Flood control operation of reservoir group using Yin-Yang Firefly Algorithm

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Abstract: Flood control operation (FCO) of a reservoir is a complex optimization problem with a large number of constraints. With the rapid development of optimization techniques in recent years, more and more research efforts have been devoted to optimizing FCO problems. However, for solving large-scale reservoir group optimization problem, this is still a challenging task. In this work, a reservoir group FCO model is established with minimum flood volume stored in each reservoir and minimum peak flow of downstream control point during the dispatch process. At the same time, a flood forecast model for FCO of a reservoir group is developed by coupling Yin-Yang firefly algorithm (YYFA) with ε constrained method. As a case study, the proposed model is applied to a three-reservoir flood control system in Luanhe River Basin consisting of reservoirs, river channels, and downstream control points. Results show that optimal operation of three reservoirs systems can efficiently reduce the occupied storage capacity for flood control and flood peaks at downstream control point of the basin. The proposed method can be extended to FCO of other reservoir groups with similar conditions.

Key words: Flood control operation; reservoir group; swarm intelligence; YYFA algorithm; ε constrained method

1 Introduction

Reservoir operation plays an important area of research in flood management, which helps to reduce flood damages, minify flood peaks, control flood and reserve flood during flood seasons (Hlavinek 2009; Luo et al. 2015; Rahimi et al. 2020). Flood control operation (FCO) of complex reservoir system is a significant non-engineering measure to effectively alleviate flood disasters by the complementarity of reservoirs (Zhu et al. 2016). A typical flood control system includes reservoirs, levee, river channel, flood-relief area, flood diversion and downstream control points, and has characteristics of large scale and nonlinearity (Chen et al., 2017). This renders it extremely difficult to attain an optimal FCO strategy. An optimization solution is considered to be one of major challenges of flood control optimal operation model.

During the past decades, many techniques have been developed to solve reservoir operation problem (Yu et al., 2019), such as linear programming (Needham et al., 2000), non-linear programming (Unver and Mays, 1990), and dynamic programming (Yakowitz, 1982; Zhao et al., 2017). Non-linear programming methods have limitations of slow convergence speed, long computation time whereas dynamic programming methods face the curse of dimensionality (Bai et al., 2015; Yeh, 1985). Recently, some nature-inspired optimization methods have been widely applied to solve multi-constrained optimization models of large-scale reservoirs (Hossain and El-shafie, 2013). Genetic algorithms (GAs) are taken as a representative approach of this type, and they have been widely applied to solve water resources system optimization (Ahmad et al., 2014; Malekmohammadi et al., 2010). These works have demonstrated that GA is superior to traditional methods in terms of computational requirements in water resources management (Luo et al., 2015). Afshar (2013) presented three constrained versions of PSO algorithm for efficient optimal operation of multi-reservoir systems. Luo et al. (2015) developed a combined PSO and estimation of distribution algorithm for solving reservoir FCO. Most recently, Chen et al. (2020) used PSO with adaptive random inertia weights for multi-objective reservoir operation. Guvengir et al. (2021) used an improved PSO for short-term flood control and long-term energy maximization in multi-reservoir systems. Although some techniques have been proposed to optimize a FCO model, solving multi-reservoir FCO problem is more difficult than a single reservoir (Li and Ouyang, 2015; Qi et al., 2017). Therefore, more investigations on FCO models and new techniques are still required to obtain an effective FCO strategy.

As a swarm intelligence algorithm, Firefly algorithm (FA) was proposed by Yang (2008), which is based on grouping behavior of fireflies (Yang, 2014). FA has been shown to perform better than GA or PSO over several numerical benchmarks (Zhou et al., 2019). Due to its simplicity, flexibility, robustness and effectiveness, it has been widely used in many fields to solve optimization problems (Altabeeb et al., 2021; Danandeh Mehr et al., 2019; Garousi-Nejad et al., 2016; Kaveh et al., 2019; Mosavvar and Ghaffari, 2019). Although these works have shown that FA is an effective optimization technique in many optimization problems, its role in exploration will be greatly weakened if the brightest firefly falls into local optimization. In order to reduce the number of times of good balance between exploration and exploitation functions, Wang et al. (2020) presented a Yin-Yang firefly algorithm (YYFA) based on dimensionally Cauchy mutation.

The objectives of this study are therefore to develop a flood forecast model for FCO of a reservoir group coupling YYFA with ε constrained method. Its practicability is then verified through a case study of complex flood control system operation in Luanhe River Basin. This research has some novelties and contributions as mentioned below. Firstly, a generalized FCO model of three reservoirs is established for flood control benefits of each reservoir and downstream flood control point safety, which can be extended to more reservoirs. Secondly, the good nodes set (GNS) strategy, self-learning strategy and randomly attraction model in YYFA can provide inspirations for solving FCO model of three reservoirs. Finally, the ε constrained method can use available information from infeasible region by relaxing constraint conditions of the optimization model and thus helping enhance global optimization ability.

The paper is organized as follows. Section 2 presents rules and mathematical model for FCO of three reservoirs. Section 3 gives a brief introduction of YYFA. Section 4 introduces the case study including the studied area, used data, forecasted inflow flood, joint FCO modelling, results and discussions. Finally, Section 5 provides the conclusions of this work.

2. FCO of multi-reservoir

2.1 Rules of FCO

During flood season, rules of FCO are usually used to guide reservoir operation according to the current storage state of reservoir group and the forecasted inflow. According to characteristics and experiences of the reservoir flood control system, three aspects need to be considered. Firstly, in the process of regulating a flood in a reservoir, the ratio of the storage capacity of the reservoir to the maximum flood control storage capacity should be as small as possible. Secondly, at the end of a flood regulation, the water storage should be close to the ideal storage capacity of the reservoir as far as possible. Finally, during the flood adjustment process, the maximum flow of the reservoir or the maximum combined flow through the downstream control point should be as small as possible. The first aspect reflects the flood safety of the reservoir itself; the second aspect considers the connection of two floods and the benefits of the reservoir; the third aspect denotes flood safety of the downstream control point.

2.2 Mathematical model

In general, a multi-reservoir flood control system in a river basin includes reservoirs, levee, river channel, flood-relief area, flood diversion and downstream control points. For particularly large basins, there are also flood storage and detention areas. This paper does not consider any flood storage and detention areas. The generalized network of a flood control system is shown in Figure 1.

Insert Figure 1

The purposes of FCO of a reservoir group are to minimize the peak flow of reservoirs and mitigate flood disasters in downstream protection areas. In the process of flood operation, the initial water level of each reservoir for flood operation is the flood limit level. In order to meet the next flood, the reservoir water level should drop back to the flood limit level at the end of flood operation. In this paper, the objectives are to control the flood volume stored in the reservoirs as small as possible and minimize the peak flow of downstream control point during the dispatch process. A typical flood process is taken as an example. The objective function of the optimization model is:

$$Ob = min(\omega_1 \cdot V_1^{'} + \omega_2 \cdot V_2^{'} + \omega_3 \cdot V_3^{'} + \omega_4 \cdot Q^{'}) \quad (1)$$

where $V_1^{'}$, $V_2^{'}$ and $V_3^{'}$ are the normalized maximum storage capacities of three reservoirs after treatment during FCO, respectively. $Q^{'}$ represents the normalized peak flow at downstream control point. ω_1, ω_2, ω_3 and ω_4, are weights of objectives 1 to 4, respectively. In order to eliminate the influence of different units, the raw values are first normalized by Eqs. (2) and (3) as follows:

$$V_i^{'} = \frac{V_{z,i} - V_i}{V_{z,i} - V_{l,i}} (i = 1,2,3) \quad (2)$$

$$Q^{'} = \frac{Q}{Q_{max}} \quad (3)$$

where V_i denotes the maximum storage capacity of the *i-th* reservoir during flood control operations; $V_{z,i}$ is the total flood control capacity of the *i-th* reservoir; $V_{l,i}$ is the storage capacity corresponding to the flood control limit water level of the *i-th* reservoir; Q is the peak flow of downstream control point during FCO; Q_{max} is the maximum discharge volume without disasters at the downstream control point on the basis of historical data. $V_{z,i}$-$V_{l,i}$ represents the storage capacity of the *i-th* reservoir between the flood control limit water level and the maximum water level, which is termed the maximum flood control storage capacity. Thus, $V_i^{'}$ indicates the proportion of flood storage capacity occupied during the dispatching process of the *i-th* reservoir. For the *i-th* reservoir, the smaller is $V_i^{'}$, the safer is the reservoir. Besides, for the downstream control point, the smaller is $Q^{'}$, the less likely the river channel is affected by the flood.

The constraints of the optimization model are given as follows (Luo et al. 2015):

(1) Water balance constraint:

$$V_{t+1,i}\text{-}V_{t,i}=\left(Q_{t+1,i}\text{-}q_{t+1,i}\right)\cdot\Delta t \tag{4}$$

where $V_{t+1,i}$ is the *i-th* reservoir storage at the end of the period (10^8m^3); $V_{t,i}$ is the *i-th* reservoir storage at the beginning of the period (10^8m^3); $Q_{t+1,i}$ is the *i-th* reservoir inflow in the *t*-th period (m^3/s); $q_{t+1,i}$ is the *i-th* reservoir discharge flow in the *t*-th period (m^3/s); Δt is the length of the computational period.

(2) Reservoir water level constraint:

$$Z_{min,i}\le Z_i\le Z_{max,i}\left(i=1,2,3\right) \tag{5}$$

where Z_i means the water level of the *i-th* reservoir during flood control operations (m); $Z_{min,i}$ denotes the lowest allowable water level during flood control operations, which denotes the flood limit water level (m); $Z_{max,i}$ means the allowable highest water level during flood control operations, which denotes the check water level (m).

(3) Discharge flow limit constraint:

$$0\le q_i\le q_{max,i}\left(i=1,2,3\right) \tag{6}$$

where q_i is the discharge of the *i-th* reservoir; $q_{max,i}$ is the discharge capacity of each period for the *i-th* reservoir (10^8m^3).

(4) Terminal water level constraint:

$$Z_{end,i}=Z_{e,i}\left(i=1,2,3\right) \tag{7}$$

where $Z_{end,i}$ and $Z_{e,i}$ are the terminal and targeted terminal water levels for *i-th* reservoir (m), respectively.

3. Yin-Yang Firefly Algorithm

In order to improve the performance of FA, Wang et al. (2020) presented a YYFA algorithm based dimensional Cauchy mutation. A detailed introduction of YYFA and its theoretical background can be found in Wang et al. (2020). On the basis of the effectiveness of YYFA to solve continuous unconstrained optimization problems, we make modifications on the attraction model and the mutation mode in the YYFA for a more powerful search capability. The main procedure of YYFA for FCO is stated as follows.

3.1 GNS strategy

In YYFA, if the initial population is able to respond to the spatial characteristic of the search space, the population will obtain better information. This can improve the optimization quality. In YYFA, the GNS strategy proposed by Xiao et al. (2007), is employed to initialize locations of fireflies. Hua and Wang (1978) proved that deviations of GNS strategy generation points were much smaller than those of random generation points.

3.2 Attraction model

In YYFA, a random attraction model (RAM) proposed by Wang et al. (2016) was originally adopted to meet the exploration function of YYFA. Considering the complex inequality constraints in flood control process, a more effective attraction and search model inspired by Pan et al. (2019) is incorporated into YYFA instead of RAM. Firstly, the full attraction model is adopted with all equations in the random attraction model retained. If the chosen firefly is not better than the current firefly, the current firefly will move according to Eq. (8). Finally, the firefly will cancel the move if it gets worse. Details about the search strategy can be referred to Pan et al. (2019).

$$x^{*}_{current,d} = x_{current,d} + \varphi(x_{current,d} - x_{chosen,d}) \tag{8}$$

where $x_{current,d}$, $x_{chosen,d}$ are the dth dimension positions of the current firefly and its chosen objective, respectively and φ is a random value generated uniformly in the range [- 1, 1].

3.3. Yin-Yang firefly self-learning strategy (YYFSS)

YYFA explores the search space through YYFSS and performs high-level data mining to obtain the best fireflies by Cauchy mutation (Wang et al., 2020). After the population position is updated, YYFA chooses the firefly $x_{p,d}$ with the best fitness as the "Yang firefly" and then it is given a certain self-learning time. Next, a new firefly $x_{o,d}$ is randomly created as "Yin firefly" in the search space. In this paper, we replace Cauchy mutation with a more advantageous technique of Lévy flight. Lévy flight has been used widely to enhance the performance of optimization algorithms (Dinkar and Deep 2018; Ingle and Jatoth 2020; Liu et al. 2020; Zhang et al. 2020). The position of $x_{o,d}$ is corrected and updated according to the following equation:

$$x_{o,d} = x_{p,d} + \text{Lévy} \cdot \left(x_{r1,d} - x_{r2,d}\right) \tag{9}$$

where $x_{o,d}$ is the position of Yin firefly in dth dimension, $x_{p,d}$ the position of Yang firefly in dth dimension, *Lévy* is a random value generated by the Lévy distribution. $x_{r1,d}$, $x_{r2,d}$ represent the position in D-dimension of two fireflies randomly chosen from the population, respectively; The mathematical form of Lévy distribution and its index settings can be found in Zhang et al. (2020).

3.4. YYFA

The main computation steps and equations of YYFA are given as follows (Wang et al., 2020):

Let D be the dimension of the search space. According to the movement characteristics of fireflies, the location update equation is given as:

$$x_{i,d}(t+1) = x_{i,d}(t) + \alpha\left(x_{j,d}(t) - x_{i,d}(t)\right) + \beta(t)\varepsilon(i) \tag{10}$$

where $x_{i,d}$ and $x_{j,d}$ denote the position in D-dimension of fireflies i and j, respectively, α is the attractiveness , t is the iteration number, β is the step factor, and ε is within a uniform distribution between [−0.5, 0.5]. The step factor α and attractiveness β in the proposed approach are updated by Eqs. (11) and (12), respectively.

$$\alpha = \alpha_{\min} + \left(\alpha_0 - \alpha_{\min}\right) e^{-\gamma r_{ij}^2} \tag{11}$$

$$\beta(t+1) = \beta(t)\left(1 - \frac{t}{T}\right) \tag{12}$$

where $\alpha_{\min}$ denotes the lower bound of attractiveness, T is the upper limit of iteration. In this paper, for YYFA, we set $\beta(0) = 0.5$, $\alpha_{\min} = 0.1$, $\alpha_0 = 1$ and $\gamma=1$. r_{ij} is the distance between two fireflies as defined in Wang et al. (2020):

$$r_{ij} = \left\| X_i - X_j \right\| = \sqrt{\sum_{d=1}^{D} \left(x_{i,d} - x_{j,d}\right)^2} \tag{13}$$

4. Case Study

4.1 Study area and data

Luan River originates from foothills of Bayantugur in Fengning County, Hebei Province, and flows through 27 cities, counties, and districts in Hebei Province, Inner

Mongolia Autonomous Region, and Liaoning Province. Luanhe River is connected with Bohai Sea in Leting County, Hebei Province. The river has a total length of 888km and controls a drainage area of 44600 km^2, of which 98% are mountainous areas and 2% are plains. The Luanhe River system is shown in Figure 2. The average annual precipitation of the basin is 595mm, and the precipitation is mainly concentrated in the summer, accounting for about 67-76% of the total precipitation of the whole year. The average annual runoff is 46.94 $10^8 m^3$. The maximum peak discharge mainly appears in July or August.

Insert Figure 2.

There are three large reservoirs in the middle and lower reaches of Luanhe River, namely Panjiakou Reservoir, Daheiting Reservoir and Taolinkou Reservoir, which jointly undertake the flood control task in lower reaches. Panjiakou Reservoir is located in middle reaches of Luanhe River in Hebei Province, China. It is the source of Luanhe River diversion project. It controls a drainage area of 33,700 km^2, accounting for 75% of Luone River drainage area. The total storage capacity of the reservoir is 2.93 billion m^3. Its main functions are flood control, water supply and power generation. Daheiting reservoir is located on the mainstream of Luan River in Tangshan City, Hebei Province, 30km away from Panjiakou reservoir and controls a drainage area of 35300 km^2. Daheiting reservoir is an annual regulating reservoir with a total storage capacity of 3.37 billion m^3. An important role of Daheiting Reservoir is to undertake the water regulation of Panjiakou Reservoir, and undertake tasks of water supply, flood control and power generation. Taolinkou Reservoir is located on Qinglong River, the main tributary of Luanhe river, with a controlled drainage area of 5060 km^2 and a total storage capacity of 8.59 billion m^3. The reservoir mainly provides agricultural production and urban water for Tangshan and Qinhuangdao cities. It is a modern large-scale water conservancy project with comprehensive functions such as water supply, power generation, tourism and aquaculture. Characteristics of the above three reservoirs are shown in Table 1.

Insert Table 1

4.2 Flood routing

Xinanjiang Model was presented by Zhao et al. (1980) and has been successfully and widely applied to flood forecasting (Wang et al. 2012; Xu et al. 2013; Zhao 1992). The model divides the whole watershed into many sub-units, and computes runoff and confluence of each sub-unit to obtain the outlet flood process of the sub-unit, and then performs river flood computation below the outlet to obtain the sub-unit outflow process for all sub-units. The watershed outflow processes are added together to obtain the total watershed outflow process. Details regarding theoretical background and parameter optimization of Xinanjiang model can be found in Xu et al. (2013) and Zhao (1992).

In the downstream of Daheiting Reservoir, Luanhe River flows through five counties including Qianxi, Qian'an, Luanxian, Luannan, Leting, etc. in Tangshan City. The reservoir group, composed of the above three reservoirs, jointly undertakes flood control tasks of lower reaches of Luanhe River. Taking Luanxian as the control point of lower reaches of Luanhe River, the upstream can be divided into 5 sub-regions according to the location of the three reservoirs. Hence, there are five regional flood processes including: flood in the upstream of Panjiakou Reservoir, interval flood between Panjiakou and Daheiting Reservoir, interval flood from Daheiting Reservoir to Luanxian, flood in the upstream of Taolinkou Reservoir, and interval flood from Taolingkou Reservoir to Luanxian. Assuming that the inflow of Panjiakou Reservoir is Q_1, the interval flood from Panjiakou Reservoir to Daheiting Reservoir is Q_2, the interval flood from Daheiting Reservoir to Luanxian control point is Q_3, the flood in the upstream of Taolinkou Reservoir is Q_4, and the interval flood from Taolinkou Reservoir to Luan County is Q_5. A generalized flood routing process in Luanhe River Basin is shown in Figure 3.

Insert Figure 3.

In this work, Xinanjiang model is applied to forecast the flood process of the above five sub-regions using meteorological data. Figure 4 gives the flood forecast of a typical rainfall in five sub-regions. The flood duration of the predicted flood is 144 hours, and the computation period is 3 hours.

Insert Figure 4.

The discharge flows of Daheiting Reservoir and Taolinkou Reservoir evolve to Luanxian through the river channel. The flood routing process is computed by linear Muskingum flood routing method, which is expressed by Eq (14) (Gill 1978; Wang et al. 2010).

$$S(t) = k[xI(t) + (1-x)O(t)] \quad (14)$$

where $S(t)$ represents the channel storage at time t; K represents the storage-time constant for the river reach and x represents weighting factor; $I(t)$ and $O(t)$ represent inflow and outflow rates at time t, respectively. The parameters of the Muskingum model in the study area are determined. The joint FCO process of the three reservoirs is described as follows:

For Panjiakou Reservoir, the reservoir inflow is Q_1, and after FCO of Panjiakou reservoir, the reservoir discharge flow is q_1.

For Daheiting Reservoir, the reservoir inflow is composed of two parts, the local inflow Q_2 and Panjiakou reservoir discharge flow q_1. Because Panjiankou Reservoir and Daheiting Reservoir are close to each other, q_1 does not need to be adjusted and computed, and can be used directly as a component of the inflow of Daheiting reservoir. After FCO of Daheiting reservoir, the reservoir discharge flow is q_2.

For Taolinkou Reservoir, the reservoir inflow is Q_4, and after FCO of discharge reservoir, the discharge flow is q_3.

For Luanxian control point, the flow Q is composed of four parts: the discharge flow q_4 of Daheiting Reservoir, which is evolved from q_2; the discharge flow q_5 of Taolinkou Reservoir, which is evolved from q_3; the interval inflow Q_3 from Daheiting reservoir to LuanXian control point; the interval inflow Q_5 from Taolinkou reservoir to LuanXian control point.

4.3 Objective weight by analytic hierarchy process

In this paper, a three-scale method is used to determine the weights of the three reservoirs and LuanXian control point. Details regarding the construction of the judgment matrix by the three-scale method is as follows:

Firstly, the experts compare the importance of each object, and give values in the three-scale comparison matrix A=$(a_{ij})_{m\times m}$. Among them: if *i-th* object is more important than *j-th* object, a_{ij} is 2; if *i-th* object is as important as *j-th* object, a_{ij} is 1; if *i-th* object is not as important as *j-th* object, a_{ij} is 0.

Secondly, the sum of the objects of the three-scale comparison matrix in the same row is computed. The maximum value is recorded as r_{max}, and the minimum value is recorded as r_{min}.

Finally, the direct comparison matrix is transformed into an indirect judgment matrix by the following formula:

$$d_{ij}=\begin{cases}\dfrac{r_i - r_j}{r_{max} - r_{min}}\left(b_m - 1\right)+1 & r_i - r_j \geq 0\\ \dfrac{1}{\dfrac{r_i - r_j}{r_{max} - r_{min}}\left(b_m - 1\right)+1} & r_i - r_j < 0\end{cases} \tag{14}$$

where b_m is the base point comparison scale, ranging between 4 to 9; r_i and r_j are the sum of the elements of *i-th* and *j-th* row of the three-scale comparison matrix, respectively.

Finally, the eigenvalues and eigenvectors of the indirect judgment matrix are computed. The vector corresponding to the largest eigenvalue is used as the weight of each object.

The weights of Panjiakou Reservoir, Daheiting Reservoir, Taolinkou Reservoir and LuanXian control point are computed as 0.2, 0.3, 0.2 and 0.3, respectively.

4.4 Constraint handing techniques

In order to address the constraints of water level and flow limit, ε constrained method proposed by Zheng et al. (2012) is adopted to guide the firefly population to move to a feasible region. The idea of ε constrained method is that the fireflies can make full use of the available information from the infeasible region by relaxing the constraint conditions, and then the relaxation shrinks to find the global optimal solution by an effective comparison rule. The implementation of ε constrained method can be illustrated with the following minimization problem containing only inequality constraints.

$$\begin{aligned} &minimize \quad f(X) \\ &s.t. \quad g_i(X) \le 0, i = 1:q \end{aligned} \tag{15}$$

where $X = (x_1, x_2, \ldots, x_n)$ is an n dimensional vector and $g_q(X) \le 0$ is the q^{th} inequality constraint. A candidate solution, which is a firefly, whose constraint violation is defined as:

$$G(X) = \sum_{i=1}^{q} max(g_i(X), 0) \tag{16}$$

The comparison between two fireflies X_1 and X_2 in YYFA is based on Eq. (17):

$$X_2 \text{ is better than } X_1 \Leftarrow \begin{cases} f(X_2) < f(X_1), \ if \ G(X_1) = G(X_2) = 0 \\ f(X_2) < f(X_1), \ if \ G(X_1) = 0 \cap 0 < G(X_2) \le \varepsilon \\ f(X_2) < f(X_1), \ if \ G(X_2) = 0 \cap 0 < G(X_1) \le \varepsilon \\ G(X_2) < G(X_1), \ if \ G(X_1) > 0 \cap G(X_2) > 0 \\ G(X_2) = 0, \ if \ G(X_1) > \varepsilon \end{cases} \tag{17}$$

The parameter ε is computed from generation to generation by Eq. (18):

$$\varepsilon(t+1) = \begin{cases} \varepsilon(t)/1.035, \ \varepsilon > 10^{-6} \\ 0, \ \varepsilon \le 10^{-6} \end{cases} \tag{18}$$

4.5 Optimal operation of joint flood control using YYFA

With the help of ε constrained method, specific steps for attaining optimal FCO of a reservoir group using Yin-Yang Firefly Algorithm are as follows:

Step 1: Set the parameters. The maximum number of iterations is set as T, and the number of populations is set as M. The self-learning times of Yang firefly (SL) and the initial constraint relaxation $\varepsilon(0)$ are also needed. The optimal T and M can be determined through multiple computations.

Step 2: Initialization of fireflies. In accordance with the given computation period of the forecasted flood inflow, the joint operation process of the reservoir group is set. Fireflies are constructed with the discharge flow of each reservoir at the end of each period as the control variable. In this paper, the flood period is 48, the number of reservoirs is 3, so the vector dimension is 144. With the defined population number M, the firefly population can be expressed in the following matrix form:

$$Y(0)=\left[X_1(0),X_2(0),\dots,X_M(0)\right]=\begin{bmatrix} x_{1,1}(0) & x_{1,2}(0) & \dots & x_{1,M}(0) \\ x_{2,1}(0) & x_{2,2}(0) & \dots & x_{2,M}(0) \\ \dots & \dots & \dots & \dots \\ x_{144,1}(0) & x_{144,2}(0) & \dots & x_{144,M}(0) \end{bmatrix} \tag{19}$$

where $X_i(0)$ is the ith initial firefly, which contains 144 elements, of which the 1st to 48-th elements represent discharge flow of Panjiakou Reservoir，and the 49-th to 96-th elements represent discharge flow of Daheiting Reservoir, and the 97-th to 144-th elements represent discharge flow of Taolinkou Reservoir at the end of each period. After the size of the fireflies' matrix is determined, GNS strategy is used to generate new data to improve the representativeness of the initial data.

Step 3: Computation of the fitness degree. Using the given objective function constructed by Eq. (1), the fitness of each firefly, that is, the brightness of the firefly is computed, and the best firefly is determined using ε constrained method with its position in the indexed swarm. After t-th iterations, the rearranged population is recorded as $[X_1(t), X_2(t), ..., X_M(t)]$

Step 4: Yin-Yang firefly self-learning. The best firefly $X_p(t)$ is selected as the "Yang firefly", that is $X_1(t)$, and a firefly in the population is randomly selected as "Yin firefly". The "Yang firefly" and the "Yin firefly" are searched according to the strategy to obtain the current global optimal firefly. They are then returned to the corresponding positions in the swarm.

Step 5: Firefly population evolution. The firefly swarm is updated according to Eq. (1) to Eq. (4).

Step 6: Termination criteria. Steps 3 to 5 are repeated until the pre-set iteration maximum is reached.

Step 7: The vector corresponding to the finally obtained brightest firefly denotes the discharge flow process after the optimal operation.

The proposed YYFA approach for flood operation is shown in Fig. 5.

Insert Figure. 5.

4.6 Results and Discussions

The main objective is to control the flood volume stored in each reservoir to be as small as possible, and to eliminate the peak flow as far as possible at the downstream control point. According to the above description, YYFA coupled with ε constrained method is adopted to solve the real-world multi-reservoir FCO problems of Panjiakou Reservoir, Daheiting Reservoir and Taolinkou Reservoir. The determination of some important parameters of YYFA algorithm, for example population size and maximum iteration times, has a great impact on the model. The maximum number of iterations is set to 100000. For the purpose of comparison, the algorithm is run 10 times independently using different population sizes. 'Std', 'Min', 'Mean', 'Median', 'Max, represent standard deviation, minimum value, average value, Median value and maximum value of the proposed models, respectively. Statistical results of optimal joint flood control operation of the reservoir group are shown in Table 2. It can be observed that the best objective value can be obtained when the population size is 200. Figures 6 to 8 give the operation process of the three reservoirs. The combined flow process after optimal joint operation, original combined flow process, routing discharge flow of each reservoir and two sub-region inflows at Luanxian control point are shown in Figure 9. From results of Figures 6 to 9 and Table 3, we can see that the occupied flood control capacities of Panjiakou Reservoir, Daheiting Reservoir and Taolinkou Reservoir are 81.13%, 89.65% and 88.63%, respectively. This provides operational space for flood forecasting uncertainty. The maximum flood peak flow is clipped 26.68% at Luanxian control point. Hence, the proposed YYFA coupled with ε constrained method well achieves the objective of joint FCO. In order to validate the feasibility of the proposed method and make benchmark comparison, original PSO and FA are employed to solve this problem under the same conditions. Unfortunately, they cannot find a feasible solution. As an illustration, Figures 10 to 11 give operation results of Panjiakou reservoir only.

Insert Table 2.

Insert Table 3.

Insert Figure 6.

Insert Figure 7.

Insert Figure 8.

Insert Figure 9.

Insert Figure 10.

Insert Figure 11.

5. Conclusions

Reservoirs are among the most effective tools for flood management in flood control system although their optimal scheduling solution is considered to be challenging. In this paper, a new optimization technique named YYFA is developed as a new tool to address this challenge. A ε constrained method is used to address complex constraints of FCO. This paper establishes an optimization model with the goal of minimizing the occupation of flood control capacity and joint minimization of flood peak at the downstream flood control points for multi-reservoir system. Taking three reservoir group systems in Luanhe River Basin in China as the research object, the proposed model and method are verified by using 3-hour predicted inflow time series. Results show that the occupied flood control capacities of Panjiakou Reservoir, Daheiting Reservoir and Taolinkou Reservoir are 81.13%, 89.65% and 88.63%, respectively, and the flood peak at Luanxian control point station can be clipped 26.68%. The results show that the presented model is effective for multi-reservoir FCO system.

Furthermore, YYFA algorithm can also be used as an effective tool to solve other practical engineering optimization problems.

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Table captions

Table 1. Characteristics of the reservoirs

Table 2. Operation results using different population sizes

Table 3. Statistical results of the joint flood control optimal operation

Figure captions

Figure 1. The generalized network of a flood control system

Figure 2. The location of Luanhe River reservoir group

Figure 3. Generalized flood routing process in Luanhe River Basin

Figure 4. Flood forecast of a typical rainfall in five sub-regions

Figure 5. Flood control operation using YYFA approach

Figure 6. Operation process of Panjiakou Reservoir

Figure 7. Operation process of Daheiting Reservoir

Figure 8. Operation process of Taolinkou Reservoir

Figure 9. Flood Routing processes of Luanxian control point

Figure 10. Operation process of Panjiakou Reservoir using PSO

Figure 11. Operation process of Panjiakou Reservoir using FA