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Research papers

Flood control operation coupled with risk assessment for cascade reservoirs

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ABSTRACT

A flood hazard is one of the most common and destructive natural disasters. Flood risk reduction with non-engineering measures has become the primary goal for flood management. This paper proposes an approach to improve the flood control operation for cascade reservoirs by minimizing flood control risk. A framework of reservoir flood control operation coupled with risk assessment (RFCORA) and the corresponding RFCORA model are proposed to reduce risk. The model contains three sub-modules. A real-time reservoir flood control operation simulation module is developed, in which a flood discharge control chart is used to determine the flood magnitude, and flood release is obtained by operation rules. Entropy-weighted fuzzy comprehensive evaluation method is applied to assess the risk level in the flood risk assessment module. Finally, the flood release is updated according to the developed outflow adjustment optimization module aimed at minimizing flood control risk by combing future inflow information. In addition, another model without outflow adjustment optimization is set to be a comparative experiment. The water system of the Upper Yellow River is selected as a case study to verify the model. The results show that the framework and RFCORA model developed in this paper can decrease the time duration in the highest risk level without increasing the maximum water level and maximum outflow of reservoirs. The approach proposed in this paper based on flood control operation and flood risk assessment can be extended to flood mitigation in other water systems in similar situations.

1. Introduction

Flooding is probably the most devastating, widespread and frequent natural disaster facing human societies (Teng et al., 2017). In the past several decades, nearly one third of all natural disasters in the world were floods. Recent research has shown that the intensity, frequency and severity of floods can increase due to global climate change (Apurv et al., 2015; Arnell and Gosling, 2016; Alfieri et al., 2017). Dams and reservoirs play a vital role in water flow regulation and flood peak reduction, which is considered a major engineering measure for flood control. With the improvement of hydrological observation and management, non-engineering measures, especially reservoir operation plays an important role in flood management. (Ahmad and Simonovic, 2000; Chang et al., 2014a; Chang et al., 2014b; Jenkins et al., 2017).

Reservoir flood control operation (RFCO) is a complex multi-objective decision-making problem. The key issues are how to balance the conflict between the safety of the reservoir itself and the downstream and how to balance the water resources utilization benefits and flood control. Furthermore, the objectives vary constantly with the flood control situation, thereby increasing the difficulty of decision making. Scientists have been striving to identify good methods to solve these problems. Current studies on RFCO can be roughly classified into optimization model and simulation model. The former especially the multi-objective optimization model can provide optimal solutions based on the given flood process. In these models, the highest water level and maximum release are often taken into account to ensure the safety of the upstream and downstream (Luo et al., 2015; Qi et al., 2017), while the final water level and power generation are regarded as objectives for water resources utilization (Liu et al., 2017; Qin et al., 2009). However, the flood process is unknown in real-time reservoir flood control operation (RRFCO). In addition, an oversimplified optimization model may lead to unreasonable solutions due to the solving method limitation for a large-scale flood control system with multiple reservoirs and multiple tasks. Therefore, the managers prefer to choose a rules-based simulation model to determine water release according to real-time flood information and updated forecast information. Specifically, several researchers developed a multi-phase RRFCO model considering the differences in decision mechanisms and targets between each flood phase (i.e. before flood, before peak flow and after peak flow) (Hsu et al., 2015; Chou and Wu, 2015). Another common approach for RRFCO is multi-hierarchical operation model. This approach means that the flood control rules are decomposed into several hierarchies

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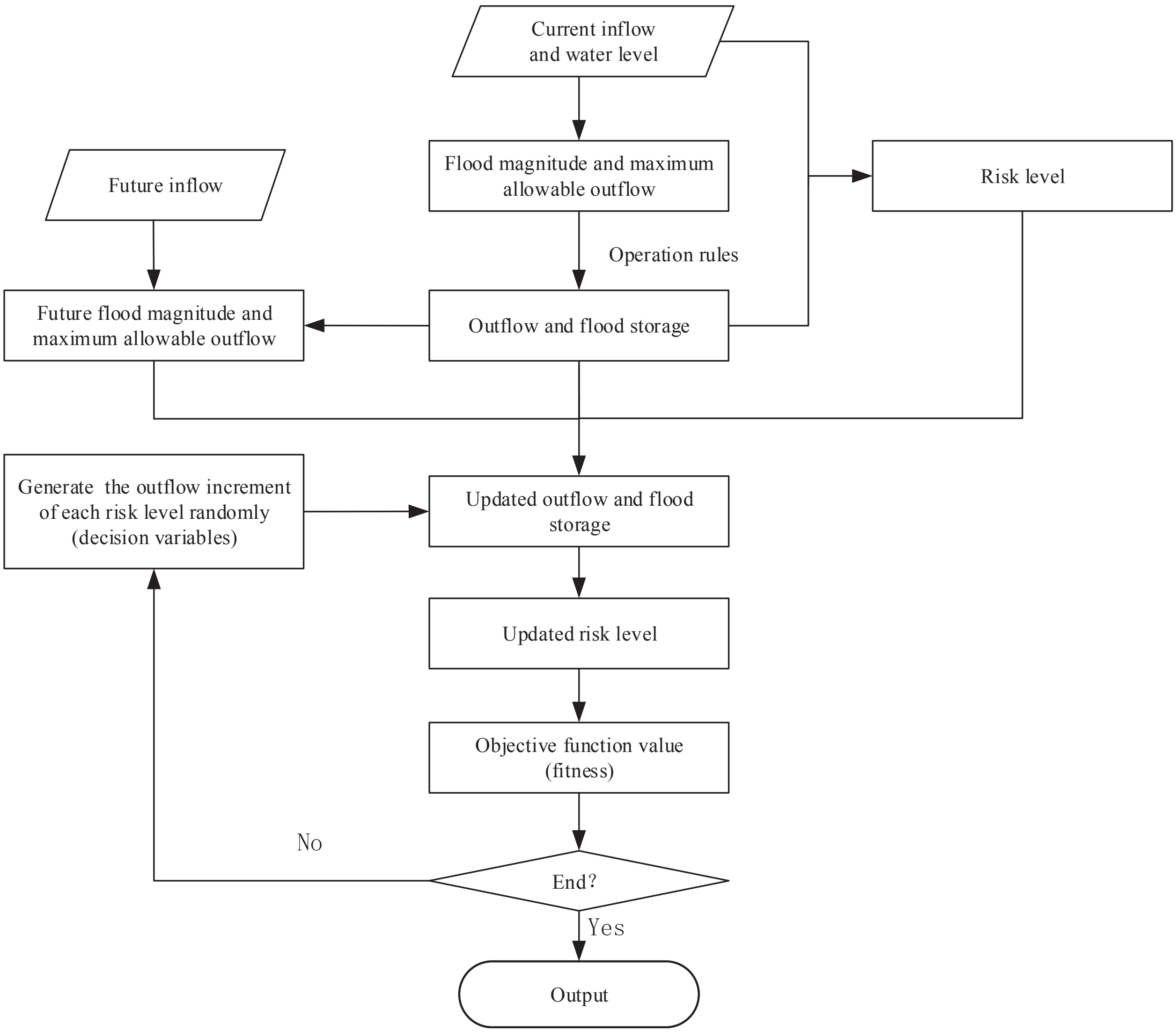

Fig. 1. Flow chart of the RFCORA model.

according to the flood magnitude, which presents different operation modes and different objectives. Moreover, it is consistent with the actual decision-making process and is easily implemented for managers. Hu et al. (2015) described hierarchical rules of the Three Gorges reservoir based on the inflow and water level of the reservoir, which can significantly improve the regulation in flood season and the comprehensive utilization benefits. Sun et al. (2005) set up a flood forecasting and dispatching model system according to the flood peak and volume, which has already been successfully used in the reservoir flood control decision-support system.

However, there exist some problems when using the simulation models. For instance, the rules-based simulation model is strongly dependent on the operation rules, which are often predefined at the planning stage of the reservoir construction through simulation techniques (Zhou et al., 2015). In other words, the rules were made based on the designed floods and did not consider the future inflow, which may not suitable for all floods especially in the changing environment derived from climate change and human activities. Therefore, it is necessary to improve the reservoir water release for real-time floods by combining future inflow. Further, the inflow or water level or both of them is often used to determine the flood magnitude and water release (Lei et al., 2018). In fact, there are large uncertainties in this process that can introduce risks. Therefore, another significant issue for managers is how to assess the flood risk and decrease it. The research focus of flood risk assessment (FRA) is on the probability of unexpected events and the magnitude of negative consequences (Kellens et al., 2013). For the former, flood risk probability or rate is usually adopted to assess the generalized risk (Fan et al., 2017; Zhou et al., 2018), and the vulnerability and resilience are also considered to formulate risk (Joyce et al., 2018). For the latter, the flood risk is often divided into several levels (Albano et al., 2017; Xiao et al., 2017; Chen et al., 2015). Specifically, in RRFCO, the prediction error is one of the main sources of risk. A lot of studies have explored the flood risk derived from prediction error and its influence on flood limited water level (Huang et al., 2018; Ding et al., 2015). Moreover, the dividing standard of flood magnitude and flood damage is characteristic of fuzziness. It is not objective to determine the flood magnitude or flood damage by judging whether the inflow or water level exceeds a fixed value or not. This fuzziness is related to the preference of decision maker and causes risk in flood control operation. Therefore, it is worth assessing the flood risk degree according to the real-time flood conditions and impacts.

Further, flood defense or flood control is gradually turning into flood risk management or risk reduction in recent years according to the idea of risk management (Norén et al., 2016). For most water systems with multiple reservoirs, how to reduce the flood risk through non-engineering measures is an important issue. Hence, calculating the systemic risk level and advancing appropriate measures for risk reduction according to the reservoir flood control operation mode are of great significance for flood management. Huang and Hsieh (2010) developed an early warning model for real-time reservoir flood operation, and introduced responses that increase water release as a result of a specific alert signal. This study has offered a good example of real-time flood operation for one reservoir. However, this problem becomes more complex for water systems with multiple reservoirs due to the multi-dimensional RFCO, multi-factorial FRA and the difficulty of response measures determination. Therefore, we intend to extend this early warning system for real-time flood operation from one reservoir to cascade reservoirs and improve the determining manners for response measures.

This study aims to improve the flood control operation for cascade reservoirs by minimizing flood risk. For this purpose, a framework of reservoir flood control operation for cascade reservoirs coupled with risk assessment (RFCORA) and the corresponding RFCORA model are proposed. Specifically, the model contains three sub-modules: real-time reservoir flood control operation simulation module for conventional flood water release, flood risk assessment module for risk level, and outflow adjustment optimization module for updated flood release. Next, the model and methodology are performed in the upstream of the Yellow River with multiple reservoirs and protection objects to demonstrate its effectiveness on risk mitigation compared to a conventional model without outflow adjustment optimization. The major contributions are as follows. (1) A RFCORA model for cascade reservoirs is developed by coupling real-time reservoir flood control operation and flood risk management. (2) An outflow adjustment optimization method is proposed to obtain updated water release for risk reduction by combing future inflow.

2. Methodology

In this research, the RFCORA model contains three modules, namely, a real-time reservoir flood control operation simulation module, a flood risk assessment module and an outflow adjustment optimization module. It can be divided into three steps (shown in Fig. 1).

Step 1: Develop a real-time reservoir flood control operation simulation module (module 1) to obtain the conventional reservoir water release. In this module, we need to estimate the flood magnitude first. Next, the outflow at every period can be determined based on the given operation rules.

Step 2: Construct a multi-factorial flood risk assessment module (module 2) to obtain the risk level according to the results obtained by sub-module 1. In this module, the entropy-weighted fuzzy comprehensive evaluation method is applied to calculate the risk level. In addition, the influence factors and evaluation levels must be determined in advance.

Step 3: Establish an outflow adjustment optimization module (module 3) and get the applicable outflow increment of each risk level. This step contains four detailed procedures:

(1) Determine the response measures and their implementing mode with future inflow to address the different risk levels.
(2) Obtain the updated reservoir release according to the original results obtained by module 1 and the outflow increment (decision variables) generated by Cuckoo Search (CS) randomly. Note that the updated reservoir outflow is subject to the future maximum allowable outflow that is determined by the future flood magnitude.
(3) Calculate the updated flood risk level according to the updated reservoir release with the flood risk assessment module (module 2) in step 2.
(4) Calculate the value of objective function (fitness) and determine whether the algorithm meets the termination condition (maximum number of iterations). If the algorithm meets the termination condition, output the optimal results; otherwise, return to procedure (2).

2.1. Real-time reservoir flood control operation module

A multi-hierarchical simulation model is usually applied to real-time reservoir flood control operation due to its clear operation rules and good feasibility of the implementation plan. Note that there are two major issues in the model for one reservoir. First, flood magnitude judgment is a crucial procedure for flood control operation. In general, flood control operation is typical complex decision-making regarding problems with multiple objectives, multiple constraints and multiple stages. This operation is often considered in multi-dimensional trade-offs between not only the upstream and downstream but also the flood control and benefit promotion. In actual operation, the flood control operation objective and adaptive mode are often determined according to the flood magnitude. Specifically, for small and medium floods, the decision-makers focus on the comprehensive utilization benefits of the reservoir, while the safety of the dam and protected objects in the downstream is the primary task for large floods.

Moreover, making flood control operation rules is another key factor for flood management, because these rules determine the flood water release process of reservoirs. Further, the operation objectives of the water system are tightly related to deriving operation rules for flood control. In the process of RRFCO, we need judge the flood magnitude first, then determine the flood water release according to the operation rules that can be in the form of scheduling functions. The flood control scheduling function of one reservoir is generally defined as follows:

$$Q_{out} = f(Q_{in}, Z) = \begin{cases} Q_{out(1)},\ Q_{in} \in (Q_{(1)}^{\min}, Q_{(1)}^{\max}),\ Z \in (Z_{(1)}^{\min}, Z_{(1)}^{\max}) \\ Q_{out(2)},\ Q_{in} \in (Q_{(2)}^{\min}, Q_{(2)}^{\max}),\ Z \in (Z_{(2)}^{\min}, Z_{(2)}^{\max}) \\ \vdots \\ Q_{out(K)},\ Q_{in} \in (Q_{(K)}^{\min}, Q_{(K)}^{\max}),\ Z \in (Z_{(K)}^{\min}, Z_{(K)}^{\max}) \end{cases} \quad (1)$$

where Q_{out}, Q_{in}, and Z are the outflow, inflow and water level of reservoir, respectively. $Q_{out(k)}$ is the maximum allowable outflow for hierarchy k, $k = 1, 2, ...,K$. $Q_{(K)}^{min}$ and $Q_{(K)}^{max}$ represent the boundaries of reservoir inflow for hierarchy k. $Z_{(K)}^{min}$ and $Z_{(K)}^{max}$ are the boundaries of water level for hierarchy k. One or both of the two indexes is used to determine the flood magnitude and water release for different reservoirs. Sometimes the water level can be replaced with water storage. Note that the flood control scheduling function works in the rising limb of a flood. In the falling limb, the reservoir releases flood water as soon as possible in the main flood season or stores some flood water at the end of flood season. In particular, for the cascade reservoirs that have strong hydraulic connections and share the flood control tasks of a water system, the joint operation rules of cascade reservoirs are necessary. The difference is that the joint operation rules are relatively complex because they must consider the regulating capacity of each reservoir and the region floods combination. Therefore, for different water systems, the joint operation rules are various and difficult to be expressed as a unified flood control scheduling function.

In general, if one reservoir undertakes the flood control task, the flood control operation rules have been made in the planning and design stage. In actual operation, the designed rules may be used or modified as actual operation rules. Hence, we can use the actual operation rules to set up the real-time reservoir flood control operation model. For cascade reservoirs, we can build the joint operation model according to the flood control task and the flood water allocation rules between different reservoirs that have been predefined in the planning and design stage.

2.2. Flood risk assessment module

At present, there are various alternative methods for flood risk assessment, including fuzzy comprehensive evaluation, projection pursuit evaluation, and artificial neural network. Given that the risk concept itself is vague, fuzzy mathematics is usually used to assess flood risk (Chen et al., 2015; Albano et al., 2017). Further, it is identified as more suitable compared to other traditional evaluation methods (Jiang, et al., 2009). It is noted that the determination of weights is an indispensable part of these methods. However, subjective method is usually applied to weights determination, which is closely related to human influence and subjective preference. Thus, the evaluation results are easy to deviate from the objective situation. It is important to seek simple and practical evaluation methods for flood risk that simultaneously consider subjective and objective weights. Since the entropy-weighted fuzzy comprehensive evaluation method combines both weights of various factors, it was applied to the risk assessments of water shortage, flood hazard and other fields (Luo et al., 2008; Wang et al., 2012; Mei et al., 2016). There are two main steps for this method. First, the fuzzy comprehensive evaluation method was used to build a flood risk evaluation model. Next, information entropy was adopted to calculate the comprehensive weights combined with the subjective weights.

2.2.1. Fuzzy comprehensive evaluation method

The fuzzy comprehensive evaluation method was first proposed by Wang (1980) to resolve complex decision-making problems with multiple factors and levels based on fuzzy transformation principle, which can reflect the vague feature of the evaluation object. Due to the simplicity and validity of the method, it has been broadly applied in many fields. To systematically address this method, the steps are shown below.

Step 1: Determine the influence factors and evaluation levels

In this paper, the risk comes from the fuzziness of flood magnitude judgment and the flood damage degree classification. Therefore, the parameters related to flood magnitude judgment and the flood control standard of downstream projects can be considered as influence factors, including rainfall inflow, outflow, water storage and water level. In particular, for cascade reservoirs that have strong hydraulic connections and share the for flood control tasks, we need select the influence factors that are related to the joint operation rules that are the basis of real-time reservoir flood control operation. Further, the evaluation levels can be divided according to the value of influence factors and management requirement. For example, if there are five stages for the reservoir floods, the evaluation level of outflow can be divided into five levels or more.

Step 2: Establish the fuzzy evaluation matrix

$$U = \begin{Bmatrix} u_{(1,1)} & u_{(1,2)} & \cdots & u_{(1,N)} \\ u_{(2,1)} & u_{(2,2)} & \cdots & u_{(2,N)} \\ \vdots & \vdots & \ddots & \vdots \\ u_{(M,1)} & u_{(M,2)} & \cdots & u_{(M,N)} \end{Bmatrix} \tag{2}$$

where $m = 1, 2, ...,M$, $n = 1, 2, ...,N$; M and N are the number of influence factors and evaluation levels, respectively. $0 \leqslant u_{(m,n)} \leqslant 1$, and $u_{(m,n)}$ denotes the membership degree of factor m to level n, which is generally determined with membership functions, such as triangular, parabolic and trapezoidal distribution.

Step 3: Calculate the weight set

$$W = \{w_1, w_2, ...,w_M\} \tag{3}$$

where w_m is the weight coefficient and $0 \leqslant w_m \leqslant 1$, $\sum_{m=1}^{M} w_m = 1$, which reflects the importance of each factor. In this paper, the weight of each factor is the comprehensive weight that contains objective and subjective weight. The objective weight is calculated by the following entropy weight method (in chapter 2.2.2), while the subjective weight is determined from the decision maker.

Step 4: Determine the evaluation result

$$R = W \circ U = \{r_1, r_2, ...,r_N\} \tag{4}$$

where r_n is the integrated membership degree; $\circ$ is the fuzzy operator and is written as $M(\bullet, \oplus)$ in this paper. In general, the maximum acts as the final evaluation result. However, this approach may not be suitable in certain cases. For instance, if the maximum is less than 0.5, the integrated risk level can be obtained by cumulative membership degree. The cumulative membership degree should satisfy the following formula (Huang and Hsieh, 2010)

$$\sum_{n=1}^{L} r_n > 0.5 > \sum_{n=1}^{L-1} r_n \tag{5}$$

where $\sum_{n=1}^{L} r_n$ is the cumulative membership degree of r_n, $(n = 1, 2, ...,L)$. The integrated risk level L is obtained when the cumulative membership degree begins to exceed 0.5.

2.2.2. Entropy weight method

Information entropy can reflect the degree of disorder of information and be used to measure the validity of information. In other words, if the entropy value is small, the information is useful, and the corresponding evaluation object is important, indicating that it should obtain a high weight. Otherwise, the evaluation object gains a small weight. Therefore, the entropy weight method is an objective approach for weight determination. It was often applied to the comprehensive evaluation combining the fuzzy comprehensive evaluation model in many fields (Luo et al., 2008; Wang et al., 2012; Mei et al., 2016).

According to the fuzzy evaluation matrix, the entropy of factor i is expressed as follows:

$$H_m = -\frac{1}{\ln M} \sum_{n=1}^{N} \varphi_{(m,n)} \ln \varphi_{(m,n)} \tag{6}$$

where $\varphi_{(m,n)}$ denotes the frequency of factor m, and $\varphi_{(m,n)} = u_{(m,n)} / \sum_{n=1}^{N} u_{(m,n)}$. However, when $\varphi_{(m,n)} = 0$, $\ln \varphi_{(m,n)}$ is not allowed mathematically. Therefore, we suppose $\varphi_{(m,n)} \ln \varphi_{(m,n)} = 0$ when $\varphi_{(m,n)} = 0$. Thus, the objective weight of factor i is calculated as follows:

$$w_{om} = \frac{1 - H_m}{M - \sum_{m=1}^{M} H_m} \tag{7}$$

Next, combining the subjective weight, the comprehensive weight is shown below:

$$w_m = \frac{w_{om} w_{sm}}{\sum_{m=1}^{M} w_{om} w_{sm}} \tag{8}$$

where w_{om} and w_{sm} are the objective and subjective weight, respectively; and w_m is the comprehensive weight coefficient. Thus the method combines the expert opinions and objective data attributes together, which is considered more scientific and credible to some extent.

2.3. Outflow adjustment optimization module

2.3.1. Problem formulation

For flood management, besides issuing warnings, it is more significant for administrators to take measures to manage and mitigate the flood impacts. Specifically, adjusting the water release process is one manner of risk treatment that can be implemented for reservoirs. Further, this risk treatment means selections among various options. How to choose the best option is another crucial problem of this module. Therefore, we select an optimization method to solve the problem, which can obtain the ideal scheme with the lowest risk rapidly. In the optimization module, the outflow adjustment corresponding to risk level is regarded as the decision variables and obtained by the optimized algorithm (i.e. CS). The details are shown below.

To reduce the risk, the expected scheduling results should achieve two objectives: one is the minimization of the highest risk level, and the other is the minimization of time duration in the highest risk level. With the weighted method, the two objectives is transformed into single objective which is defined as:

$$f = \min(\alpha * L_{\max} + T_{\max}) \tag{9}$$

where $L_{\max}$ is the highest risk level; $T_{\max}$ is the number of period in the highest risk level; α is a coefficient, and is 100 in this paper. Because the highest risk level has a priority compared with the number of period in the highest risk level. Given the number of computing periods (45 in this paper), we set the value of the coefficient as 100 which is larger than the number of computing periods. The main constraint conditions are shown below. In addition, except the decision variables constraint, the others are satisfied in the joint reservoir operation model, which can alleviate the burden of optimization.

(1) Decision variables constraint
$Q_{d2} \leqslant Q_{d3} \leqslant Q_{d4} \leqslant Q_{d5}$ (10)
(2) Water balance constraint
$V(i, t+1) = V(i, t) + (Q_{in}(i, t) - Q_{out}(i, t)) \times \Delta t$ (11)
(3) Reservoir water level constraint
$Z^{\min}(\mathrm{i, t}) \leqslant \mathrm{Z(i, t)} \leqslant \mathrm{Z}^{\max}(\mathrm{i, t})$ (12)
(4) Outflow constraint
$Q_{out}^{\min}(i, t) \leqslant Q_{out}(i, t) \leqslant Q_{out}^{\max}(i, t)$ (13)

where Q_{d2}, Q_{d3}, Q_{d4}, and Q_{d5} represent the outflow increments corresponding to the risk levels of 2, 3, 4, and 5, respectively. $V(i, t)$ and $V(i, t+1)$ are the storage of reservoir i at period t and period $t+1$, respectively. $Q_{in}(i, t)$ and $Q_{out}(i, t)$ means the inflow and outflow of reservoir i at period t, respectively. $Z(i, t)$, $Z^{\min}(\mathrm{i, t})$ and $Z^{\max}(\mathrm{i, t})$ are the water level, the minimum and maximum water level of reservoir i at period t, respectively. $Q_{out}^{\min}(i, t)$ and $Q_{out}^{\max}(i, t)$ represent the minimum and maximum outflow of reservoir i at period t, respectively.

Note that this module can be applied to water system with one reservoir or cascade reservoirs. In particular, if there are two cascade reservoirs that have strong hydraulic connections and share the flood control tasks, selecting one reservoir to implement outflow adjustment optimization and change the outflow of the other reservoir according to the joint operation rules is more practical and reasonable than independent outflow optimization of the two reservoirs. This is because the real-time reservoir flood control operation and risk assessment are based on the joint operation rules.

2.3.2. Model solution

Cuckoo Search (CS) is a heuristic optimization algorithm that was first proposed by Yang and Deb (2009). This method is based on the brood parasitism of cuckoos and Lévy flight (Walton et al., 2011). Specifically, cuckoos may lay their eggs in the nest of other host birds, the host birds may find the eggs with a probability P_a, and these birds will either throw the eggs away or abandon the nest. This phenomenon means the cuckoos have to find a new nest elsewhere. In addition, Lévy flight is a random walk that performs the search pattern. The detailed theory and idealized rules can be observed in the reference (Yang and Deb, 2013). This method just has one parameter, i.e., the probability for an alien egg to be discovered, besides the number of populations. Moreover, this method is proved to be higher solution quality, higher search efficiency and shorter computing time over other methods such as PSO, DE, and GA (Nguyen and Vo, 2015). Therefore, it has been used in many fields due to its advantages of fewer parameters and good global searching ability (Basu and Chowdhury, 2013; Thang et al., 2014; Amed and Salam, 2014). In this paper, it is applied to solve the optimization model for applicable new water release in the outflow increment optimization model. The flow chart of this algorithm is shown in Fig. 2.

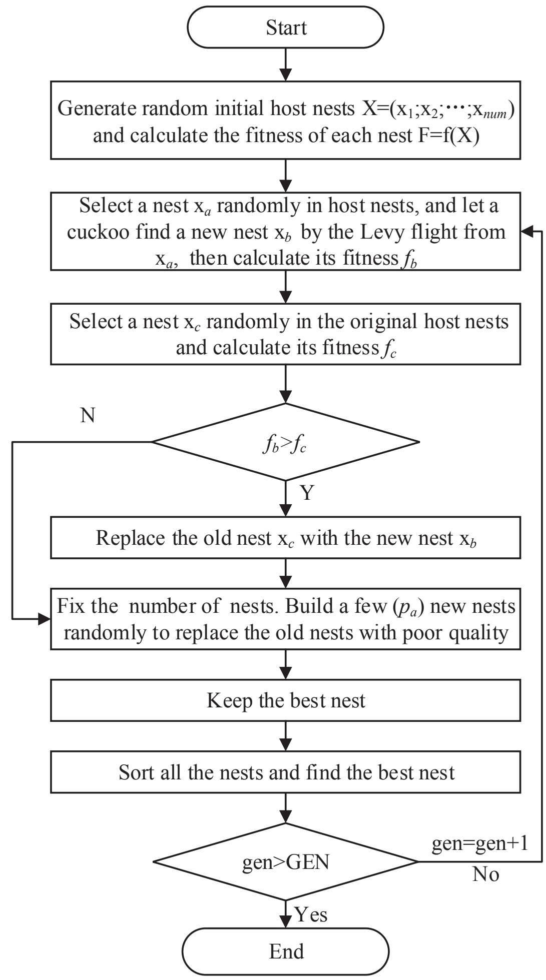

Fig. 2. Flow chart of Cuckoo Search.

3. Case study

3.1. Study area

The Yellow River (YR), possessing a length of 5464 km and a drainage area of $7.95 \times 10^5\,\mathrm{km}^2$, is the second-longest river in China. The upstream portion of the Yellow River (UYR) accounts for 51.3% of the total area of the Yellow River Basin, and it yields 54% of the total runoff of the YR. Specifically, the upper reach is rich in both water resources and hydropower resources. Therefore, there are several reservoirs in this reach that shoulder the significant tasks of benefit promotion and damage reduction. However, as one of the five flood sources of the YR, it often suffers from floods, which may cause major disasters to the downstream. With the comprehensive effect of climate change, regional water transfer and sediment accumulation, the channel flow capacity significantly reduces, thereby even increasing the flood control pressure of this reach (Liu et al., 2017).

The flood water of the UYR is primarily from the upper reach to Lanzhou, due to the long duration and large area of precipitation. In addition, with the regulation and storage of vegetation and marshes, the fluctuation of a flood is relatively gentle. Generally, a flood in this area usually occurs in July or September and lasts approximately 40 days. This flood water brings threats to the downstream, especially the Lanzhou City and Ningxia-Inner Mongolia reach of the YR, or even flow into the middle and lower reaches of the YR, which may lead to the coincidence of floods. For instance, in 1981, the flood peak flow was $5600\,\mathrm{m}^3/\mathrm{s}$ in Lanzhou station with continuous rain for 35 days; next, it became $7000\,\mathrm{m}^3/\mathrm{s}$ in Huayuankou station (in the downstream) after encountering the flood of the Weihe River (a tributary of the YR). Therefore, it is of great significance to research flood management of this water system.

At present, the Longyangxia reservoir (LYX) and the Liujiaxia reservoir (LJX) have been sharing the major flood control task of the complex system with multiple reservoirs since 1987, while the other reservoirs in the downstream are regarded as protection objects. The distribution and flood control standard of the reservoirs in the UYR are

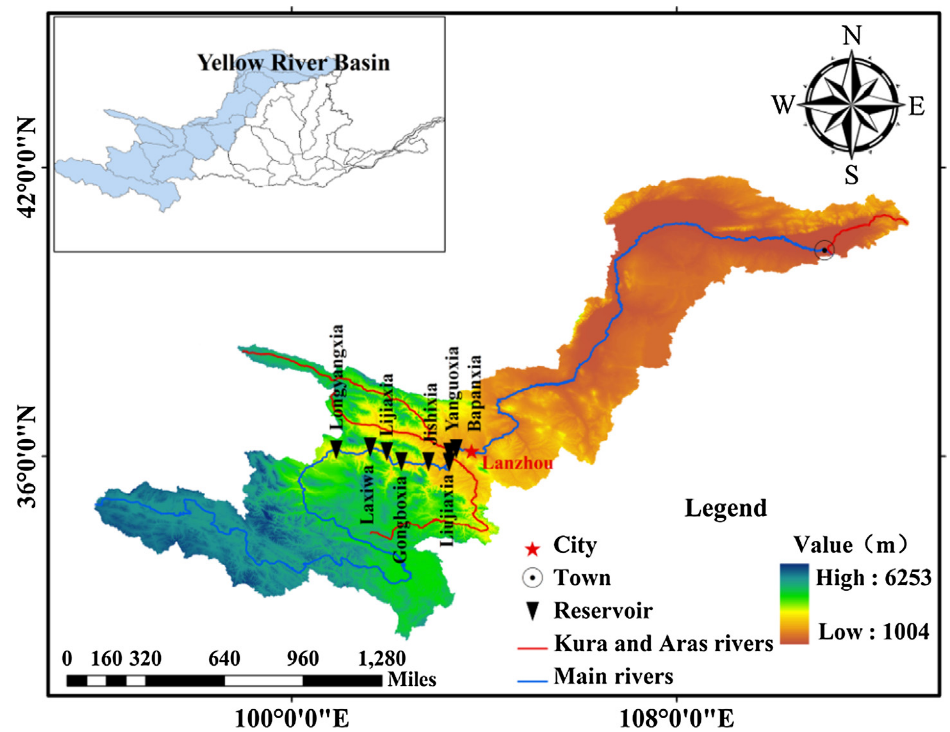

Fig. 3. Location of cascade reservoirs in the Upper Yellow River. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Flood control standard of the protected objects.

Objects	Flood frequency (%)	Maximum outflow (m^3/s)	Maximum allowable outflow of LYX (m^3/s)	Maximum allowable outflow of LJX (m^3/s)
LYX	PMF	6000	6000	—
LJX	PMF	open	6000	open
Yanguoxia	0.05	7260	6000	7260
Bapanxia	0.1	7350	4000	4510
Lanzhou	1	6500	4000	4290

PMF: probable maximum flood.

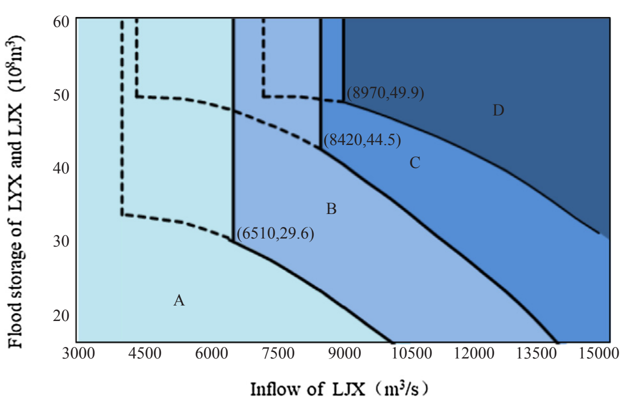

Fig. 4. Flood discharge control chart of LJX.

shown in Fig. 3 and Table 1, respectively. Even though LYX and LJX have impounded most of the flood water depending on joint flood control operation, the system still lacks an effective flood risk management mechanism for flood mitigation. The data employed in this paper is the design floods of different frequencies, which is provided by the Northwest Survey and Design Institute of State Power Corporation of China, now renamed the Northwest Engineering Corporation Limited of Power Construction Corporation of China.

3.2. Real-time reservoir flood control operation

LYX and LJX have been sharing the major flood control task of the complex system with multiple reservoirs since 1987, thereby reducing the flood damage in the upstream of the YR. According to the design objectives, they need to not only ensure the safety of the dams and the protected objects in the downstream but also maximize the utilization of flood resources. In this paper, by considering the characteristics of flow compensation and flood volume compensation, a flood discharge control chart (shown in Fig. 4) is applied to the flood magnitude judgment for LJX, which is a design result of flood control (Northwest Investigation and Design Institute of State Power Corporation, 2003). This chart means that both the flood peak flow and total flood storage in the corresponding period are greater than the corresponding design value of a particular frequency, the flood of LJX is identified less than the frequency. Specifically, if $(Q_{in}(2,\ t),\ W)$ that means the daily inflow of LJX (m^3/s) and the total flood storage of LYX and LJX (10^8 m^3) lays on area A, the flood frequency is greater than 1%, and the maximum allowable discharge is 4290 m^3/s. If $(Q_{in}(2,\ t),\ W)$ lays on area B, the flood frequency is less than 1% and greater than 0.1%, the maximum allowable discharge is 4510 m^3/s. Similarly, if $(Q_{in}(2,\ t),\ W)$ lays on area C, the flood frequency is less than 0.1% and greater than 0.05%, the maximum allowable discharge is 7260 m^3/s. if $(Q_{in}(2,\ t),\ W)$ lays on area D, the flood frequency is less than 0.05%, and LJX remains open. The dotted line means that just one factor (flood storage) exceeds the

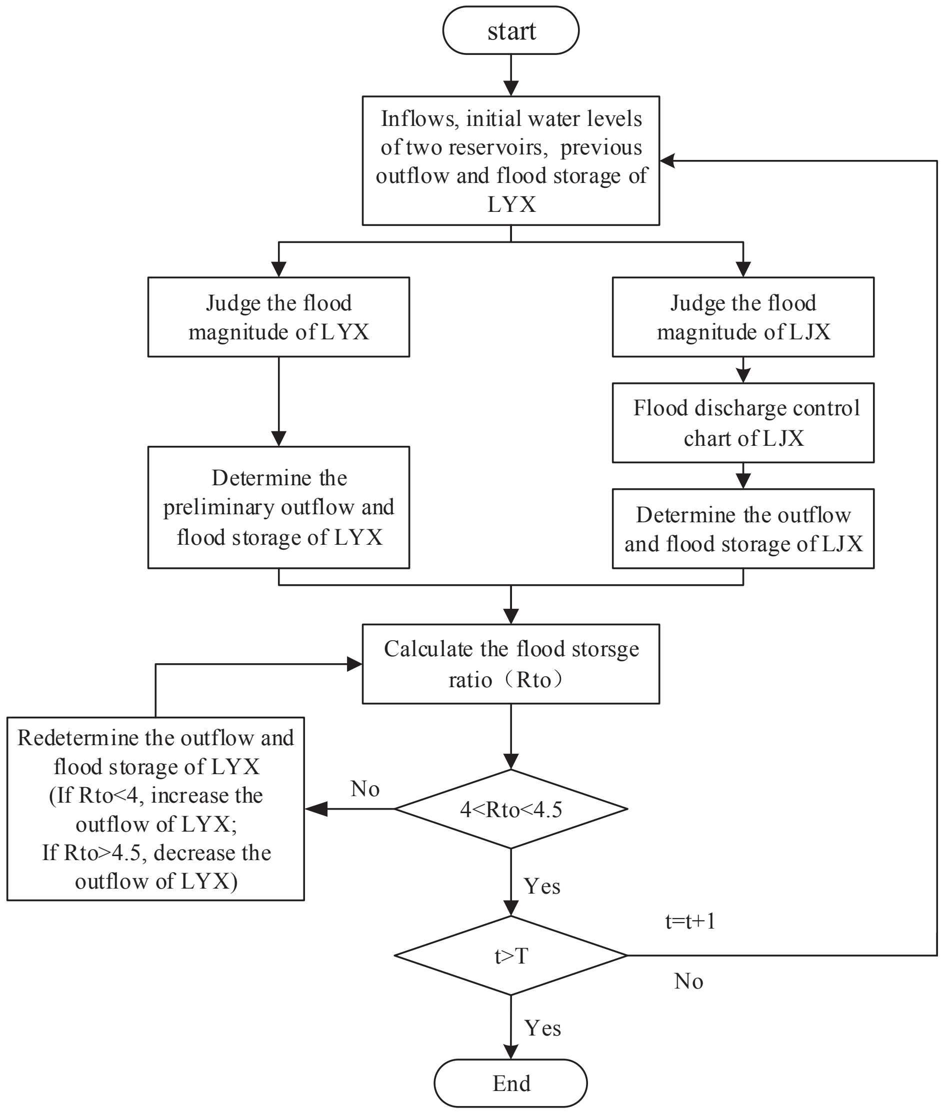

Fig. 5. Sketch of flood control operation of LYX and LJX.

designed value. However, the inflow does not reach to the designed value. Therefore, the flood frequency is unchanged and the reservoir has no need to increase outflow. In contrast, for LYX, the design flood peak flow is the only judgment index employed. In other words, if $Q_{in}(1, t) < 4200$ (inflow of LYX, m^3/s), the maximum allowable discharge is $2000\, m^3/s$. If $4200 \leqslant Q_{in}(1, t) < 7040$, the maximum allowable discharge is $4000\, m^3/s$. If $Q_{in}(1, t) \geqslant 7040$, the maximum allowable discharge is $6000\, m^3/s$.

More importantly, the flood control operation rules of the two reservoirs are also different. Specially, LJX uses the single reservoir flood control rules, as shown in formula (1). Note that the water level is replaced with water storage, and the water storage is the total flood storage of LYX and LJX. In contrast, LYX uses compensation scheduling rules by controlling the flood storage ratio of LYX and LJX. Note that its outflow also satisfies the maximum allowable discharge constraint. This joint operation mode can well realize the flow compensation and water volume compensation, especially the latter, between the two reservoirs. All the joint operation rules are summarized as follows:

(1) LYX and LJX should store the flood water according to the ratio of (4.0–4.5) to 1.0.
(2) The discharge flow of LYX and LJX must not be greater than the maximum permissible discharge of the corresponding frequency flood in all periods and must not be greater than the average daily inflow in rising limb.
(3) The water level of LYX and LJX must be below the corresponding design water level.
(4) The outflow varies within the range of $1000\, m^3/s$.

Furthermore, a joint reservoir flood control operation simulation model was built based on the flood discharge control chart and operation rules. The sketch is shown in Fig. 5. In practice, the interval is one day, and the travel time from LYX to LJX is approximately one day. Hence, the total flood storage at period t is the sum of the flood storage of LYX at period t - 1 and flood storage of LJX at period t in this model. Moreover, the actual inflow of LJX is equal to the outflow of LYX plus the intervening area flow. It is noted that the flood storage ratio of LYX to LJX is used to solve the regional flood composition problem for simplified calculation. For the real-time flood control of cascade reservoirs, a simulation model with simulation rules can ensure the maneuverability of flood control schemes.

3.3. Flood risk assessment

In this paper, entropy-weighted fuzzy comprehensive evaluation was applied to assess the flood operation risk. First, three applicable

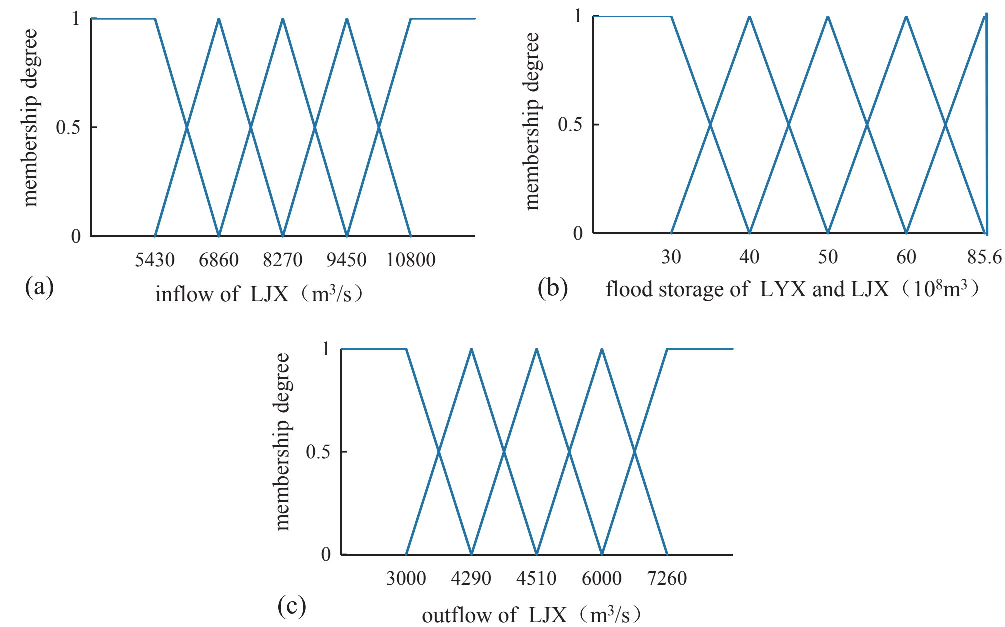

Fig. 6. Membership functions of inflow (a), flood storage (b) and outflow (c).

Table 2
Primary statistical parameters of the two scenarios.

Flood frequency (%)	Scenario	Maximum water level (m)		Final water level (m)		Maximum outflow (m^3/s)		Highest risk level	Time in the highest risk level (day)
		LYX	LJX	LYX	LJX	LYX	LJX		
0.1	1	2599.95	1735.29	2597.06	1732.61	4000	4510	3	22
	2	2600.10	1735.77	2598.81	1727.69	4000	4510	3	23
0.01	1	2599.45	1735.31	2592.65	1727.93	6000	7260	4	6
	2	2600.50	1734.98	2593.85	1727.87	6000	7539	4	9
PMF	1	2603.13	1736.24	2598.45	1730.26	6000	7767	5	5
	2	2604.67	1735.99	2600.63	1729.03	6000	7679	5	5

evaluation factors that are closely related to reservoir flood control were selected. One is the natural inflow of LJX (natural inflow of LYX plus the intervening area flow), which reflects the flood magnitude of the region. The second is the total flood storage of LYX and LJX, which represents the utilization of flood control storage capacity of cascade reservoirs. In addition, the last is the outflow of LJX, which signifies the security threat to the downstream. Thus, the flood operation risk is identified as the comprehensive risk that involves the flood situation, reservoir safety and protected object security. Next, we use five levels (1, 2, 3, 4, 5) to evaluate the risk degree of each factor. Moreover, the higher the level, the greater the risk. Specifically, for the first and last indicator, the design flood peak flow and maximum allowable outflow of different frequencies are adopted to grade, respectively. In addition, considering the large difference between 4510 m^3/s and 7260 m^3/s, an outflow of 6000 m^3/s is added in grading. For the second factor, based on the maximum flood storage of different frequency floods, the total reservoir capacity for flood control of LYX and LJX is graded. Next, we apply triangular and trapezoidal distributions to build membership functions of the three indicators. The membership degree of each factor to the levels is determined by the membership functions. The membership functions with the range of [0, 1] established in this paper are shown in Fig. 6.

In this way, the fuzzy evaluation matrix is developed. Thus, the comprehensive weights of these factors are calculated with the entropy weight method using formula (7). Note that a given subjective weight set is needed to perform this task. In this paper, we presume that w_{s1}, the subjective weight of inflow, is 0.3. For the subjective weight of flood storage, we first calculate p, the proportion of flood storage to total flood control capacity, and then calculate the weight with $w_{s2} = (1 - w_{s1}) \times p$. Thus the subjective weight of outflow can be expressed with $w_{s3} = 1 - w_{s1} - w_{s2}$. In this way, the subjective weight varies with time. If the total flood storage is large, its subjective weight is heavy, while the subjective weight of outflow is small. In other words, the dam safety is a priority when suffering large flood. After getting the weight set, the flood operation risk can be calculated by formulas (4) and (5).

3.4. Outflow adjustment optimization

Given that the outflow of LJX is determined first in the flood control operation module. Next, the outflow of LYX is calculated based the flood storage ratio of the two reservoirs (shown in Fig. 5). Therefore, increasing the outflow of LJX and adjusting the flood storage of LYX based on risk level are regarded as easily implemented response strategies, which can also be called feedback operation. The specific procedures are as follows:

(1) Pre-estimate the future flood magnitude and the future maximum allowable discharge of LJX according to the future inflow for the next three days and the discharge control chart of LJX.
(2) Determine the updated outflow of LJX at current period according to the original outflow of LJX (obtained by sub-module 1) and the value of outflow adjustment (the decision variables of the optimization module). Note that the updated outflow of LJX is the sum of

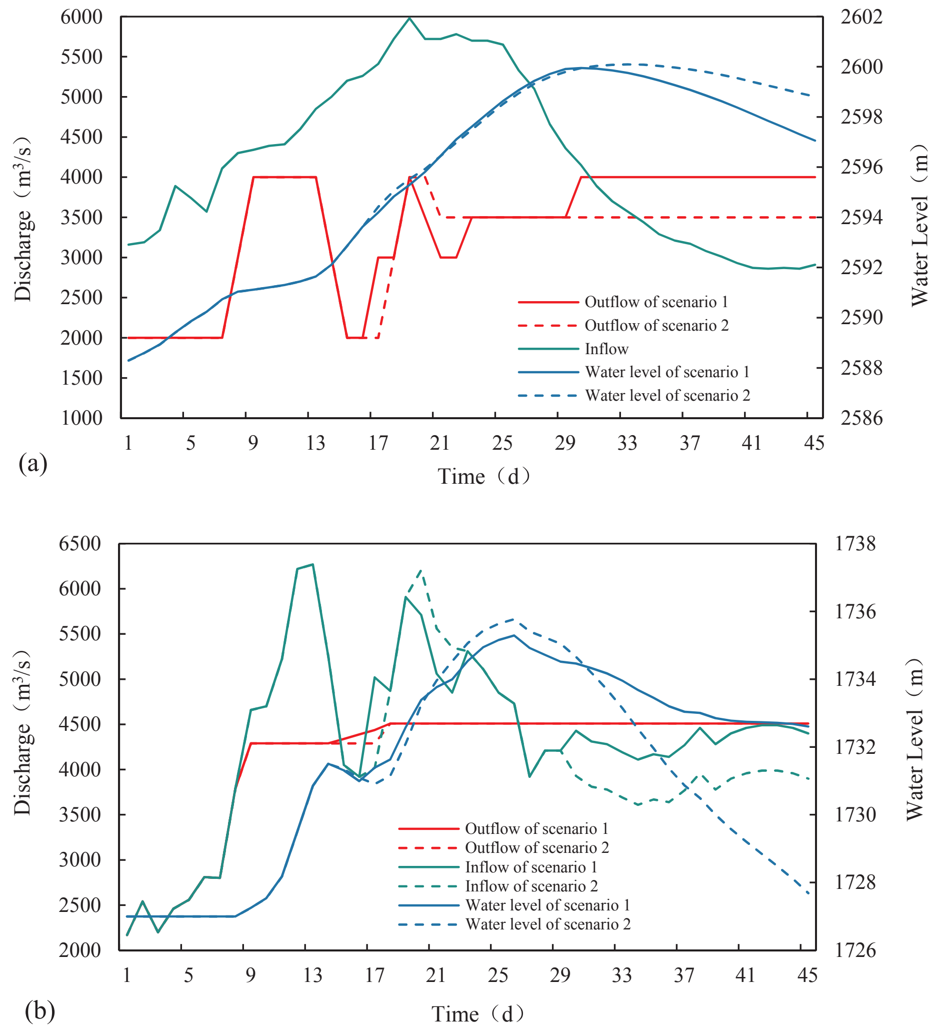

Fig.7. Operation results of LYX (a) and LJX (b) for the flood with 0.1% frequency.

the original outflow of LJX and the value of outflow adjustment, and the future maximum allowable discharge of LJX is the constraint condition of current updated outflow.

(3) Calculate the updated outflow of LYX at current period according to the original outflow of LYX (obtained by sub-module 1) and the flood storage ratio of the two reservoirs. In other words, if the flood storage ratio is larger than 4.5, increase the outflow of LYX. Conversely, if the flood storage ratio is small than 4.0, decrease the outflow of LYX.

In particular, for LJX, different warning signals represent different outflow increments. Except for level 1, the other four levels signify updated reservoir releases. Moreover, the higher the level, the greater the outflow increment. For LYX, its outflow changes with the flood storage based on the flood storage ratio. It can be observed that the feedback operation is equal to pre-discharge approach, thereby decreasing the flood risk. Note that future inflow and scheduling results based on the joint reservoir operation model are needed in this process. In this paper, the future inflow is derived from the design floods rather than forecast model because this paper focuses on flood control operation.

4. Results and discussion

Based on this model, the design floods were used as inputs to obtain flood control results. Next, we selected the optimal solution to analyze the reasonability of the model (scenario 1). In addition, these data were also used to enable a two-scenario analysis based only on the first and second modules without outflow adjustment optimization (scenario 2). The comparison results are shown in Table 2 and Figs. 7–9.

It is seen from Table 2 that for the flood with 0.1% frequency, the days with the highest risk level in scenario 1 decrease by one day without increasing the maximum water level and maximum outflow of LYX and LJX compared with scenario 2. The maximum water level of LYX and LJX in scenario 1 are even lower than those in scenario 2. However, the final water level of LJX in scenario 1 are even higher than that in scenario 2. From Fig. 7, it can be seen that the outflow of LYX in scenario 1 is larger than that in scenario 2 (not exceeding the maximum outflow 4000 m^3/s) at period 17 and period 30–45, indicating that LYX pre-releases flood water in rising limb and releases more flood water in falling limb in scenario 1. Unlike LYX, LJX pre-releases some flood water only in rising limb in scenario 1, and the outflow stays at 4510 m^3/s to the end due to the operation rules. Therefore, the maximum water level and final water level of LYX in scenario 1 are lower compared with scenario 2, while the final water level of LJX in scenario 1 becomes higher. Namely, LJX stores more flood water in falling limb compared with scenario 2. The primary reason for this phenomenon is the flood storage ratio of the two reservoirs. In response measures, LYX needs to adjust its outflow again based on the ratio in scenario 1, and the real ratio is too large from period 30 to 45 in scenario 2. Therefore, LYX discharges more water to increase the ratio at these times, while LJX undertakes more flood storage risk to alleviate the LYX and

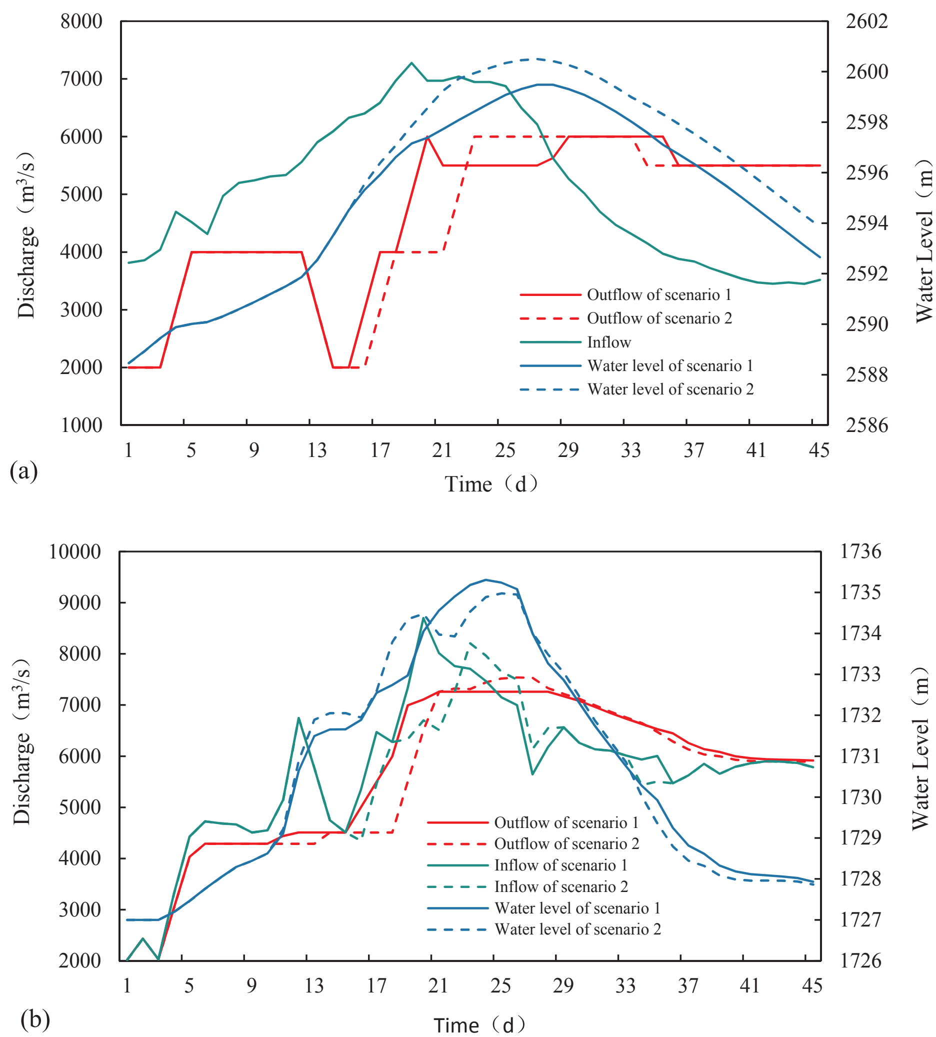

Fig. 8. Operation results of LYX (a) and LJX (b) for the flood with 0.01% frequency.

downstream risks in falling limb in scenario 1. Note that the maximum and final total flood storage volume of LYX and LJX in scenario 1 are smaller than those in scenario 2. This operation mode does not increase the maximum risk but keeps the total risk of the water system the lowest, because risk does not go away. The key of risk response is risk transfer and sharing. The purpose of risk transfer is to reduce global risk through various measures, which means minimize the flood losses with minimum cost. In this flood, the cost is extending the time of reservoir flood control operation.

It can be seen from Table 2 and Fig. 8 that for the flood with 0.01% frequency, the days with the highest risk level in scenario 1 decrease by three days without increasing the maximum water level of LYX, the maximum outflow of LYX and LJX compared with scenario 2. The maximum outflow of LJX even decreases to 7260 m^3/s in scenario 1, which is the maximum allowable discharge of flood with 0.05% frequency, thereby lowering the risk of downstream. However, both the maximum water level and final water level of LJX increase slightly in scenario 1. In terms of flood regulating processes of reservoirs, both LYX and LJX pre-release some flood water in rising limb in scenario 1. Note that the maximum and final total flood storage volume of LYX and LJX in scenario 1 are still smaller than those in scenario 2. In short, the results show that the model proposed in scenario 1 can reduce the flood control operation risk compared with scenario 2.

The Table 2 and Fig. 9 show that, unlike the previous two floods, there is no change of the days with the highest risk level between the two scenarios, but the flood release of LYX and LJX have varied. Similarly, LYX and LJX pre-release some flood water in rising limb in scenario 1. The maximum water level, final water level and maximum outflow of LYX in scenario 1 do not exceed those in scenario 2 and are even less than them. Nevertheless, all of the three statistical parameters mentioned above for LJX in scenario 1 are larger than those in scenario 2. Note that the maximum and final total flood storage volume of LYX and LJX in scenario 1 are still smaller than those in scenario 2. Moreover, the real flood storage ratios of the two reservoirs in falling limbs in scenario 1 decrease compared with scenario 2, which is still larger than 4.5. In other words, a part of risk shifts from LYX to LJX and downstream in scenario 1, thereby making the risk share more balanced compared with scenario 2.

The change rules of the comprehensive risk level are shown in Fig. 10. This figure shows that the highest risk level varies from 3 to 5 with the decrease of the flood frequency, indicating that the greater the flood is, the higher the risk degree is. Furthermore, the days with the highest risk level for the floods with frequency of 0.1% and 0.01% decrease by 1 and 3 days, respectively. This result shows that the model proposed in scenario 1 can reduce the flood risk compared with scenario 2. In addition, the risk level changes from the fluctuation of the flood. Specifically, for the flood with 0.1% frequency, the risk level increases from 1 to 3 at first and later decreases to 2. Likewise, for the flood with 0.01% frequency, it increases from 1 to 4 at first and ultimately decreases to 1. For the PMF, it rises from 1 to 4 at first and falls to 2 and 3 at last in scenario 1 and scenario 2, respectively. Moreover, even though the highest risk level and its duration do not change

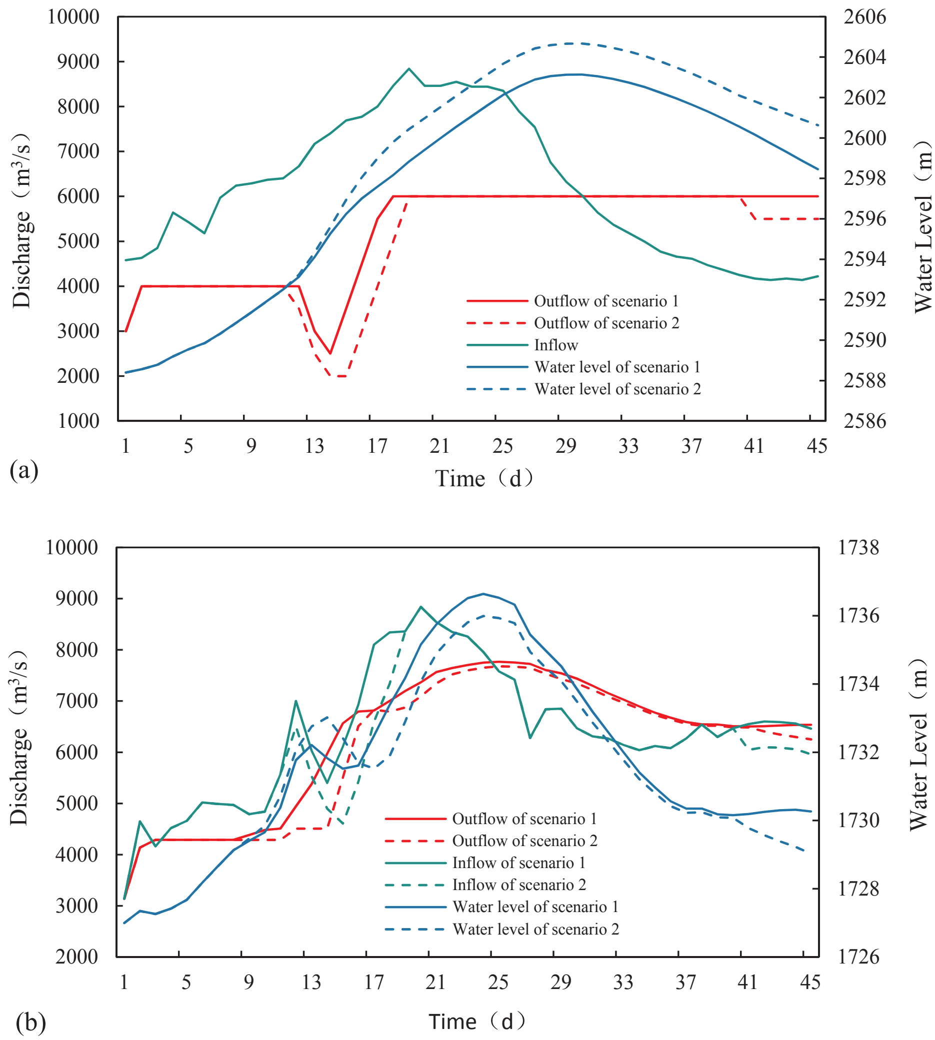

Fig. 9. Operation results of LYX (a) and LJX (b) for the probable maximum flood (PMF).

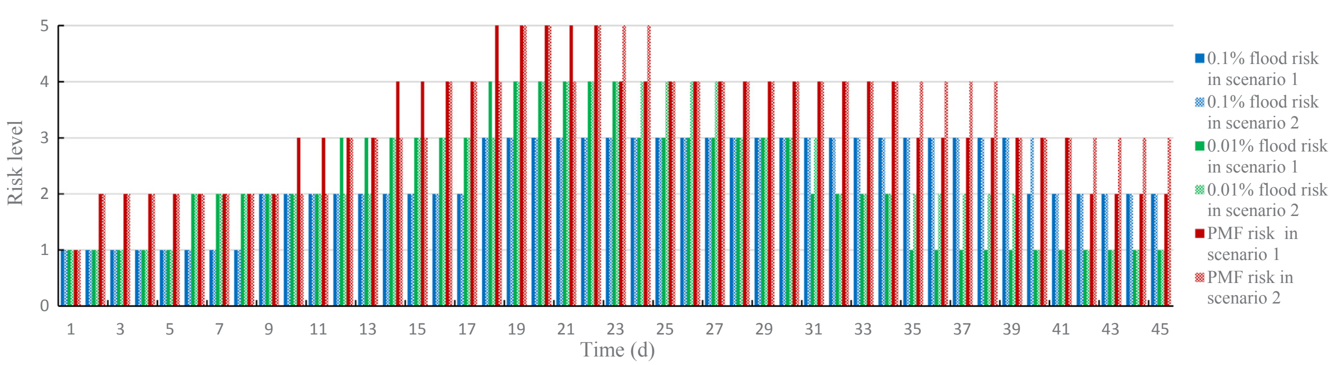

Fig. 10. Comprehensive risk level of different floods.

between the two scenarios, the days with the second highest risk level decrease by 2 days in scenario 1 compared with scenario 2. In conclusion, the results can verify the rationality and superiority of the model proposed in scenario 1.

Finally, we select the second flood to analyze the risk level change of each factor (shown in Fig. 11 and Table 3). It should be noted that the inflow risks in scenario 1 and in scenario 2 are the same because the input is the design flood. It can be seen from Fig. 11 and Table 3 that the inflow risk level varies from 1 to 4 and drops to 1 at the end. Similarly, the outflow risk level rises from 1 to 5 but eventually drops only to 4 in scenario 1 and in scenario 2. The reason is that the final water level of the reservoir still exceeds the flood limited water level, indicating that the reservoir must release flood water with a large flow. In addition, the difference between the two scenarios is that the outflow risk level increases earlier in scenario 1 due to the flood pre-discharge dispatching of the reservoir. For the flood storage risk, the highest risk level in scenario 1 is less than that in scenario 2, indicating that the maximum flood storage has decreased compared to scenario 2. We can find that the comprehensive risk level is only 1 in the last several periods, even though the outflow risk is 4, since both the inflow and flood storage

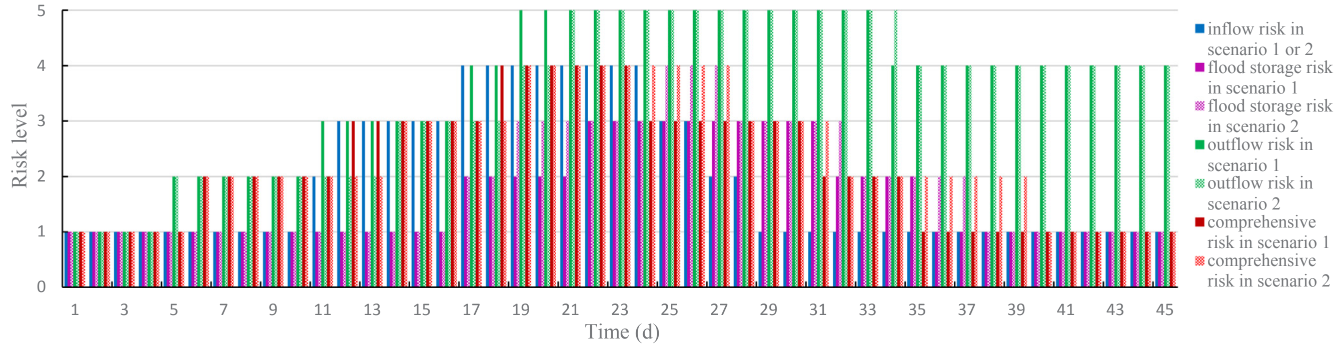

Fig. 11. Risk level of three factors for the flood with 0.01% frequency.

Table 3
Value and risk level of three factors for the flood with 0.01% frequency.

Natural inflow (m^3/s)	Inflow risk	Scenario 1					Scenario 2				
		Flood storage (10^8m^3)	Flood storage risk	Outflow (m^3/s)	Outflow risk	Comprehensive risk	Flood storage (10^8m^3)	Flood storage risk	Outflow (m^3/s)	Outflow risk	Comprehensive risk
3834	1	1.6	1	2021	1	1	1.6	1	2021	1	1
4294	1	3.2	1	2436	1	1	3.2	1	2436	1	1
4072	1	4.9	1	2032	1	1	4.9	1	2032	1	1
5007	1	6.6	1	3032	1	1	6.6	1	3032	1	1
4943	1	7.4	1	4032	2	1	7.4	1	4032	2	1
5038	1	8.1	1	4290	2	2	8.1	1	4290	2	2
5656	1	9.3	1	4290	2	2	9.3	1	4290	2	2
5862	1	10.6	1	4290	2	2	10.6	1	4290	2	2
5751	1	11.9	1	4290	2	2	11.9	1	4290	2	2
5862	1	13.2	1	4290	2	2	13.2	1	4290	2	2
6480	2	15.0	1	4439	3	2	15.1	1	4290	2	2
8304	3	18.3	1	4510	3	3	18.6	1	4290	2	2
8672	3	21.9	1	4510	3	3	22.4	1	4290	2	2
8838	3	25.6	1	4510	3	3	26.1	1	4510	3	3
8838	3	29.3	1	4510	3	3	29.9	1	4510	3	3
8746	3	32.6	1	5004	3	3	33.5	1	4510	3	3
9059	4	35.7	2	5498	4	3	37.4	2	4510	3	3
9243	4	38.5	2	5992	4	4	41.5	2	4510	3	3
9611	4	40.7	2	6992	5	4	45.1	3	5510	4	4
9667	4	42.9	2	7107	5	4	47.8	3	6510	4	4
9483	4	44.9	2	7260	5	4	49.7	3	7260	5	4
9298	4	46.6	3	7260	5	4	51.4	3	7323	5	4
9151	4	48.3	3	7260	5	4	53.0	3	7314	5	4
8912	4	49.7	3	7260	5	3	54.3	3	7444	5	4
8525	3	50.8	3	7260	5	3	55.2	4	7520	5	4
7991	3	51.4	3	7260	5	3	55.5	4	7539	5	4
6354	2	50.6	3	7260	5	3	54.5	4	7533	5	4
6179	2	49.7	3	7260	5	3	53.5	3	7331	5	3
5831	1	48.5	3	7171	5	3	52.3	3	7217	5	3
5276	1	47.0	3	7082	5	3	50.7	3	7122	5	3
4832	1	45.1	3	6963	5	2	48.9	3	6997	5	3
4579	1	43.2	2	6842	5	2	46.9	3	6871	5	2
4325	1	41.1	2	6735	5	2	44.8	2	6760	5	2
4088	1	38.9	2	6630	4	2	42.6	2	6651	5	2
3977	1	36.7	2	6529	4	1	40.4	2	6474	4	2
3850	1	34.5	1	6447	4	1	38.3	2	6289	4	2
3961	1	32.5	1	6259	4	1	36.4	2	6131	4	2
4072	1	30.7	1	6137	4	1	34.7	1	6034	4	2
3787	1	28.7	1	6082	4	1	32.8	1	5998	4	2
3834	1	26.8	1	6000	4	1	31.0	1	5932	4	1
3834	1	25.0	1	5960	4	1	29.2	1	5906	4	1
3850	1	23.2	1	5941	4	1	27.5	1	5897	4	1
3866	1	21.4	1	5933	4	1	25.7	1	5898	4	1
3818	1	19.6	1	5926	4	1	23.9	1	5897	4	1
3803	1	17.8	1	5915	4	1	22.1	1	5892	4	1

risks are small.

5. Conclusions

Given the limitations of multi-hierarchical simulation model for real-time flood control operation and the idea of flood risk management, this paper is aiming to improve the flood control operation for cascade reservoirs by minimizing flood risk. Therefore, a framework of reservoir flood control operation for cascade reservoirs coupled with risk assessment and the corresponding RFCORA model that contains three sub-modules are proposed. Further, the methodology regarding the determination of the flood risk level and reservoir release to mitigate flood risk is presented. The Upper Yellow River with multiple reservoirs and multiple protection objects was selected as a case study. Another model without outflow adjustment optimization is set to be a comparative experiment. The results show that the framework and RFCORA model developed in this paper can reduce the flood risk of a water system with cascade reservoirs. The methodology can be adopted in the real-time operation of a flood control system by integrating the flood forecast.

However, further research is needed to improve the flood risk management of water systems. As the influence factors play a highly important role in the risk estimation, other factors associated with flood management can further enhance the comprehensiveness to assess the flood risk. Moreover, because reliable flood forecasting information is needed as input, adding a flood forecast sub-module can make the model more complete. In addition, multiple floods through Monte-Carlo simulation experiment can be used to make new flood control operation rules. Though certain restrictions exist in this study, it provides an alternative way of flood risk reduction, which is of significance for decision makers to improve the flood control operation by identifying the flood risk degree and implementing response strategies in the reservoir flood control operation.

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