programming (DP) combined with Progressive Optimality Algorithm (POA) and Particle Swarm Optimization (PSO)) algorithm. (a) DP gets the initial solution; (b) POA-PSO optimized initial solution.

2.3.1. Dynamic Programming (DP)

DP is widely used in reservoir operation of hydropower generation, flood control, water storage, and so on. This paper uses DP to obtain the initial solution of reservoir operation. The recursive function of DP used in the multi-period optimal operation of the reservoir is described as Equation (10); DP is used to optimize reservoir operation from

upstream to downstream. In this stage, the influence of river channel flood routing is not considered. The result of DP is used as the initial solution of the model.

$$\begin{aligned} \min G_t(Z_{n,t}) &= g_t(Z_{n,t}, Q_{n,t,out}) + G_{t-1}(Z_{t-1}) \\ g_t(Z_{n,t}, Q_{n,t,out}) &= \sum_{n=1}^N \left(a_n \frac{Z_n^{up} - Z_n^{min}}{Z_n^{max} - Z_n^{min}} + \frac{b_n Q_{n,t,in}^2 + c_n Q_{n,t,out}^2}{Q_{n,max}^2} \right) + \sum_{m=1}^M \left(d_m \frac{Q_{m,t}^2}{Q_{m,max}^2} + e_m \frac{Q_{m,t,E} \Delta t}{\sum_{t=1}^T Q_{m,t,E} \Delta t} \right) \\ s.t. (1) \quad &V_{n,t}(Z_{n,t}) + Q_{n,t,out} \Delta t = V_{n,t-1}(Z_{n,t-1}) + Q_{n,t,in} \Delta t \\ (2) \quad &Q_{m,t} = \sum_h Q_{h,m,t} + \Delta q_{m,t} \end{aligned} \quad (10)$$

where $V_{n,t}(Z_{n,t})$ is storage of the n -th reservoir at t -th period; $G_t(Z_{n,t})$ is the minimum cumulative utility from the $G_t(Z_{n,t})$ is the minimum cumulative utility from the first period (begin of operation period) to the t -th period (current operation period); $g_t(Z_{n,t}, Q_{n,t,out})$ is the t -th period utility function, when the DP is used to optimize the operating water level of the n -th reservoir at t -th period, the operating water level in other periods remains unchanged, so only the utility value of the reservoir during the t -th period is calculated, which effectively reduces the amount of calculation [23]; $Q_{h,m,t}$ is the discharge of the h -th reservoir without considering the flood routing at the m -th point at the t -th period, $Q'_{h,m,t}$ in Equation (7) that uses the Muskingum method for flood routing is simplified into $Q_{h,m,t}$. The detailed steps at this stage are as follows:

Step 1: According to the operation requirements, the water level of the reservoirs is discretized into a water level sequence, and the discrete water level is set as a state variable. In this paper, the discrete step length of the reservoir is 0.01 meters.

Step 2: From upstream to downstream, the DP is used to optimize the reservoir operation process in turn.

2.3.2. Progressive Optimality Algorithm (POA)

POA can effectively avoid the “dimensional disaster” suffered by DP, and it can also consider the flood routing. On the basis of the initial solution, the multi-stage optimal operation problem is decomposed into a two-stage optimal operation sub-problem. The decision vector of sub-problem between the t -th and $t+1$ -th period is described in Equation (11):

$$\begin{aligned} F(Z_{n,t-1}, Z_{n,t}, Z_{n,t+1}) &= \min_{Z_{n,t} \in C_{n,t}} \{g_{t-1}(Z_{n,t-1}, Q_{n,t-1,out}) + g_t(Z_{n,t}, Q_{n,t,out})\} \\ s.t. (1) \quad &V_{n,t}(Z_{n,t}) + Q_{n,t,out} \Delta t = V_{n,t-1}(Z_{n,t-1}) + Q_{n,t,in} \Delta t \\ (2) \quad &Q_{m,t} = \sum_h Q'_{h,m,t} + \Delta q_{m,t} \end{aligned} \quad (11)$$

where $C_{n,t}$ is the range that $Z_{n,t}$ can take at the t -th period and is determined by constraint 3, $Q_{n,t-1,out}$ and $Q_{n,t,out}$ are calculated by $s.t.(1)$ using $Z_{n,t-1}$, $Z_{n,t}$, and $Z_{n,t+1}$. $F(Z_{n,t-1}, Z_{n,t}, Z_{n,t+1})$ is the optimal objective at the t -th and $t+1$ -th period. The detailed steps at this stage are as follows [45,46]:

Step 1: Select the n -th reservoir from upstream to downstream for optimization calculation, and the operating water levels of other reservoirs remain unchanged.

Step 2: The water level of the n -th reservoir from the second period to the $T-1$ -th period is optimized in turn. When the water level of the t -th period is optimized, the water level of the n -th reservoir remains unchanged in other periods, the optimization objective is shown in Equation (11).

Step 3: After optimizing the operation water level of the n -th reservoir is completed, the operating water level of the $n+1$ -th reservoir is optimized using the method in step 2.

Step 4: After optimizing the operation water levels of all reservoirs, repeat steps 1, 2, and 3 until the optimization results remain stable.

2.3.3. Particle Swarm Optimization (PSO)

PSO is derived from the research on the predation behavior of bird swarms. Each particle in the particle swarm represents a possible solution to the problem. Through the simple behavior of individual particles, the information interaction within the particle swarm realizes the intelligence of problem solving. Due to its simple operation and fast convergence speed, PSO has been widely used in many fields such as function optimization, image processing, and geodesy [31]. The paper uses PSO to solve the problem that POA is easy to fall into local optimal solutions. However, if the optimization calculation is performed during the entire operation period, the length of the particles will be too long, thereby reducing the convergence speed. Therefore, this paper combines POA, and PSO, and selects several consecutive operation periods as the “operation window”. PSO is used to optimize the operation process in the “operation window”, and keeps the operation process in other periods unchanged. When the operation process optimization in the “operation window” is completed, the window moves backward and optimizes the operation process. Each particle in PSO evolves according to the set strategy. The formula for updating the velocity and position of the particles is as follows:

$$V_{id}(r+1) = wV_{id}(r) + C_1 \text{random}(0,1)(P_{id} - X_{id}(r)) + C_2 \text{random}(0,1)(P_{gd} - X_{id}(r)) \quad (12)$$

$$X_{id}(r+1) = X_{id}(r) + V_{id}(r+1) \quad (13)$$

where $X_{id}(r)$ is the position of the i -th particle in the r round of optimization, the value of $X_{id}(r)$ in each dimension represents the operating water level of a reservoir in a period; $V_{id}(r)$ is the velocity of the i -th particle with d dimensions in the r round of optimization, the value of $V_{id}(r)$ in each dimension represents the change value of the operating water level of a reservoir in a period; P_{id} is the best position where the i -th particle has appeared so far; P_{gd} is the best position where all particles have appeared so far; C_1 and C_2 are the learning constants; w is the weight of inertia; $\text{random}(0,1)$ is a random number between 0 and 1. The detailed steps at this stage are as follows [47–49]:

Step 1: Based on experience, the “operation window” is set to contain k periods. If k is set to be relatively large, the convergence speed will be slower. On the contrary, if k is set to be relatively small, the search ability will be reduced. The recommended interval is [10,30], and k is set to 20 in this paper;

Step 2: Set the number of particles, and initialize the velocity and position of particles. Each particle contains the water level of k periods of N reservoirs in the “operation window”, so the particle contains $k \times N$ dimensions. The result of POA in the “operation window” is used as one of the particles.

Step 3: According to the fitness function shown in Equation (14), calculate the fitness value of each particle.

$$F(j,k) = \sum_{n=1}^N \left(a_n \frac{Z_n^{up} - Z_n^{min}}{Z_n^{max} - Z_n^{min}} + \sum_{t=j}^{j+k} \frac{b_n Q_{n,t,in}^2 + c_n Q_{n,t,out}^2}{Q_{n,max}^2} \right) + \sum_{m=1}^M \left(\sum_{t=j}^{j+k} d_m \frac{Q_{m,t}^2}{Q_{m,max}^2} + e_m \frac{\sum_{t=j}^{j+k} Q_{m,t,E} \Delta t}{\sum_{t=1}^T Q_{m,t,E} \Delta t} \right) \quad (14)$$

where j is the starting period of the “operation window”. When optimizing the reservoir operating water level process in the “operation window” from the j -th period to the $j+k$ -th period, the water levels in other periods remain unchanged, so only the periods in the window need to be considered when calculating the fitness. If j and k are set to 1 and T respectively, it can be discovered that this fitness function is the objective function.

Step 4: According to the fitness value of the particles, update the historical best position of each particle and the best position of the particle swarm [31].

Step 5: Update the velocity and position of each particle according to Equations (12) and (13).

Step 6: Repeat steps 3, 4, and 5 until the best position of the particle swarm remains stable.

Step 7: The “operation window” moves backward p periods, and the water level from the $j+p$ -th period to the $j+p+k$ -th period in the “operation window” is optimized. p is recommended not to be more than one-third of k , which is taken as 5 in this paper.

3. Study Area

3.1. Introduction of Study Area

The middle and upper Yangtze River is selected as a case study. As the largest river in China, the Yangtze River has a total length of about 6300 km. The area, population, GDP, and grain output of the Yangtze River Basin account for 18.8%, 36%, 40%, and 40% of the country respectively [50]. However, floods in the Yangtze River Basin often occur, killing thousands of people and causing millions of dollars in damage. For example, the flood of 1954 directly caused 30,000 deaths, and more people died of starvation and plague caused by the flood [51]. Therefore, flood control in the Yangtze River Basin has always been the focus of general attention, and flood prevention and disaster reduction in the Yangtze River Basin has been given top priority. The middle and upper Yangtze River are the most severely flooded areas and the key to flood control in the entire basin.

After decades of flood control construction, the Yangtze River Basin has basically formed a comprehensive flood control system with the Three Gorges Reservoir (TG) as the backbone. However, the contradiction between the river discharge capacity and the large flood peaks of the middle and lower reaches of the Yangtze River is still prominent. The 22.15 billion m³ flood control storage capacity of the TG only accounts for about 5% of the 451 billion m³ average annual runoff at the dam site. In extreme flood events, if only the Three Gorges Reservoir participates in flood control operation, the downstream flood diversion and storage area needs to be used, and the loss is very huge. Therefore, it is necessary for the upstream reservoirs to cooperate with the TG for joint flood control operation.

The flood control system consisting of key reservoirs and flood control points in the middle and upper Yangtze River is shown in Figure 3. The system includes six reservoirs including Xiluodu (XLD), Xiangjiaba (XJB), Pubugou (PBG), Tingzikou (TZK), Goupitan (GPT), Three Gorges (TG), and eight flood control stations including Chengkun Railway, Yibin, Luzhou, Chongqing, Langzhong, Sinan, Jingjiang, Chenglingji. In Figure 3b, Flood control point is the object that needs to be protected by the flood control operation of reservoirs, and the gauging station is the station for observing the water level and flow of the river.

Figure 3. Cont.

Figure 3. Locations of the dams, flood control points and gauging stations in the Yangtze River Basin. (a) The upper Yangtze River Basin; (b) skeleton of the upper Yangtze River Basin.

3.2. Data of Study Area

3.2.1. Data of Reservoir

XLD is located in the lower reaches of the Jinsha River and is the third-largest hydropower station in the world. The height, total storage capacity, and flood control storage capacity of the dam are 285.5 meters, 12.67 billion m³, and 4.65 billion m³, respectively. XJB is located at the downstream of XLD, which is only 157 km far from it. The flood control storage capacity of XJB is 0.90 billion m³. The two reservoirs are key reservoirs of the Jinsha River, controlling 96% of the Jinsha River basin area.

PBG is a key reservoir in the Min River which is a tributary of the Yangtze River. It is located in the west of Sichuan Province and has a drainage area of 68,500 km², accounting for about 50.4% of the Min River basin area. Its flood control storage capacity is 1.1 billion m³. TZK is a controlling water conservancy project of the Jialing River. It has a drainage area of 61,100 km², accounting for 39% of the Jialing River basin area. The flood control water level and flood control storage capacity are 447 m and 1.44 billion m³, respectively. GPT is located in Guizhou Province and is the largest key reservoir on the Wu River. It controls a drainage area of 43,300 km², accounting for 49% of the Wu River basin area. Its flood control storage capacity is 0.4 billion m³.

TG is located in Hubei Province and is the largest water conservancy project in the world. The length, height, total storage capacity, and flood control capacity of the dam are 3335 m, 181 m, 39.3 billion m³, and 22.15 billion m³ respectively. It is the key to flood control of the Yangtze River. The characteristics of the reservoirs are shown in Table 1.

Table 1. Characteristics of the reservoirs.

Reservoir	Location	Drainage Area (10 ⁴ km ²)	Normal Water Level (m)	Flood Control Water Level (m)	Total Storage Capacity (Billion m ³)	Flood Control Storage Capacity (Billion m ³)
XLD	Jinsha River	45.4	600	560	12.7	4.7
XJB	Jinsha River	45.9	380	370	5.2	0.9
PBG	Min River	6.8	850	836	5.4	1.1
TZK	Jialing River	6.1	458	447	4.1	14.4
GPT	Wu River	4.3	630	626	6.4	0.4
TG	Yangtze River	100	175	145	39.3	22.1

3.2.2. Data of Flood Control Point

The Chengkun Railway connects Sichuan Province and Yunnan Province with a total length of 1096 km. It is the most important transportation line in southwest China. According to the flood control standard stipulated by law, when the flow is not higher than $11,200 \text{ m}^3/\text{s}$, which is the peak flow of the design flood with a return period of 100 years, PBG should be used to intercept the flow below $8780 \text{ m}^3/\text{s}$, which is the maximum flow that the Chengkun Railway can withstand.

Yibin, Luzhou, and Langzhong are three cities located in Sichuan Province. The populations of the three cities are 5.5 million, 5.8 million, and 0.83 million respectively, and GDP are 37.7 billion, 31.1 billion, 3.7 billion dollars respectively. The current flood control capacity of the three cities is to ensure safety in the event of a flood with a return period of 20 years, the corresponding peak flows of the flood are $51,000 \text{ m}^3/\text{s}$, $52,600 \text{ m}^3/\text{s}$, and $25,100 \text{ m}^3/\text{s}$, respectively. According to the flood control standard stipulated by law, upstream reservoirs should protect the three cities from the design flood with a return period of 50 years, the corresponding peak flow of the flood is $57,800 \text{ m}^3/\text{s}$, $58,100 \text{ m}^3/\text{s}$, and $32,880 \text{ m}^3/\text{s}$.

Chongqing is the largest city in southwestern China and the center of economy, finance, science and technology, shipping, and logistics in the upper reaches of the Yangtze River. It has a population of 31.2 million, a GDP of 352.3 billion dollars, and an area of $82,400 \text{ km}^2$. The discharge capacity of the river channel in Chongqing is $83,100 \text{ m}^3/\text{s}$ which is the peak flow of the design flood with a return period of 50 years, and the upstream reservoirs should protect Chongqing from the design flood with a return period of 100 years, the corresponding flood peak flow is $88,700 \text{ m}^3/\text{s}$, according to the flood control standard stipulated by law.

Sinan is a county located in the northeast of Guizhou Province, with an area of 2230.5 km^2 , a population of 684,500, and a GDP of 2 billion dollars. According to the flood control standard stipulated by law, when the flow is not higher than $11,500 \text{ m}^3/\text{s}$ which is the peak flow of the design flood with return period of 5 years, GPT should be used to intercept the flow below $9320 \text{ m}^3/\text{s}$ which is the peak flow of the design flood with a return period of 2 years.

Jingjiang is an important production base for grain, cotton, oil, fruits, and aquatic products in China. It has a population of 9.6 million, 16.6 million acres of arable land, many important railways and highways. Once floods occur, they will directly threaten the safety of Wuhan which is the most important city in central China. On the other hand, the flood discharge capacity of the Jingjiang is only $60,600 \text{ m}^3/\text{s}$, which is seriously insufficient compared to the huge amount of inflow. Therefore, the Jingjiang River has always been the difficulty and focus of the Yangtze River flood control. Chenglingji is located in Yueyang City, Hunan Province. It is the exit of Dongting Lake into the Yangtze River. Chenglingji is the area where flood disasters occur most frequently in the Yangtze River Basin.

In this flood control system, the flood control objectives of the Chengkun Railway, Yibin, Luzhou, Chongqing, Langzhong, and Sinan are transformed into constraints to ensure that they meet the flood control standards. Then, this paper focus on solving the flood control problems of Jingjiang and Chenglingji.

3.2.3. Muskingum Parameters of the Basin

The Muskingum parameters of each reach in the basin are shown in Table 2. The flood routing time of each river segment is 6 h.

Table 2. Muskingum parameters of the basin.

Upper Section	Lower Section	Number of Segments	C ₀	C ₁	C ₂
XLD	XJB	0	-	-	-
XJB	Yibin	1	0.283	0.498	0.219
PBG	Chengkun railway	1	0.291	0.476	0.233
Chengkun railway	Yibin	3	0.283	0.498	0.219
Yibin	Luzhou	3	0.290	0.430	0.280
Luzhou	Chongqing	2	0.240	0.420	0.340
TZK	Langzhong	1	0.293	0.467	0.240
Langzhong	Chongqing	3	0.243	0.417	0.340
Chongqing	TG	8	0.187	0.430	0.383
GPT	Sinan	0	-	-	-
Sinan	TG	8	0.187	0.430	0.383

4. Application

4.1. Design Flood Hydrographs

The flood control operation of the reservoirs is to ensure the safety when a large or extreme flood occurs [52]. The common method is to determine the flood control standard based on the importance of the flood control point, and then the design flood corresponding to the standard is used as the input of the operation model [28,53]. There are two methods commonly used in design flood calculation: homogeneous frequency enlargement and homogeneous multiple enlargement. The homogeneous frequency enlargement is widely used in the case of a large number of reservoirs and flood control points because of its ease of use [54–56]. The steps of this method to calculate the design flood are as follows:

Step 1: The design flood parameters of the control section are obtained by calculating the frequency of the annual maximum flood peak and n -day volumes data. The control section of this study is the Yichang gauging station, and its design flood parameters are shown in Table 3. In the table, E_x , C_v , and C_s are the mean value, coefficient of variation, and coefficient of skewness of design flood respectively [54].

Step 2: The typical flood hydrographs were determined. An observed flood hydrograph with a large peak, large flood volume, or an operation not conducive to flood control was usually selected [57]. This study selected floods in 1954, 1968, 1980, 1981, 1982, 1988, 1996, 1998, 1999, and 2010 as a typical flood hydrograph. The 1954 and 1998 floods were respectively the first and second largest floods in the Yangtze River in the 20th century, and caused serious disasters to the entire basin. Large floods occurred in the middle reach of the Yangtze River in 1968, 1988, and 1999. The 1980 flood caused severe flood disasters to the Jinsha River and Jialing River, which are tributaries of the Yangtze River. In 1981, the Jinsha River, the Minjiang River, and the Jialing River experienced large floods at the same time, which put great pressure on flood control safety. In 1982, The largest flood in history occurred in Tuojiang which is a tributary of the Yangtze River. In 2010, the Minjiang River and the Jialing River experienced large floods at the same time, and the flood peak of the Cuntan gauging station reached 64,000 m³/s. The 11 selected typical flood hydrographs can represent the worst flood characteristics in the middle and upper Yangtze River.

Step 3: The design flood hydrographs were determined. According to the ratio of the peak or n -day volumes between the observed typical flood and the design flood at the control section, the typical flood hydrographs of reservoirs and flood control points in the basin are enlarged and become the basin design flood hydrographs. Usually, the flood volume ratio close to the peak ratio is selected for enlarging to ensure that the flood peak and flood volume of the design flood match. In this study, the 1954 and 1998 floods used the ratio of 30-day volume, and other floods used the ratio of 15-day volume.

The start time and end time of the design flood are June 1 and September 30, respectively. Due to space limitations, this study only shows the 1954 and 1998 typical year design flood with return period of 100-year, as shown in Figures 4 and 5, respectively.

Figure 4. Design flood hydrographs based on the typical flood hydrograph of 1954 (100 years).

Table 3. Design flood parameters of the basin (flood peak: m^3/s ; volumes: billion m^3).

Category	Parameters			Return Period (year)				
	E_x	C_v	C_v/C_s	10,000	1000	100	50	20
flood peak	52,000	0.21	4	113,000	98,800	83,700	79,000	72,300
7-day volumes	275	0.19	3.5	547.2	486.8	420.8	400	368.5
15-day volumes	524	0.19	3	1022	911.8	796.5	757	702.2
30-day volumes	935	0.18	3	1767	1590	1393	1330	1234

Figure 5. The design flood hydrographs based on the typical flood hydrograph of 1998 (100 years).

4.2. Optimal Reservoir Operation Results

In this study, a joint flood control optimal operation model of the flood control system composed of six reservoirs and eight points in the upper and middle reaches of the Yangtze River was established, and 1954, 1968, 1980, 1981, 1982, 1988, 1996, 1998, 1999, and 2010 typical year design floods with different return periods were used as the inputs of the

model. Then, the DP-POA-PSO proposed in this paper is used to solve the optimal model. The system has three main flood control goals: first, the flood diversion volumes of Jingjiang is reduced to the lowest; second, the flood diversion volumes of Chenglingji is reduced to the lowest; third, the highest operation water level of TG is the lowest. The importance of the three goals decreases in order. The programming tool, programming language, and database use eclipse, java, and MySQL respectively. On a computer with a CPU frequency of 4.0 GHz, the calculation time of using this algorithm to solve the model is about 180 s.

4.2.1. Influence on the Inflow Flood of TG

The operation of the upstream reservoir can reduce the inflow flood of the TG. The operation results of this part are shown in Table 4. In the current method, each reservoir is operated separately and no joint optimal operation is realized. In the table, the design value is the inflow peak of TG without reservoir operation; the reduction is the difference between the design value and the inflow peak after reservoir operation; the comparison is the difference between the peak flows of the current method and the optimal operation.

Table 4. Comparison of Three Gorges (TG) inflow peak under different operation methods (m^3/s).

Typical Flood Hydrograph	Return Period	Design Value	Current Method		Optimal Method		Comparison
			Inflow	Reduction	Inflow	Reduction	
1954	1000	76,676	70,693	5983	65,886	10,790	4807 (80%)
	100	67,025	61,456	5570	59,914	7112	1542 (27%)
	50	63,720	58,327	5394	56,822	6898	1505 (28%)
1968	1000	96,390	86,911	9479	78,094	18,296	8817 (93%)
	100	83,916	74,855	9061	69,812	14,104	5043 (56%)
	50	79,834	70,886	8947	66,278	13,555	4608 (51%)
1980	1000	104,369	100,250	4119	90,369	14,000	9881 (239%)
	100	79,661	71,532	8129	67,531	12,130	4001 (49%)
	50	75,730	67,643	8087	63,920	11,810	3723 (46%)
1981	1000	111,200	102,116	9084	97,494	13,706	4621 (51%)
	100	97,092	89,195	7896	86,505	10,586	2690 (34%)
	50	92,922	84,406	8515	81,830	11,091	2576 (30%)
1982	1000	92,040	82,497	9543	75,844	16,196	6654 (70%)
	100	80,417	71,275	9142	70,712	9705	563 (6%)
	50	76,523	67,396	9127	66,885	9638	511 (6%)
1988	1000	80,106	73,462	6644	68,683	11,423	4780 (72%)
	100	69,773	63,759	6014	61,329	8444	2430 (40%)
	50	66,360	60,527	5833	58,139	8221	2388 (41%)
1996	1000	78,501	72,972	5529	69,848	8653	3125 (57%)
	100	68,555	62,813	5742	61,171	7384	1642 (29%)
	50	65,185	59,570	5614	58,017	7167	1553 (28%)
1998	1000	77,125	72,560	4565	68,931	8194	3629 (79%)
	100	67,438	63,126	4312	61,567	5871	1559 (36%)
	50	64,168	59,984	4184	58,585	5583	1399 (33%)
1999	1000	90,153	80,476	9677	72,982	17,171	7494 (77%)
	100	78,643	69,232	9411	64,598	14,045	4634 (49%)
	50	74,787	65,427	9360	61,015	13,772	4412 (47%)
2010	1000	109,705	101,932	7773	96,770	12,935	5162 (66%)
	100	96,408	87,967	8441	82,567	13,841	5400 (64%)
	50	91,089	82,820	8269	77,942	13,146	4877 (59%)
Average Value	1000	91,250	83,313	7936	77,939	13,311	5375 (68%)
	100	78,751	71,287	7464	68,493	10,258	2794 (37%)
	50	74,890	67,491	7399	64,863	10,027	2628 (36%)

The operation results show that the joint optimal operation of the reservoirs can make full use of the flood control capacity of the upstream reservoirs to reduce the inflow of TG and reduce its flood control pressure. Therefore, the flood control effect of TG on Jingjiang and Chenglingji has been greatly improved. For the designed floods with return periods of 1000 years, 100 years, and 50 years, compared with the current method, the optimal operation increases the inflow peak reduction by 68%, 37% and 36%, respectively. Figure 6 shows the inflow of TG when different methods are used to operate the 1980 and 2010 typical year design flood with a return period of 1000 years. The results show that the joint optimal operation can make the inflow flatter and the peak smaller, which will increase the flexibility of TG for flood control operation of Jingjiang and Chenglingji.

Figure 6. The inflow of TG under different operation methods, (a) 1980, (b) 2010.

4.2.2. Operation Results of Jingjiang and Chenglingji

Considering that the Chengkun Railway, Yibin, Luzhou, Langzhong, and Sinan can all meet the flood control standards after reservoir operation, many studies [58–61] have been focusing on the operation effect of the reservoir group on Jingjiang and Chenglingji,

especially the flood diversion of these two areas. In order to prove the feasibility of the optimal flood control operation model and DP-POA-PSO algorithm proposed in this paper, the results of the optimal operation model are compared with the current methods. The flood diversions in Jingjiang and Chenglingji are shown in Tables 5 and 6, respectively.

Table 5. Comparison of the flood diversion in Jingjiang under different operation methods (billion m³).

Typical Flood Hydrograph	Return Period	Without Operations	Current Method		Optimal Method		Comparison
			Diversion	Reduction	Diversion	Reduction	
1954	1000	23.7	2.93	20.77	0.51	23.18	2.41 (11%)
	100	8.4	0	8.4	0	8.4	0 (0%)
	50	4.78	0	4.78	0	4.78	0 (0%)
1968	1000	56.45	9.72	46.73	7.58	48.87	2.13 (5%)
	100	24.02	0	24.02	0	24.02	0 (0%)
	50	16.96	0	16.96	0	16.96	0 (0%)
1980	1000	24.83	22.18	2.64	17.52	7.3	4.65 (176%)
	100	11.07	0	11.07	0	11.07	0 (0%)
	50	8.51	0	8.51	0	8.51	0 (0%)
1981	1000	38.12	2.34	35.78	2.15	35.97	0.19 (1%)
	100	18.48	0	18.48	0	18.48	0 (0%)
	50	14.02	0	14.02	0	14.02	0 (0%)
1982	1000	25.99	4.13	21.85	3.18	22.81	0.95 (4%)
	100	11.31	0	11.31	0	11.31	0 (0%)
	50	8.26	0	8.26	0	8.26	0 (0%)
1988	1000	26.7	1.04	25.65	0	26.7	1.04 (4%)
	100	10.51	0	10.51	0	10.51	0 (0%)
	50	5.86	0	5.86	0	5.86	0 (0%)
1996	1000	42.12	20.09	22.02	17.6	24.51	2.49 (11%)
	100	15.9	0	15.9	0	15.9	0 (0%)
	50	9.7	0	9.7	0	9.7	0 (0%)
1998	1000	29.38	17.62	11.76	16.17	13.21	1.45 (12%)
	100	12.91	0	12.91	0	12.91	0 (0%)
	50	6.02	0	6.02	0	6.02	0 (0%)
1999	1000	37.47	15.87	21.59	14.3	23.16	1.56 (7%)
	100	15.23	0	15.23	0	15.23	0 (0%)
	50	9.35	0	9.35	0	9.35	0 (0%)
2010	1000	29.38	3	26.38	2.07	27.31	0.92 (3%)
	100	17.22	0	17.22	0	17.22	0 (0%)
	50	13.36	0	13.36	0	13.36	0 (0%)
Average	1000	33.41	9.89	23.52	8.11	25.30	1.78 (8%)
	100	14.51	0	14.51	0	14.51	0 (0%)
	50	9.68	0	9.68	0	9.68	0 (0%)

The Table 5 show that the flood control optimal operation model of reservoirs can greatly improve the flood control safety of the Jingjiang. When floods with return period of 50 or 100 years occur, the flow after the reservoir operation does not exceed the discharge capacity of the Jingjiang, and there is no need to use the flood diversion areas. In the event of the flood with return period of 1000 years, the optimized model reduced Jingjiang's flood diversion volumes by 25.3 billion m³ on average, especially the flood diversion volume of the 2010 design floods reduced by 48.8 billion. Compared with the current method, the Jingjiang flood diversion volumes has been reduced by 1.78 billion m³ on average.

On the other hand, Table 6 shows that the flood control safety of Chenglingji area has also been greatly improved. In the event of floods with return period of 50 years, there is no need to use the flood diversion areas in Chenglingji, this will greatly reduce the pressure

of flood diversion in Chenglingji. Compared with the current method, the Chenglingji's flood diversion volumes has been reduced by 0.16, 0.25, and 1.96 billion m³ respectively on average when floods with return period of 50, 100, and 1000 years occur.

From the operation results of Jingjiang and Chenglingji, it can be seen that the flood control optimal operation model of reservoirs and DP-POA-PSO algorithm proposed in this paper can significantly reduce the flood diversion of these two flood control points compared with the current method. When the flood is not large, the goal of no flood diversion can be achieved, which will greatly reduce the flood disaster loss.

Table 6. Comparison of the flood diversion in Chenglingji under different operation methods (billion m³).

Typical Flood Hydrograph	Return Period	Without Operations	Current Method		Optimal Method		Comparison
			Diversion	Reduction	Diversion	Reduction	
1954	1000	6.48	5.53	0.94	5.42	1.05	0.1 (11%)
	100	3.34	1.87	1.47	1.7	1.64	0.17 (12%)
	50	2.42	1.59	0.83	0	2.42	1.59 (191%)
1968	1000	11.14	9.56	1.57	9.38	1.75	0.18 (10%)
	100	7.58	3.64	3.94	3.18	4.39	0.45 (11%)
	50	5.84	3.47	2.37	0	5.84	3.47 (146%)
1980	1000	9.58	6.51	3.06	6.16	3.42	0.35 (10%)
	100	3.82	2.44	1.37	2.29	1.53	0.15 (13%)
	50	1.88	1.83	0.04	0	1.88	1.83 (4600%)
1981	1000	9.31	7.08	2.23	6.83	2.48	0.25 (10%)
	100	4.42	2.42	1.99	2.19	2.22	0.22 (12%)
	50	3.33	1.96	1.36	0	3.33	1.96 (144%)
1982	1000	5.25	5.17	0.08	5.16	0.08	0 (0%)
	100	2.89	2.14	0.75	2.05	0.84	0.08 (12%)
	50	2.04	1.61	0.42	0	2.04	1.61 (385%)
1988	1000	5.84	4.92	0.91	4.82	1.01	0.1 (11%)
	100	2.89	1.23	1.66	1.04	1.85	0.19 (12%)
	50	1.87	0.98	0.89	0	1.87	0.98 (110%)
1996	1000	7.18	6.9	0.28	6.86	0.31	0.03 (10%)
	100	5.7	2.49	3.21	2.12	3.57	0.36 (12%)
	50	4.64	2.3	2.33	0	4.64	2.3 (99%)
1998	1000	9.09	4.66	4.43	4.15	4.94	0.5 (10%)
	100	6.53	2.48	4.04	2.01	4.51	0.46 (12%)
	50	5.17	2.89	2.27	0	5.17	2.89 (127%)
1999	1000	7.93	7.24	0.69	7.16	0.76	0.07 (11%)
	100	4.72	2.31	2.4	2.04	2.68	0.27 (12%)
	50	3.82	1.91	1.91	0	3.82	1.91 (100%)
2010	1000	4.42	4.18	0.24	4.15	0.27	0.02 (11%)
	100	2.13	1.35	0.78	1.26	0.87	0.09 (10%)
	50	1.58	1.02	0.56	0	1.58	1.02 (182%)
Average	1000	7.622	6.175	1.443	6.009	1.607	0.16 (12%)
	100	4.402	2.237	2.161	1.988	2.41	0.25 (9%)
	50	3.259	1.956	1.298	0	3.259	1.96 (151%)

4.2.3. Operation Results of TG

The highest operating water level of TG is shown in Table 7. The lower water level can reduce the flood control risk of the reservoir itself and increase the flexibility of flood control operation. Compared with the current method, the water level has been reduced by 1.72, 1.58, and 0.38 m respectively on average when floods with return period of 50, 100, and 1000 years occur. In the event of a flood with a return period of 1000 years, the maximum highest water level is 175 m, and the minimum highest water level is 171.51 m. These

results show that the flood control capacity of the reservoir is fully used in order to reduce the flood diversion of Jingjiang and Chenglingji when a large flood occurs. Conversely, when the flood with return period of 50 years occur, the maximum and minimum highest water level are 166.24, 158.57 m, respectively. These results show that when the flood is not large, the highest water level of the reservoir is reduced as much as possible under the premise of ensuring the minimum flood diversion volumes of Jingjiang and Chenglingji to reduce the flood control risk of the reservoir itself.

Table 7. The highest operating water level of TG under different operation methods (m).

Typical Flood Hydrograph	Return Period	Current Method	Optimal Method	Comparison
1954	1000	172.56	172.54	0.02
	100	165.58	162.69	2.89
	50	160.38	158.57	1.81
1968	1000	175	175	0
	100	166.24	164.05	2.19
	50	163.27	161.21	2.06
1980	1000	175	175	0
	100	168.45	166.44	2.01
	50	165.54	163.21	2.33
1981	1000	170.45	170.22	0.23
	100	171.14	170.71	0.43
	50	166.98	166.24	0.74
1982	1000	171.51	171.51	0
	100	165.83	165.38	0.45
	50	162.77	162.68	0.09
1988	1000	174.81	172.86	1.95
	100	165.37	163.23	2.14
	50	164	158.67	5.33
1996	1000	175	175	0
	100	169.56	167.64	1.92
	50	161.35	159.16	2.19
1998	1000	175	175	0
	100	166.68	165.5	1.18
	50	160.3	158.65	1.65
1999	1000	175	175	0
	100	167.83	165.92	1.91
	50	161.76	160.02	1.74
2010	1000	173.94	172.97	0.97
	100	167.52	166.3	1.22
	50	162.03	160.08	1.95
Average	1000	173.96	173.58	0.38
	100	167.08	165.5	1.58
	50	162.65	160.93	1.72

Figure 7 shows the results of the TG under different operation methods, using as the designed flood the 1954 typical year with return periods of 50 and 1000 years. The figure shows that the results obtained by the optimal operation model are usually better than that of the current method, because inflow and outflow of TG are much smaller and much flatter. In particular, the operation water level of TG is also lower.

It can be seen from Tables 4–7 that for 10 design floods with different encounter characteristics, the model and algorithm proposed in this paper can effectively reduce the peak inflow of the reservoir, the highest operating water level of the reservoir, and the flood diversion of flood control points. On the other hand, when the flood is large, the goal of

reducing the amount of flood diversion is achieved. When the flood is small, the operating water level of the reservoir is further reduced, and the flood control risk of the reservoir itself is reduced. These show that the method has good adaptability.

Figure 7. Operation results of TG under different operation methods, (a) 1000 years; (b) 50 years.

5. Conclusions and Discussion

In this study, a joint flood control optimal operation model with multiple reservoirs and flood control points was established, which gave full play to the flood control potential

of the reservoirs, and balanced the flood control demand between reservoirs and flood control points. The impact of transposition and attenuation of flood cannot be ignored, so the Muskingum routing method is used by the operation model. A DP-POA-PSO optimization algorithm is proposed to solve the optimal operation model. Then, a flood control system consisting of six reservoirs and eight flood control points in the middle and upper Yangtze River is selected as a case study. The study mainly aims at minimizing the flood diversion volumes of Jingjiang and Chenglingji, the maximum inflow of TG and the highest operating water level of TG. The main conclusions are summarized as follows.

(1) This article has two main innovations. The first innovation is that an optimal operation model for multiple reservoirs and flood control points was proposed. The flood control potentiality of the reservoirs is fully utilized, and the flood loss and risk of the system are significantly reduced. In addition, compared with simplified methods such as time delay, the use of the Muskingum method makes the river channel flood routing more accurate, which makes the operation result more in line with the actual project. The second innovation is the proposed DP-POA-PSO optimization algorithm, which combines the advantages of each algorithm in solving the optimal operation of the reservoir, avoiding the “dimensional disaster”, local optimal solution, slow convergence speed, and so on. It shows excellent performance in practical applications.

(2) The optimal operation model and algorithm proposed in this paper can significantly reduce the inflow of the Three Gorges Reservoir. For the design flood with return periods of 1000 years, 100 years, and 50 years, the average reduction of inflow peak is 13,311 m³/s, 10,258 m³/s, and 10,027 m³/s, respectively, the corresponding rate of reduction is 14.6%, 13.0%, and 13.4% respectively. Compared with the current method, the optimal operation increases the inflow peak reduction by 5375 m³/s, 2794 m³/s, and 2628 m³/s respectively.

(3) The joint flood control optimal operation of reservoirs can greatly improve the flood control safety of Jingjiang and Chenglingji. When floods with return period of 50 or 100 years occur, the flow after the reservoir operation does not exceed the discharge capacity of the Jingjiang, and there is no need to use the flood diversion areas. In the event of a flood with a return period of 1000 years, the optimized model reduced Jingjiang's flood diversion volumes by 25.3 billion m³ on average. Compared with the current method, the Jingjiang flood diversion volume has been reduced by 1.78 billion m³ on average. On the other hand, in the event of a flood with a return period of 50 years, there is no need to use the flood diversion areas in Chenglingji, this will greatly reduce the pressure of flood diversion in Chenglingji. Compared with the current method, Chenglingji's flood diversion volumes have been reduced by 0.16, 0.25, and 1.96 billion m³ respectively on average when floods with return period of 50, 100, and 1000 years occur.

(4) The results show that the optimal operation model has good adaptability and flexibility. When a large flood occurs, the flood control capacity of the reservoir is fully used in order to reduce the flood diversion of Jingjiang and Chenglingji. Conversely, when the flood is not large, the highest water level of Three Gorges Reservoir is reduced as much as possible under the premise of ensuring the minimum flood diversion volumes of Jingjiang and Chenglingji to reduce the flood control risk of the reservoir itself.

In real-time flood operation, the inflow at each point in the basin can be obtained through forecasting, and then the model and algorithm proposed in this paper are used to operate the forecasted inflow. The operation results can provide program support for real-time flood control operation. In addition, the operation results of design floods can provide guidance for the formulation of the joint flood control operation rules of reservoirs and flood control points. It can be seen from the operation results that although the operation of the six reservoirs has reduced the flood diversion volumes of Chenglingji, the flood control pressure is still very high, so more reservoirs and more efficient algorithms need to be considered to solve this problem.

In addition, there are many uncertain factors in the operation, which will affect the flood control effect of reservoirs. Research by Hu et al. [62], Krzysztofowicz et al. [63],

Chen et al. [64], and Vermuyten et al. [65] showed that among all the uncertain factors in flood control operation, the uncertainty of flood forecast has the greatest impact on operation results, especially in long-term operation. The uncertainty of the forecast mainly includes three aspects: the error of inflow, the error of flood volume, and the error of flood hydrograph shape. At the same time, the water level-storage curve and the water level-discharge capacity of reservoir curve also have an influence on operation [65]. In order to reduce the difficulty of model solving and increase the speed of calculation, this study did not consider these uncertain factors. Uncertainty can be considered in future research to further improve the operation effect.

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