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Flood Control Optimization of Reservoir Group Based on Improved Sparrow Algorithm (ISSA)

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Abstract: The optimal control problem of reservoir group flood control is a complex, nonlinear, high-dimensional, multi-peak extremum problem with many complex constraints and interdependent decision variables. The traditional algorithm is slow and easily falls into the local optimum when solving the problem of the flood control optimization of reservoir groups. The intelligent algorithm has the characteristics of fast computing speed and strong searching ability, which can make up for the shortcomings of the traditional algorithm. In this study, the improved sparrow algorithm (ISSA) combining Cauchy mutation and reverse learning strategy is used to solve the flood control optimization problem of reservoir groups. This study takes Sanmenxia Reservoir and Xiaolangdi Reservoir on the mainstream of the Yellow River as the research object and Huayuankou as the downstream control point to establish a joint flood control optimization operation model of cascade reservoirs. The results of the improved sparrow algorithm (ISSA), particle swarm optimization (POS) and sparrow algorithm (SSA) are compared and analyzed. The results show that when the improved ISSA algorithm is used to solve the problem, the maximum flood peak flow of the garden entrance control point is 11,676.3 m^3, and the peak cutting rate is 48%. The optimization effect is obviously better than the other two algorithms. This study provides a new and effective way to solve the problem of flood control optimization of reservoir groups.

Keywords: Sanmenxia Reservoir; Xiaolangdi Reservoir; flood control operation; SSA algorithm; ISSA algorithm

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1. Introduction

Flooding has always been one of the most serious, frequent and extensive natural disasters faced by human beings, posing a serious threat to human life and property [1]. In recent years, under the influence of global climate change, floods have become more frequent and extreme. The reservoir plays an important role in flood management in flood season, as it helps to reduce flood peak, reduce flood damage, and prevent floods, making it an important flood control engineering measure [2]. Reservoir flood control operation, as a non-engineering measure combined with reservoir, has always been a hot field of research. We can make a reasonable dispatching scheme to make the reservoir play its role in flood control [3]. Therefore, it is necessary to study a suitable method for reservoir group joint operation.

Reservoir flood control optimization is a complex and conflicting optimization problem with many interdependent decision variables [4]. The conflict of optimal operation of reservoir flood control mainly focuses on the safety of the upstream dam and downstream dike. When ensuring the safety of the upstream dam, the reservoir is required to discharge as much flood as possible to ensure that the water level is maintained at the safety line. In order to ensure the safety of the downstream river, the reservoir is required to store as much water as possible to reduce downstream risks. Obviously, in a flood control decision, to take care of both requires the decision maker to use a "balanced" solution [5]. In order to

solve the above problems, early scholars used dynamic programming (DP) [6,7] and linear programming (LP) [8,9]. However, with the increase in computing dimensions, problems such as dimension disaster and slow computing speed would appear [10,11].

With the rapid development of computers, some heuristic intelligent optimization algorithms have provided some new ideas for flood control scheduling decision. Intelligent optimization algorithms such as genetic algorithm (GA) [12,13] have been gradually applied to solve the problem of optimal flood control scheduling of reservoirs. Subsequently, some scholars successively applied ant colony algorithm (ACO) [14,15], differential evolution algorithm (DE) [16], particle swarm optimization algorithm (PSO) [17,18], and so on, to solve the flood control optimization and dispatching problem of reservoir. Although the swarm intelligent algorithm makes up for the shortcomings of traditional optimization algorithms, the swarm intelligent algorithm often has the disadvantages of precocious convergence and poor convergence performance when solving problems, and it cannot ensure the convergence to the best advantage [19].

The sparrow algorithm (SSA) is a new swarm intelligence algorithm, proposed by Xue Jiankai [20] in 2020, which is inspired by sparrow's foraging behavior and anti-predation behavior. This algorithm is novel, has the advantages of strong optimization searching ability and fast convergence speed, and has been widely used in many fields [21]. In view of the problem that the population diversity of the basic sparrow search algorithm (SSA) decreases in the late iteration period and is easy to fall into local extremum, Mao Qinghua proposed an improved sparrow algorithm (ISSA) that combines Cauchy mutation and reverse learning [22]. However, the basic sparrow search algorithm (SSA) also faces the problem of falling into local extremum when the population diversity decreases in the late iteration period. To solve the above problems, Mao Qinghua proposed an improved sparrow algorithm (ISSA) that combines Cauchy mutation and reverse learning.

In this paper, the ISSA algorithm is firstly used to solve the problem of flood control operation of reservoirs. In order to verify the feasibility and effectiveness of the ISSA algorithm in the joint flood control operation of reservoirs, this paper takes Sanmenxia Reservoir and Xiaolangdian Reservoir in the mainstream of the Yellow River as the research objects and establishes the maximum flood peak cutting model of Huayuankou. The ISSA, SSA and POS algorithms are applied to solve this model, and the calculation results of the three algorithms are compared. The results show that the ISSA algorithm is superior to other algorithms selected in this paper, which provides a new method to solve the joint flood control scheduling problem of reservoir groups.

The structure of the paper is as follows. The second chapter introduces the optimal operation model of reservoir joint flood control. The third chapter introduces the sparrow algorithm (SSA) and the improved sparrow algorithm (ISSA). The fourth chapter is the model analysis part, which mainly introduces the solution steps of the flood control operation model, the research area of the flood control operation model, and the interval flood analysis of the flood control operation model. The fifth chapter is the results and discussion. The sixth chapter is the conclusion of the article.

2. Reservoir Joint Flood Control Dispatching Model

2.1. Objective Function

The flood control system consists of embankments, flood diversion projects and reservoirs. During flood control regulation, it is necessary to give full play to the advantages of various projects and control and regulate flood in a planned and unified way. In flood season, reservoir flood control operation rules are usually used to guide the operation of the reservoir in flood season according to the current storage state and inflow flow of the reservoir. In this paper, the maximum peak clipping criterion is used to establish the flood control optimal operation model of cascade reservoirs. Assuming that there are N reservoirs in series, the reservoir inflow and interval flood are known, and the total number of dispatching periods is T. See Figure 1 for the schematic diagram of cascade reservoirs of N level.

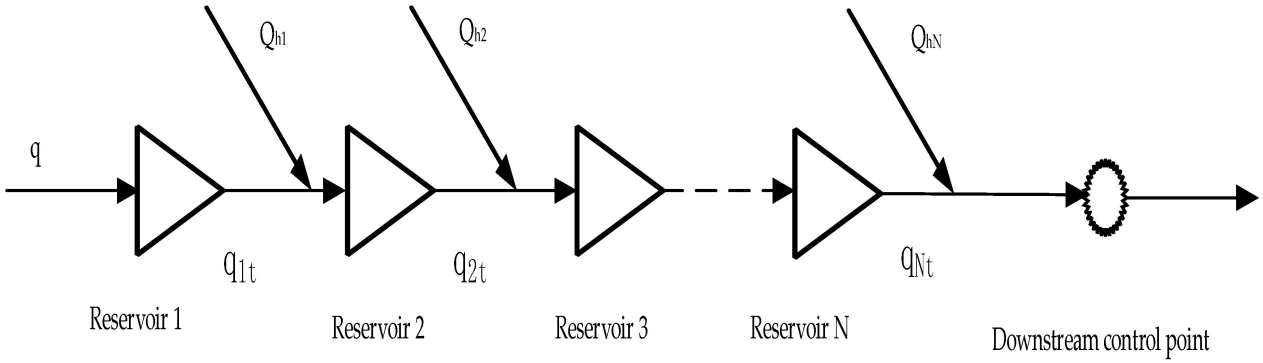


Figure 1. Diagram of N-level cascade reservoirs.

The objective function established by the maximum peak clipping criterion of control points:

$$f(q) = \min \sum_{t=1}^{T} \left[(q_{1t} + Q_{h1})^2 + (q_{2t} + Q_{h2})^2 + \cdots + (q_{Nt} + Q_{\mathrm{hN}})^2 \right] \quad (1)$$

where T is the total number of scheduling periods; t is the number of periods; q_{1t} is the average discharge of the first upstream reservoir in t period; q_{2t} is the average discharge of the second upstream reservoir in t period; q_{Nt} is the average discharge of the Nth upstream reservoir in period t; Q_h is the average interval inflow during t period.

2.2. Condition of Constraint

(1) Water balance constraint:

$$V_t = V_{t-1} + ((Q_t + Q_{t+1})/2 - (q_t + q_{t+1})/2)\Delta t \quad (2)$$

V_t is the average storage capacity of time period t; V_{t-1} is the average storage capacity in the $T-1$ period; Q_t, Q_{t+1} is the average inbound flow in time period t and time period $t+1$; q_t, q_{t+1} is the average discharge volume in time period t and $t+1$.

(2) Constraints on reservoir water level:

$$\mathrm{Z}_{\min,k} \le \mathrm{Z}_{\mathrm{k}} \le \mathrm{Z}_{\max,k} (k = 1, 2) \quad (3)$$

where T represents the water level of the k reservoir during flood control operations (m); $\mathrm{Z}_{\min,k}$ stands for the lowest allowable water level during flood control operations, which is the flood limit water level; $\mathrm{Z}_{\max,k}$ T stands for the maximum allowable water level during flood control operations, which is the check water level;

(3) Letdown flow constraint:

$$0 \le q_k \le q_{\max,k} (k = 1, 2) \quad (4)$$

where q_k is the discharge of the kth reservoir; $q_{\max,k}$ is the maximum discharge capacity of the kth reservoir.

(4) Initial water level constraint:

$$Z_0 = Z_{\min,k} (k = 1, 2) \quad (5)$$

where Z_0 is the initial water level; $Z_{\min,k}$ is the lowest allowable water level during flood control operation.

(5) Terminal water level constraint:

$$Z_{end} = Z_{\min,k} (k = 1, 2) \quad (6)$$

where Z_{end} is the water level of the reservoir at the end of flood control regulation; $Z_{\min,k}$ is the lowest allowable water level during flood control operation.

3. Sparrow Optimization Algorithm

3.1. Basic Sparrow Search Algorithm (SSA)

The sparrow algorithm (SSA) was first proposed by Xue Jiankai [20] in 2020, which is a new intelligent optimization algorithm based on the feeding and anti-predation behavior of the sparrow population. According to the position and energy level of sparrows in the population, sparrows are mainly divided into three categories: discoverer, joiner and watcher. Among them, the discoverer is responsible for finding food, the joiner is responsible for catching prey after the discoverer finds food, and the watcher is responsible for sensing natural enemies to ensure population safety.

The population matrix form composed of n sparrows can be expressed as follows:

$$X = \begin{pmatrix} x_{1,1} & x_{1,2} & \cdots x_{1,d} \\ x_{2,1} & x_{2,2} & \cdots x_{2,d} \\ \vdots & \vdots & \vdots \\ x_{n,1} & x_{n,2} & x_{n,d} \end{pmatrix} \tag{7}$$

where d represents the dimension of the variable to be optimized, and n represents the number of sparrows. Then, the fitness values of all sparrows can be expressed as follows:

$$F_x = \begin{pmatrix} f([x_{1,1}x_{1,2}\cdots x_{1,n}]) \\ f([x_{2,1}x_{2,2}\cdots x_{2,n}]) \\ \vdots \\ \vdots \\ f([x_{n,1}x_{n,2}\cdots x_{n,n}]) \end{pmatrix} \tag{8}$$

where f represents the fitness value.

In the sparrow algorithm (SSA), the discoverer with better fitness value will give priority to getting food during the search process. In addition, the discoverer is responsible for finding food for the whole sparrow population and providing the direction for all participants. During each iteration, the location of the discoverer is updated as follows:

$$X_{i,j}^{t+1} = \begin{cases} X_{i,j}^{t} \cdot \exp(-\frac{i}{\alpha \cdot iter_{\max}}) & if\ R_2 < ST \\ X_{i,j}^{t} + Q \cdot L & if\ R_2 < ST \end{cases} \tag{9}$$

where t represents the current iteration algebra, j = 1, 2, 3, . . . , d. $iter_{\max}$ is a constant representing the maximum number of iterations. $X_{i,j}$ represents the position information of the ith sparrow in the jth dimension. $\alpha \in (0, 1]$ is a random number. R_2 ($R_2 \in [0, 1]$) and ST ($ST \in [0.5, 1]$) represent early warning value and safety value, respectively. Q is a random number subject to normal distribution. L represents a $1 \times d$, where each element in the matrix is 1. When $R_2 < ST$, it means that there are no predators around the foraging environment at this time, and the finder can perform extensive search operations. If $R_2 \geq ST$, it means that some sparrows in the population have found predators and sent an alarm to other sparrows in the population. At this time, all sparrows need to quickly fly to other safe places for feeding.

For predators, in the process of foraging, some participants will constantly monitor the finder. Once they realize that the discoverer has found better food, they will immediately

leave their current position to compete for food. The location updates of the participants are described as follows:

$$X_{i,j}^{t+1} = \begin{cases} Q \cdot \exp(\frac{X_{worst} - X_{i,j}^t}{i^2}) & if\ i > n/2 \\ X_p^{t+1} + \left| X_{i,j}^t - X_p^{t+1} \right| \cdot A^+ \cdot L & otherwise \end{cases} \quad (10)$$

where X_p is the optimal position occupied by the current discoverer; X_{worst} represents the current global worst position. A represents a $1 \times d$, and each element is randomly assigned to 1 or -1 and $A^+ = \mathrm{AT}\ (\mathrm{AAT})^{-1}$. When $i > n/2$, it indicates that the i-th finder with low fitness value has not got food and is in a very hungry state. At this time, it needs to fly to other places to forage for more energy.

In the simulation, we assume 10 to 20 percent of the total number of watchmen. The initial positions of these sparrows were randomly generated within the population. Its mathematical expression can be shown as follows:

$$X_{i,j}^{t+1} = \begin{cases} X_{best}^t + \beta \cdot \left| X_{i,j}^t - X_{best}^t \right| & if\ f_i > f_g \\ X_{i,j}^t + K \cdot (\frac{\left| X_{i,j}^t - X_{worst}^t \right|}{(f_i - f_w) + \varepsilon}) & if\ f_i = f_g \end{cases} \quad (11)$$

where X_{best} is the current global optimal position. As a step control parameter, β is a random number subject to the normal distribution with mean value of 0 and variance of 1. $K \in [-1, 1]$ is a random number, and f_i is the fitness value of the current sparrow individual. f_g and f_w are the current global best and worst fitness values, respectively. ε is the smallest constant to avoid zeros in the denominator.

For simplicity, when $f_i > f_g$ indicates that the sparrow is at the edge of the population and is extremely vulnerable to predators. X_{best} means that the sparrow in this position is the best and safe position in the population. When $f_i = f_g$, it indicates that the sparrows in the middle of the population are aware of the danger and need to get close to other sparrows to minimize their risk of being preyed on. K indicates that the direction of movement of the sparrow is also a step control parameter.

3.2. Improved Sparrow Algorithm (ISSA)

(1) Sin chaos initialization population

The Sin chaos model is a model with an infinite number of mapping folds. In this paper, Sin chaos is used to initialize the population of the sparrow algorithm. The one-dimensional self-mapping expression of Sin chaos is as follows:

$$\begin{cases} x_{n+1} = \sin \frac{2}{x_n}, n = 0, 1, \cdots, N \\ -1 \le x_n \le 1, x_n \ne 0 \end{cases} \quad (12)$$

In Formula (12), to prevent fixed points and zeros from being generated in $[-1, 1]$ $[-1, 1]$ $[-1, 1]$, the initial value cannot be set to 0.

(2) Dynamic adaptive weight

With reference to the idea of inertia weight, the dynamic weight factor ω is introduced into the discoverer position updating mode to make it have a larger value in the early iteration, which can be better explored globally, and reduce adaptively in the late iteration, so as to better perform local search and improve the convergence speed. The calculation formula of the weight coefficient ω and the updated method of the discoverer's position after improvement are as follows:

$$\omega = \frac{e^{2(1-t/iter_{\max})} - e^{-2(1-t/iter_{\max})}}{e^{2(1-t/iter_{\max})} + e^{-2(1-t/iter_{\max})}} \quad (13)$$

$$X_{i,j}^{t+1} = \begin{cases} (X_{i,j}^t + \omega(f_{j,g}^t - X_{i,j}^t)) \cdot rand, R_2 < ST \\ X_{i,j}^t + Q, R_2 \geq ST \end{cases} \quad (14)$$

In Formula (14), $f_{j,g}^t$ is the global optimal solution of the jth dimension in the previous generation.

(3) An improved formula for updating the position of the watchman

$$X_{i,j}^{t+1} = \begin{cases} X_{best}^t + \beta(X_{i,j}^t - X_{best}^t), f_i \neq f_g \\ X_{best}^t + \beta(X_{worst}^t - X_{best}^t), f_i = f_g \end{cases} \quad (15)$$

(4) Fusion of Cauchy Variation and Reverse Learning Strategy

In order to enable individuals to better find the optimal solution, the reverse learning strategy is integrated into the sparrow algorithm. The mathematical representation is as follows:

$$X'_{best}(t) = ub + r \oplus (lb - X_{best}(t)) \quad (16)$$

$$X_{i,j}^{t+1} = X'_{best}(t) + b_1 \oplus (X_{best}(t) - X'_{best}(t)) \quad (17)$$

where $X'_{best}(t)$ is the inverse solution of the optimal solution of generation t. ub, lb is the upper and lower bounds, respectively. r is 1 subject to normal uniform distribution $\times$ d (d is the space dimension); b_1 represents the information exchange control parameter, and the formula is as follows:

$$b_1 = (iter_{\max} - \frac{t}{iter_{\max}})^t \quad (18)$$

To further improve the optimization performance of the algorithm, Cauchy operator perturbation is incorporated into the sparrow algorithm, and the mathematical expression is as follows:

$$X_{i,j}^{t+1} = X_{best}(t) + cauchy(0,1) \oplus X_{best}(t) \quad (19)$$

where Cauchy(0, 1) is the standard Cauchy distribution. The generating function of the Cauchy distribution random variable is $\eta = \tan[(\xi, -0.5)\,\pi]$.

In order to further improve the optimization performance of the algorithm, a dynamic selection strategy is adopted to update the target position. The reverse learning strategy and Cauchy mutation operator perturbation strategy are alternately executed under a certain probability to dynamically update the target position. In the reverse learning strategy, the reverse solution is obtained through the reverse learning mechanism to expand the search field of the algorithm. In Cauchy mutation strategy, Cauchy mutation operator is used to perturb and mutate at the optimal solution position to obtain a new solution, which improves the defect that the algorithm falls into local area. As for which strategy to adopt for target location update, it is determined by the selection probability P_s, and its calculation formula is as follows:

$$P_s = \exp(1 - \frac{t}{iter_{\max}})^{-20} + \theta \quad (20)$$

In the formula, θ is the adjustment parameter, and its value can be 0.05. The specific selection strategy is as follows: if rand < P_s, choose (16)~(18) reverse learning strategy to update the position; otherwise, choose (8) Cauchy mutation perturbation strategy to update the target position. Although the above two perturbation strategies can enhance the ability of the algorithm to jump out of local space, it is impossible to determine that the new position obtained after the perturbation mutation is better than the fitness value of the original position. Therefore, after the perturbation mutation update, the greedy rule is introduced to determine whether to update the position by comparing the fitness values of

the new and old positions. The greedy rule is shown in Equation (21), and f(x) represents the location fitness value of x.

$$X_{best}(t) = \begin{cases} X_{i,j}^{t+1}, \ f(X_{i,j}^{t+1}) < f(X_{best}(t)) \\ X_{i,j}^{t+1}, \ f(X_{i,j}^{t+1}) \geq f(X_{best}(t)) \end{cases} \quad (21)$$

4. Model Analysis

4.1. Solution Method of Flood Control Operation Model

This study uses the improved sparrow algorithm (ISSA) in Section 3.2 to solve the optimal operation model of Sanmenxia and Xiaolangdi reservoirs for joint flood control. The solution steps of the model are shown in Figure 2.

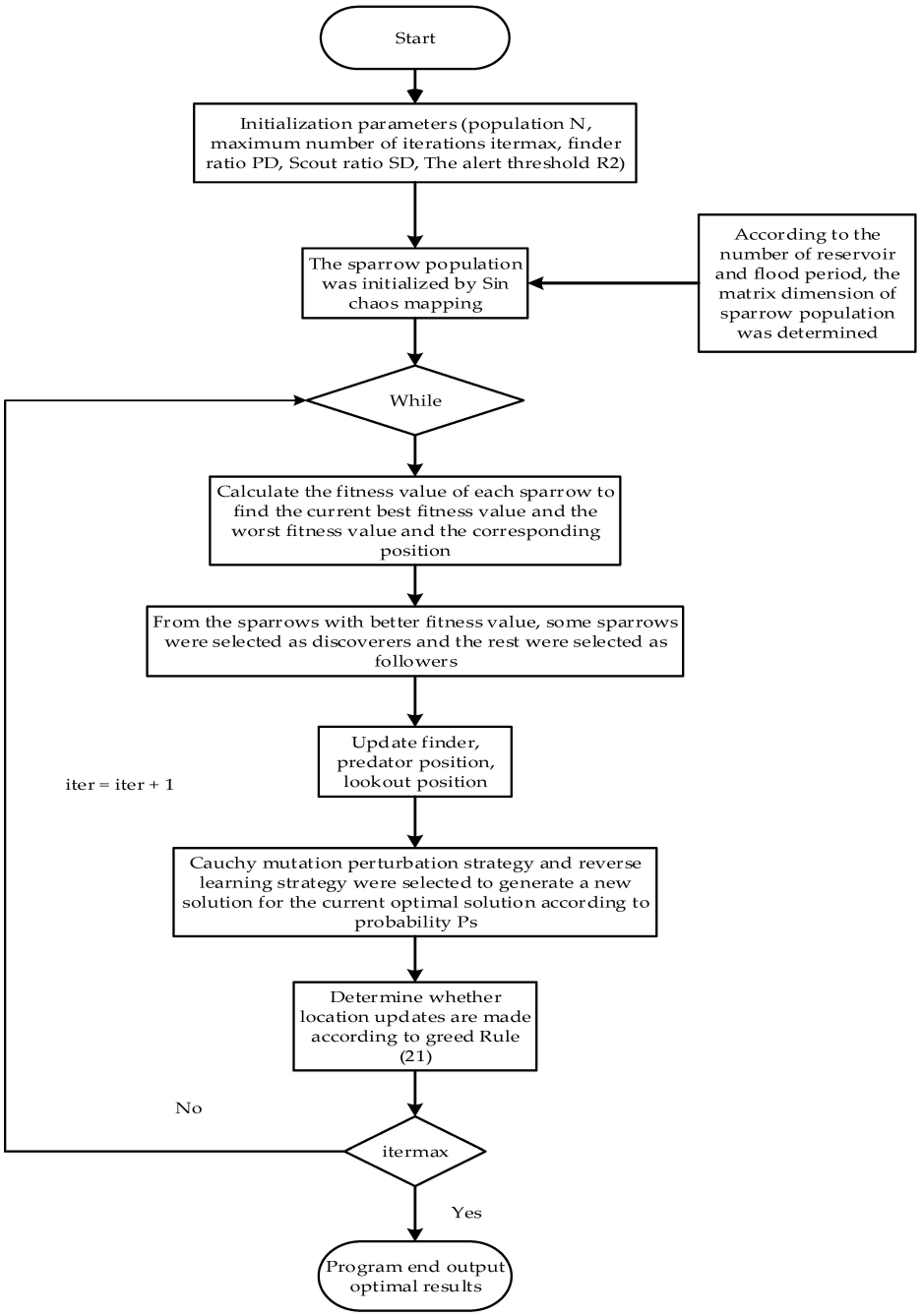


Figure 2. Flow chart of model calculation steps.

(1) Initialization parameters, such as population number N, maximum iteration number $iter_{\max}$, discoverer proportion PD, joiner proportion SD, alert threshold R_2 and initialization of sparrow population using the Sin chaotic map of Equation (12) according to the calculation period given by flood flow. The sparrow is constructed with the discharge of each reservoir at the end of each cycle as the control variable. The flood lasts 78 periods and has two reservoirs, so the vector dimension is 156. Then, the matrix form of sparrow population:

$$Y(0) = [Z_1(0), Z_2(0), \ldots X_n(0)] = \begin{pmatrix} z_{1,1}(0) & z_{1,2}(0) & \cdots & z_{1,n}(0) \\ z_{2,1}(0) & z_{2,2}(0) & \cdots & z_{2,n}(0) \\ \vdots & \vdots & \vdots & \vdots \\ z_{156,1}(0) & z_{156,2}(0) & \cdots & z_{156,n}(0) \end{pmatrix} \quad (22)$$

$Z_i(0)$ is the ith initial sparrow, including 156 elements. 1~78 represents the reservoir water level at the end of the Sanmenxia Reservoir period, and 79~156 represents the end of the Xiaolangdi Reservoir period.

(2) Calculate the fitness value of each sparrow and find out the current optimal fitness value, the worst fitness value, and the corresponding position.
(3) From the sparrows with better fitness values, select some sparrows as the discoverers, and update their positions according to Formula (14).
(4) The remaining sparrows will be the participants, and their positions will be updated in the original way.
(5) Randomly select some sparrows from the sparrows as watchers and update their positions according to Formula (15).
(6) According to probability P_s, the Cauchy mutation perturbation strategy and reverse learning strategy are selected to perturb the current optimal solution to generate a new solution.
(7) Determine whether to update the location according to the greedy rule (21).
(8) Judge whether the end conditions are met. If the end conditions are met, proceed to the next step; otherwise, skip to step (2).
(9) The program ends and the optimal result is output.

4.2. Study Area of Flood Control Operation Model

This paper selects the section from Sanmenxia Reservoir to Huayuankou in the middle and lower reaches of the Yellow River as the research area. The Yellow River is a big river in northern China, one of the longest rivers in the world and the second longest river in China. The total length of the Yellow River is about 5464 km, and its drainage area is about 752,443 km^2. The Yellow River basin has many tributaries and developed water system, which also leads to frequent floods in the Yellow River basin. The water system of the Yellow River basin is shown in Figure 3.

This paper chooses Sanmenxia and Xiaolangdi Reservoir as the research objects. Sanmenxia Reservoir and Xiaolangdi Reservoir are two large reservoirs located in the middle and lower reaches of the mainstream of the Yellow River. They are the backbone projects of the Yellow River hydraulic engineering system. They are of great significance to the development and utilization of water conservancy and hydropower resources in the Yellow River basin and the relief of flood control pressure in the lower reaches of the Yellow River. Under the condition of ensuring the flood control safety of Huayuankou, the optimal operation of Sanmenxia Reservoir and Xiaolangdi Reservoir in the Yellow River basin is studied. See Figure 4 for the locations of Sanmenxia, Xiaolangdi Reservoir and Huayuankou control points.

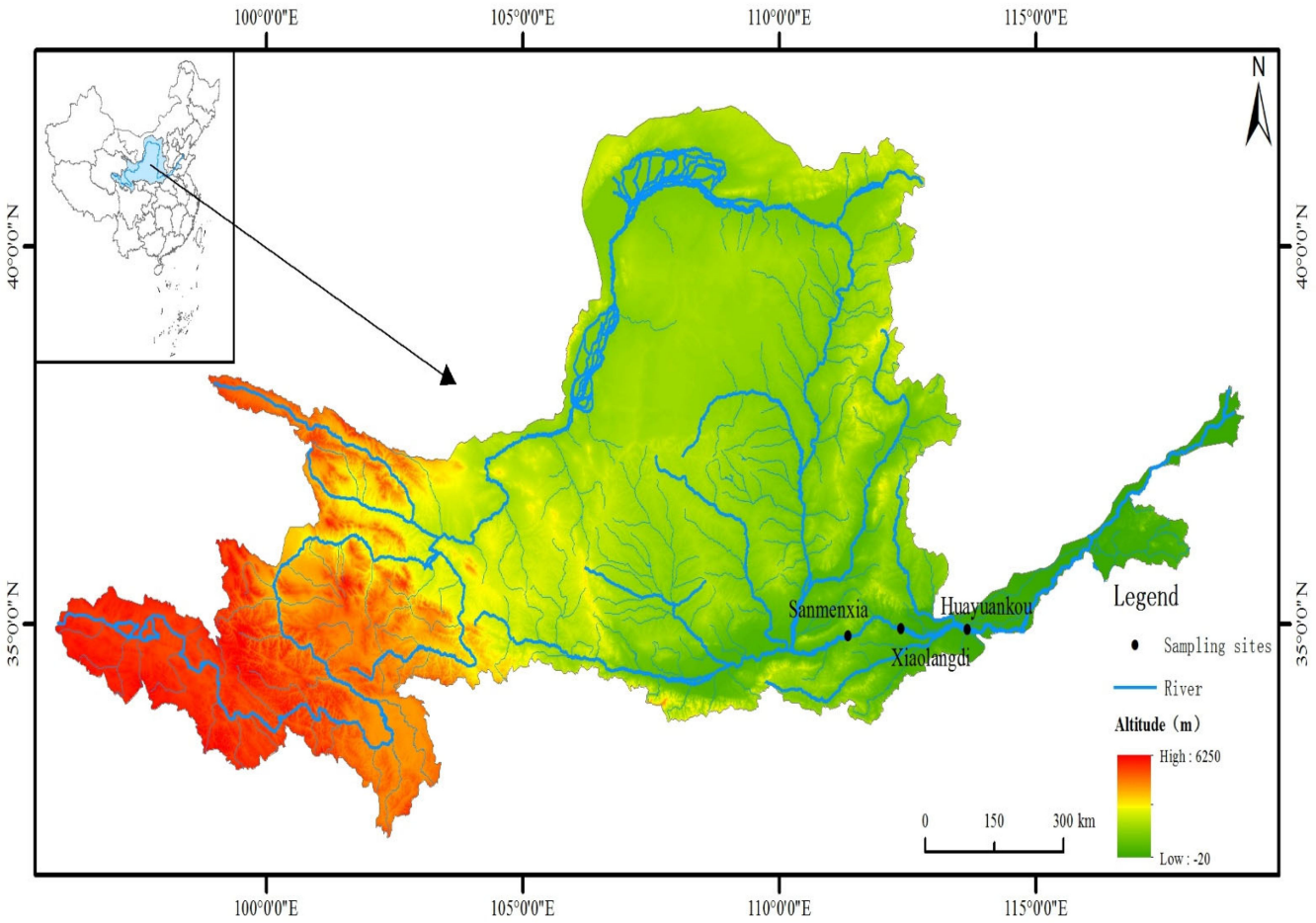


Figure 3. Water system of the Yellow River basin.

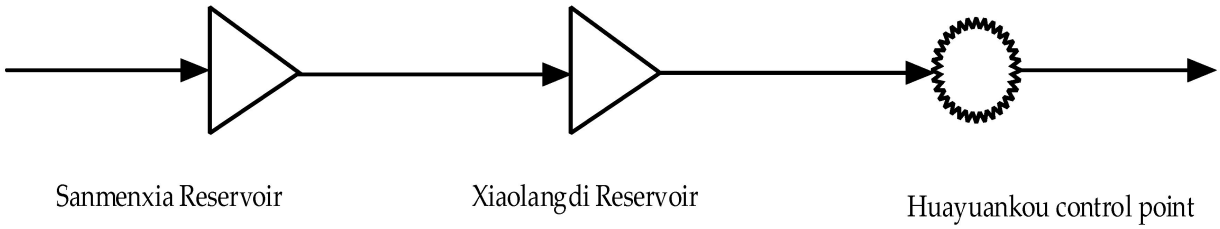


Figure 4. Location of Sanmenxia, Xiaolangdi Reservoir and Huayuankou.

Sanmenxia Reservoir is a key project in the middle reaches of the Yellow River. It is 120 km away from Tongguan Station and 260 km away from Huayuankou Station. The total storage capacity of the reservoir is 16.2 billion cubic meters. The drainage area controlled by the reservoir is 688,400 km^2, accounting for 91.49% of the total drainage area. Sanmenxia Reservoir is a large comprehensive reservoir focusing on flood control and considering irrigation and power generation. Xiaolangdi Reservoir is 130 km away from Sanmenxia Reservoir. The total storage capacity of the reservoir is 12.65 billion cubic meters, and the controlled drainage area is 694,000 km^2, accounting for 92.3% of the total area of the Yellow River basin. It is the only large-scale comprehensive water conservancy project with large storage capacity in the middle and lower reaches of the Yellow River except Sanmenxia. See Table 1 for the current situation of Sanmenxia Xiaolangdi Reservoir.

Table 1. Current situation of Sanmenxia and Xiaolangdi Reservoirs.

Reservoir	Sanmenxia Reservoir	Xiaolangdi Reservoir
Control watershed area	688,400 km^2	694,000 km^2
Flood control limited water level	305 m	220 m
Flood control high water level	335 m	275 m
Total reservoir capacity	16,200,000,000 m^3	12,650,000,000 m^3

4.3. Interval Water Supply Analysis of Flood Control Operation Model

Taking Huayuankou as the control point, the upstream can be divided into three areas according to the location of Sanmenxia reservoir and Xiaolangdi reservoir. Therefore, there are three regional flood processes in the mainstream of the Yellow River above Huayuankou, including the upstream flood of Sanmenxia Reservoir, the interval flood between Sanmenxia and Xiaolangdi Reservoir, and the interval flood between Xiaolangdi and Huayuankou. Assume that the inflow flow of Sanmenxia is Q_1, the interval flow between Sanmenxia and Xiaolangdi is Q_2, and the interval flow between Xiaolangdi Reservoir and Huayuankou is Q_3. It is assumed that the discharge of Sanmenxia Reservoir is q_1, and the discharge will evolve into q_2 through the river channel. The sum of interval flow Q_2 and flow q_2 of Sanmenxia Reservoir and Xiaolangdi Reservoir is the inflow flow of Xiaolangdi Reservoir. The outflow flow q_3 of Xiaolangdi reservoir evolves into flow q_4 through the river, and the sum of q_4 and flow Q_3 is used as the flood flow at Huayuan Estuary of the control point. The flood routing process of the flood control system is shown in Figure 5.

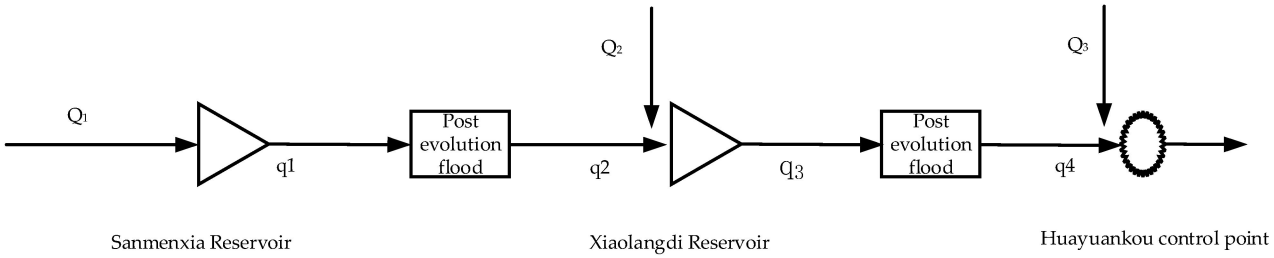


Figure 5. Flood evolution process.

For the calculation of evolution flood, the Muskin method is adopted. Its basic principle: ignoring the inertia term, the dynamic equation can be simplified as the tank storage equation, as shown in the following formula:

$$W = K[xI + (1 - x)\mathrm{Q}]\mathrm{Q}' \tag{23}$$

$$\frac{1}{2}(I_1 - I_2)\Delta t - \frac{1}{2}(O_1 - O_2)\Delta t = W_2 - W_1 \tag{24}$$

where W is the water storage capacity of the river, and Q' is the storage flow. K is the slope of the storage flow relationship, and x is the flow specific gravity coefficient.I_1, I_2 are the inflow of upstream section at the beginning and end of the calculation period. O_1, O_2 are the downstream section flow at the beginning and end of the calculation period. Δt is the length of the calculation period. Simultaneous water balance equation and tank storage equation are solved:

$$O_2 = C_0 I_2 + C_1 I_1 + C_2 O_1 \tag{25}$$

$$C_0 = \frac{\frac{1}{2}\Delta t - Kx}{K - Kx + \frac{1}{2}\Delta t} \tag{26}$$

$$C_1 = \frac{\frac{1}{2}\Delta t + Kx}{K - Kx + \frac{1}{2}\Delta t} \tag{27}$$

$$C_2 = \frac{K - Kx - \frac{1}{2}\Delta t}{K - Kx + \frac{1}{2}\Delta t} \tag{28}$$

$$C_0 + C_1 + C_2 = 1 \tag{29}$$

Due to the different characteristics of river courses, the values of parameters K and x are different for different research river sections. See Table 2 for the values of relevant parameters.

Table 2. Relevant parameters.

Name of River Section	Flood Propagation Time	Number of Flood Routing Sections	K	x	Δt
Sanmenxia–Xiaolangdi	8 h	2	3.875	0.2	4 h
Xiaolangdi–Huayuankou	12 h	3	4.576	0.3	4 h

5. Results and Discussion

The real data of 58 years typical millennium flood in the mainstream of the Yellow River are selected for this study. The authenticity and reliability of the research are guaranteed. The total duration of this flood is 312 h, which is divided into 78 periods of 4 h each. The initial population number of ISSA algorithm is N = 50, the maximum iteration number is itermax = 1000, the proportion of discoverers is PD = 0.7, the proportion of scouts is SD = 0.2, and the alert threshold is R2 = 0.6. Under the same conditions, ISSA, SSA and POS algorithms are used to solve the joint flood control optimal operation model of Sanmenxia and Xiaolangdi reservoirs. Figures 6 and 7 show the operation process of Sanmenxia and Xiaolangdi reservoirs when the ISSA algorithm is used to solve the model. Figure 8 shows the flood process of the Huayuankou control point without reservoir regulation and when three different algorithms are used to solve the model.

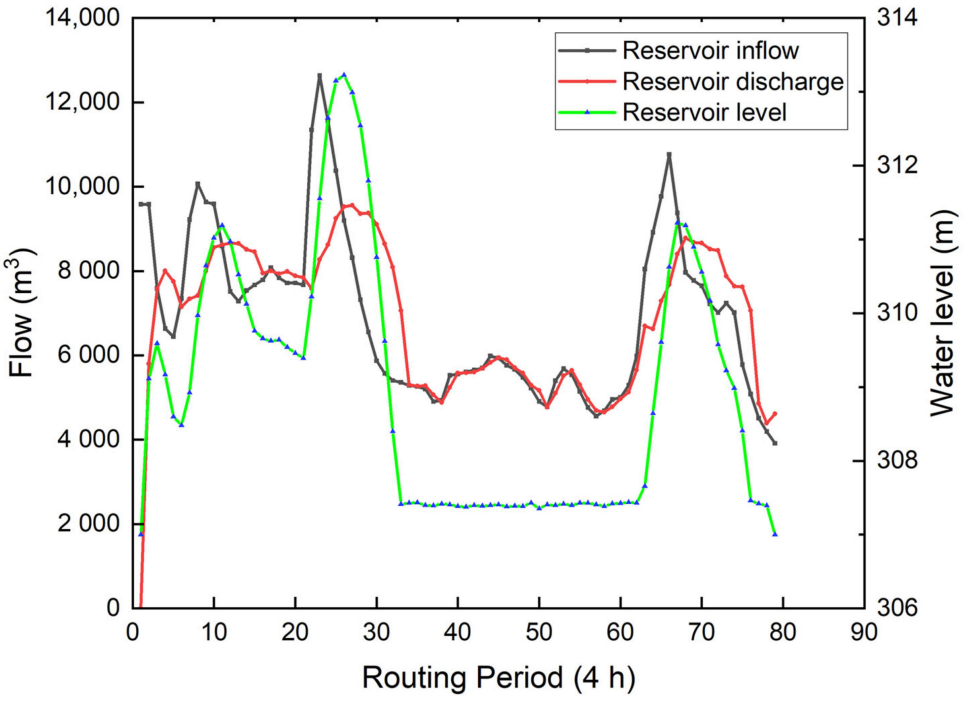


Figure 6. Sanmenxia Reservoir operation process.

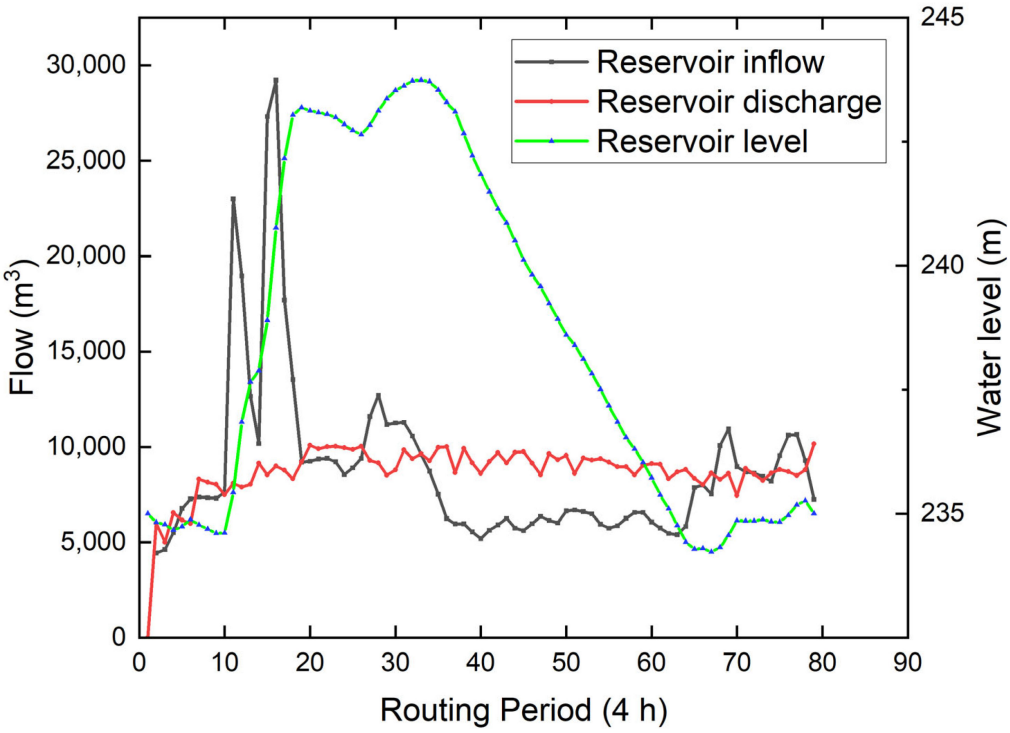


Figure 7. Xiaolangdi Reservoir operation process.

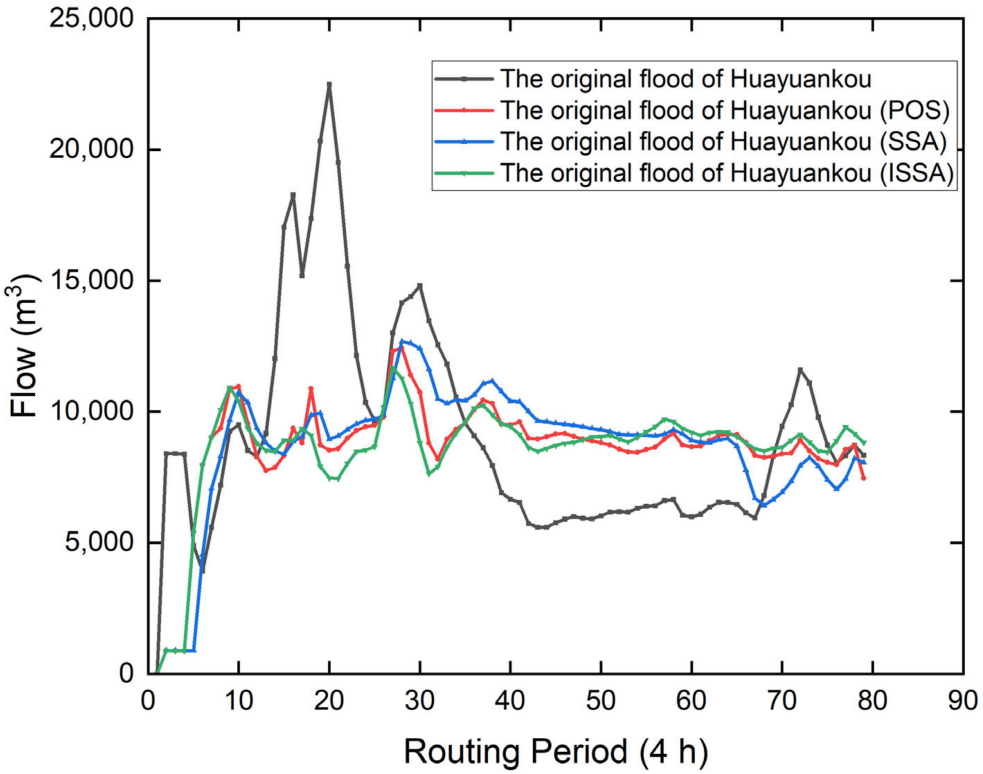


Figure 8. Flood process of Huayuankou control point.

It can be seen from Figures 6 and 7 that when the inflow flow of Sanmenxia Reservoir and Xiaolangdi Reservoir is small, the reservoir discharge flow is equal to the inflow flow, and the water level of the reservoir remains basically unchanged. When the inflow of Sanmenxia Reservoir and Xiaolangdi Reservoir is large, considering the discharge capacity of the reservoir and the bearing capacity of the downstream river channel, the

reservoir begins to store water and the water level starts to rise, sharing the pressure for the downstream flood control. After the reservoir completes a flood control operation without considering the water storage, the water level should return to the initial regulation level to cope with the arrival of the next flood. From Figures 6 and 7, the water level of Sanmenxia and Xiaolangdi reservoirs returned to the initial regulation level at the end of flood control regulation. It not only ensures the flood control safety of the reservoir itself and the downstream, but also provides guarantee for the next flood control operation of the reservoir.

Figure 8 shows the flood process of Huayuankou, a downstream control point. The black line on the top represents the flood process of control points when there is no reservoir regulation. The red, blue and green lines represent the flood process of control points when the POS algorithm, SSA algorithm and ISSA algorithm are used to solve the model. It can be seen from Figure 8 that when the ISAA, SSA and POS algorithms are used to solve the model, the flood peak at the control point at Huayuankou can be reduced. However, different algorithms have different effects when solving the model. See Table 3 for flood data and algorithm initialization parameters of the Huayuankou control point.

Table 3. Flood data of Huayuankou control point and initialization parameters of the algorithm.

Algorithm	Population Quantity (N)	Maximum Iterations (Itemax)	Maximum Peak Flood Discharge	Peak Clipping Rate
ISSA	50	1000	11,676.3 m^3/s	48%
SSA	100	1000	12,673.65 m^3/s	45%
POS	80	1000	12,408.23 m^3/s	44%

In this paper, the optimal operation model of Sanmenxia and Xiaolangdi reservoirs for joint flood control is established based on the maximum peak cutting criterion of the Huayuankou control point. It can be seen from Table 3 that when ISSA, SSA and POS algorithms are used to solve the problem, the maximum peak flood flow of the garden entrance control point is 11,676.3, 12,673.65 and 12,408.23 m^3/s, respectively, meeting the flood control requirements of 22,000 m^3/s for this section. When the ISSA algorithm is used to solve the model, the peak clipping rate of the Huayuankou control point is 48%, which is significantly higher than that of the other two algorithms. Additionally, the flood process of the Huayuankou control point is more stable when the ISSA algorithm is used to solve the problem. It shows that the ISSA algorithm is superior to the other two algorithms in solving the joint flood control operation problem of reservoirs.

6. Conclusions

Sanmenxia Reservoir and Xiaolangdi Reservoir are taken as the research object, and Huayuankou is taken as the downstream control point. Based on the maximum peak clipping criterion, the joint flood control operation model of Sanmenxia and Xiaolangdi Reservoirs is established. The main constraints of the model are water level constraints, flow constraints and water balance constraints. The ISSA algorithm is first used to solve the problem of joint flood control operation of reservoirs. The model solution results of the ISSA algorithm, POS algorithm and SSA algorithm under the same conditions are compared and analyzed.

(1) From the solution results of the model, it can be seen that the construction of this model not only guarantees the flood control safety of the reservoir itself when encountering the flood with the return period of 1000 years, but also guarantees the flood control safety of the downstream, indicating the rationality and applicability of the model.
(2) In this paper, ISSA, SSA and POS algorithms are used to study the flood control operation of tandem cascade reservoirs including Sanmenxia Reservoir and Xiaolangdi Reservoir on the Yellow River mainstream. The comparison of the solution results of the three optimization algorithms shows that the ISSA algorithm is more efficient

than the conventional SSA algorithm and POS algorithm and can fully play the role of reservoir capacity compensation to achieve the best flood control effect. The results show that the ISSA algorithm can effectively solve the flood control optimal operation problem of cascade reservoirs. It provides a new method to solve the problem of joint flood control operation of cascade reservoirs. It also provides a reference for the ISSA algorithm to be applied to other research fields.

(3) Without the regulation of Sanmenxia Reservoir and Xiaolangdi Reservoir, the maximum flood peak flow at the Huayuankou control point is 24,325 m^3/s, far exceeding the flood control requirement of 22,000 m^3/s at the Huayuankou control point section. Through the joint flood control operation of Sanmenxia Reservoir and Xiaolangdi Reservoir, the flood peak of the Huayuankou control point is reduced, making the maximum peak flow of the Huayuankou control point 11,676.3 m^3/s, ensuring the flood control safety of the Huayuankou control point when encountering the millennium flood. This shows that it is necessary to study the joint flood control operation of Sanmenxia Reservoir and Xiaolangdi Reservoir, and further explains the significance of this study.

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