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Dimensionality Reduction Method of Dynamic Programming under Hourly Scale and Its Application in Optimal Scheduling of Reservoir Flood Control

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Abstract: In flood control scheduling of reservoirs, the usual conventional scheduling fails to obtain the optimal solution to the problem. The dynamic programming method is applied to the field. However, the problem of 'dimensional disaster' restricts its application. To solve these problems, the improved DP is constructed according to the principle of period inflow and water balance, which includes a variable dispersion mechanism of the retraction space and a calculation method for the smallest discrete points of each discrete range. Taking Dongjiang Reservoir as the research object, based on the maximum peak clipping criterion and the maximum flood control safety guarantee criterion, the improved DP is used for optimization. The results find that when the former criterion is used for scheduling, the discharge flow processes of the two floods are more uniform than conventional scheduling. When the latter criterion is used for scheduling, the minimum water levels of the two floods are lower than the conventional scheduling. As such, it is found that in the two flood dispatches, the calculation time after the first flood DP dimensionality reduction processing is reduced by about 65%, and the second flood is reduced by about 59%, which greatly improves the calculation efficiency of the DP.

Keywords: flood control optimal scheduling; dynamic programming; hourly scale; dimensionality reduction; Dongjiang Reservoir

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1. Introduction

Reservoir flood control scheduling is usually a multi-constrained, multi-stage, nonlinear, and complex decision-making process. The commonly used conventional scheduling method is a semi-empirical and semi-theoretical method with the help of scheduling criteria. This method uses empirical charts, such as the flood control scheduling map of the reservoir, to implement the operation, so the flood control scheduling plan obtained is often only a feasible solution or a reasonable solution rather than an optimal solution. Therefore, to further improve the flood control benefits of the reservoir and ensure the safety of the reservoir and downstream protection objects, it is very necessary to research the optimization of flood control scheduling in combination with the characteristics of the flood control scheduling of the reservoir.

After nearly 50 years of research, there are many existing mathematical models of reservoir scheduling. They can be divided into four categories according to system input and functional characteristics: deterministic reservoir optimal scheduling model; random reservoir optimal scheduling model; fuzzy reservoir optimal scheduling model; and multi-objective decision-making theory and its application in reservoir optimal scheduling. At present, many optimization algorithms have been applied to the solution of the reservoir flood control optimal scheduling model. The traditional optimization algorithms include linear programming (LP) [1], nonlinear programming (NLP) [2], and dynamic programming (DP) [3]. Dynamic programming has many advantages: First, Bellman's optimality principle promotes a two-stage formula that greatly simplifies the multi-stage decision process (Bellman 1957) [4]. Second, the DP discretizes the continuous storage state of the reservoir and searches for the optimal decisions numerically. The numerical search efficiently deals with nonlinear and non-continuous objective functions and constraints [5–7]. Third, the two-stage formulation of DP quantifies the trade-offs between current and future time periods and provides insights into black-box optimization models. However, the DP method also has shortcomings, such as serious dimensionality problems. Especially when the scheduling period is a small time scale, and the flow of a period is very small, to ensure the validity of the calculation the dispersion is very large and the calculation time will be very long in the whole calculation process. If the dispersion is reduced, the DP penalty mechanism will be destroyed, and the negative discharge flow will occur.

Based on the above shortcomings of DP, many improved DP algorithms have emerged. For example, Larson and Korsak (1970) [8] proposed the dynamic programming successive approximations (DPSA) technique which reduced the number of DP optimized reservoirs by decomposing the multi-reservoir problem into a series of single reservoir problems. Heidari et al. (1971) [9] provided the discrete differential dynamic programming (DDDP) approach, whose characteristic is that it reduces the number of DP runs by iteratively searching in a constantly changing corridor. Bai et al. (2015) [10] and Zhang et al. (2016) [11] applied a hybrid approach, combining the progressive optimality algorithm (POA) and dynamic programming successive approximation (DPSA) to multi-reservoir operation, inheriting the advantages of the two methods. Cheng et al. (2014) [12] and He et al. (2019) [13] used parallel computing technology to solve the problem of multi-reservoir operation and reduced the execution time of the search program. Feng et al. (2020a) [14] applied the Latin hypercube sampling technique to the optimization of the cascade reservoir system, reducing the computational burden of DP. Although these methods can alleviate the ‘dimensional disaster’ problem to a certain extent, with the increase of the calculation scale or the decrease of the calculation time scale, they will still face a serious ‘dimensional disaster’ problem. In addition, Zhang et al. (2015) [15] alleviated the dimension disaster problem of dynamic programming from the perspective of parallel computing but did not do relevant research on the solving mechanism. Ji et al. (2015) [16] proposed a multi-dimensional dynamic programming algorithm with nested structure for medium and long term scheduling problems, and studied the problem of dimension disaster in multi-library joint scheduling. Jiang et al. (2017) [17] proposed two-dimensionality reduction methods of multidimensional dynamic programming, but the model solving speed was improved mainly through the coupling application of a stepwise search method and multi-dimensional dynamic programming, as well as the optimization mechanism of coarse, fine, and granularity coupling. Moreover, the research problem was the medium and long-term optimization scheduling problem of power generation. At present, there are few researches on short-term scheduling and reservoir flood control optimal scheduling.

In this paper, to make the DP method better applied to the flood control optimal scheduling of reservoir, a dynamic programming dimensionality reduction method on the hourly scale is proposed to further alleviate the dimensional disaster of DP and avoid the negative discharge flow. Taking the two floods of Dongjiang Reservoir during the flood season as an example, they are applied to the solution of the flood control optimal scheduling problem of the reservoir. The maximum peak clipping criterion and the maximum flood control safety guarantee criterion are adopted as the control objectives of the optimal scheduling models. By comparing the results of conventional scheduling and optimal scheduling, the characteristics of optimized scheduling and the effectiveness of the proposed DP dimensionality reduction method are analyzed. According to the scheduling results, the feasible measures for improving the flood control level of the reservoir are summarized and extracted.

2. Reservoir Flood Control Scheduling Model

Reservoir flood control scheduling is mainly divided into conventional scheduling and optimal scheduling. Conventional scheduling mainly relies on empirical charts, such as scheduling charts to implement operations. Optimal scheduling mainly relies on the establishment of optimal scheduling models, including system inputs, objective functions, and constraint equations. In this paper, the maximum peak clipping criterion and the maximum flood control safety guarantee criterion are used as the objective functions of optimal scheduling.

2.1. Reservoir Optimal Scheduling Model

In this paper, the maximum peak clipping criterion and the maximum flood control safety guarantee criterion are used as the optimal scheduling model. The specific introduction is as follows.

2.1.1. Objective Function

Maximum Peak Clipping Criterion

The criterion is to take the minimum value of the maximum flow ($q_{\max}$) of the downstream protection point as the control target of the model under the premise of controlling the maximum water level of the reservoir. The objective function is divided into no interval inflow at the reservoir Equation (1) and interval inflow at the reservoir Equation (2):

$$\min f = \int_{t_0}^{t_d} {q_t}^2 dt \tag{1}$$

$$\min f = \int_{t_0}^{t_d} (q_t + q_{\text{int},t})^2 dt \tag{2}$$

where t_0 is the beginning of the scheduling period, t_d is the end of the scheduling period, q_t is the outbound flow of the reservoir during the t period and is also a variable for model optimization, and $q_{\text{int},t}$ is the interval flow during the t period. In this paper, Formula (2) is taken as the objective function.

Maximum Flood Control Safety Guarantee Criterion

The criterion is based on the lowest value of the highest water level ($Z_{\max}$) of the reservoir as the control objective. The objective function is as follows:

$$\min z = \sum_{t=1}^{T} [V_t + (Q_t - q_t)\Delta t]^2 \tag{3}$$

where T is the total number of scheduling periods, t is the number of periods, q_t is the outbound flow of the reservoir during the t period, Q_t is the inbound flow of the reservoir during the t period, Δt is the length of a period, and V_t is the storage capacity at the end of the period and is also a variable for model optimization.

2.1.2. Constraint Conditions

(1) Reservoir water balance constraint

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

where V_t is the storage capacity at the end of the period, V_{t-1} is the storage capacity at the beginning of the period, Q_t is the inbound flow of the reservoir at the end of period t, q_t is the outbound flow of the reservoir at the end of period t, and Δt is the length of a period.

(2) Water level constraint

$$Z_{\min} \leq Z_t \leq Z_{\max} \quad (5)$$

where Z_t is the water level of the reservoir during the t period, $Z_{\min}$ is the lowest water level allowed by the reservoir during the t period, and $Z_{\max}$ is the highest water level allowed by the reservoir during the t period.
(3) Discharge capacity constraint

$$q_{\Delta t} \leq q(Z_t, B_t) \quad (6)$$

where $q_{\Delta t}$ is the average discharge flow during the t period, B_t is the operation mode of the spillway, Z_t is the water level of the reservoir, and q is the discharge flow during the t period.
(4) Variability constraint of outbound flow

$$|q_t - q_{t-1}| \leq \nabla q \quad (7)$$

where $|q_t - q_{t-1}|$ is the amplitude of change of outbound flow in adjacent periods, and ∇q is the allowable value of the amplitude of outbound flow in adjacent periods.
(5) Flood control storage capacity constraint

$$\sum_{t_0}^{t_D}((Q_{ave} - q_{\Delta t})\Delta t) \leq V_{pre} \quad (8)$$

where t_0 is the start time of the flood exceeding the downstream safe discharge, t_D is the end time of the flood exceeding the downstream safe discharge, Q_{ave} is the average inbound flow during the period Δt, $q_{\Delta \mathrm{t}}$ is the average discharge flow during the t period, V_{pre} is the flood control capacity of the reservoir, and Δt is the length of a period.
(6) Flood control strategy constraint

$$q_t \leq q_{saf}, q_t \leq Q_{\max} \quad (9)$$

where q_{saf} is the downstream safe discharge, $Q_{\max}$ is the maximum discharge flow of the flood control strategy, and q_t is the discharge flow during the t period.
(7) Regarding the maximum flood control safety guarantee criterion, the following constraint should be added to convert the maximum discharge flow into constraint:

$$Q_t + q_{\mathrm{int},t} \leq q_t^{\max} \quad (10)$$

where Q_t represents the inbound flow of the reservoir during the t period, $q_{\mathrm{int},t}$ represents the interval flow during the t period, and ${q_t}^{\max}$ represents the maximum discharge flow allowed by the downstream protection point during the t period.

2.2. Reservoir Conventional Scheduling Model

The conventional scheduling method is relative to the mathematical model, which is a general term for a class of methods that can make flood control scheduling decisions without complicated calculations. At present, the most common forms are scheduling charts and scheduling rules. The scheduling diagram is a two-dimensional graph composed of a set of water level process lines, and the discharge process of the reservoir is decided according to the position of the water level on the scheduling chart.

2.2.1. Conventional Scheduling Rules

The conventional reservoir scheduling rules are an important part of the conventional reservoir scheduling procedures and the basis for generating the reservoir scheduling plan. It is the specific regulations and operating instructions for determining reservoir flood control operation which are formulated according to the tasks of reservoir flood control scheduling, flood control characteristic water level, reservoir flood control method, reservoir discharge flow, etc. Its function is to specify how the reservoir should store and discharge under various possible conditions, such as inbound flow and the reservoir water level.

(1) Judgment of the highest water level

During the flood scheduling, the level of the inbound flood is determined according to the highest flood level of which frequency the actual reservoir water level reaches. The discharge flow of the reservoir is then controlled according to the flood regulation rules of the corresponding level of flood. This method is generally used for reservoirs with large flood regulation capacity and heavy downstream flood control tasks.

(2) The maximum flow judgment method

During flood scheduling, the level of flooding in the reservoir is judged according to the peak flow of the inbound flow (known by the forecast) to which frequency the flood reaches. The reservoir is then determined to control the discharge flow according to the flood regulation rules of the corresponding level of flood. This method is generally applicable to reservoirs with a small flood capacity.

(3) Comprehensive judgment method

During flood scheduling, the level of the flood is judged according to which of the reservoir water level and the inbound flow meets the respective maximum value first. The reservoir is then determined to control the discharge flow according to the flood regulation rules of the corresponding level of flood. In addition, there is a method (flood discriminant chart method) that comprehensively considers the inflow of the reservoir, the initial storage volume of the reservoir, and the steepest recession curve in the later stage to determine and control the discharge.

2.2.2. Application of Conventional Flood Control Scheduling Rules

It is assumed that flood forecasting is not considered in the flood regulation process, the initial flood water level is the flood limit water level, and the initial discharge capacity is Q_{dis}. The general flood control scheduling steps are as follows:

Step 1: When the flood first starts, the inbound flow Q_{inb} is less than Q_{dis}, and at this time, the gate opening should be controlled to make the outbound flow equal to the inbound flow. When it is greater than Q_{dis} but less than the safe discharge amount Q_{saf} of the downstream channel, the gate should be fully opened.

Step 2: When the inbound flow is greater than the safe discharge of the downstream channel, the gate should be closed gradually at this time to make the reservoir discharge according to the safe discharge of the downstream channel to protect the downstream safety.

Step 3: When the reservoir water level exceeds the high flood control level Z_{hig}, it indicates that the flood has exceeded the downstream flood control guarantee. At this time, all gates should be opened in time for flood discharge to ensure the safety of the reservoir.

Step 4: When the reservoir water level exceeds the design flood level Z_{des}, extraordinary flood discharge facilities should be activated to ensure the safety of the reservoir.

Step 5: Once the highest flood level is reached, the inbound flow decreases to be less than the discharge flow. The level then drops until it reaches the flood control limit level, when the discharge is stopped.

3. Model Solution and Dimensionality Reduction of Dynamic Programming Based on the Hourly Scale

The maximum peak clipping criterion and the maximum flood control safety guarantee criterion are taken as examples, and the optimal scheduling model is solved based on the DP algorithm after dimensionality reduction.

3.1. The Idea of Model Solving Based on Dynamic Programming

The mathematical model of the DP algorithm is relatively flexible. Generally, as long as it can constitute a multi-stage decision-making process, this method can be used to solve the problem [18]. When the maximum peak clipping criterion is used as the optimal scheduling objective, the algorithm steps of DP are as follows:

Step 1: Divide the periods: divide the scheduling periods into multiple periods.

Step 2: Define state variables: use the water level Z or reservoir capacity V at the end of each period as the state variable. In period t, V_t (initial reservoir storage) at the start time is the initial state, and $V_{t\text{-}1}$ at the terminal time is the terminal state.

Step 3: Define decision-making variables: the average discharge flow of the reservoir in each period (q_t) is taken as the decision-making variable.

Step 4: Define the state transition equation: $V_t = V_{t-1} + (Q_t - q_t)\Delta t.$

Step 5: Define the stage index: take the square of the discharge flow during the period (${q_t}^2$) as the stage index.

Step 6: Recursive equation: according to the state variable of the current period and the benefit function of the reserved period at the previous moment, the value of the benefit function of the reserved period at the next moment is pushed out. The recursive equation is:

$$F_t(V_{t-1}) \ = \min_{\Omega}\left\{q_t^2\Delta t + F_{t+1}(V_t)\right\} \tag{11}$$

where V_t is the state variable at time t, V_{t-1} is the state variable at time $t-1$, $F_t(V_{t-1})$ is the benefit function of the reserved period at time $t-1$, $F_{t+1}(V_t)$ is the benefit function of the reserved period at the time t, and ${q_t}^2$ is the state variable at time t.

When the maximum flood control safety guarantee criterion is used as the optimal scheduling objective, the algorithm steps are similar to those of the maximum peak clipping criterion. The difference is that the phase goal at this time is: $V_t + (Q_t - q_t)\Delta t.$ The recursive equation is:

$$F'_t(V_{t-1}) \ = \min_{\Omega}\left\{[V_t + \ (Q_t - q_t)\Delta t]^2 + F'_{t+1}(V_t)\right\} \tag{12}$$

where V_t is the state variable at time t. V_{t-1} is the state variable at time $t-1$. $[V_t + (Q_t - q_t)\Delta t]$ is the state variable at time t.

3.2. Dimensionality Reduction Processing of DP Based on Changing Retracting Space

In the DP calculation, the upper and lower limits of the initially given water level are generally high. For example, the upper and lower limits of the water level in the flood control scheduling are generally taken from the flood limit water level to the design flood level, etc. If, in the process of DP discrete calculation, the same retraction space is discretized at each period, to achieve a better numerical calculation effect, the dispersion requirement will be very large and the calculation time will be very long.

To solve this problem, the rules for determining the upper and lower limits of the dynamic water level are proposed in this paper. The process is shown in Figure 1. According to the amount of inbound flow and initial storage capacity in each period, the upper limit of the water level in each period is determined according to the total inbound flow into the reservoir (as shown in Figure 2). The lower limit of the water level at each period is determined based on the outbound flow equal to the inbound flow or the principle of maximum discharge. In this way, a dynamic upper and lower limit of the water level is obtained, and at the same time, unnecessary discrete calculation of DP in the initial retraction space is avoided, which can greatly reduce the calculation time.

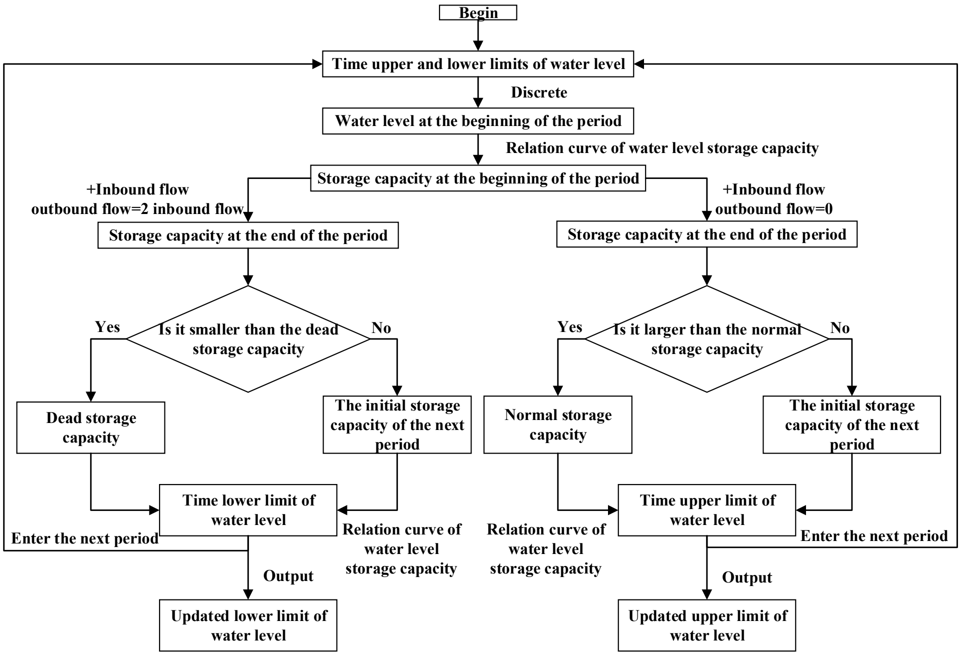

Figure 1. Flow chart for determining the upper and lower limits of the water level during the period.

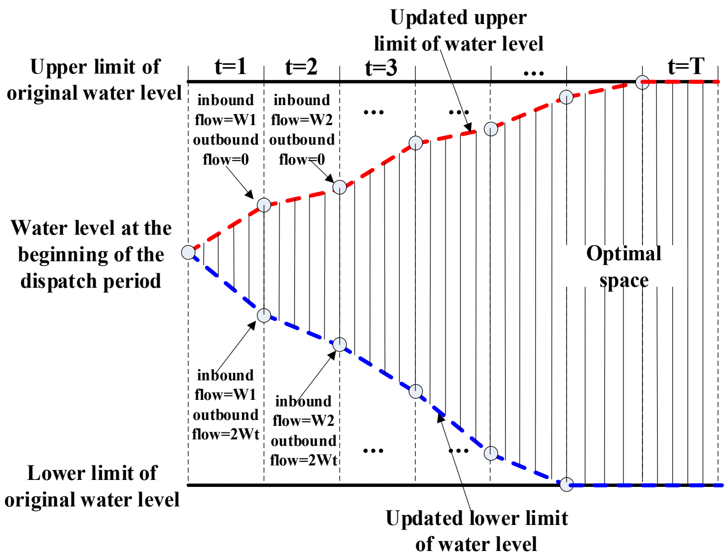

Figure 2. Schematic diagram of determining the upper and lower limits of the water level during the period.

3.3. Reason Analysis and Processing of Negative Value of Drainage Flow in DP Calculation

In the DP calculation, when the period is very small, such as on the hourly scale, if the degree of dispersion is insufficient, the discharge flow will often be negative in the calculation result. At this time, the total amount of water in a period is very small. When there are fewer discrete points of storage capacity, each discrete storage capacity is very large, so even if all the water in a period is stored, it cannot meet the demand for upward fluctuation of a discrete point. At this time, the penalty mechanism of DP calculation will be destroyed. Eventually, to meet the requirements of the final water level of the scheduling, the water level will forcibly rise, and then there will be a negative discharge flow (as shown in Figure 3). To solve this problem, an effective variation dispersion mechanism is proposed in this paper. That is, according to the amount of inbound flow in each period, the discrete degree of reservoir capacity is dynamically determined to ensure that inbound flow can make the discrete point of water level change upward by at least one point. The process is shown in Figure 4. The rules for determining the minimum number of discrete points in each period are as follows:

$$N_t = \left(V_t^{up} - V_t^{lo}\right)/W_t \tag{13}$$

where N_t is the minimum variable discrete points in the tth period, ${V_t}^{up}$ is the upper limit of the storage capacity in the tth period, ${V_t}^{lo}$ is the lower limit of the storage capacity in the tth period, and W_t is the total inbound flow in the tth period. In actual calculations, the number of discrete points of variation N_t in the tth period is the lower limit. To achieve higher accuracy, the number of discrete points can be a multiple of N_t, but the calculation time will increase at this time.

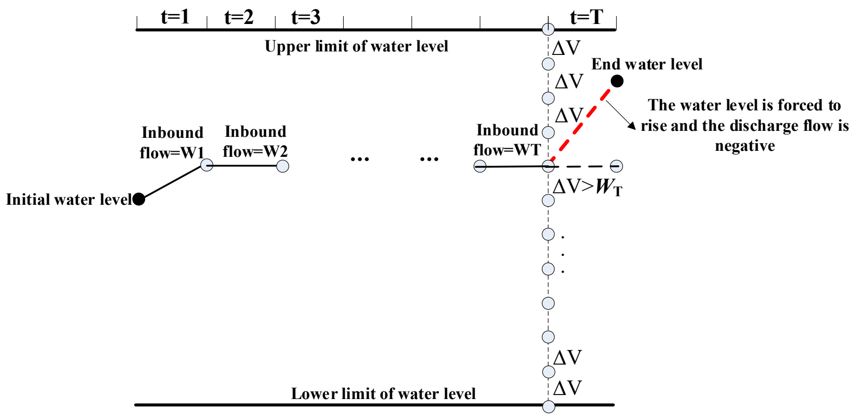

Figure 3. Schematic diagram of the negative value of discharge flow.

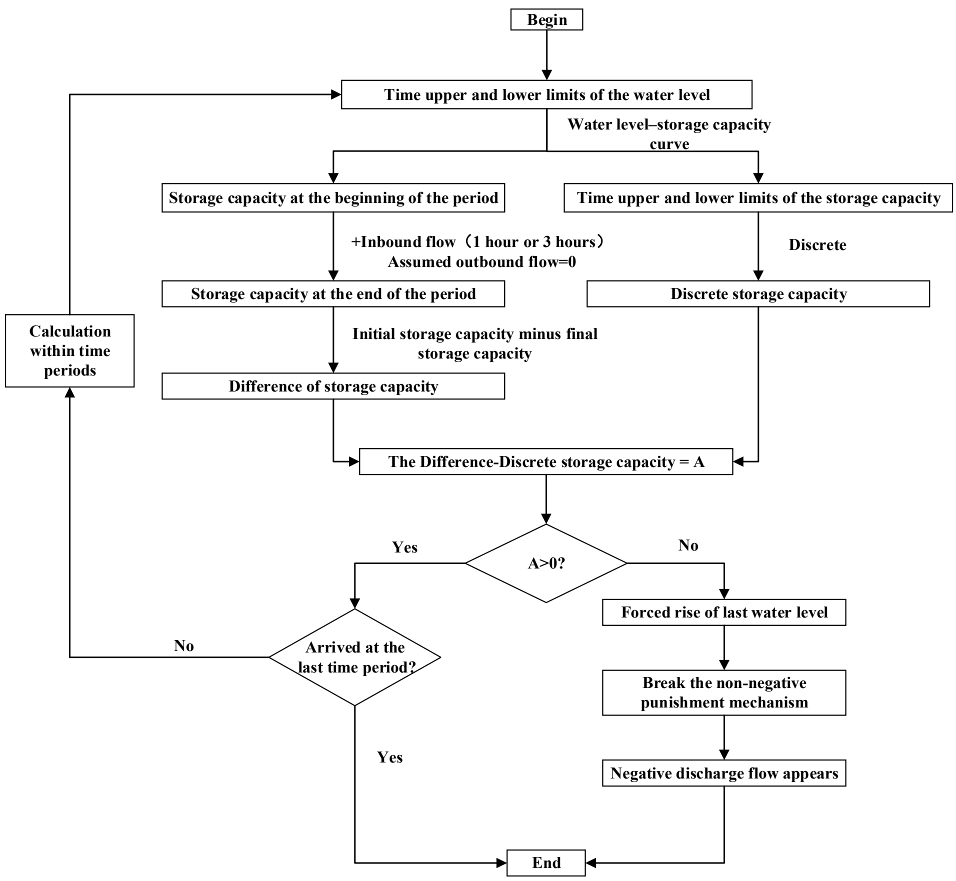

Figure 4. Flow chart of the negative value of discharge flow.

3.4. Overall Scheme of Algorithm Implementation

In this paper, Dongjiang Hydropower Station is taken as the research object and the dimension reduction method based on dynamic programming under the hour scale is adopted to further alleviate the dimension disaster of DP and avoid negative discharge. The specific implementation scheme is as follows in Figure 5:

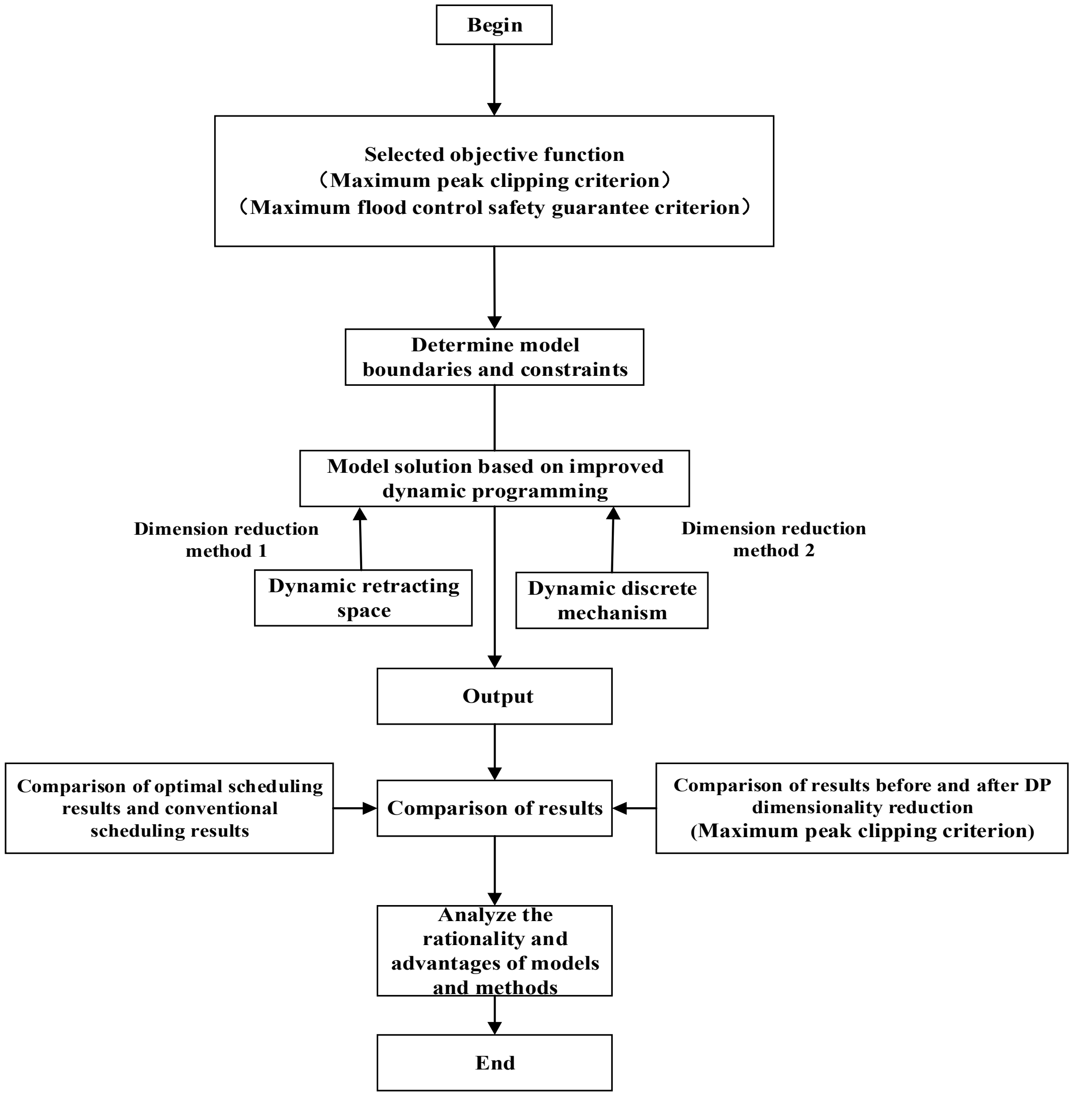

Figure 5. Implementation scheme diagram of improved DP algorithm.

4. Case Study

This paper takes Dongjiang Reservoir as an example to study two typical flood processes in flood season and compares their conventional and optimal scheduling.

4.1. Overview of Dongjiang Reservoir Project

The Dongjiang Hydropower Station (as shown in Figure 6) is located in an ashlar canyon 11 km upstream of Dongjiang Town, Zixing County, Hunan Province, China. It is the leading project in the cascade development of the Leishui River Basin. The installed capacity of the Dongjiang Reservoir is 615 MW, the normal storage level of the reservoir is 285 m, and the total installed capacity of the downstream cascade power stations is 265 MW. The effective volume of the Dongjiang Reservoir is 5.25 billion m^3 and the storage capacity coefficient is 1.16. It has excellent regulation performance. The flood control design standard of the Dongjiang Dam is a thousand-year flood, and the check flood standard is a ten thousand-year flood. The flood control limit water level of the reservoir is 284 m. The downstream farmland flood control standard is a five-year flood, and the discharge flow of the Dongjiang River does not exceed 1500 m^3/s. The flood control standard for the Leiyang section of the Beijing-Guangzhou Railway is a hundred-year flood, and the discharge flow of the Dongjiang River does not exceed 3500 m^3/s.

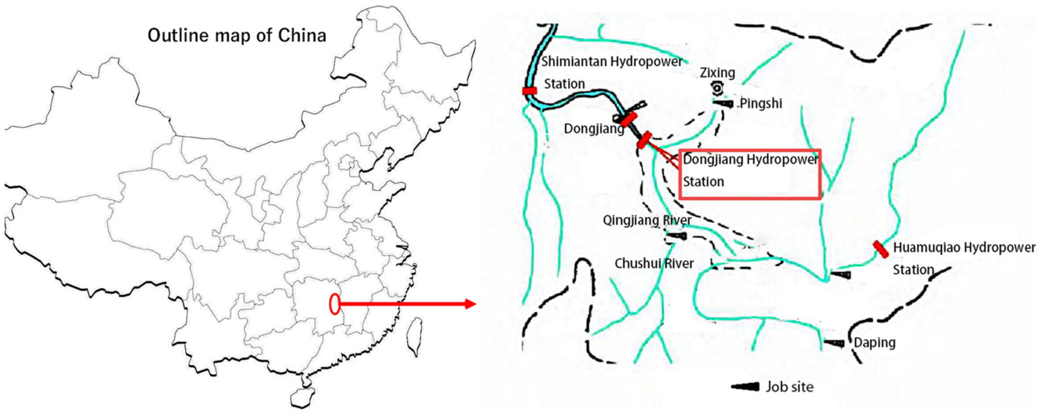

Figure 6. Dongjiang River Basin Map.

4.2. Conventional Scheduling Rules of Dongjiang Reservoir

According to the conventional scheduling rules in Section 2.2.1 and the technical scheme recorded in literature by Hunan Power Grid Corporation of China, it can be known that the 'comprehensive judgment method' is adopted by the scheduling of Dongjiang Reservoir to judge the flood level of entering the reservoir. Combined with the 'Dongjiang Reservoir Scheduling Regulations', the flood control scheduling procedures of the Dongjiang Reservoir can then be obtained as follows:

(1) In a five-year flood, The peak flow is 3730 m^3/s, the five-day flood volume is 569 million m^3, the starting water level is 284 m, the discharge flow does not exceed 1500 m^3/s, and the maximum water level of the reservoir does not exceed 285 m.
(2) In a twenty-year flood, the peak flow is 5850 m^3/s, the five-day flood volume is 900 million m^3, the starting water level is 284 m, the discharge flow does not exceed 3500 m^3/s, and the maximum water level of the reservoir does not exceed 285.40 m.
(3) In a hundred-year flood, the peak flow is 10,100 m^3/s, the five-day flood volume is 1.34 billion m^3, the starting water level is 284 m, the discharge flow does not exceed 3500 m^3/s, and the maximum water level of the reservoir does not exceed 286.65 m.
(4) In a thousand-year flood, the peak flow is 15,300 m^3/s, the five-day flood volume is 19.4 billion m^3, the starting water level is 284 m, the discharge flow does not exceed 3500 m^3/s. When the water level of the reservoir is less than 286.65 m, the discharge flow does not exceed 3500 m^3/s. After the water level exceeds 286.65 m, the control discharge flow does not exceed 4090 m^3/s, and the maximum control water level of the reservoir does not exceed 288.88 m.
(5) In a ten thousand-year flood, the peak flow is 20,600 m^3/s, the five-day flood volume is 25.4 billion m^3, and the starting water level is 284 m. When the water level of the reservoir is below 286.65 m, the control discharge flow does not exceed 3500 m^3/s. When the water level does not reach 288.88 m, the control discharge flow does not exceed 4090 m^3/s. When the water level exceeds 288.88 m and the inbound flow of the reservoir exceeds the thousand-year flood, the water level of the reservoir does not exceed 291.92 m, and the maximum discharge flow can reach 4130 m^3/s.

4.3. Input Data

The input data of the flood control optimal scheduling model is as follows:

(1) From the technical scheme recorded in the literature by the Hunan Power Grid Corporation of China (2015), it can be seen that the flood control limit water level is 284 m, which is also the starting water level of the reservoir. As such, during the scheduling, the starting water levels of the two floods are 284 m. The water level at the end of the scheduling period is set to be consistent with the initial water level.

(2) The designed flood level of Dongjiang Reservoir is 288.88 m and the dead water level is 242 m. Therefore, the lower limit of the water level in the DP calculation is set to 242 m, and the upper limit of the water level is 288.88 m.

(3) The scheduling time intervals of the two floods are 1 h. The scheduling periods of the first flood are 136 periods; the scheduling periods of the second flood are 89 periods. Among them, the first flood began on 17 March 2020, and stopped on 22 March 2020 and the second flood began on 1 April 2020, and stopped on 5 April 2020.

(4) The inflow process of the first flood is shown in Figure 7, and the inflow process of the second flood is shown in Figure 8.

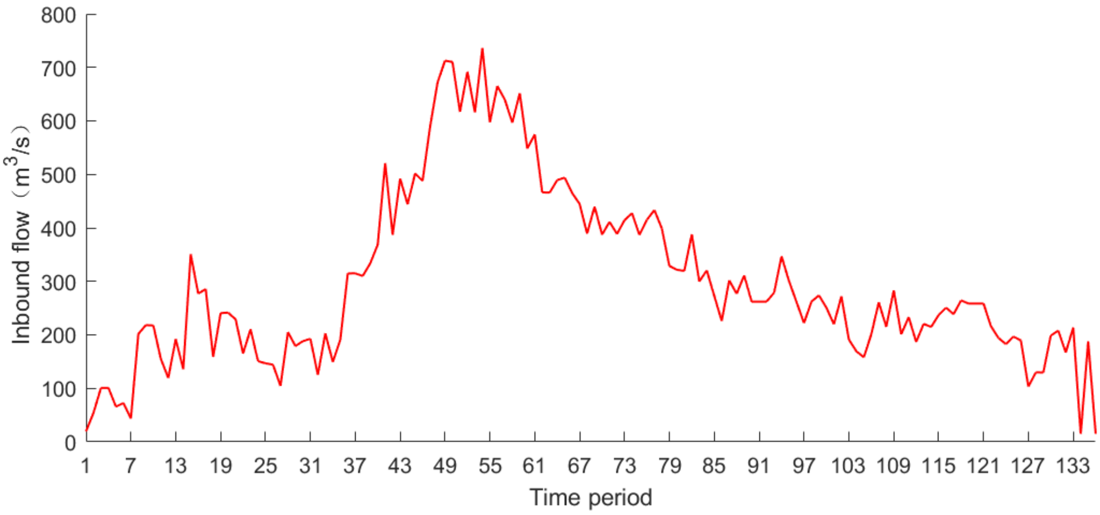

Figure 7. The inflow process line of the first flood.

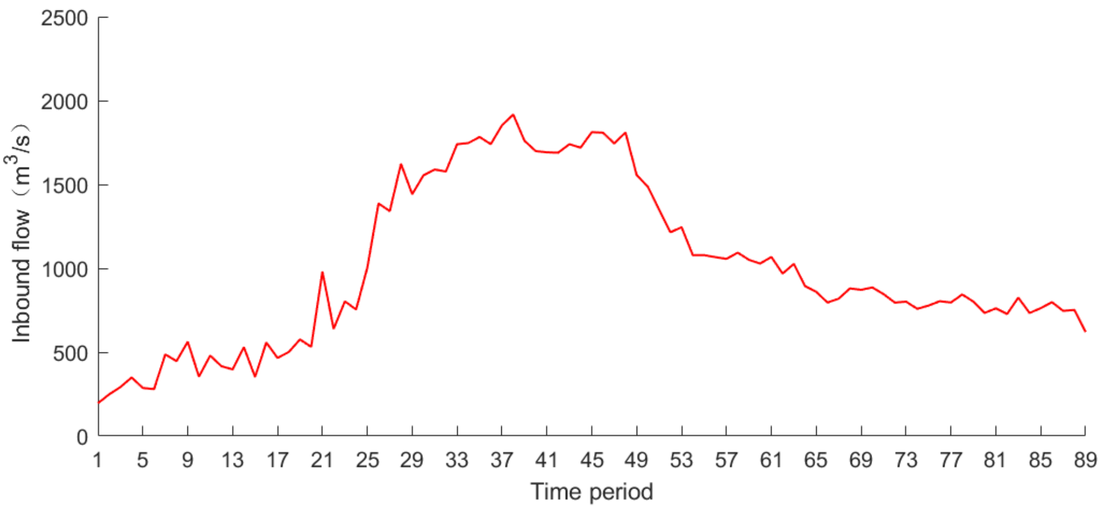

Figure 8. The inflow process line of the second flood.

4.4. Calculation Results and Analysis

The two typical floods in Dongjiang Reservoir are selected for conventional scheduling and optimal scheduling, and the results are as follows.

4.4.1. Conventional Scheduling Results

It can be seen from Figure 7 that the maximum peak flow is about 736.4 m^3/s. The comprehensive judgment method is used to know that the first flood is a five-year flood, and, similarly, the second flood is also a five-year flood. The conventional flood control scheduling rules described in Section 2.2.2 and flood control scheduling procedures of the Dongjiang Reservoir described in Section 4.2 are adopted in scheduling. The conventional scheduling results of two floods are shown in Figures 9 and 10.

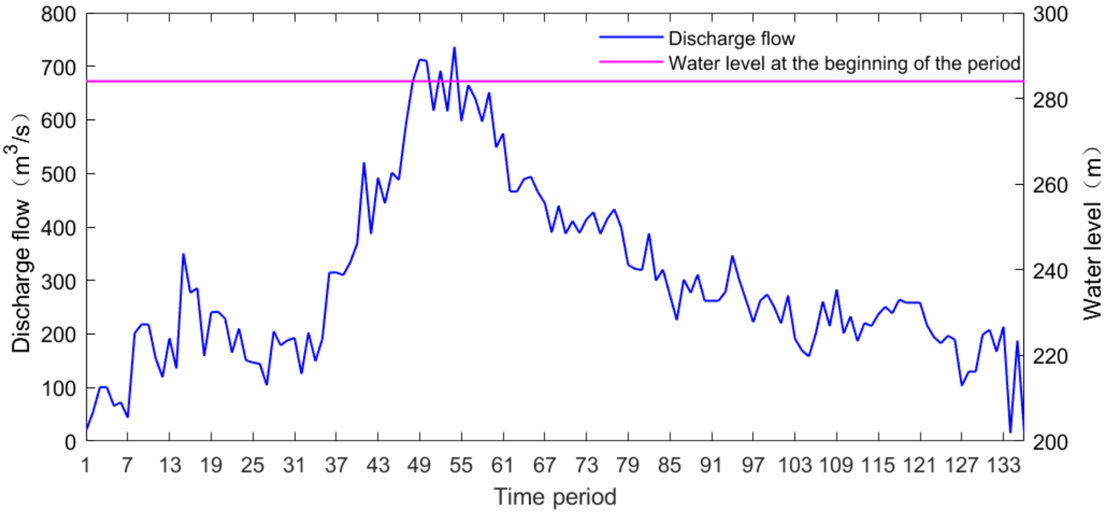

Figure 9. Conventional scheduling results of the first flood.

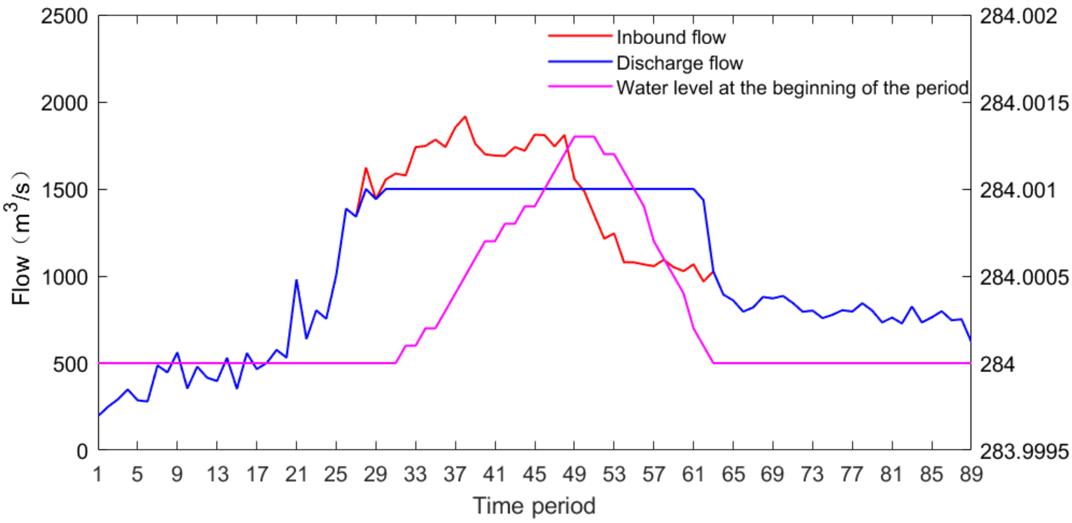

Figure 10. Conventional scheduling results of the second flood.

4.4.2. Optimal Scheduling Results

The maximum peak clipping criterion and the maximum flood control safety guarantee criterion are combined with the improved DP algorithm to optimize the scheduling of two floods of Dongjiang Reservoir. The results of optimal scheduling with the maximum peak clipping criterion are shown in Figures 11 and 12, and the results of optimal scheduling with the maximum flood control safety guarantee criterion are shown in Figures 13 and 14.

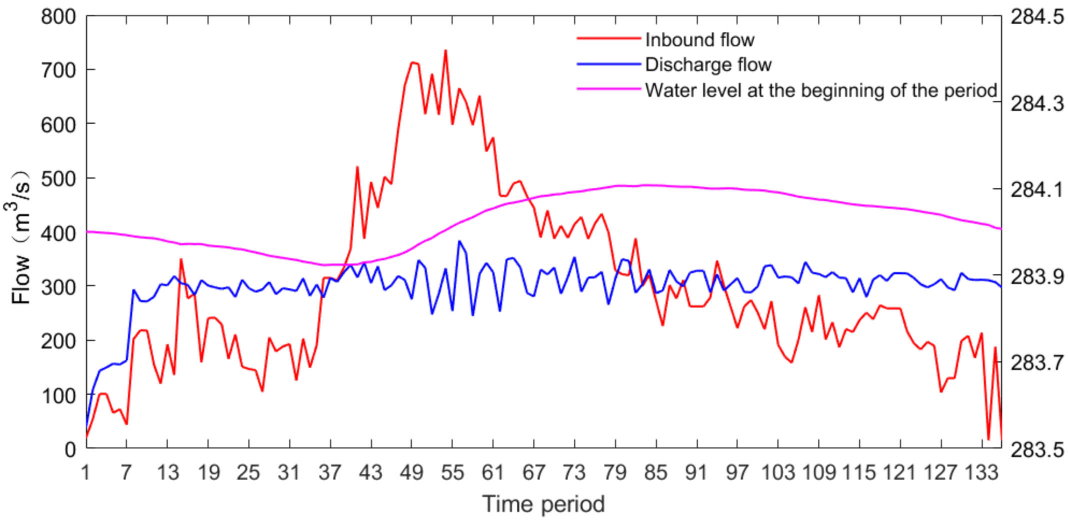

Figure 11. Optimal scheduling results of the first flood with the maximum peak clipping criterion.

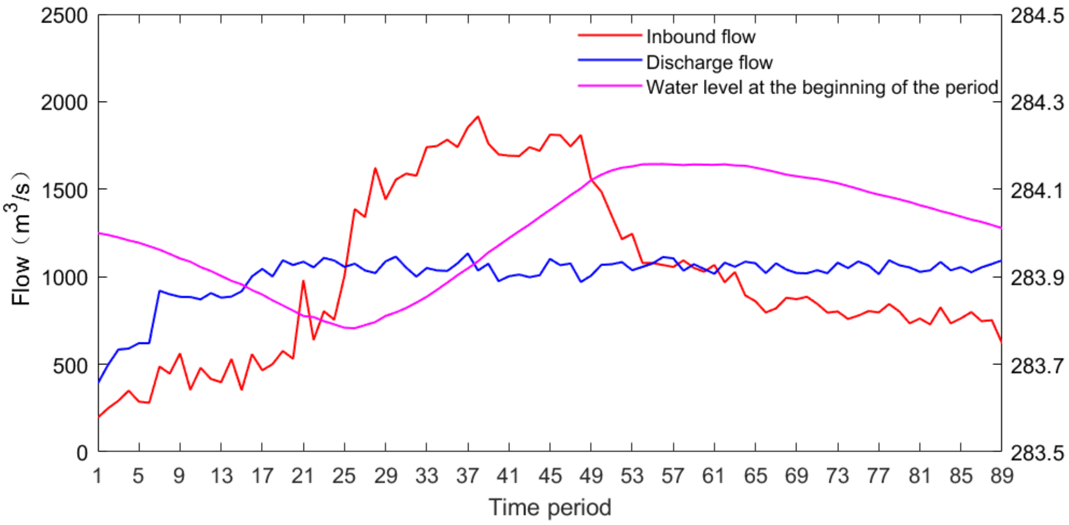

Figure 12. Optimal scheduling results of the second flood with the maximum peak clipping criterion.

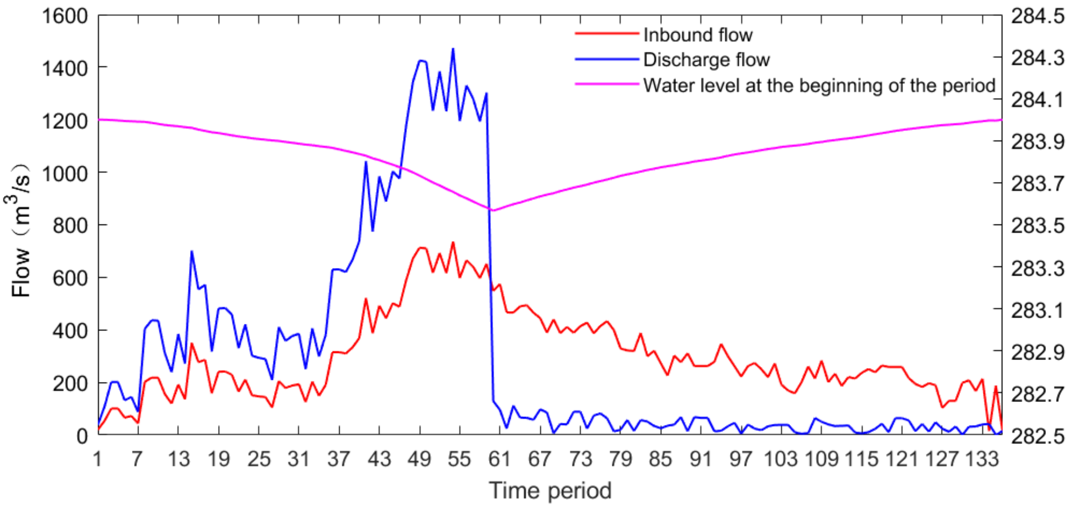

Figure 13. Optimal scheduling results of the first flood with the maximum flood control safety guarantee criterion.

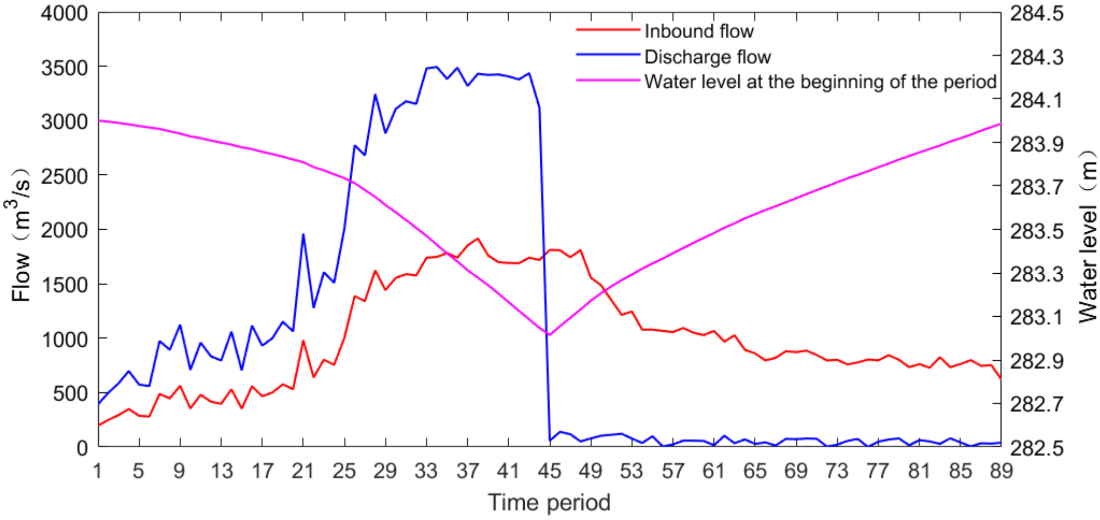

Figure 14. Optimal scheduling results of the second flood with the maximum flood control safety guarantee criterion.

4.4.3. Comparative Analysis of Results of Conventional Scheduling and Optimal Scheduling

The two floods are five-year floods and, when scheduling, the corresponding scheduling rules are adopted. It can be seen from Figure 9 that the upstream inbound flow in the entire process of the first flood is lower than the maximum discharge flow. The discharge flow is equal to the inbound flow to ensure the reservoir water level remains unchanged and ensure the water utilization requirements. Therefore, the maximum discharge flow during the entire discharge process is the maximum inbound flow of 736.4 m^3/s, and the water level remains unchanged at 284 m. It can be seen from Figure 10 that at the beginning of the second flood, the inbound flow of the reservoir is lower than the maximum discharge flow. To keep the reservoir water level unchanged, the discharge flow is equal to the inbound flow. With the increased inflow of the reservoir, the upstream inbound flow of the second flood exceeds the maximum discharge. At this time, the gate is opened and the maximum discharge flow is 1500 m^3/s, and the water level remains unchanged at 284 m.

When scheduling, according to the maximum peak clipping criterion the discharge flow of the entire discharge process is relatively uniform. It can be seen from Figure 11 that the discharge flow of the first flood is mainly concentrated at about 300 m^3/s. It can be seen from Figure 12 that the discharge flow of the second flood is mainly concentrated at about 1000 m^3/s, and the maximum discharge flow of the two floods during the entire discharge process is lower than the conventional scheduling, which is conducive to the stability of the downstream protection objects. When scheduling, according to the maximum flood control safety guarantee criterion, the water level during the entire discharge process shows a trend of the first decline and then rise. It can be seen from Figure 13 that the water level of the first flood first drops to about 283.6 m, and then rises to about 284 m. It can be seen from Figure 14 that the water level of the second flood first drops to about 283.1 m, and then rises to about 284 m. The lowest reservoir water levels of the two floods are both lower than the 284 m of the conventional scheduling, which can increase the flood control capacity of the reservoir and benefit the safety of the reservoir itself and the downstream protection objects.

4.4.4. Results before and after DP Dimensionality Reduction Processing

This paper takes the maximum peak clipping criterion as an example to compare and analyze the effects of the DP algorithm before and after dimensionality reduction processing. The specific results are shown in Table 1 and Figures 15 and 16.

Table 1. Comparison of results before and after dimensionality reduction of the maximum peak clipping criterion.

Comparative Items	Before the First Flood DP Dimensionality Reduction Processing	After the First Flood DP Dimensionality Reduction Processing	Before the Second Flood DP Dimensionality Reduction Processing	After the Second Flood DP Dimensionality Reduction Processing
Calculated time (s)	162	56	63	26
The average number of discrete points in each period	1500	800	1000	735

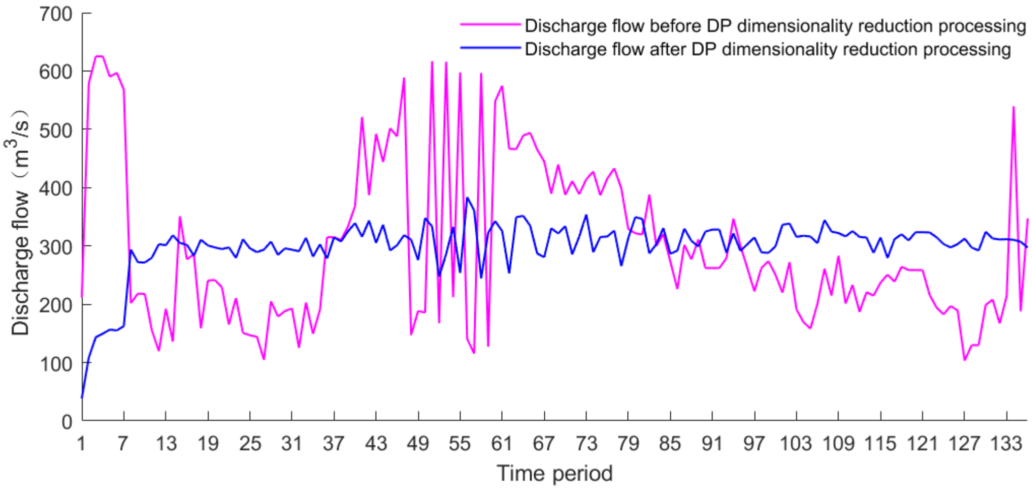

Figure 15. Comparison of discharge flow before and after DP dimensionality reduction processing in the first flood.

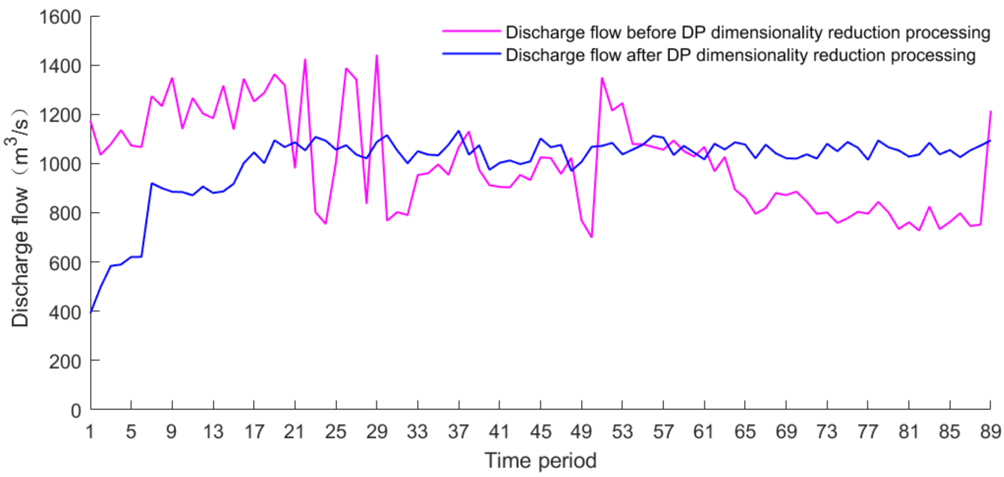

Figure 16. Comparison of discharge flow before and after DP dimensionality reduction processing in the second flood.

4.4.5. Comparative Analysis of Results before and after DP Dimensionality Reduction Processing

It can be seen from Table 1 that after the DP processing, the calculation time is lower than that before the processing due to the formation of a variable retraction space. The first flood is reduced by 106 s, which is equivalent to a reduction of 65%, and the second flood is reduced by 37 s, which is equivalent to a reduction of 59%. It can be seen from Figure 15 that, on the whole, after the DP dimensionality reduction processing, the discharge flow is concentrated around 300 m^3/s, and the flow before processing fluctuates in the range of 100 m^3/s–600 m^3/s, which is extremely unstable. Especially in the 49–61 period, the contrast is obvious. For the same reason, it can be seen from Figure 16 that the discharge flow after DP dimensionality reduction processing is mainly concentrated around 1000 m^3/s, and the flow before processing fluctuates in the range of 800 $m^3/$–1400 m^3/s, which is not concentrated near a certain fixed value.

5. Conclusions

In this paper, aiming at solving the problem of reservoir flood control optimal operation, the variable cable space of DP is constructed by improving the application of the DP algorithm, and the variable discrete mechanism of cable space is proposed to solve the problem of negative downstream discharge, which effectively reduces the calculation amount of DP to improve the calculation speed of DP and avoids the negative downstream discharge. The conclusions are as fol1ows by taking the Dongjiang Reservoir as an example to conduct research.

(1) Through the analysis of the results of conventional scheduling and optimal scheduling, it is found that the conventional scheduling is scheduled according to the five-year flood standard, the maximum discharge flow does not exceed the allowable value during scheduling, and the reservoir water level remains unchanged. This paper is based on the improved DP algorithm, when scheduling with the maximum peak clipping criterion, the discharge flows of the two floods in the whole process are concentrated near a certain fixed value, and both are lower than the maximum discharge flow of conventional scheduling, which is more conducive to the safety of downstream protection objects. When scheduling under the maximum flood control safety guarantee criterion, the lowest water level of the reservoir is lower than the conventional scheduling result, which increases the flood control storage capacity of the reservoir and is beneficial to the safety of the reservoir itself and the downstream protection objects.

(2) In terms of the DP dimensionality reduction processing method, due to the proposed variable discrete mechanism of retracting space, the computation amount of DP is reduced, so the calculation time after processing is lower than that before processing. The calculation time after the first flood dimensionality reduction processing is reduced by about 65%, and the second flood is reduced by about 59%, which effectively reduces the calculation time of the DP algorithm. Therefore, when this method is applied to the joint scheduling of reservoirs and flood scheduling on an hourly scale, the calculation efficiency and the accuracy of the calculation results will be greatly improved.

In addition, the selected floods in this paper are all small floods that occur once in five years. Whether this improved algorithm will have the same effect on the application of large floods needs further verification. The algorithm has only been successfully applied in this reservoir to date. Whether it can adapt to the optimal operation of other reservoirs requires further verification.

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