Optimal Scheduling Model for Flood Control of Xin anjiang Reservoir based on IGWO Considering Reservoir Gate Scheduling

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Abstract. The scheduling of reservoir floodgates is a crucial component of flood control measures. This paper introduces an optimised reservoir flood control scheduling model that takes into account the scheduling of reservoir gates. The objectives of this model are to minimise the number of gate operations, maximise the flood peak reduction rate, and maintain the highest water level of the dam at the lowest level. Improved Grey Wolf Optimizer (IGWO) is suggested to be the solution for this model. The model was applied to the Xin anjiang Reservoir using flood data from June 1956 as input. When comparing the solution results with the conventional routine scheduling, it is evident that IGWO is capable of producing scheduling plans within a relatively brief timeframe. Furthermore, the generated scheduling plan outperforms traditional scheduling results in terms of the number of gate operations, flood peak reduction rate, and the impact on the highest water level of the dam. The multi-objective optimal scheduling model presented in this paper, along with the IGWO method, offers useful references for the management of reservoir flood control. Both approaches provide significant guidance for developing effective scheduling strategies.

Keywords: Flood control scheduling, IGWO, Reservoir gates control.

1 Introduction

The investigation into the optimal scheduling for reservoir flood control is structured around five main areas, each focusing on a distinct aspect of the scheduling process. The areas include: basic principles of scheduling, objective function, constraints,

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optimisation algorithms and applied research. [1] This is a complex nonlinear optimisation problem. In addition to considering the upstream and downstream flood control safety of the reservoir, it is also imperative to consider the structural integrity and safety of the dam itself [2]. When it comes to gate scheduling, it is generally necessary to take into account the requirement of minimising the number of gate operation times in order to reach the requirement of minimum gate scheduling cost. For such problems, domestic and foreign experts and scholars often use MILP [3] ,the present two-stage linear programming(TSLP) [4] and progressive optimality algorithm [5] (POA) to answer. However, the MILP method often introduces a considerable amount ofinteger variables, which greatly increases the solution burden. And POA has high complexity and its performance varies with different parameter settings. In contrast, the IGWO inherits the advantages of simple operation and strong convergence of the grey wolf algorithm, at the same time increasing the complexity of its initial solution and the equilibrium coefficients in order to increase the algorithm's ability to escape local optima. This paper establishes an optimal scheduling model and solves it with IGWO, taking the June 1956 flood of Xin anjiang Reservoir as the input of the model, and the results confirm its rationality and validity, which can be used as a useful reference for the scheduling and management of reservoir flood control operations.

2 Study area and Methods

2.1 Study area

The Xin anjiang River Basin is located at longitude 117°40'~119°30' East and latitude 29°20'~30°20' North. Xin anjiang River serves as the primary stream in the upper reaches of Qiantang River. The entire basin extends over a length of 364km. In addition, it encompasses a total catchment area measuring 11850 km^2. Xin anjiang Reservoir is located at about 7.5km above the Baisha town of Jiande, and the segment of the river that stretches upstream from the dam site measures 323 km in length, with a basin area of 10442 km^2, accounting for 88.1% of the total basin area. The flood relief equipment of Xin anjiang Reservoir is a 9-hole spillway, the weir top elevation of the spillway is 99 m, the net width of each hole is 13 m, the total net width is 117 m, and the size of each gate is 13×10.5 m. Each hole is not opened locally. The normal storage level of Xin anjiang Reservoir is 108m, the dead level is 88m, and the flood control limit level is 106.5m.

2.2 Standard Grey Wolf optimizer

In 2014, Mirjalili. et al [6] put forward the Grey Wolf Optimizer (GWO) algorithm, which was developed by drawing upon the hunting behaviors characteristic of wolves. The algorithm will classify wolves into four classes, namely alpha, beta, delta and omega, in which alpha wolves have the highest decision-making priority; beta wolves have the second highest decision-making priority; delta wolf decision priority is one level lower than beta; and omega wolf decision priority is the lowest and obeys all commands of the above three levels. The grey wolf optimization algorithm is fundamentally based on several key principles. Searching is essential for locating potential solutions. Encircling plays a crucial role in refining the search area by surrounding the potential solutions. Hunting further advances the algorithm by simulating the capture of prey. Attacking is employed to finalize the process by aggressively targeting the optimal solution.

The first step is encircling the prey, the mathematical expression for which is:

$$x(t+1) = x_p(t) - A \circ d \tag{1}$$

where $\circ$ is the dot product operation; t denotes the iteration number; $x_p(t)$ is the prey's position vector at iteration t; $x(t)$ is the grey wolf's position vector at iteration t; d is the distance vector between the grey wolf and the prey; A is the coefficient vector. The calculation formula for these components is as follows:

$$A = 2a \circ r_1 - a \tag{2}$$

$$c = 2r_2 \tag{3}$$

where r_1 and r_2 are both uniformly distributed random vectors within the interval [0, 1]; a is the convergence factor, which gradually decreases from a value of 2-linear to 0 with the iteration process count, calculated as:

$$a = 2 - 2 * \frac{t}{MaxIt} \tag{4}$$

where $MaxIt$ is the upper threshold for the number of iterations.

The Omega wolves receive guidance from the Alpha, Beta, and Delta wolves during their coordinated hunts. This hierarchical guidance ensures that the Omega wolves follow strategic and efficient hunting patterns. To optimize their actions and increase the likelihood of hunting success, the study will be based on the best-performing individuals among these collared wolves, and each Omega wolf's position will be updated according to the following formula:

$$x(t+1) = \frac{x_1 + x_2 + x_3}{3} \tag{5}$$

$$\begin{cases} x_1 = \left| x_\alpha - A_1 \circ d_\alpha \right| \\ x_2 = \left| x_\beta - A_2 \circ d_\beta \right| \\ x_3 = \left| x_\delta - A_3 \circ d_\delta \right| \end{cases} \tag{6}$$

$$\begin{cases} d_\alpha = \left| c_1 \circ x_\alpha - x(t) \right| \\ d_\beta = \left| c_2 \circ x_\beta - x(t) \right| \\ d_\delta = \left| c_3 \circ x_\delta - x(t) \right| \end{cases} \tag{7}$$

The process involves repeating the encirclement and hunting behavior of the prey continuously. This iterative method is maintained until the optimal solution is obtained. Alternatively, the procedure continues until the maximum number of iterations is achieved.

2.3 Improved Grey Wolf optimizer

Nonlinear adjustment. The convergence factor a in the standard grey wolf optimisation algorithm directly affects whether the algorithm focuses on global exploration or local exploitation in the search space. Since the multi-objective heuristic algorithm is mostly used to solve highly nonlinear optimisation problems, its search process presents nonlinear dynamic changes. While a is linearly decreasing in the original algorithm, it cannot accurately describe the nonlinear optimisation search process. However, optimisation problems are often nonlinear. For this reason, a nonlinear adjustment strategy is used to update the convergence factor so that it is larger at an early stage, which promotes the algorithm's progression towards the global optimum as early as possible [7], which is calculated as:

$$\boldsymbol{a} = 2 - 2\left(\frac{t}{MaxIt}\right)^k \tag{8}$$

where k is the nonlinear adjustment factor.

Logistic-Tent Chaos Mapping Initialisation Population. Logistic-Tent mapping combines the nonlinear system characteristics of both Tent mapping and Logistic mapping, so that the initialised weights are not only random but also have strong dynamic change characteristics, which can significantly improve the complexity of the population, thereby mitigating the risk of the algorithm converging prematurely to a local optimum [8]. And the mathematical expression of Logistic-Tent chaotic initialisation is shown in equation (9).

$$x_{n+1} = \begin{cases} [rx_n(1-x_n) + \frac{4-r}{2}x_n] \bmod 1, if \quad x_n < 0.5 \\ [rx_n(1-x_n) + \frac{4-r}{2}(1-x_n)] \bmod 1, if \quad x_n \geq 0.5 \end{cases} \tag{9}$$

where x_n is a system variable, while r denotes a control parameter, with $x \in [0,1]$, and $r \in (0,4)$, where *mod* is a mathematical notation for solving for a remainder.The distribution of the Logistic-Tent chaotic system within the interval (0,1) is illustrated in Fig.1.

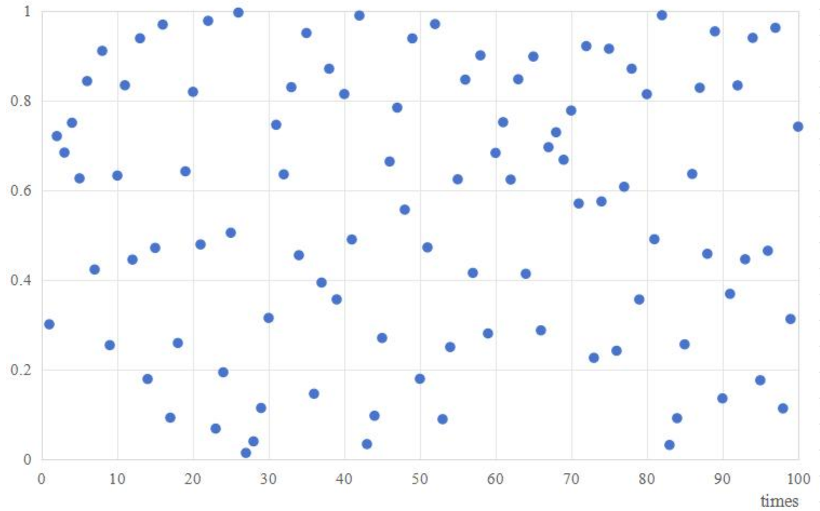


Fig. 1. Logistic-Tent mapping trajectory distribution

From Fig. 1, it can be seen that the Logistic-Tent mapping has a more uniform distribution of output sequences when it is in the range of (0,1), and has better chaotic properties than the Tent mapping and the Logistic mapping.

3 A multi-objective optimal scheduling model for flood control considering reservoir gate scheduling

3.1 Objective function

In this study, we establish a multi-objective optimal scheduling model for reservoir flood control that takes into account gate scheduling. The objectives of this optimization are threefold: to maximize the flood peak reduction rate before and after scheduling, to minimize the number of gate operation times, and to minimize the maximum water level of the dam. The calculation formula for each of these objectives is detailed as follows:

Maximum flood peak reduction rate

$$f_1 = \max \frac{Q_{\max} - q_{\max}}{Q_{\max}} \tag{10}$$

where $Q_{\max}$ is the peak of the incoming flood, and $q_{\max}$ is the maximum value of the discharged flow.

Minimum number of reservoir gates operation times

$$\begin{cases} f_2 = \min \sum_{i=0}^{N-1} \omega_i \\ \omega_i = \begin{cases} 0, if \quad n_{t-1} = n_t \\ 1, if \quad n_{t-1} \neq n_t \end{cases} \end{cases} \tag{11}$$

where *T* is the entire span of time slots within the scheduling period; n_t is the number of gates which are open at time *t* in the scheduling process.

Minimum maximum water level in the dam

$$f_3 = \min\{\max Z\} \tag{12}$$

where Z is the highest water level attained by the dam throughout the scheduling period.

The three research objectives demonstrate the three requirements of the dispatch scheme for the downstream flood safety requirements of the dam, the safety of the dam itself, and the scheme itself should be simple to operate and low cost. However, in the event of a conflict between the three requirements, the safety of the downstream flood control of the dam should be prioritised, followed by the safety of the dam itself and finally, the cost of dispatching the dam should be considered for reduction. In this paper, the multi-objective problem is converted into a single objective for computation, and the weighting method is used to quantify the three objectives into one objective for consideration.

3.2 Restrictive condition

The following constraints need to be observed during the construction of the multi-objective optimal scheduling model:

Water balance constraints

$$V_t = V_{t-1} + (Q_t - q_t)\Delta t \tag{13}$$

where V_t and V_{t-1} are the reservoir's capacity at time *t* prior to and subsequent to scheduling, respectively; Q_t and q_t are the inflow into and outflow from the reservoir at time *t*.

Water level constraints

$$Z_i^{\min} \le Z_i \le Z_i^{\max} \tag{14}$$

$$Z_0 = Z^{begin} \tag{15}$$

where $Z_i^{\min}$ and $Z_i^{\max}$ are the upper and lower bounds of water level constraints at time *t*; Z_i is the water level of the reservoir at time *t*; Z_0 is the initial water levels of the reservoir during the scheduling process and Z^{begin} is the initial water level of the reservoir at the beginning of the observation period.

Outflow constraints

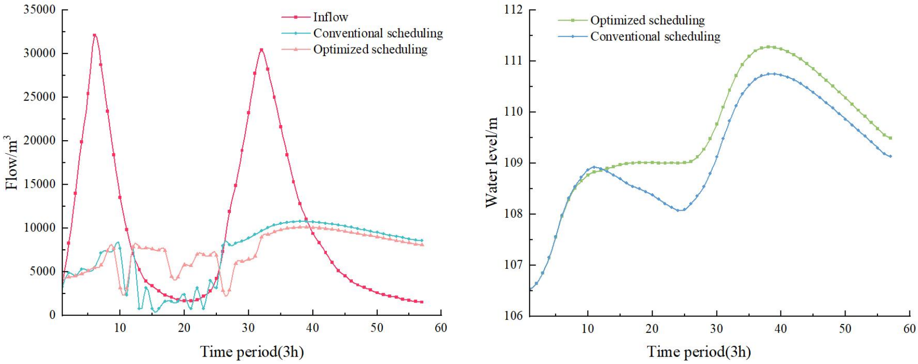
$$Q_t^{\min} \le Q_t \le Q_t^{\max} \tag{16}$$

where $Q_t^{\min}$ and $Q_t^{\max}$ denote the minimum and maximum discharge flows allowable for the reservoir at time *t*. Among them, the latter reflects the constraints on the safe flow for flood control at the downstream control point.

Nonnegative constraint. Throughout the scheduling process, each variable such as water level and flow is greater than or equal to zero.

4 Results and discussion

The flood of Xin anjiang Reservoir in June 1956, hereinafter referred to as "195606" flood. The flood was of bimodal type, with a long flood duration, and the time interval between the double peaks of the flood was 78 h. he initial water level of the Xin Anjiang Reservoir at the onset of the flood season is set at 106.5 meters, which constitutes the limit for the reservoir's water level during this period, the beginning of the scheduling, the flow rate into the reservoir rose rapidly, open the reservoir part of the flood gate continued to rise. At the beginning of scheduling, the incoming flow rises rapidly, and part of the reservoir is opened, the level of water in the reservoir persists in ascending, and when the second flood comes, all the flood gates of the reservoir are opened, and the reservoir is released in accordance with its maximum discharge capacity, ensuring that the outflow do not exceed the upper capacity limit.



(a)The flow process of optimal and conventional scheduling operation

(b) The level process of optimal and conventional scheduling operation

Fig. 2. The process of optimal and conventional scheduling operation for the “195606” flood

Table. 1. Indicators for the evaluation of the movement control process

	Flood peak reduction rate	Maximum water level (m)	The final water level(m)	Number of gates operation
IGWO	68.53%	110.74	109.13	9
Regular scheduling	66.47%	111.27	109.49	18

Analysing the results of conventional and optimized dispatching of flood "195606", it can be seen that: conventional dispatching started to release flood water at the maximum flood discharge capacity at time 26. At time 38, the water level reached its peak, attaining the highest point of 111.27 m, in addition, the maximum discharged flow rate of 10762.0 m^3/s. Optimized dispatching process was basically the same as the conventional scheduling process at the appearance of the first flood peak. But in the valley of the peak of the flood, the optimized scheduling scheme timely flood discharge, retained part of the flood control reservoir capacity, so that the maximum discharge flow rate down to 10102.6 m^3/s. At moment 39, water level of the dam reaches the highest, which is 111.74m. Comparison of the two scheduling results found that the scheme generated by IGWO can effectively improve the flood peak shaving rate, reduce the maximum flood peak of the reservoir, and reduce the number of gates operation times.

5 Conclusion

Reservoirs, as the main bearer of flood control tasks in the basin, a reasonable and effective flood control scheduling programme can effectively assist reservoirs to complete flood control tasks and reduce flood losses in the basin. Due to the many influences and constraints, how to develop an accurate and effective flood control scheduling programme for reservoirs has become a complex subject. The scheduling model for flood control of Xin anjiang Reservoir for this study is constructed with the optimisation objectives of maximum peak shaving rate, minimum pre-dam level, and minimum number of operation times of the gate scheduling process, which are considered in the study. The "195606" flood was used as the input to the model, and IGWO was applied to prevent and control floods in the basin. The outcomes demonstrate that the multi-objective optimal scheduling model constructed by the study is more effective than the traditional model in guaranteeing downstream flood safety and saving scheduling cost. The IGWO used in the paper has a fast convergence rate and can generate non-inferior solutions quickly. It is clear that the multi-objective optimal scheduling model for flood control and the IGWO used in the papaer can provide new ideas and innovative approaches for the comprehensive scheduling and management of reservoir flood control operations.

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