Research On The Risk And Benefit Cooperative Decision of Reservoir Flood Limited Water Level

Xiaoying Li
Hohai University
Yan Zhang (744631343@qq.com)
Hohai University https://orcid.org/0000-0001-6397-2200
Zechun Tong
Hohai University
Guo-Yue Niu
The University of Arizona

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Research On The Risk And Benefit Cooperative Decision Of Reservoir Flood Limited Water Level

Xiaoying Li[a], Yan Zhang [a,*], Zechun Tong[a] ,Guo-Yue Niu[b]

[a] College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China.

[b] Department of hydrology and atmospheric sciences, the University of Arizona, Tucson, Arizona, USA

***Corresponding author**

Yan Zhang, Master degree candidate.

College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, 210098, China.

ORCID number: https://orcid.org/0000-0001-6397-2200

E-mail address: 191302030016@hhu.edu.cn

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Abstract: The inconsistency between water consumption and the annual rainfall distribution makes it important to make full use of the flood water resource. The adjustment of the flood limited water level (FLWL) is an effective way to improve the flood water utilization, where the staged control of the FLWL plays an important role. Flood season segmentation is the basis for determining the FLWL and tapping the utilization potential of flood resources. The circular distribution method is used to segment, and the relative frequency method is used to verify. Maintaining the balance between benefit and flood control safety is the key work for the FLWL decision. The performances of water supply and hydropower generation are selected to be benefit index, and the extreme risk rate is risk index. Based on the game theory, the multi-objective cooperative decision-making model is established. Nash negotiation solution of staged FLWL is obtained by Nash negotiation theorem. The optimal scheme is determined according to the fuzzy pattern recognition theory. A reservoir is taken as an example, firstly, considering that the risk and benefit are equally valued, the FLWL of the optimal scheme in the pre-flood season is 129.0m, and the post-flood season is 128.5m. By adjusting the preference value for risk and benefit, the optimal FLWL scheme under different preferences for risk and benefit in each stage is determined.

Keywords: flood season segmentation; extreme risk rate; multi-objective cooperative decision; Nash negotiation; adjustment of flood limited water level

1 Introduction

Reservoir is significant for comprehensive development and management of water resources. It plays an important role in meeting social water demand (Chen et al., 2013; Jiang et al., 2015; Zhou et al., 2014). Reservoir operation is an effective measure to realize the optimal allocation of water resources. Rainfall in China is unevenly distributed throughout the year, and most of the annual runoff is concentrated in the flood season. The control of flood limited water level (FLWL) is a significantly resultful method of reservoir operation. (Li et al., 2010; Liu et al., 2015). Flood season segmentation is a fundamental prerequisite for adjusting the FLWL and tapping the utilization potential of flood resources. It is an important subject to alleviate the contradiction between flood control and utilization benefit.

The study of flood season segmentation (Chen et al., 2015; Jiang et al., 2019) has gone through a process of in-depth research from qualitative to quantitative, from single index to multiple indexes. Advances primarily involve the techniques of mathematical statistics method, genesis analysis method, fuzzy clustering method, fractal theory, relative frequency and directional statistics method, and so on. The mathematical statistics and genesis analysis methods (Black A and Werritty, 1997; Singh et al., 2005) needed a large number of flow data and hydrometeorological analysis. They had high requirements for data and can be time-consuming. Besides, the results involved subjectivity in deciding the segmentation. The fuzzy clustering method (Ju et al., 2020) made use of soft decisions through the use of membership functions, It determined the staging results according to the selected threshold value, which is subjective. The results of fractal theory (Qian et al., 2018) were relatively objective, but the workload of analysis and calculation was heavy. The directional statistics method (Cunderlik et al., 2004a; Cunderlik et al., 2004b) convert the occurrence time of each sample into radians and draw the vector statistical graph to determine the segmentation. It only considered the occurrence time of flood, and its results are mainly judged visually according to the distribution density of data points in the vector graph, which is subjective. The circular distribution method (Fang, et al., 2007) had the characteristics of simple and convenient calculation and flexible analysis. It comprehensively considered the concentration degree and concentration period of flood occurrence. It also takes the flood magnitude into account. To a certain extent, the circular distribution method reduced the influence of subjectivity. Based on the analysis of the daily discharge data in 62 years, the circular distribution method will be implemented to segment the flood season in this study, and the relative frequency method will be used to verify.

For the control of FLWL of a single reservoir, on the premise of meeting the downstream flood control safety, the utilization of flood resources will be improved by the adjustment of the FLWL (Huang et al., 2017). The benefits of hydropower generation and water supply can be added. However, adjusting the FLWL will not only improve the utilization efficiency, but also increase the flood control risk (Zhou et al., 2015). There have been many studies on how to realize the effective control of the FLWL. The staged control of FLWL is proved to be a more helpful measure. The widely used methods (Jiang et al., 2015a) mainly include fuzzy set analysis method (Yun et al., 2008) and multi-objective optimization method (Chen et al., 2020; Ma et al., 2020; Xie et al., 2018; Ouyang et al., 2015), etc. Zhou et al. (2009) taking Biliuhe reservoir as an example, for the purpose of determining the FLWL in the post-flood season, they divided the general objectives of FLWL control into flood control and benefit. They established an index set, considered each index layer by layer, and analyzed it by using multi-layer and multi-objective fuzzy optimization theory. Finally, the optimal membership degree of each FLWL scheme was obtained. Liu et al. (2019) considered the comprehensive needs of flood control and hydropower generation. Based on dynamic control method, a multi-objective optimal operation model for dynamic control of FLWL of cascade reservoirs was constructed. Researchers have made extraordinary achievements in producing suitable operating methods, whereas most of the existing studies do not consider the FLWL of each stage in the flood season separately. Generally speaking, in order to ensure the flood control safety in the pre-flood season, the decision-makers often prefer risk, while in the post-flood season, in order to ensure the benefit, the decision-makers often prefer benefit. Therefore, the FLWL in different stages should be considered severally. The preference is adjusted to coordinate the relationship between benefit and risk.

After staging the flood season, this paper has established the benefit index set and risk index set of FLWL control based on game theory. A multi-objective cooperative decision-making model of risk and benefit is set up. Taking a reservoir as an example, according to the flood control task and design flood hydrograph, the FLWL in the main flood season was chosen as the original design. The adjustment mainly focused on the pre-flood season and post-flood season. The extreme risk rate was selected as the risk index. In addition to the increased water supply benefit, the increased hydropower generation benefit was also selected as the benefit index. Using Nash negotiation theory, the nonlinear programming method was used to solve the model. On the basis of fuzzy pattern recognition theory, the membership degree of each scheme was calculated to determine the optimal scheme. Finally, considering the different preferences for risk and benefit in different sub-seasons, taking the current point as the base point of negotiation. The optimal scheme under different preferences was obtained by adjusting the current point.

2. The division of flood season

2.1 Circular distribution method

2.1.1 Concept

Circular distribution method is a statistical method. It transforms the periodic data into linear through trigonometric function transformation. The circular distribution method regards the flood events as a vector, and then calculates the vector eigenvalues to determine the flood season segmentation (Chen et al., 2010).

2.1.2 Computing method

Suppose that the length of the calculation period is T. Meanwhile, the occurrence time of the flood peak of the i-th flood sample is D_i, and the magnitude is q_i. The equations of the coordinate value (x_i, y_i) of flood occurrence time without considering and considering the flood magnitude are as follows:

$$\left(x_i, y_i\right)=\begin{cases}\left(\cos\alpha_i, \sin\alpha_i\right) & \textit{without considering the magnitude of flood} \\ \left(q_i\cos\alpha_i, q_i\sin\alpha_i\right) & \textit{considering the magnitude of flood}\end{cases} \tag{1}$$

$$\left(\bar{x}, \bar{y}\right)=\left(\sum_{i=1}^{N} x_i / N, \sum_{i=1}^{N} y_i / N\right) \tag{2}$$

Where N is the sample size, and $\alpha_i = D_i\frac{2\pi}{T}$ is the occurrence time of the i-th flood.

The concentration period $\bar{\alpha}$ and concentration r are respectively：

$$\bar{\alpha}=\begin{cases}\arctan \bar{y}/\bar{x} & \bar{x}>0, \bar{y}>0 \\ 2\pi+\arctan \bar{y}/\bar{x} & \bar{x}>0, \bar{y}<0 \\ \pi+\arctan \bar{y}/\bar{x} & \bar{x}<0 \\ \pi/2 & \bar{x}=0, \bar{y}>0 \\ 3\pi/2 & \bar{x}=0, \bar{y}<0 \\ \text{不定} & \bar{x}=0, \bar{y}=0\end{cases} \tag{3}$$

$$\mathrm{r}=\begin{cases}\sqrt{\bar{x}^2+\bar{y}^2} & \textit{without considering the magnitude of flood} \\ \sqrt{\bar{x}^2+\bar{y}^2}\Big/\bar{q} & \textit{considering the magnitude of flood}\end{cases} \tag{4}$$

Where $\bar{q}$ is the mean flow value of N samples, and the concentration day corresponding to concentration period $\bar{\alpha}$ is $D_i = \bar{\alpha}\frac{T}{2\pi}$.

Concentration r is a statistical indictor. It describes the central tendency of α_i in the circular distribution, $0 \le r \le 1$. The closer r is to 0, the more uniform the distribution of flood occurrence time is. When r is closer to 1, it means that the flood occurrence time is more concentrated in a certain area. s is the standard deviation of α_i. The relationship between r and s is as follows:

$$s = \sqrt{-2\ln r} \tag{5}$$

Where s is an index indicating the discrete trend of the flood occurrence time. Then the starting and ending dates D_1 and D_2 of the main flood season in the calculation period are respectively:

$$D_1 = \frac{\bar{\alpha} - s}{2\pi}T \tag{6}$$

$$D_2 = \frac{\bar{\alpha} + s}{2\pi}T \tag{7}$$

2.2 Relative frequency method

The entire flood season is divided into k periods, and the amount of the maximum flood in each period is counted. The equation for the relative frequency of each period is:

$$RF_k = \frac{b_k}{n} \tag{8}$$

Where RF_k is the relative frequency of the k-th period. b_k is the number of annual maximum floods in the k-th period, and n is the number of years of flow data.

If the unit is ten days, since the length of each period is different, in order to make each period have the same length, it needs to be adjusted by multiplying the time coefficient. For the last ten-day of the big moon, the ten-day frequency should be multiplied by 10/11, and for the last ten-day frequency of February, it should be multiplied by the coefficient 10/8 (leap year multiplied by 10/9). When the algebraic sum s of the initial frequency RF_k is not equal to the total of the adjusted RF_k' s', generally each RF_k' is multiplied by the coefficient s/s', that is, the adjusted relative frequency is:

$$RF_k' = RF_k \cdot \frac{s}{s'} \tag{9}$$

3. Analysis on Risk and Benefit

The flood season staged operation is to adopt different FLWL control schemes. A higher FLWL will bring more benefits, but it will often increase the flood control risk (Apel et al., 2004; Wu et al., 2011; Zhou et al., 2014). On the contrary, a lower FLWL will improve the safety, but it will also result in less utilization benefits. How to raise the FLWL and improve the utilization benefits, and meanwhile ensure the safety of the water conservancy project itself and control flood for the downstream, the most important thing is to conduct a cooperative decision-making analysis on the risk and benefit.

3.1. Risk Analysis

During the operation, the events will be happened that are not conducive to the dam safety, threaten the flood control safety of downstream and affect the benefit of reservoir. The occurrence probability and loss of these events is called flood control risk. The flood control risk rate in the extreme state is referred to as the extreme risk rate. With the FLWL Z_0 as the initial water level, the design flood hydrograph of each frequency is calculated for flood routing. Suppose that Z_m is the highest water level of flood routing for the design flood hydrograph of a certain frequency. When Z_m is exactly equal to a selected safe level, the frequency is the extreme risk rate $P_{\lim}$. The selected safe level takes the design flood level Z_d. The extreme risk rate can be expressed by the following equation:

$$P_{\lim} = P\left\{Z_m \geq Z_d\right\} \tag{10}$$

The procedure for calculating the extreme risk rate is as follows, first select the typical flood hydrograph, and then obtain the design flood hydrograph of different frequencies P_l (l=1, 2, …, k) by zooming in on the typical flood hydrograph. Started to regulate from different FLWL Z_i(i=1, 2, …, m, …, n), the highest water level Z_{ml} of each frequency is obtained. Finally, plot the different frequencies P_l against the highest water level Z_{ml}, that is, n different water levels can draw n empirical frequency curves. According to this empirical frequency curve family, the extreme risk rate of a certain FLWL can be found out.

3.2 Benefit Analysis

Under the premise of ensuring the flood control safety, the FLWL can be raised as much as possible. It can increase the water head of hydropower generation and water storage. Therefore, the utilization benefit of hydropower generation and water supply are improved accordingly.

3.2.1 Water Supply Benefit

Rainfall is mainly concentrated in the flood season. As the FLWL raises, the added water supply capacity mainly comes from the increased storage of abandoned water. In the dry years, there is no water to store after the flood season, the benefits of FLWL adjustment can be clearly reflected. On the contrary, in the wet years, the reservoir can be reserved to the normal water level even if the FLWL is not raised. Raising the FLWL at this time will only bring about the hydropower generation benefit caused by the increased water head, and will not improve the water supply benefit. Therefore, the multi-year average water supply that can be increased by raising the FLWL should be deducted from wet years. In wet years, regardless of the elevation of the FLWL, the water storage task can also be completed. The added water supply volume can be obtained as:

$$\Delta V_2 = \Delta V_1 \times (1-\lambda) \tag{11}$$

Where ΔV_2 is the increased water supply storage. ΔV_1 is the increased water storage capacity. According to the curve between water level and capacity, the increased water storage under different FLWL can be obtained. λ is the proportion of wet years that can also complete the water storage task with no raising the FLWL.

The increased water supply benefit brought about by the adjustment of the FLWL is:

$$B_{\Delta} = \Delta V_2 \times \delta \tag{12}$$

Where B_{Δ} is the increased water supply benefit. δ is the water supply benefit of one cubic meter of water.

3.2.2 Hydropower generation Benefit

The improvement of hydropower generation benefit is caused by added water capacity and increased water head. The benefit brought by the increased water capacity is obtained by counting the total hydropower generation water consumption and total hydropower generation of the hydropower station in recent years. The average annual hydropower generation water consumption and annual average hydropower generation are calculated, so as to obtain the average water consumption rate of per unit electric energy. The additional electricity generated by the increased water capacity is expressed as:

$$E_1 = \Delta V_2 / \varphi \tag{13}$$

Where E_1 is the additional electricity generated by the increased water volume. ΔV_2 is the added water supply capacity, and φ is the average water consumption rate of per unit electricity.

The benefit generated by increased water head is expressed by the following equation:

$$E_2 = 9.81 \cdot \eta \cdot Q_T \cdot \Delta H \cdot \Delta T \tag{14}$$

Where E_2 is the additional electricity generated by increased water head. η is the efficiency of the hydropower station, $\eta \in (0,1)$. Q_T is the maximum hydropower generation flow. ΔH is the increased height of water head caused by the adjustment of the FLWL, and ΔT is the calculation time length, here refers to the time length for benefit analysis.

4 Construction of multi-objective cooperative decision-making model

4.1 Establishment of multi-objective cooperative decision-making model

In the comprehensive utilization of reservoirs, flood season operation mainly focuses on flood control operation, and takes into account the water storage to some extent. It is a typical multi-objective decision-making problem. Assuming that the decision-making system has n alternative schemes to choose from, the pros and cons of n schemes are judged according to the characteristic values of m indexes. Then the eigenvalue matrix of m indexes of each scheme is:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} = \left\{ x_{ij} \right\} \tag{15}$$

Where x_{ij} is the eigenvalue of the j-th index of the i-th scheme, $1 \le i \le n$ and $1 \le j \le m$.

In the actual decision-making, indexes can be divided into three categories: one is benefit index, that is, the larger the index value, the better. The second is the risk index, that is, the smaller, the better. The third type is the intermediate index. Its membership function generally increases first and then decreases, and it reaches the maximum in the middle part or at a certain point. Due to the different measurement units among indexes, it is impossible to realize union calculation. Various measurement units must be unified quantization, that is, the data of each index must be normalized.

For the benefit index, the equation of the relative membership degree of the evaluation index is (Fang et al., 2019):

$$r_{ij\max} = \frac{x_{ij} - x_{i\min}}{x_{i\max} - x_{i\min}} \tag{16}$$

For the risk index, the equation is:

$$r_{ij\min} = \frac{x_{i\max} - x_{ij}}{x_{i\max} - x_{i\min}} \tag{17}$$

For the intermediate index, the equation is

$$r_{ijmid} = \begin{cases} 1 - \dfrac{x_i' - x_{ij}}{x_i^*} & x_{ij} < x_i' \\ 1 & x_i' \le x_{ij} \le x_i'' \\ 1 - \dfrac{x_{ij} - x_i''}{x_i^*} & x_{ij} > x_i'' \end{cases} \tag{18}$$

Where $[x_i', x_i'']$ is the best stable interval of x_{ij}.

In equations (14) - (16), $x_{i\max}$ and $x_{i\min}$ are respectively the largest and smallest eigenvalues in the j-th ($1 \le j \le m$) index set.

Based on the above, after quantifying and normalizing the indexes in the eigenvalue matrix X, the relative superior membership degree matrix R is obtained.

$$\mathrm{R} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} = \left\{ r_{ij} \right\} \tag{19}$$

Therefore, in the multi-objective decision-making problem of reservoir operation in flood season, m objectives can be divided into p benefit indexes and (m-p) risk indexes. Then the problem can be described as:

$$\begin{aligned} &\max F\left(u_1(x), u_2(x)\right) \\ &s.t.\quad g_k(x) \ge 0, k = 1, 2, \cdots, T \end{aligned} \tag{20}$$

Where $F(x)$ is the objective function, and T is the number of constraint conditions. The multi-attribute utility function $u_1(x)$, $u_2(x)$ is expressed by the following equations:

$$u_1^j(x) = \omega_1 r_{1j} + \omega_2 r_{2j} + \cdots + \omega_p r_{pj} \tag{21}$$

$$u_2^j\left(x\right)=\omega_{p+1}r_{(p+1)j}+\omega_{p+2}r_{(p+2)j}+\cdots+\omega_m r_{mj} \tag{22}$$

The decision maker obtains the utility winning function by assigning weights to multiple indexes. Based on the above, a multi-objective cooperative decision-making model for reservoir operation in flood season is constructed..

4.2 Solution of multi-objective cooperative decision-making model

When establishing a multi-objective cooperative decision-making model, the problem of cooperative decision-making of two index sets is considered. The two index sets are benefit index set DM_1 and risk index set DM_2. The cooperation of the two sets means negotiation and agreement can be reached. Let N={1,2} be the sequence number of index sets. For any $i\in$N, there are k_i indexes in the i-th decision indexes set.

$$f_i\left(x_1,x_2\right)=\left(f_{i1}\left(x_1,x_2\right),f_{i2}\left(x_1,x_2\right),\cdots,f_{iki}\left(x_1,x_2\right)\right)\in G_i \tag{23}$$

Where $G_i\subset R^{ki}$ is the reachable target set. $x_i\in\Omega_i\subset R^{mi}$ is the decision vector. R^{ki} and R^{ki} are ki-dimensional and mi-dimensional real vector spaces respectively. In the model, the winning function of the index set is represented by the utility function. The multi-attribute utility function of the i-th indicator set is:

$$u_i\left(x_1,x_2\right)=u_i\left(f_i\left(x_1,x_2\right)\right) \tag{24}$$

According to the multi-attribute utility theory, $u_i(f_i(x_1,x_2))$ is a strictly monotonic increasing function of each component in f_i ,that is, $\forall i,j$=1,2,…,ki and $i\neq j$, if $f_i(x_1,x_2)>f_j(x_1,x_2)$, $u_i(f_i(x_1,x_2))>u_i(f_j(x_1,x_2))$.

A pair of utility functions are mapped into a subset E of the two-dimensional Euclidean space R^2, and $E\subset R^2$ represents the joint reachable utility set. The joint reachable utility set of the two index sets is:

$$E=\left\{\left(u_1\left(f_1\right),u_2\left(f_2\right)\right)\in R^2\middle| f_i\left(x_1,x_2\right)\in G_i,x_i\in\Omega_i,i=1,2\right\} \tag{25}$$

If E is a closed bounded convex set, d=(d_1,d_2)$\in E$ is the current point, and it exists $u \in E$，$u > d$. The current point (d_1,d_2) represents the winning function value that can be accepted when the two index sets cannot reach an agreement. The relationship between E and d is called a multi-objective negotiation decision-making problem. If the decision maker assigns $d_1 > d_2$, it means that the index set DM_1 has greater initiative in the process of negotiation, and the final negotiation result will also be biased towards the index set DM_1 and vice versa. Suppose that $h(E,d) \in E$ is the solution of (E,d), let $h^*(E,d)=u^*$, for all $u \in E$，$u > d$ and $u \neq u^*$, there are:

$$\left(u_1^* - d_1\right)\left(u_2^* - d_2\right) > \left(u_1 - d_1\right)\left(u_2 - d_2\right) \tag{26}$$

At this time, $h^*(E,d)=u^*$ becomes the Nash negotiation solution to the multi-objective problem.

If no feasible schemes is exactly the same as the Nash negotiation solution, the fuzzy pattern recognition theory is used to determine the closest, which is the optimal.

5 Application

5.1 Study site

The reservoir is a large size (1) year regulating reservoir with a watershed area of 1400km^2. The main task of the reservoir is flood control, and the comprehensive utilization of water supply and hydropower generation are taken into account. The total storage capacity is 2.632 billion m^3. The flood of 1 in 1 000 year's frequency is the designed flood and the flood of 1 in 10000 year's frequency is the checked flood. The designed flood control level is 139.10m, the corresponding storage capacity is 2.228 billion m^3, and the checked flood control level is 143.60m. The maximum hydropower generation flow of the power station is 200 m^3/s.

The flood season is from May 1st to October 1st, and the designed FLWL is 125.0m. There is 500 million m^3 of flood control capacity above 125.0m that is responsible for downstream flood control and peak reduction tasks. When the reservoir water level exceeds 125.0m, the flood discharge tunnel is used for the hydrologic regime of mainstream of the Huai River. When the reservoir water level exceeds 132.60m, the tunnel is fully opened, with a maximum discharge volume of 618m^3/ s.

5.2 Segmentation of flood season

The restored daily flow during the flood season of years 1956 - 2017 was used as the basic data for calculation. That is, the sample size N=62 years, and the length of the calculation period T=154 days.

5.2.1 Segmentation of flood season by the circular distribution method

The samples were taken according to different time intervals t (t=1, 3, 5, 7, 10, 15) to stage the flood season. Firstly, the maximum discharge q_{Lt} (L = 1, 2,..., n) of t days is selected from the L-th-year daily discharge in the flood season. Then, various indexes of flood situation are calculated by **Eq.**(1) - (7). **Table 1** and **Fig. 1** denote the results of segmentation of different sampling intervals.

Table 1 The result of flood season segmentation by circular distribution method

Sampling intervals t/天	Whether to consider the flood level	r	$\overline{\alpha}$	$\overline{D}$	Pre-flood season	Main flood season	Post-flood season
1	N	0.352	2.580	7/2	5/1-5/17	5/18-8/7	8/8-10/1
	Y	0.392	3.072	7/14	5/1-6/9	6/10-8/17	8/18-10/1
3	N	0.497	2.366	6/27	5/1-5/28	5/29-7/26	7/27-10/1
	Y	0.418	2.838	7/9	5/1-6/9	6/10-8/17	8/18-10/1
5	N	0.230	2.453	6/29	5/1-5/17	5/18-8/10	8/11-10/1
	Y	0.270	3.233	7/18	5/1-6/9	6/10-8/17	8/18-10/1
7	N	0.437	2.038	6/19	5/1-5/17	5/18-7/21	7/22-10/1
	Y	0.349	2.703	7/5	5/1-5/30	5/31-8/10	8/11-10/1
10	N	0.438	1.978	6/17	5/1-5/16	5/17-7/19	7/20-10/1
	Y	0.359	2.553	7/2	5/1-5/26	5/27-8/6	8/7-10/1
15	N	0.539	1.969	6/17	5/1-5/20	5/21-7/15	7/16-10/1
	Y	0.456	2.362	6/27	5/1-5/26	5/27-7/28	7/29-10/1

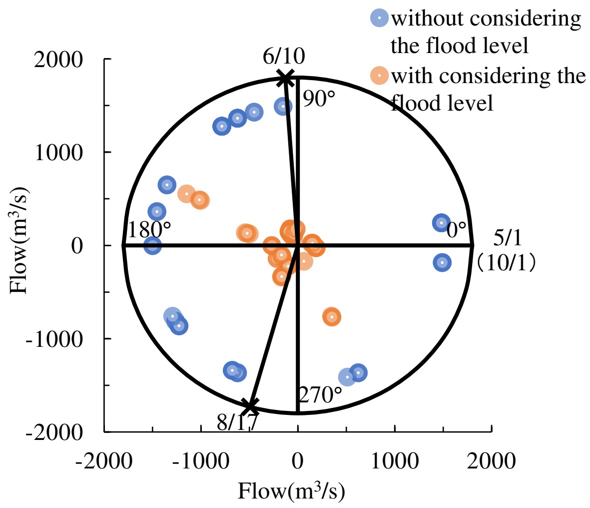


Fig.1 The result of Flood season segmentation by circular distribution method

The segmentation is obtained mainly based on the results of the maximum t-day discharge (t = 1, 3, 5) considering the flood magnitude. **Table 1** indicated that the calculated main flood season is from June 10 to August 17. Therefore, the main flood season of the reservoir can be obtained as June 10 - August 17.

Fig. 1 shows the occurrence time of the maximum discharge which are expressed in angle. The distribution of data points considering and ignoring the magnitude of the flood which are expressed by the coordinate value of the occurrence time multiplied by the magnitude. Obviously, the points considering the magnitude are concentrated in the period from June 10th to August 17th.

Based on the above, combining the actual situation of the reservoir, the segmentation considering the flood magnitude are selected. The main flood season of the reservoir is gained as June 10 - August 17.

5.2.2 Segmentation of flood season by the relative frequency method

Ten days is selected as the unit interval, the whole flood season is divided into 15 periods (October 1 is classified as late September). In each period, the occurrence times of daily maximum discharge over the years 1956-2017 are counted to calculate the relative frequency. The results are shown in the following table.

Table 2 The result of flood season segmentation by relative frequency method

Period		Times	Relative frequency RF_k'
May.	Early ten days	0	0.00%
	Middle ten days	0	0.00%
	Late ten days	0	0.00%
Jun.	Early ten days	7	11.41%
	Middle ten days	11	17.93%
	Late ten days	13	21.19%
Jul.	Early ten days	6	9.78%
	Middle ten days	3	4.89%
	Late ten days	7	10.37%
Aug.	Early ten days	8	13.04%
	Middle ten days	7	11.41%
	Late ten days	0	0.00%
Sept.	Early ten days	0	0.00%
	Middle ten days	0	0.00%
	Late ten days	0	0.00%

It can be seen from the **Table 2** and **Fig. 2** that the relatively high frequency is mainly concentrated in the first ten days of June to the middle of August, which is consistent with the flood season segmentation results gotten by the circular distribution method.

5.3 Analysis of Risk and Benefit

5.3.1 Risk Analysis

Several typical flood hydrographs are selected in the pre-flood season and post-flood season severally, and amplified at the same frequency according to flood peak and flood volume. The flood hydrographs with different design frequencies are deduced. Considering with the flood situation in the reservoir area, the values of frequency P are selected as 0.01%, 0.10%, 0.20%, 1%, 2%, 3.30%, 5%, 10% and 20% respectively. For the selection of the dynamic domain of FLWL, considering that the original FLWL of the reservoir is 125.0 m, and the normal water level is 130.0 m, the

FLWLs start at 125.0 m and increase at a step of 0.5 m to a maximum of 130.0 m. Then, taking Z_i of each scheme as the starting water level, flood regulation is carried out according to the predetermined dispatching rules. The flood hydrograph that is most unfavorable for the reservoir flood control is selected, and the time interval is 3 h. The relationship between the highest flood regulation water level $Z_m(Z_i)$ and the corresponding frequency $P(Z_i)$, i=1，2，…，n is obtained.

According to the design results of the reservoir, in the pre-flood season, the design flood peak is much smaller than that in the main flood season, but the flood volume is large and the peaks are dense. The flood in 1974 with peak discharge of 3938.84 m^3/s is selected as the typical. **Table 3** presents the results of high water level of flood regulating in the pre-flood season.

Table 3 High water level of flood regulating for different frequency flood under each scheme in the pre-flood season

Scheme	FLWL /m	High water level of flood with different frequencies *P*/m								
		0.01%	0.10%	0.20%	1.00%	2.00%	3.30%	5.00%	10.00%	20.00%
1	125.0	138.887	136.918	136.347	135.124	134.616	134.247	133.898	133.941	133.051
2	125.5	139.244	137.292	136.730	135.522	135.026	134.657	134.310	134.355	133.470
3	126.0	139.610	137.671	137.116	135.924	135.427	135.070	134.726	134.772	133.894
4	126.5	139.971	138.047	137.492	136.315	135.830	135.472	135.140	135.179	134.312
5	127.0	140.326	138.420	137.875	136.709	136.230	135.881	135.549	135.588	134.736
6	127.5	140.681	138.796	138.255	137.101	136.627	136.282	135.959	135.999	135.155
7	128.0	140.912	139.178	138.640	137.494	137.029	136.687	136.360	136.403	135.573
8	128.5	141.247	139.552	139.017	137.880	137.414	137.081	136.757	136.800	135.985
9	129.0	141.584	139.932	139.398	138.270	137.810	137.477	137.160	137.201	136.393
10	129.5	141.928	140.305	139.786	138.664	138.211	137.881	137.564	137.604	136.808
11	130.0	142.306	140.689	140.177	139.072	138.619	138.290	137.981	138.019	137.228

In the post-flood season, the design flood is lighter than that in the main flood season. While compared with the pre-flood season, it has high peak, large volume and many fluctuations, which can reach the standard of once-in-a-thousand-year flood. The flood in 2005 with peak discharge of 7942.69 m^3/s is chosen as the typical. **Table 4** shows the results of high water level of flood regulating in the post-flood season.

Table 4 High water level of flood regulating for different frequency flood under each scheme in the post-flood season

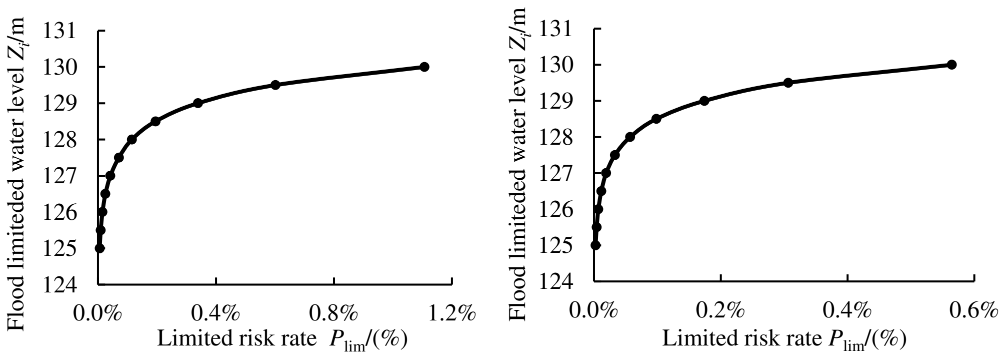
Scheme	FLWL Z_i /m	High water level of flood with different frequencies P/m							
		0.01%	0.10%	0.20%	1.00%	2.00%	3.30%	5.00%	10.00%
1	125.0	138.186	136.426	135.893	134.661	134.182	133.796	133.479	133.030
2	125.5	138.550	136.808	136.279	135.070	134.593	134.209	133.898	133.447
3	126.0	138.915	137.191	136.664	135.473	135.008	134.624	134.315	133.870
4	126.5	139.280	137.569	137.052	135.876	135.410	135.042	134.733	134.292
5	127.0	139.649	137.953	137.437	136.274	135.819	135.450	135.151	134.715
6	127.5	140.018	138.330	137.822	136.669	136.223	135.859	135.561	135.134
7	128.0	140.383	138.714	138.208	137.070	136.627	136.268	135.980	135.553
8	128.5	140.737	139.091	138.585	137.457	137.022	136.666	136.376	135.965
9	129.0	141.094	139.472	138.975	137.854	137.420	137.072	136.783	136.374
10	129.5	141.438	139.860	139.362	138.251	137.822	137.476	137.193	136.788
11	130.0	141.788	140.249	139.762	138.658	138.233	137.891	137.608	137.209

Taking the designed flood control level (139.10m) as the selected safe level, the curve of water level and frequency of each scheme is extended or interpolated. Then, the frequency when the flood regulation high water level starting from each FLWL is exactly equal to the selected safe level is obtained, which is named as extreme risk rate. The results of different schemes and corresponding extreme risk rates are displayed in **Table 5**.

Table 5 Extreme risk rate under different flood limited water levels in the flood season

Scheme	Flood limited water level *Zi/m*	Extreme risk rate P_{lim}（%）	
		Pre-flood season	Post-flood season
1	125.0	0.006	0.004
2	125.5	0.009	0.007
3	126.0	0.015	0.011
4	126.5	0.025	0.019
5	127.0	0.042	0.032
6	127.5	0.071	0.056
7	128.0	0.115	0.096
8	128.5	0.195	0.167
9	129.0	0.339	0.293
10	129.5	0.602	0.523
11	130.0	1.107	0.978

As shown above, with the designed flood control level as the selected safe level, **Fig. 2** presents the relationship curve between different FLWLs Z_i and the corresponding extreme risk rate P_{lim}.



(a) Limited risk rate under different flood limited water levels in the pre-flood season

(b) Limited risk rate under different flood limited water levels in the post-flood season

Fig.2 Extreme risk rate under different flood limited water levels

5.3.2 Benefit Analysis

The reservoir is a large-scale reservoir. It has the functions of flood control, hydropower generation and water supply. With the adjustment of FLWL, its utilization benefits are mainly reflected in the increase of water supply and hydropower generation. The reservoir supplies water mainly including industrial water, agricultural water, domestic water and ecological water, where seventy percent is used for agricultural water. According to relevant research, the reservoir water supply benefit generated by every cubic water is 35.40 yuan (Zheng, 2020). The hydropower generation operation is subject to the flood control and irrigation operation. After the flood season every year, when the downstream irrigation needs water, the irrigation water is used for hydropower generation. According to the actual operation data of the hydropower station (Yu, 2010), the average annual water consumption for hydropower generation from 1991 to 2008 was 8091.0 million m^3, the average annual hydropower generation was 8268 million kW·h, and the average water consumption rate for unit electric energy was 9.786 m^3.

In the pre-flood season, in order to meet the arrival of flood, the reservoir hasn't stored water in advance. The benefit of raising the FLWL only considers the hydropower generation, which positively influenced by the increase of average water head. **Eq.** (14) is used to calculate the increased hydropower generation benefit. **Table**

6 indicates the result in the pre-flood season..

Table 6 Hydropower generation benefit of different schemes in the pre-flood season

Scheme	Water level (m)	Hydropower generation benefit (10^4 kW·h)
1	125.0	0
2	125.5	96.052
3	126.0	192.104
4	126.5	288.157
5	127.0	384.209
6	127.5	480.261
7	128.0	576.313
8	128.5	672.365
9	129.0	768.418
10	129.5	864.470
11	130.0	960.522

In the post-flood season, the reservoir begins to store water to improve the utilization benefit. Therefore, the benefits brought by the adjustment of FLWL include not only the hydropower generation benefit caused by increased water head and volume, but also the water supply benefit. With different starting water levels, the improved water supply benefit can be calculated by **Eq.** (10). According to the measured hydrological data of the watershed over the years (Hu, 2015), the proportion of wet years that can meet the water supply needs without raising the FLWL is 25%. Deducting the proportion of these years, the actual increased water supply benefit by raising the FLWL can be obtained. Then **Eq.** (12) is used to calculate the water supply benefit. **Table 7** indicates the benefit results in the pre-flood season.

Table 7 Water supply benefit of different schemes in the post-flood season

Water level (m)	Storage capacity (10^8 m^3)	Incremental storage capacity (10^8 m^3)	Increased water supply (10^8 m^3)	Increased water supply benefit (10^8 yuan)
125.0	12.272	0.000	0.000	0
125.5	12.574	0.302	0.227	8.031
126.0	12.879	0.607	0.455	16.129
126.5	13.187	0.915	0.686	24.307
127.0	13.499	1.227	0.920	32.577
127.5	13.811	1.539	1.154	40.874
128.0	14.126	1.854	1.391	49.237
128.5	14.444	2.172	1.629	57.680
129.0	14.766	2.494	1.871	66.229
129.5	15.094	2.822	2.117	74.937
130.0	15.431	3.159	2.369	83.879

Next, Using **Eq.** (13) - (14), the hydropower generation benefit caused by increased water head and volume can be calculated. **Table 8** presents the benefit results in the post-flood season.

Table 8 Hydropower generation benefits of different schemes in the post-flood season

Water level (m)	Increased water supply benefit (10^8 yuan)	Increased hydropower generation benefit	
		Water volume benefit (10^4 kW·h)	Water head benefit (10^4 kW·h)
125.0	0.000	0.000	0.000
125.5	8.031	231.839	87.675
126.0.	16.129	465.593	175.350
126.5	24.307	701.647	263.025
127.0	32.577	940.384	350.700
127.5	40.874	1179.886	438.375
128.0	49.237	1421.305	526.051
128.5	57.680	1665.023	613.726
129.0	66.229	1911.807	701.401
129.5	74.937	2163.189	789.076
130.0	83.879	2421.315	876.751

5.4 Nash negotiation solution

Based on the above calculation results, the benefit index values and risk index values of each scheme in the pre-flood season and post-flood season are listed in

Table 9 respectively.

Table 9 Benefit and risk index values of different schemes in the pre-flood season and post-flood season

Limited water level (m)	Pre-flood season		Post-flood season		
	DM_1	DM_2	DM_1		DM_2
	Hydropower generation benefit (10^4 kW·h)	Limited risk rate (%)	Water supply benefit (10^8 yuan)	Hydropower generation benefit (10^4 kW·h)	Limited risk rate (%)
125.0	0.000	0.006	0.000	0.000	0.004
125.5	96.052	0.009	8.031	319.353	0.007
126.0	192.104	0.015	16.129	640.622	0.011
126.5	288.157	0.025	24.307	964.190	0.019
127.0.	384.209	0.042	32.577	1290.440	0.032
127.5	480.261	0.071	40.874	1617.457	0.056
128.0	576.313	0.115	49.237	1946.390	0.096
128.5	672.365	0.195	57.680	2277.623	0.167
129.0	768.418	0.339	66.229	2611.921	0.293
129.5	864.470	0.602	74.937	2950.817	0.523
130.0	960.522	1.107	83.879	3296.458	0.978

In order to facilitate comparison between each index, the value of each index necessarily need to be standardized. **Eq.** (16) is used for benefit index and **Eq.** (17) is used for risk index. On account of the two benefit indexes of water supply and hydropower generation, considering that the reservoir focus on flood control and water supply, supplemented by hydropower generation, the weight of the two indexes is (0.6, 0.4). The utility payoff function values u_1 and u_2 are calculated by **Eq.** (21) - (22). **Table 10** shows the solution of payoff function values of each scheme.

Table 10 DM_1 and DM_2 payoff function values of each scheme

Payoff function value		125.0	125.5	126.0	126.5	127.0	127.5	128.0	128.5	129.0	129.5	130.0
Pre-flood season	u_1	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	u_2	1	0.997	0.991	0.982	0.967	0.941	0.901	0.828	0.697	0.459	0
Post-flood season	u_1	0	0.096	0.193	0.291	0.390	0.489	0.588	0.689	0.791	0.894	1
	u_2	1	0.997	0.992	0.984	0.970	0.946	0.903	0.829	0.695	0.459	0

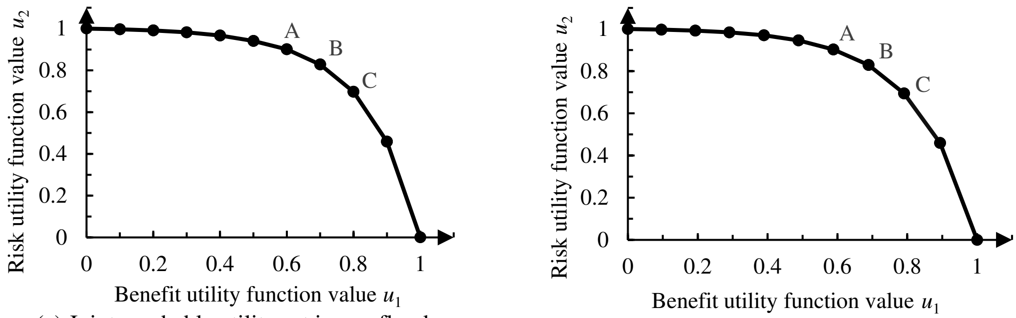
Firstly, it is assumed that the winning function values of the two index sets are both 0, that is, the current point d =(0,0). In order to obtain the joint reachable utility set E of the two index sets, the winning function values (u_1,u_2) of each flood season are marked, as shown in **Fig. 3** below. Then the problem of Nash negotiation is transformed into the following nonlinear programming problems. The corresponding constraints are the line of AB and BC in the following **Fig. 3**.

For pre-flood season:

$$\begin{aligned} &\max\ u_1u_2 \\ s.t.\ &0 \le u_1 \le 1, 0 \le u_2 \le 1 \\ &0.927u_1 + u_2 \le 1.285 \\ &1.581u_1 + u_2 \le 1.722 \end{aligned}$$

For post-flood season:

$$\begin{aligned} &\max\ u_1u_2 \\ s.t.\ &0 \le u_1 \le 1, 0 \le u_2 \le 1 \\ &0.842u_1 + u_2 \le 1.252 \\ &1.493u_1 + u_2 \le 1.683 \end{aligned}$$



(a) Joint reachable utility set in pre-flood season
(b) Joint reachable utility set in post-flood season

Fig.3 Joint reachable utility set in pre-flood season and post-flood season

Based on the above, the Nash negotiation solution u_1 in the pre-flood season is 0.918 and u_2 is 0.669. In the post-flood season, u_1 is 0.658 and u_2 is 0.874. Since the two negotiation solutions are not equal to u_1 and u_2 of each scheme, it is necessary to adopt the fuzzy pattern recognition model and grid schedule theory to calculate the membership degree and decide the optimal scheme. **Table 11** presents the membership degree of each scheme and then the optimal water level can be determined.

Table 11 Membership degree of each scheme in the pre-flood season and post-flood season

Water level /m	125.0	125.5	126.0	126.5	127.0	127.5	128.0	128.5	129.0	129.5	130.0
Pre-flood season	0.082	0.152	0.225	0.301	0.382	0.473	0.577	0.709	0.895	0.820	0.331
Post-flood season	0.342	0.424	0.509	0.597	0.690	0.791	0.908	0.956	0.777	0.528	0.126

It can be seen from the table that the membership degree is the largest when the water level in the pre-flood season is 129.0m and in the post-flood season is 128.5m. That is, when the current point d = (0,0), the FLWL of the optimal scheme in the pre-flood season is 129.0m and in the post-flood season is 128.5m.

The water level at different sub-seasons of the flood season should be considered according to the specific situation. That is to say, the flood control safety is mainly considered in the pre-flood season, so that the decision preference is risk. In the post-flood season, in order to ensure water supply, decision preference will focus on benefit. The decision-maker changes the preference by changing the current point. Increasing d_2 means that decision-making biases risk, and the flood control safety is emphatically considered. Similarly, increasing d_1 means that the decision is biased toward benefit, and the benefits of water supply and hydropower generation are mainly considered. **Table 12** presents the specific results. It can be deduced from the table that the more d_2 increases, the lower the FLWL, and the better the flood control safety can be guaranteed. On the contrary, the more d_1 increases, the higher the FLWL, and the more utilization benefits can be improved.

Table 12 Optimal flood limited water level under different decision preference

Decision preference	Pre-flood season				Post-flood season			
	Equally valued	Risk-biased			Equally valued	Benefit-biased		
(d_1,d_2)	(0,0)	(0,0.1)	(0,0.3)	(0,0.5)	(0,0)	(0.1,0)	(0.3,0)	(0.5,0)
Flood limited water level	129.0	129.0.	128.5	128.0	128.5	128.5	129.0	129.5

6 Conclusions

(1) The circular distribution method is used to calculate the concentration degree and concentration period of flood. According to whether the flood magnitude is considered, two situations are analyzed. The start and end date of the main flood season can be acquired. Combined with the results of flood season segmentation and the vector diagram of each flood occurrence time, the results considering the flood magnitude are selected. The results of circular distribution method are verified by relative frequency method, and the verification results are consistent.

(2) The extreme risk rate is selected as the risk index, the water supply benefit and hydropower generation benefit are chosen as the benefit index, normalized, and each index is weighted according to expert experience. Nash negotiation theorem is used to solve the utility payoff function of two index sets. Then, based on the game theory, a multi-objective cooperative decision-making model is established.

(3) Taking a reservoir as an example, based on the cooperative decision-making between risk and benefit, the optimal FLWL control scheme in pre-flood season and post-flood season are obtained. By adjusting the current point to reflect the decision-makers' preference, the decision-makers' expectations for risk and benefit in different sub-seasons can be realized.

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Ethics Approval Relevant research content in this paper was in accordance with the ethical standards of the institutional and national research committee.

Consent to Participate All of the authors consent to participate in the relevant research content in this paper

Consent for Publication All the authors have approved the submission and consented for the publication.

Availability of Data and Materials The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

References

Apel H, Thieken AH, Merz B, Blöschl G (2004) Flood risk assessment and associated uncertainty. Nat Hazards Earth Sys 4(2): 295-308. https://doi.org/10.5194/nhess-4-295-2004

Black A R, Werritty A (1997). Hydrology Seasonality of flooding: a case study of North Britain. J. Hydrol. 195(1-4):1-25. https://doi.org/10.1016/S0022-1694(96)03264-7

Chen JH, Guo SL, Li Y, Liu P, Zhou YL (2013) Joint Operation and Dynamic Control of Flood Limited Water Levels for Cascade Reservoirs. Water Resour Manag 27(3): 749–763. https://doi.org/10.1007/s11269-012-0213-z

Chen J, Zhong PA, Liu WF, Wan XY, Yeh WWG (2020) A multi-objective risk management model for real-time flood control optimal operation of a parallel reservoir system. J Hydrol 590:

125264. https://doi.org/10.1016/j.jhydrol.2020.125264

Chen L, Guo SL, Yan BW, Liu P, Fang B (2010) A new seasonal design flood method based on bivariate joint distribution of flood magnitude and date of occurrence. Hydrolog Sci J 55(8): 1264–1280. https://doi.org/10.1080/02626667.2010.520564

Chen L, Singh VP, Guo SL, Zhou JZ, Zhang JH, Liu P (2015) An objective method for partitioning the entire flood season into multiple sub-seasons. J Hydrol 528: 621–630. https://doi.org/10.1016/j.jhydrol.2015.07.003

Cunderlik JM, Ouarda TBMJ, Bobée B (2004a) On the objective identification of flood seasons. Water Resour Res 40(1): 1520. https://doi.org/10.1029/2003WR002295

Cunderlik JM, Ouarda TBMJ, Bobée B (2004b) Determination of flood seasonality from hydrological records Hydrolog Sci J 49(3): 511–526. https://doi.org/10.1623/hysj.49.3.511.54351

Fang YH, Zheng XL, Peng H, Wang H, Xin J (2019) A new method of the relative membership degree calculation in variable fuzzy sets for water quality assessment. Ecol Indic 98: 515–522. https://doi.org/10.1016/j.ecolind.2018.11.032

Fang B, Guo SL, Guo FQ, Liu P (2007) Identification of flood seasonality by circular distribution method. J China Hydrol 27(5): 7-11. (in Chinese)

Huang XF, Chen YQ, Lin J, Fang GH, Qu XP, Zhu LX (2017) Research on benefit of reservoir flood resources utilization based on the dynamic control of limited water level. Desalin. Water Treat 79: 214–220. https://doi.org/10.5004/dwt.2017.20857

Hu JL (2015) The study on flood period stage and limited water levels of Meishan Reservoir in Anhui province. Dissertation, Central China Normal University. (in Chinese)

Jiang H, Wang ZZ, Ye A, Liu KL, Wang XH, Wang LJ (2019) Hydrological characteristic-based methodology for dividing flood seasons: an empirical analysis from China. Environ Earth Sci 78(14). https://doi.org/10.1007/s12665-019-8392-z

Jiang HY, Yu ZB, Mo CX (2015) Reservoir Flood Season Segmentation and Optimal Operation of Flood-Limited Water Levels. J Hydrol Eng 20(9) 05014035. https://doi.org/10.1061/(asce)he.1943-5584.0001151

Jiang ZQ, Sun P, Ji CM, Zhou JZ (2015) Credibility theory based dynamic control bound optimization for reservoir flood limited water level. J Hydrol 529: 928–939. https://doi.org/10.1016/j.jhydrol.2015.09.012

Ju B, Yu YC, Zhang FH, Lei XH, You FH (2020) Flood season partition and flood limited water level determination for cascade reservoirs downstream jinshajiang river. IOP Conference Series: Earth Environ Sci. 569(1). https://doi.org/10.1088/1755-1315/569/1/012005

Li X, Guo SL, Liu P, Chen GY (2010) Dynamic control of flood limited water level for reservoir operation by considering inflow uncertainty. J Hydrol 391(1–2): 124–132. https://doi.org/10.1016/j.jhydrol.2010.07.011

Liu GJ, Qin H, Shen Q, Tian R, Liu YQ (2019) Multi-objective optimal scheduling model of dynamic control of flood limited water level for cascade reservoirs. Water 11(9): 1836. https://doi.org/10.3390/w11091836

Liu P, Li LP, Guo SL, Xiong LH, Zhang W, Zhang JW, Xu CY (2015) Optimal design of seasonal flood limited water levels and its application for the Three Gorges Reservoir. J Hydrol 527: 1045–1053. https://doi.org/10.1016/j.jhydrol.2015.05.055

Ma C, Xu R, He W, Xia JJ (2020) Determining the limited water level of early flood season by combining multi-objective optimization scheduling and copula joint distribution function: A case study of three gorges reservoir. Sci Total Environ 737. https://doi.org/10.1016/j.scitotenv.2020.139789

Ouyang S, Zhou JZ, Li CL, Liao X, Wang H (2015) Optimal Design for Flood Limited Water Level of Cascade Reservoirs. Water Resour Manag 29(2): 445–457. https://doi.org/10.1007/s11269-014-0879-5

Li Q, Yu HF, Hu LL, Yu WG, Chi YF, Li H (2018) Study on the Stage of Flood Season in Typhoon Affected Area - A case study in Tingxia. IOP Conference Series: Earth Environ Sci 189(5). https://doi.org/10.1088/1755-1315/189/5/052033

Singh VP, Wang SX, Zhang L (2005) Frequency analysis of nonidentically distributed hydrologic flood data. J Hydrol 307(1–4): 175–195. https://doi.org/10.1016/j.jhydrol.2004.10.029

Wu SJ, Yang JC, Tung YK (2011) Risk analysis for flood-control structure under consideration of uncertainties in design flood. Nat Hazards 58(1): 117–140. https://doi.org/10.1007/s11069-010-9653-z

Xie AL, Liu P, Guo SL, Zhang XQ, Jiang H, Yang G (2018) Optimal Design of Seasonal Flood Limited Water Levels by Jointing Operation of the Reservoir and Floodplains. Water Resour Manag 32(1): 179–193. https://doi.org/10.1007/s11269-017-1802-7

Yu CX (2010) Different period flood analysis and dispatch opinion for the Xianghongdian Reservoir. Jianghuai Water Resour Sci and Technol 2010(1): 19-21. (in Chinese)

Ruan Y, Singh VP (2008) Multiple duration limited water level and dynamic limited water level for flood control, with implications on water supply. J Hydrol 354(1–4): 160–170. https://doi.org/10.1016/j.jhydrol.2008.03.003

Zheng HR (2020) Analysis and evaluation of flood resources utilization in the river basin. Dissertation, Hohai University. (in Chinese)

Zhou HC, Wang FX, Liang GH (2009) Decision-making on reservoir flood control level and its control manner in post-flooding seasons for Biliuhe Reservoir. Adv Water Sci 20(6): 857-862. (in Chinese)

Zhou YL, Guo SL (2014) Risk analysis for flood control operation of seasonal flood-limited water level incorporating inflow forecasting error. Hydrol Sci J 59(5): 1006–1019. https://doi.org/10.1080/02626667.2014.901515

Zhou YL, Guo SL, Liu P, Xu CY (2014) Joint operation and dynamic control of flood limited water levels for mixed cascade reservoir systems. J Hydrol 519(PA): 248–257. https://doi.org/10.1016/j.jhydrol.2014.07.029

Zhou YL, Guo SL, Xu JJ, Zhao XF, Zhai LN (2015) Risk analysis for seasonal flood-limited water level under uncertainties. J Hydro-Environ Res 9(4): 569–581. https://doi.org/10.1016/j.jher.2015.05.001