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Study on the Three Gorges reservoir flood control operation chart considering comprehensive utilization requirements

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Abstract. This paper constructs a multi-objective flood forecasting optimization operation model based on inflow forecasting information considering flood control, power generation, and navigation. The optimization-simulation-test algorithm and modified differential evolution for multi-objective optimization (DEMO) were used. Some non-dominated solutions were derived from optimization of the inflow data of 126 years (1882-2007) and test by 1000-year design floods. The solutions were distributed uniformly and the algorithm was efficient. The flood during August 2009 was also used to test the selected solution. The results show that the optimal schemes can generate extra hydropower energy, and save great flood water resources. The navigation days for all types of ships are also increased greatly. To maximize comprehensive utilization benefits on the premise of flood control safety, the traditional design flood routing method is well combined with the optimization method by reservoir operation chart for flood control based on inflow forecasting, which provides a new way for reservoir flood control operation by considering the comprehensive utilization benefits.

1. Introduction
The flood control level is used to conduct flood control operation of the reservoir, but this single mode of operation often leads to the waste of flood resources in flood seasons and water storage after flooding. Recent years have seen the advancement of rainfall and flood forecasting techniques. Under the premise of ensuring flood control safety, domestic and foreign scholars have carried out research on flood seasons staging and dynamic control of flood level in reservoir in order to make full use of flood resources in flood seasons, and achieved some results. However, the operation rules of dynamic control of the flood control level are complicated and inconvenient in practical application [1]. The reservoir operation chart is relatively intuitive and easy to apply, thus it has been widely used in reservoir operation. However, the research and application based on that in flood control operation is still insufficient. Lu Xiaoxing et al. [2] have developed a reservoir flood control operation chart based on the relationship between inflow, water level of the reservoir and power station load, which is conducive to real-time control and operation of flood control, power generation and water level control in flood seasons. Liu Zhao et al. [1] have developed an optimal flood control forecasting schedule with flood resources as the target by introducing the change rate of inflow and the water level for effective decision. However, the above studies failed to consider the influence of forecasting errors and lack in-depth research on the comprehensive utilization of reservoirs in flood seasons. This paper introduces the concept of possible maximum water level and future inflow increase, establishes a multi-objective optimal operation model with comprehensive consideration of flood control, power generation and navigation, and constructs an "optimization-simulation-test" framework by taking into consideration the

impact of hydrological forecasting errors, that is, while using historical data for simulation optimization, continuously carry out flood control test based on the design flood. In this way, this paper develops an optimal flood control operation chart based on forecast information and the comprehensive utilization requirements by using the multi-objective differential evolutionary algorithm DEMO.

2. The optimal flood control operation model of Three Gorge Reservoir

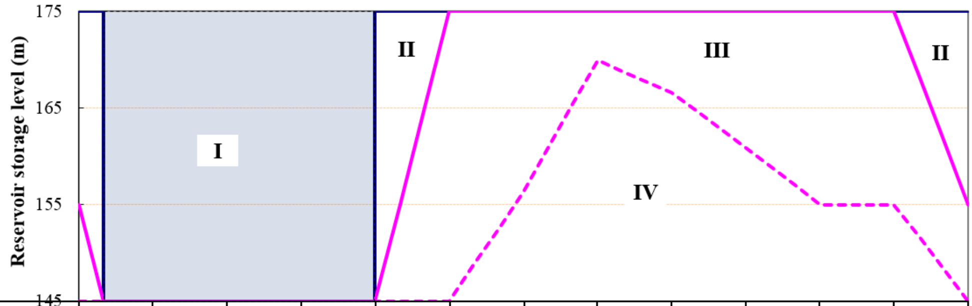
2.1. Introduction of the Three Gorges Reservoir

The Three Gorges Reservoir (TGR) is a vitally important project for the development and harnessing of the Yangtze River (YR), and also the largest multi-purpose hydro-development project ever built in the world. TGR receives inflow from a drainage area of approximately 106 km^2, with a mean annual runoff at the dam site of 4.51×10^{11} m^3. Downstream from the TGR is the plain area of the middle and lower reaches of the Yangtze River, shown in Fig. 1, which is one of the most populous and developed areas in China and which also suffers from the most frequent and disastrous flood threats.

Figure 1. Sketch of the upper Yangtze River basin.

The TGR is a typical river channel type reservoir with a length of 660 km and a flood storage capacity of 22.15×10^9 m^3, and plays a very important role in flood control of the Yangtze River. The Three Gorges Dam is the world's largest capacity hydroelectric power station with 34 generators, including 32 main generators, each with a capacity of 700 MW, and two power plant generators, each with a capacity of 50 MW, making a total capacity of 22,500 MW. Besides the comprehensive benefits from flood control and power generation, the TGR also improves the navigation conditions of the waterway in the reservoir area and downstream, and promotes the development of fishery as well as tourism.

The original design rule curves of the TGR are shown in Fig. 2. According to the scheme, the water level is kept at 145 m during the entire flood season, and is raised from 145 m on October 1 up to 175 m on October 31. The refill operation is guided by the upper and lower boundary curves. That is, water should be spilled to ensure the reservoir water level not to exceed 175 m when it is on the top of upper boundary curve (zone I), and the power station generates the firm output when the reservoir water level is below the lower boundary curve (zone III), otherwise the generators are turned to maximum output if the water level is in zone II. In zone II and III, the release can be calculated from the specific output. The designed operating rules can be regarded as a standard operating policy (SOP) [3].



Month	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Upper boundary curve	**145**	**145**	**145**	**145**	**175**	**175**	**175**	**175**	**175**	**175**	**175**	**155**
Lower boundary curve	**145**	**145**	**145**	**145**	**145**	**156.3**	**169.6**	**166.6**	**160.9**	**155**	**155**	**145**

Figure 2. The original rule curves of the TGR

2.2. Current operation Rules for Flood Control of the TGR

Affected by monsoon climate and precipitation, 60%-80% runoff in a year concentrates in the flood season (from June 1 to September 30). During the flood season, flood control is the most important issue compared with other functions of the TGR. The flood control water level (FCWL) is the operation water level in the flood season in order to offer adequate storage for flood prevention [4]. From June to September, the water level of TGR cannot always be higher than FCWL, because of the possible incidences of large floods [4].

The most important area for flood control is the Jinjiang River, which is part of the Yangtze River from the Zhicheng to the Chenglingji gauging station, as shown in Fig.1. The main purpose of the TGR for flood control is to guarantee the safety of the Jingjiang River area downstream of the TGR. Usually the TGR can control 95% flood of the Jingjiang River reach. The current operation rules for flood control of TGR is described as follows [5]. From May 20 to the beginning of June, the water level of TGR needs to be dropped to 145 m. During the flood season (from June to September), the water level should not be higher than 145 m, if there is no large flood occurring. In October, the water level needs to increase to the normal water level, 175 m. During the flood season, the reservoir release should not exceed 54,000 m^3/s for the 100-year design flood in order to keep the water level at Shashi below 44.5 m. The reservoir release should not exceed 76,000 m^3/s for the 1000-year design flood in order to keep the water level at Shashi station below 45 m.

2.3. Flood control operation chart considering forecasting

The reservoir operation chart is very effective for power generation operation; however, since the flood is much larger than the flow of expected power output of the power station, it only has a limited effect on flood operation. The operation chart of the Three Gorges Reservoir is shown in Figure 2. In flood seasons, the single operation method using the FCWL method often leads to the waste of flood resources. The reservoir operation chart is relatively more intuitive and easier to apply. Therefore, application of the flood control operation chart has been discussed by scholars at home and abroad.

Liu Zhao et al. [1] used the inflow trend as the horizontal axis of the flood control operation chart, thus making good use of the forecast information. However, it is difficult to reflect the absolute value of the future inflow change, which is more important for flood control. In addition, in order to enhance the forecast and pre-discharge of the reservoir in multiple time periods, the difference between the maximum value of inflow in the future and that in the current time period is selected as the incremental value of the future inflow I_{Δ}, and is used as the horizontal axis of flood prevention forecast.

$$I_{\Delta} = \hat{I}_{\max} - I_i \tag{1}$$

$$\hat{I}_{\max} = \max\left(\hat{I}_{i+1}, \hat{I}_{i+2}, \cdots, \hat{I}_{i+k}\right) \tag{2}$$

Where I_i is the measured flow rate of the i period (current period), $\hat{I}_{i+k}$ is the forecasting inflow rate of the i+k period, and $\hat{I}_{\max}$ is the maximum value of the forecasting inflow for the next k periods. Positive value means a rising water level in the future forecasting period, and a negative one indicates a decreasing water level.

To be more intuitive, take the highest water level as the vertical axis of the flood forecasting operation chart, and its calculation formula is

$$Z = f\left(V_i + \hat{I}_{\max}\Delta t\right) \tag{3}$$

Where Δt is the calculation period; V_i is the reservoir storage of the current period; $f(*)$ is a function of the relationship between water level and storage capacity.

2.4. Reservoir inflow forecast

Due to the influence of subjective and objective factors such as hydrological test error, forecasting scheme error and sampling error, it is inevitable to encounter errors in hydrological forecasting. Since the error of each flood forecast is uncertain, it is only possible to estimate the probability distribution based on the actual flood forecasting operation. Due to the short operation time of the Three Gorges Reservoir, there is still a lack of data concerning long-term forecast error. Therefore, this paper uses the normal distribution as the basis for the error analysis of hydrological prediction [6,7]. Assume that the relative error of the hydrological forecast ε_t obeys a normal distribution with a mean of 0 and a variance of σ^2, ie, $\varepsilon_t \sim N(0,\sigma^2)$, and set the probability that ε_t falls within the allowable error range ε_p is α, then,

$$P\left\{-\varepsilon_p < \varepsilon < \varepsilon_p\right\} = \alpha \tag{4}$$

According to the theory of normal distribution probability,

$$\sigma = \varepsilon_p \left[\Phi'\left(\frac{\alpha+1}{2}\right)\right]^{-1} \tag{5}$$

In the formula, $\Phi'\left(\frac{\alpha+1}{2}\right)$is the upper $\frac{1-\alpha}{2}$quantile value of the standard normal distribution. According to the Specifications of Hydrological Information Forecasting (SL250-2000), 20% is the permitted error in rainfall runoff forecast. In addition, it is feasible to obtain σ_k value of foreseeable period k by calculating the qualified rate of inbound flood forecast α_k of different foreseeable period *k* and introducing it into formula (5) based on flood forecasting operation. Based on the above assumption, the relative error random number $\varepsilon_{t,k}$ obeying the distribution $N(0,\sigma_k^2)$ is generated, which can turn the historical measured inbound flow sequence I_{i+k} into the forecast inbound flow $\hat{I}_{i+k}$ in the foreseeable period of *k*.

$$\hat{I}_{i+k} = I_{i+k}\left(1+\varepsilon_{t,k}\right) \tag{6}$$

2.5. Flood control operation chart of the TGR

Based on the daily flow data of the TGR from 1882 to 2007, the maximum daily flow increase is 17900 m^3/s, while the maximum daily flow increase of 1000-year design flood is slightly over 25000 m^3/s. Therefore, the range of the horizontal axis coordinate of the flood control operation chart is set to -30000 m^3/s~30000 m^3/s. Since the maximum water level is the value combining current water level and the future maximum inflow, it may exceed 175 m, but not 180 m. In addition, when the TGR encounters low water or flood forecasting, its water level can be a little bit lower than the FCWL of 145 m. According to the actual operation plan of 2009, the lower limit is set to be 144.5 m, so the probable maximum water level of the vertical axis can be set to 144.5m~180m.

As shown in Figure 3, the four control lines in the operation chart of the TGR respectively correspond the discharging value of 25000m^3/s, 40,000m^3/s, 54000m^3/s, and 76,000m^3/s, with the water level of 40 m, 43 m, 44.5 m, and 45 m (flood storage measures are needed) at Shashi Station. The inflow in flood seasons is generally large, but small in some dry years with the minimum daily flow of only 6140 m^3/s. To ensure the safety and stability of navigation, ecological water utilization and power system, the minimum discharge flow shall be above 8000m^3/s. When the reservoir water level is lower than the control line of 25000m^3/s, take the flow of 8000m^3/s corresponding to 144.5 m in the flow chart to facilitate interpolation calculation. This interval (Zone I) is mainly designed for the reservoir operation in the years with less water in flood seasons, while other intervals are mainly used for flood control. When using the operation chart, it is necessary to determine the operation interval according to the water level and the inflow, and then determine the outflow based on the interpolation calculation of the upper and lower control lines. In addition, artificial flood peaks are not allowed during flood control, and several control points are set on each control line for optimization and determination.

126-year daily runoff data in flood seasons from 1882 to 2007 (from June 11 to September 30) are used to obtain design floods in flood seasons. Based on the analysis of the process of various types of floods, this paper takes the flood in 1935, 1981 and 1998 flood seasons as typical examples and conducts co-frequency amplification of 30-day flood process using the annual maximum sampling based on the 1000-year design flood.

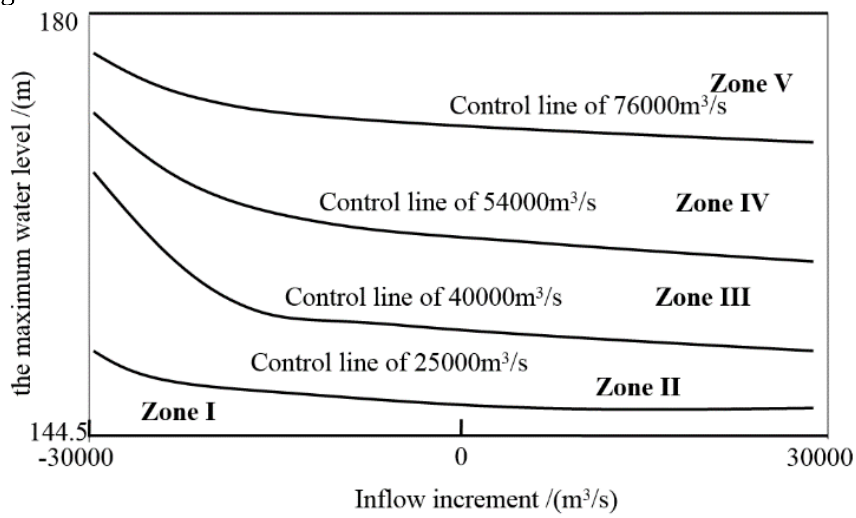


Figure 3. Flood control operation chart of the TGR

2.6. Optimal operation model of the TGR

2.6.1. Objective functions. The TGR operation in flood seasons mainly focuses on flood control, taking into account power generation and navigation. In view of the complexity of the operation objectives, it is necessary to build a multi-objective evaluation system when formulating the optimal flood control operation chart. This paper uses the following indicators to optimize calculation:

(1) Flood control operation objective: On one hand, it is required that the maximum water level for flood control before flood seasons be as low as possible; on the other hand, the peak clipping rate should be is as large as possible [8], that is,

$$\min\ Z_{peak} \tag{7}$$

$$\max\quad \left\{\sum_{i=1}^{n_f}\left[Q_{in(i)} - Q_{out(i)}\right]\right\}\left(\sum_{i=1}^{n_f} Q_{in(i)}\right)^{-1} \tag{8}$$

Where Z_{peak} is the highest water level for flood control in simulation using the measured data sequence; n_f is the number of days in which the inflow in the measured data sequence exceeded 40,000 m^3/s (corresponding to the warning water level of the Shashi Station. $Q_{in(i)}$and $Q_{out(i)}$ are the inflow and outflow values of the TGR exceeding 40,000 m^3/s at the i-th time.

(2) Power generation objectives: First, the power generation benefit which is expressed by the annual average power generation during the operation period, should be maximized. Second, the annual average water waste should be the smallest during flood seasons, that is,

$$\max \ \frac{1}{n}\sum_{i=1}^{n}\left(\sum_{j=1}^{m} P_{i,j}\Delta t\right) \tag{9}$$

$$\min \ \frac{1}{n}\sum_{i=1}^{n}\left(\sum_{j=1}^{m} Q_{W(i,j)}\Delta t\right) \tag{10}$$

Where Δt is the time period during the day; $P_{i,j}$ and $Q_{W(i,j)}$ are the daily average total output and the abandonment flow of the Three Gorges Power Station on the j-th day of the flood season in the i-th year, respectively; *m* is the number of days of flood seasons (*m*=112), and *n* is the number of years of simulated operation data. (*n*=126).

(3) Navigation objective: the navigation benefit should be maximized. According to the Supplementary Provisions on the Navigation Management Measures for the Initial Operation Period of the TGR [9] approved by the Ministry of Transport, the traffic flow in the area between the TGR and the Gezhou Dam is divided into 7 flow intervals: less than 25000m^3/s, 25000～30000m^3/s, 30000～35000m^3/s, 35000～40000m^3/ s, 40000～45000m^3/s, 45000～56700m^3/s and 56700m^3/s and above. When the flow is higher than 25000m^3/s, it is necessary to limit the navigation of ships with different power based on the flow interval. The larger the flow is, the more ships should not be allowed to navigate. This paper sets the objective of (11) to reduce the peak flow and outflow fluctuations during flooding.

$$\min \ \left\{\frac{1}{k}\sum_{i=1}^{k}\left[Q_{out(i)} - Q_r\right]^2\right\}^{\frac{1}{2}} \tag{11}$$

Where Q_r is the threshold for traffic flow, which is 25000m^3/s; $Q_{out(i)}$ is the i-th flow value in the outflow sequence higher than Q_r; k is the total number of time periods when the outflow sequence is higher than Q_r.

2.6.2. Constraints.
(1) Constraints of reservoir water balance and water storage:

$$V_{i,j+1} = V_{i,j} + \left(Q_{in(i,j)} - Q_{out(i,j)}\right)\Delta t \quad i = 1,2,\cdots,n;\ j = 1,2,\cdots,m \tag{12}$$

$$V_{j\min} \le V_{i,j} \le V_{j\max} \quad i = 1,2,\cdots,n;\ j = 1,2,\cdots,m \tag{13}$$

(2) Output constraints:

$$P_{\min} \le P_{i,j} \le P_{\max} \quad i = 1,2,\cdots,n;\ j = 1,2,\cdots,m \tag{14}$$

(3) Outflow constraints. Large amount of water in flood seasons can generally meet the minimum flow requirements for power generation and navigation. The paper mainly takes into consideration that the daily variation of the Three Gorges outflow is not more than 8000m^3/s, namely:

$$\left|Q_{out(i,j)} - Q_{out(i,j-1)}\right| \le \Delta Q \quad i = 1,2,\cdots,n;\ j = 2,\cdots,m \tag{15}$$

(4) Boundary conditions: The initial operation water level and the flood-routing water level are both set at 145 m.

(5) Shape constraints of operation lines. Each line should not cross and should be as smooth as possible.

Where $V_{i,j}$, $Q_{in(i,j)}$, and $P_{i,j}$ are the initial daily water storage, daily inflow and daily output on the j-th day of the flood season in the i-th year of the simulation data sequence. $V_{j\min}$ and $V_{j\max}$ are the minimum and maximum water storage on the j-th day in the flood season respectively. $P_{\min}$ and $P_{\max}$ are ensured output and installed output of the power station, respectively. ΔQ is the maximum change of daily outflow in flood seasons.

2.6.3. Constraint processing. There are various constraints in the operation optimization. For some constraints that are conflicting with each other and are difficult to fully satisfy, it is only possible to lower the degree and frequency of the optimization result violating the constraint. Some crucial constraints need to be considered as infeasible constraints, the violation of which will lead to infeasible solutions. For example, the reservoir water level exceeding the upper and lower boundaries is considered as the infeasible constraint. Some constraints that are non-critical or difficult-to-implement are considered as feasible constraints, that is, the violation of those constraints leads to feasible, but not optimal solutions, such as flow change constraint, shape constraint of operation curves, etc. Penalty approaches are adopted in constraint processing. The goal of optimization for penalty that violates feasible constraints shall be minimized. In addition, some additional constraints are needed in order to get more realistic results. For example, the maximum peak flow of the daily runoff data is about 71000 m^3/s; according to operation regulations, the water level in the Shashi Station needs to be controlled at less than 44.5 m and the maximum outflow less not more than 54000 m^3/s. Therefore, penalties are required when the outflow in the simulated operation is above 54000 m^3/s.

3. Multi-objective optimization algorithm

3.1. Multi-objective differential evolutionary algorithm

The optimization problem in this paper is complex with many constraints, variables and objectives. Therefore, it is important to choose a good algorithm for model optimization. Differential Evolution (DE) is proposed by Storn and Price [10] in 1995 to solve the Chebyshev polynomial problem. It is a kind of evolutionary algorithm based on group differences and has three main operators: variation, hybridization, and selection, which is similar to the genetic algorithm. The difference is that the differential evolutionary algorithm mutates first and then hybridizes. In addition, their variation mechanisms are also quite different. Its basic principle is to weigh the difference vector of any two individuals in the population and obtain a new individual by adding a third individual according to a certain rules. If the value of the value of the objective function of the new individual is smaller than that of the objective function of a pre-determined individual in the population, replace it with the new one, otherwise keep the original one. DE is simple in principle, with few controlled parameters, thus it can implement random, parallel and direct global search with fast convergence speed and easy implementation. It is an effective heuristic evolutionary algorithm and has been widely used in many complex optimization problems. For details, see literature [10].

DE shows its obvious advantages in handling single-objective optimization problems; its extension can enable it to deal with multi-objective optimization problems. Based on that, a variety of multi-objective DE have emerged in recent years. Robič and Filipič et al. [11] have proposed a new multi-objective optimization algorithm (Differential Evolution for Multi-objective Optimization, DEMO) in 2005, which is highly regarded for its outstanding performance. DEMO has been extended and improved by Tušar et al. [11] to form a relatively more stable version as it is today. DEMO inherits the advantages of DE while integrating the efficient multi-objective selection environment of evolutionary algorithms such as NSGA-II, IBEA and SPEA2, therefore showing better performance in approaching the optimal frontier of real Pareto and evenly distributing the solution set along the optimal frontier [12]. The core of DEMO is that if the candidate individual superior to the parent individual will replace the parent one, so that the newly generated superior individual can participate in the generation of other contemporary candidate individuals and the replacement of the parent individuals. The kind of elite selection strategy can help to achieve the optimal frontier the real Pareto. There are three types of DEMO, namely DEMO/parent, DEMO/closest/dec and DEMO/closest/obj, see literature [12]. This paper takes the most basic DEMO/parent and uses DE/rand/1/bin mode as individual generation method, that is, the variable to be mutated is randomly selected with the number of residual vector of 1 while the independent binomial experiment is used as the interleaved method. DEMO integrates three selection environments of NSGA-II, IBEA and SPEA2, and this paper adopts NSGA-II selection method, namely, fast non-dominated hierarchical sorting and crowding distance mechanism.

DEMO’s constraint processing mechanism only adopts one infeasible penalty method, meaning that multiple penalties must be weighted into one, making it impossible to deal with feasible and infeasible constraint penalties at the same time, thus less effective. In order to handle various constraints in operation, it is necessary to improve the constraint handling mechanism of DEMO. Specifically speaking, the solution to penalty=0 dominates that to penalty ≠ 0. When the infeasible penalty=0, determine the dominance relationship by comparing the target value; if still not determined, compare the feasible constraint penalties.

3.2. Simulation-optimization-test Framework

The model algorithm is composed of optimization, simulation and test. The optimization module generates some operation diagrams according to a certain algorithms, and selects the optimal solution by comparing each indicator. The simulation module stimulates operation based on the forecast chart obtained by the optimization module using the forecast flow data sequence converted from the measured runoff data, and then calculate the objective function values of each indicator. The inspection module tests whether the operation chart can guarantee the flood control safety of the reservoir and downstream in a catastrophic flood by adopting 1000-year design flood in flood seasons; if the test is passed, then it is a feasible solution. In addition, the operation line correction module adjusts and corrects the shape of the operation line. It is necessary because the lines may cross or leap after the crossover operation. The constraint penalty module simulates the results of operation and the design flood test based on the measured data and sets penalty values separately. The model algorithm process is shown in Figure 4.

The operation chart is determined using the flood control calculation and utilization benefits optimization. Since the flood control process is closely related to the incoming water and the operation line, a test using the design flood is a must when the line is adjusted and optimized The design flood control test is dynamically integrated in the optimization program through the test module, that is, constantly test and correct the optimization result using the design flow while optimizing the targets based on the historical data, which not only helps to increase the ability to control small-and medium-sized floods, but also meet the flood control safety requirements for the mega-floods, thereby organically combining the utilizable benefit and flood control operation.

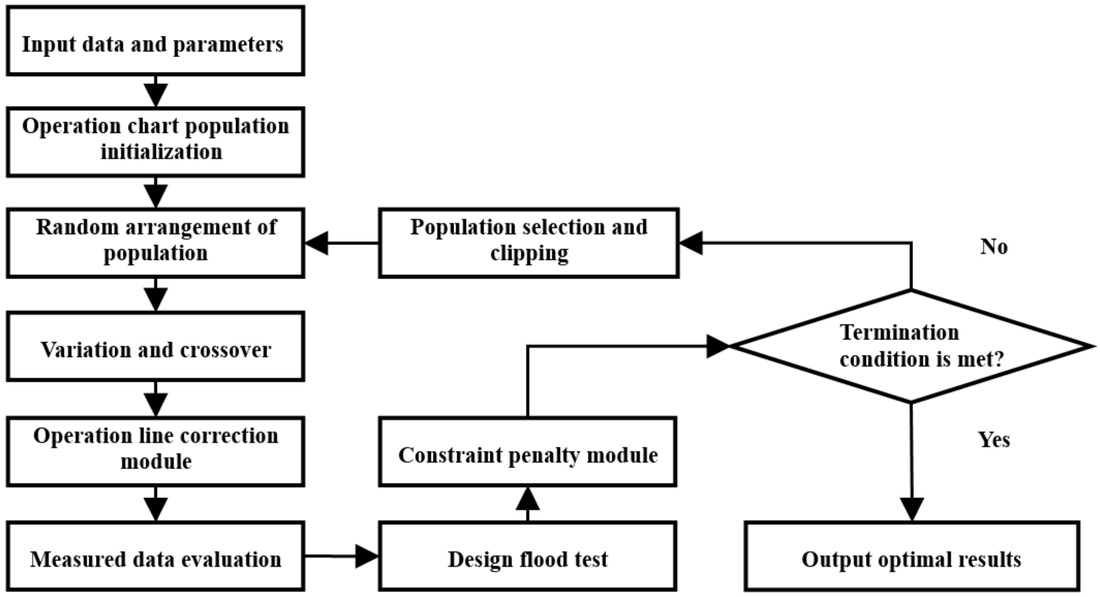


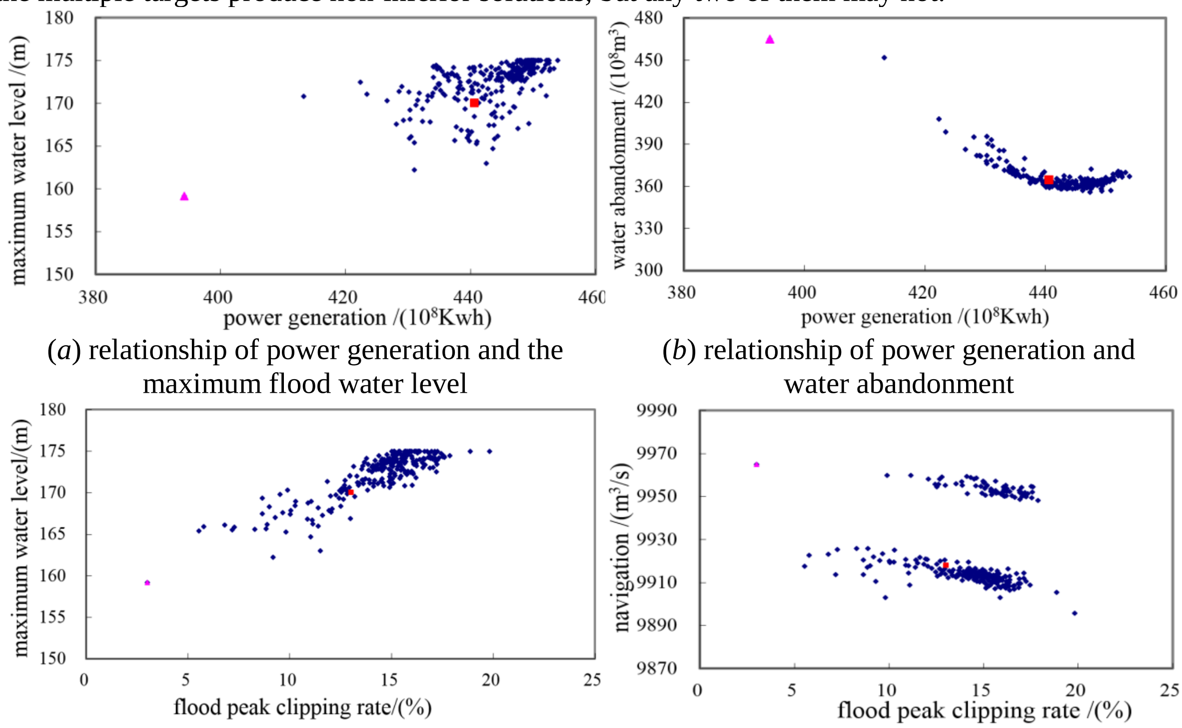
Figure 4. Flow diagram of algorithm

4. Results analysis

The data is divided into two parts, namely, the fixed period and the test period of the parameter calibration of the operation chart. This paper takes the daily runoff data from 1882 to 2007 (126 years) as the parameter calibration and conducts optimization calculation using the improved DEMO. The measured flood in August 2009 is taken as the test period for operation test. Due to the high accuracy of short-term flood forecasting of the TGR, the 3-day qualified forecast rate can reach 85%+ (Class A accuracy standard), therefore, qualified forecast rates of the first, second and third days are temporarily set to be 95%, 90%, and 85%, respectively. Since the flow range varies from -30000 m^3/s to 30,000 m^3/s, the flow variable is rounded and optimized by an integer multiple of 1000 considering intuitiveness and convenience. For the smoothness, time efficiency and optimization effect of the operation line, preset the number of control points of each line k=5; the number of population=300; the variation factor F=0.5; the crossover rate=0.2; the evolution frequency=500,000 times, thereby obtaining the optimal flood control forecasting operation chart of the TGR, with flood control, power generation, navigation and water abandonment taking into comprehensive consideration.

4.1. Optimization results

This paper chooses the final distribution graph of optimal solutions, as shown in Figure 5. It can be seen from Figure 5(a) that the power generation increases with the increase of the maximum flood water level, which is because higher water level leads to higher water head, thus greater power generation. Figure 5(b) shows that with the increase of power generation, the water abandonment decreases first and then increases, which is because lower water level leads to larger water efficiency and less water abandonment, thus more power generation, while higher water level leads to higher water head and more power generation, thus more water abandonment in order to keep the water level within the limit. As can be seen from Figure 5(c), the flood peak clipping rate increases with the increase of the highest water level of flood control, which is because higher peak clipping rate leads to higher water level of the reservoir to some extent. It can be seen from Figure 5(d) that the target value of navigation decreases as the peak clipping rate increases, which is because lower flood peaks is conducive to the improvement of navigation conditions (the reduction of the navigation target value). The points in Figure 5 are more scattered, making it difficult to identify non-inferior relationship, which is mainly because the higher the correlation between the targets is, the more concentrated the points are. In addition, the five out of the multiple targets produce non-inferior solutions, but any two of them may not.



(a) relationship of power generation and the maximum flood water level

(b) relationship of power generation and water abandonment

(c) relationship of the peak clipping rate and the maximum flood water level

(d) relationship of the peak clipping rate and navigation

◆optimal solutions ■the reference solution ▲ the existing simulation result

Figure 5. Obtained non-dominated solutions with DEMO

Table 1 shows the partial optimization result and its comparison with the result of the existing simulation operation when the highest water level of the flood control series is an integer. The optimal plan raises the maximum water level of flood control in simulation and is able to pass the design flood test, thus it is safe for flood control. This paper selects the plan when the highest water level of flood control is 170 m as the reference solution. Table 2 focuses on the comparison of power generation, water abandonment and peak clipping rate of this plan and the existing one. It can be seen that the optimal plan delivers significantly greater power generation, much less water abandonment, and significantly higher peak clipping rate during flood seasons, thus much greater benefits.

Table 1. Results of partial optimization and existing plan

Plan	Maximum water level in flood control /(m)	Average power generation in flood seasons /(10^8 Kwh)	Navigation target /(m^3/s)	Average water abandonment /(10^8 m^3)	Peak clipping rate /(%)
Existing plan	**159.2**	**393.9**	**9963**	**465.3**	**3**
Optimal plan 1	163	442.5	9919	362.5	10
Optimal plan 2	166	439.5	9921	369.0	11
Optimal plan 3	168	429.2	9958	381.7	12
Optimal plan 4	169	446.3	9925	360.2	10
Optimal plan 5	**170**	**440.6**	**9918**	**364.8**	**13**
Optimal plan 6	171	442.5	9916	363.3	13
Optimal plan 7	172	441.9	9915	365.5	13
Optimal plan 8	173	446.6	9914	363.0	14
Optimal plan 9	174	449.7	9913	364.2	15
Optimal plan 10	175	453.9	9905	367.2	19

Table 2. Comparison between selected optimal plan and existing plan

Plan	Average power generation /(10^8Kwh)	Average water abandonment /($10^8 m^3$)	Peak clipping rate /(%)
Existing plan	393.9	465.3	3
Optimal plan 5	440.6	364.8	13
Increment	46.7	-100.5	10

Table 3 shows the outflow of the optimal and the existing plans. It can be seen that the number of days in which the outflow rate between 25,000 m^3/s and 40,000 m^3/s increased greatly while that in which the outflow rate is greater than 40,000 m^3/s decreased greatly, thereby an increase of days of navigation. Since the mean value of inflow rate exceeding 25,000 m^3/s is 34161m^3/s, the navigation objective function makes the outflow flow move closer to the mean value. Although the number of days of traffic below 25,000 m^3/s is reduced, there are still obvious navigation benefits.

Table 3. Comparison of the navigation days in each flow range of optimal plan 5 and the existing plan (a total of 14112 days in the 126-year flood seasons)

Plan	Less than 25000m^3/s	25000～30000 m^3/s	30000～35000 m^3/s	35000～40000 m^3/s	40000～45000 m^3/s	45000～56700 m^3/s	56700m^3/s and above
Existing plan	6869	2592	1843	1124	865	819	0
Optimal plan 5	6794	2904	2115	1326	617	356	0
Increment	-75	312	272	202	-248	-463	0

4.2. Analysis of optimal operation

Figure 6 shows the flood control operation chart of the optimal plan 5, indicating that with the increase of the water level of the reservoir and the flow rate, the optimal operation lines are gradually reduced, which is conducive to increasing the flood discharge; in the water-decreasing stage with a large extent of the flow rate reduced, the reservoir water level can be maintained at a relatively high level, which is conducive to increasing power generation efficiency. Therefore, this flood control operation chart is rational.

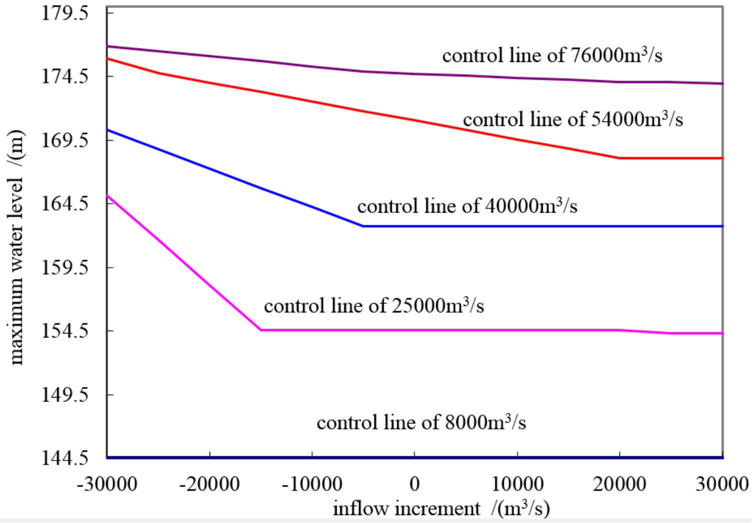


Figure 6. Reservoir flood control operation chart for the selected solution

4.3. Operation analysis of design floods in typical years

The average daily flow of flood peaks in flood seasons in 1981 was nearly 70,000 m^3/s, which is a quite large one in history. Figure 7 shows the results of the whole inflow process in flood seasons in 1981, during which the maximum water level of flood control is 161.4 m, the largest outflow rate is 50904 m^3/s, and the peak flow rate is reduced by 18000 m^3/s. After the flood, the water level of the reservoir is quickly reduced in order to prepare for the next flood, showing the rationality of the optimal flood control operation chart. Figure 8 shows the flood control process of 1000-year design flood (typical flood in 1981). When a large flood occurs during the foreseeable period, an obvious pre-discharge process can be observed, during which the water level of the reservoir is reduced to prepare for the flood. The maximum water level for flood control is 168.9 m, and the maximum outflow rate is 76000 m^3/s.

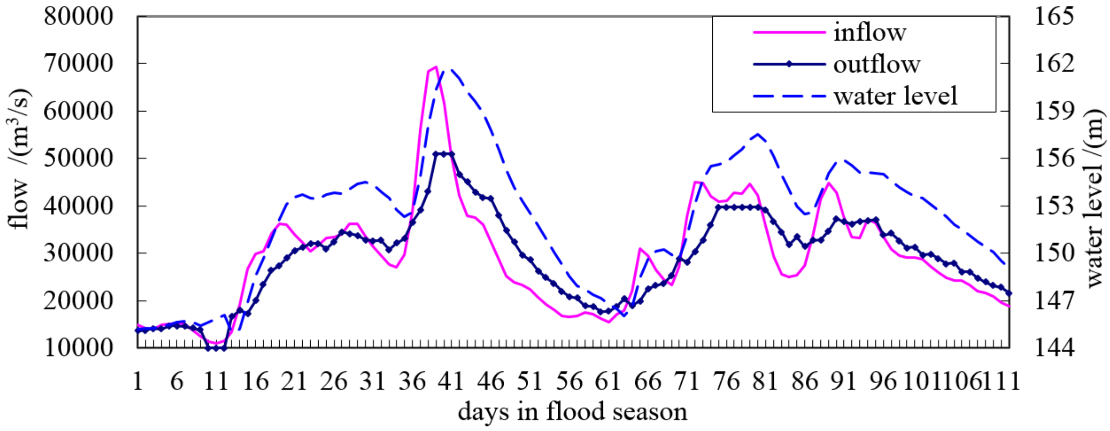


Figure 7. Operation processes during 1981 flood season

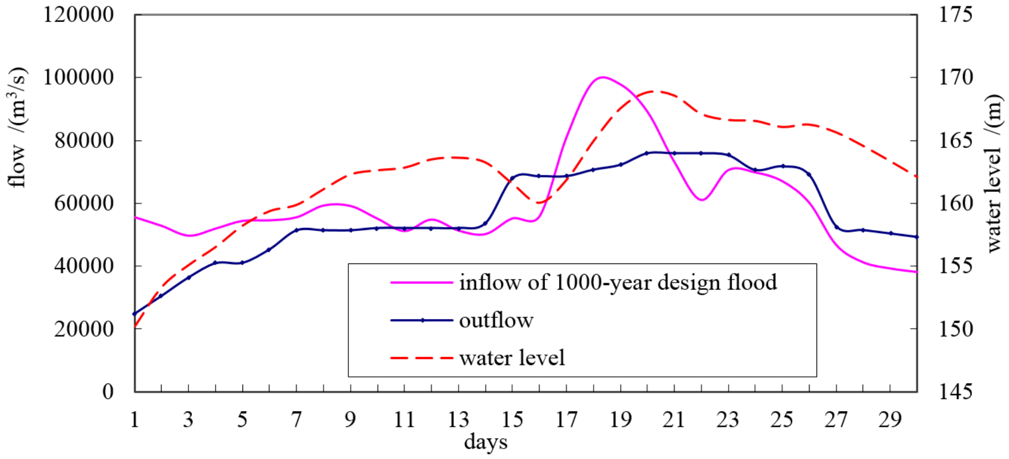


Figure 8. Operation processes of the 1000-year design flood hydrograph

4.4. Flood operation evaluation in August 2009

The operation chart is optimal based on the data from 1882 to 2007. This paper takes the flood season in 2009 (a total of 33 days from August 1 to September 2) as the test period, and test the flood control operation, and compares the operation results. The highest flood peak flow was close to 55,000 m^3/s, so it is a small-and medium-sized flood. This paper stimulates operation of this flood using the optimal flood control operation chart and compare the result with that of actual operation, see Table 4. The actual operation process of the TGR is obtained according to the water level.

Table 4. Actual flood operation results in August 2009

Plan	Highest water level in flood control /(m)	Total power generation /(10^8 Kwh)	Average daily water abandonment /(10^8 m^3)	Peak clipping rate /(%)	Navigation target /(m^3/s)	Maximum outflow rate /(m^3/s)	Final water level /(m)
Actual process	153.8	137.3	163.8	22	9784	39200	145.9
Optimal plan	157.0	148.0	118.3	33	9619	39542	151.7

In the optimal plan, the maximum outflow rate is 39,542 m^3/s, which is close to the actual maximum outflow. The power generation is increased, water abandonment is reduced, and the peak clipping rate is increased. It can be seen from Figure 9 that the optimal plan not only greatly reduces the flood peak, but also makes the outflow flow more even. The optimal plan also raises the flood level; since the flow rate at the end of the period is not large (about 22000 m^3/ s), raising water level of the reservoir is conducive to power generation.

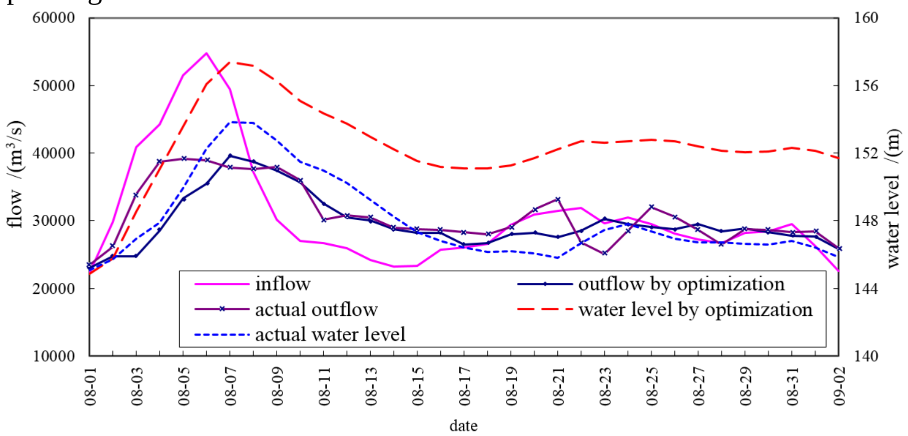


Figure 9. Comparison of the outflow and water level hydrograph during 2009-08 flood operation

5. Conclusion

By comprehensively considering the requirements of reservoir flood control, power generation and navigation, this paper establishes the multi-objective flood control model of the TGR, designs the algorithm flow of “optimization-simulation-test”, and obtains the flood control forecasting operation chart of the reservoir by adopting the multi-objective differential evolutionary algorithm. The result shows that under the premise of ensuring flood control safety, the optimal plan can deliver higher power generation and greater benefits with less water abandonment in the simulated operation and the flood operation in August 2009. The “optimization-simulation-test” mode with forecast error taking into consideration integrates the traditional design flood test into the optimal technology, thus realizing the organic combination of flood control and utilization benefit optimization, which provides a new idea and method for studying the flood control and operation taking into full consideration the comprehensive utilization of large reservoirs.

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