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Reservoir Flood Season Segmentation and Risk–benefit Cooperative Decision of Staged Flood Limited Water Level

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Abstract

Investigation of seasonal inconsistency between water consumption and rainfall variation is important for more efficient use of floodwater resources. Adjustment of the flood limited water level (FLWL) is an effective way to improve the floodwater use efficiency. Flood season segmentation provides the basis for determining the FLWL and tapping the potential use of floodwater resources. Compromise between the benefit of floodwater use and flood control is crucial to FLWL decision. We use the circular distribution method for flood season segmentation and the relative frequency method for verification. We select the performances of water supply and hydropower generation as the benefit index and the extreme risk rate as the risk index. On the basis of the game theory, we establish a multi-objective cooperative decision-making model and obtain a Nash negotiation solution of staged FLWL. An optimal scheme is determined according to the fuzzy pattern recognition theory. When the risk and benefit are equally valued, the resulting FLWLs of the optimal scheme are 129.0 m, and 128.5 m for a selected reservoir in the pre-flood season and the post-flood season, respectively. By adjusting the preference values of the risk and benefit indexes, we determine the optimal FLWL scheme under different preferences to risk and benefit for each stage.

Keywords Flood season segmentation · Extreme risk rate · Multi-objective cooperative decision · Nash negotiation · Adjustment of flood limited water level

1 Introduction

Reservoir operation is significant for management of water resources and sustainable socioeconomic developments (Tan et al. 2017; Xu et al. 2021). The control of flood limited water level (FLWL) is a significantly productive method of reservoir operation.

FLWL is an important index to compromise the risk of flood and the benefit of floodwater use. It is mainly determined by reservoir regulation based on the biggest

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floods. However, in actual operation, most of the floods are medium or small. This means that the storage capacity, which is originally vacated for large floods, is only used to store the medium or small floods, and thus the rest of the flood control capacity is wasted. In China, the floods in most watersheds show a strong seasonal variation due to the monsoon climate, varying significantly throughout the whole flood season. If the entire flood season operates with an annually fixed FLWL, it inevitably causes a low FLWL, which would lead to waste of floodwater resources. To solve these problems, the entire flood season should be better divided into several sub-seasons according to the seasonal variations of flood. On the basis of flood season segmentation, FLWL of each stage is determined respectively. It cannot only ensure the flood control safety in the flood season but also improve the benefit to a greater extent.

The study of flood season segmentation (Jiang et al. 2019) has gone through a process of in-depth research. Advances primarily involve the techniques of statistical method, genesis analysis method (Singh et al. 2005), fuzzy clustering method (Ju et al. 2020), fractal theory (Li et al. 2018), relative frequency and directional statistics method (Cunderlik et al. 2004), and so on. Owing to the seasonality of floods, the beginning and end of the flood season have the characteristics of periodic change. The circular distribution method (Villarini 2016) is a method to analyze the phenomenon of periodic change and find its internal law. It has the characteristics of simple and convenient calculation and flexible analysis. It also takes the flood magnitude into account, and its results are more accurate than other methods. Besides, the relative frequency method is used to recheck the results of the circular distribution method. Although its result cannot be as precise as the other method down to a day, it is simple and requires less data. Using 62-year daily discharge data, we select the circular distribution method and the relative frequency method to segment the flood season in this study.

On the premise of meeting the downstream flood control safety, the efficiency of floodwater use has improved through adjustment of FLWL (Huang et al. 2017; Liu et al. 2019). There have been many studies on how to realize effective control of FLWL. The staged control of FLWL is proved to be a more efficient measure. The widely used methods (Jiang et al. 2015) mainly include fuzzy set analysis method (Ruan and Singh 2008) and multi-objective optimization method (Xie et al. 2018) etc. Researchers have made extraordinary achievements in producing suitable operating methods (Ma et al. 2020; Mo et al. 2022; Wu and Zhong 2018), whereas most of the existing studies do not separately consider FLWL at each stage. Generally, in the pre-flood season, to meet the storage requirement of an incoming flood, the decision-makers would mainly focus on flood safety control and thus prefer risk to benefit, resulting in a lower FLWL. Conversely, in the post-flood season, the decision-makers would prefer benefit to risk as the concern of water supply increases, expecting a higher FLWL. Therefore, FLWL in different stages should be considered respectively to compromise the benefit and risk.

In this paper, on the basis of flood segmentation, we establish a set of benefit and risk indexes of FLWL control following the game theory and a multi-objective cooperative decision-making model of risk and benefit. Taking Xianghongdian (XHD) reservoir as an example, we choose FLWL in the main flood season as the original design with a focus on the pre-flood and post-flood seasons according to the goal of flood control and design of flood hydrograph. Starting with the Nash negotiation theory, we obtain the optimal FLWL scheme under different preferences between risk and benefit in each stage.

2 The Division of Flood Season

2.1 Circular Distribution Method

2.1.1 Concept

Circular distribution method transforms the periodic data into linear through trigonometric function transformation. Treating the flood events as a vector, it calculates the vector eigenvalues to determine the flood season segmentation (Chen et al. 2010).

2.1.2 Computing Method

Assuming that the length of the calculation period is T, 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 are:

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

and

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

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 $\overline{\alpha}$ and concentration r are respectively:

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

and

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

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

Concentration r describes the central tendency of α_i in the circular distribution with $0 \le r \le 1$. When r is closer to 1, it means that the flood occurrence time is more concentrated in a specific area, not vice-versa. s is the standard deviation of α_i. The relationship between r and s is:

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

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 are, respectively:

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

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

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 each period is 10 days, the length of each period of a month is different. To make each period has the same length, the period needs to be adjusted by multiplying a coefficient. For the last ten-day of a longer month (e.g., Jan. with 31 days), the last 10-day period should be multiplied by 10/11; and for the last 10-day of February, it should be multiplied by a coefficient of 10/8 (10/9 for a leap year). 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 of Risk and Benefit

The flood season staged operation is to take different FLWL control scheme and schedule strategy for each segmentation. To raise the FLWL for improving the benefits of water conservancy while ensuring the flood control safety for the project and the downstream, we first conduct a cooperative decision-making analysis of risk and benefit.

3.1 Risk Analysis

During reservoir operation, events that are not conducive to the dam safety, threaten the flood control safety of downstream, and affect the benefit of reservoir will happen. The occurrence probability and loss due to these events is called flood control risk (Zhou and Guo 2014). 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 at a certain frequency. When Z_m is exactly equal to a selected safe level, the frequency is the extreme risk rate P_{lim}. We take the design flood level Z_d as the selected safe level. The extreme risk rate can be expressed by the following equation:

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

3.2 Benefit Analysis

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

3.2.1 Water Supply Benefit

As the FLWL rises, the added water supply capacity mainly comes from the increased storage of abandoned water. In dry years, there is no water to store after the flood season, and the benefits of FLWL adjustment can be clearly reflected. On the contrary, in wet years, the reservoir can be reserved to the normal water level even if FLWL is not raised. Raising the FLWL will only bring about the hydropower generation benefit caused by the increased water head. Therefore, the multi-year average water supply, which can be increased by raising FLWL, should be deducted from wet years. 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, and 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.

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, and δ is the water supply benefit of per cubic meter of water.

3.2.2 Hydropower Generation Benefit

Added water capacity and increased water head cause the improvement of hydropower generation benefit. The benefit brought by the increased water capacity is calculated by the average water consumption rate of per unit electric energy, which is obtained by counting the average annual hydropower generation water consumption and annual average hydropower generation in recent years. 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, ΔV_2 is the added water supply storage, 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 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 Design of Multi-objective Cooperative Decision-making Model

4.1 Establishment of Multi-objective Cooperative Decision-making Model

In the efficient use of reservoirs, flood season operation 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, $1 \leq i \leq n$ and $1 \leq j \leq m$.

In the actual decision-making, indexes can be divided into three categories: one is benefit index, the second is the risk index, and the third is an intermediate index. Due to the different units among these indexes, 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

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

where $\left[x_i, x_i\right]$ is the best stable interval of x_{ij}. In Eqs. (16) and (17), $x_{i\max}$ and $x_{i\min}$ are respectively the largest and smallest eigenvalues in the j-th ($1 \leq j \leq$ m) index set, and $x_i^{*} = \max\{x_i^{\prime} - x_{i\min}, x_{i\max} - x_i^{\prime\prime}\}$.

Then, we obtain the relative superior membership degree matrix R:

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

Therefore, m objectives can be divided into p benefit indexes and (m-p) risk indexes. Then the problem can be described as:

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

where $F(x)$ is the objective function, and T is the number of constraint conditions. The multi-attribute utility functions $u_1(x)$ and $u_2(x)$ are:

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

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

A decision maker can thus obtain the utility winning function by assigning weights to the multiple indexes. Based on the above, we construct a multi-objective cooperative decision-making model for reservoir operation in flood seasons.

4.2 Solution of Multi-objective Cooperative Decision-making Model

We consider the problem of cooperative decision-making of two index sets, benefit index set DM_1 and risk index set DM_2.. 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.

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

where $G_i \subset R^{k_i}$ is the reachable target set, $x_i \in \Omega_i \subset R^{m_i}$ is the decision vector, R^{k_i} and R^{m_i} are k_i-dimensional and m_i-dimensional real vector spaces, respectively. The winning function of the index set is represented by the utility function. The utility function of the i-th indicator set is:

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

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

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

If E is a closed bounded convex set, $d = (d_1, d_2) \in E$ is the current point. 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 $u \neq u^*$,

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

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

If no feasible scheme 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 Overview of the Study Reservoir

XHD reservoir on the West source of the Pi River Basin, which is one of the upper tributaries of the Huai River in China, is selected as the study object. The river basin is an area affected by the subtropical monsoon climate and frequently subjected to rainstorms and floods. The average annual precipitation in the Pi River basin is 1334 mm. XHD reservoir is a large size, 1 year regulating reservoir with a watershed area of 1400 km^2. The Pi River basin and the location of XHD reservoir are shown as Fig. 1.

The annual average runoff of the reservoir is 33.1 m^3/s. The main task of the reservoir is flood control, and the comprehensive utilization of water supply and hydropower generation are taken into account. The design flood control level is 139.10 m, the corresponding storage capacity is 2.228 billion m^3, and the check flood control level is 143.60 m. The maximum hydropower generation flow of the power station is 200 m^3/s.

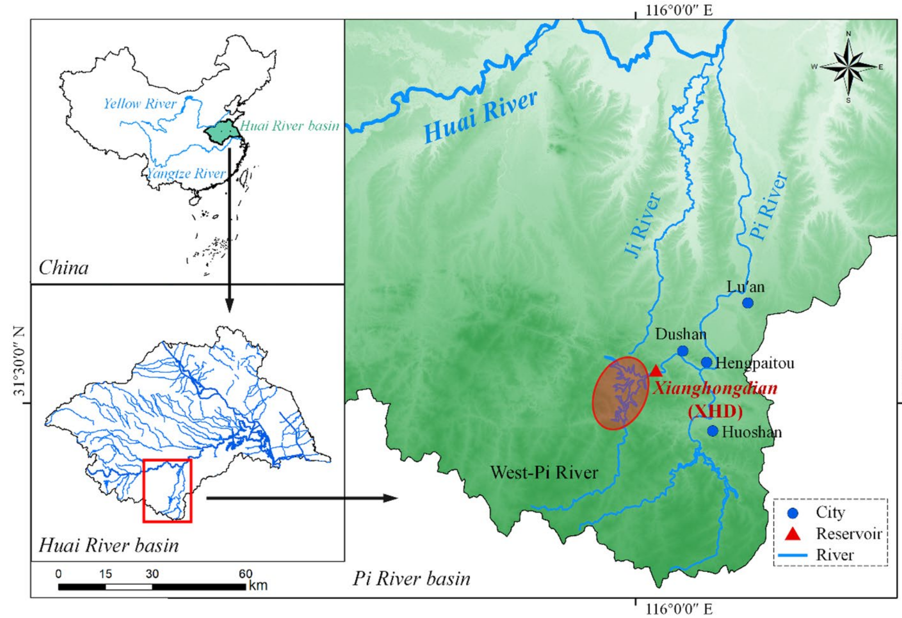


Fig. 1 Maps of the Pi River basin and XHD reservoir location

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

5.2 Segmentation of Flood Season

The restored daily inflow of the reservoir 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 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} ($L = 1, 2, \ldots, n$) 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 Eqs. (1)–(7). Table 1 and Fig. 1 denote the results of segmentation of different sampling intervals.

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.

Figure 2 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 is 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 10 to August 17.

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

Sampling intervals t/d	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

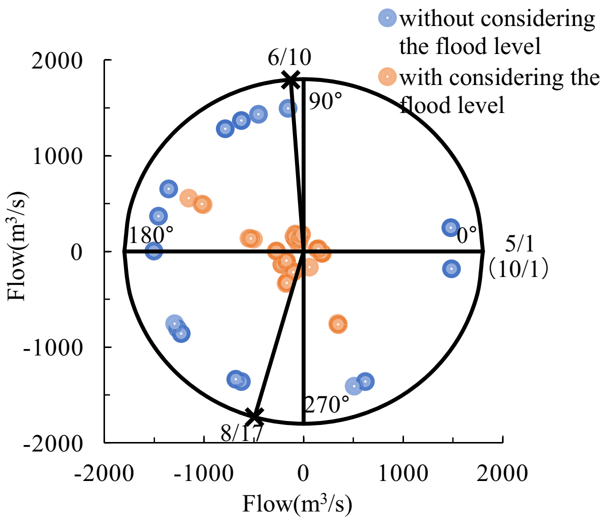


Fig. 2 The vector distribution of maximum flood occurrence time by the circular distribution method

Based on the above, combining the actual situation of the reservoir, 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

The whole flood season is divided into 15 periods (October 1 is classified as the 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.

It can be seen from the Table 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 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 the flood hydrographs with different design frequencies are derived. Considering 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.

The flood hydrograph that is most unfavorable for the reservoir flood control is selected. 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 3,938.84 m^3/s is selected as the typical. 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 a high peak, large volume and

Table 2 The results 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%

many fluctuations. The flood in 2005 with peak discharge of 7,942.69 m^3/s is chosen as the typical.

Then, taking Z_i of each scheme as the starting water level, the time interval is 3 h, flood regulation is carried out according to the predetermined dispatching rules. The relationship between the highest flood regulation water level $Z_m(Z_i)$ and the corresponding frequency $P(Z_i)$, $i=1, 2, \ldots, n$ is obtained.

Taking the designed flood control level (139.10 m) as the selected safe level, the frequency when the flood regulation upper water level starting from each FLWL is exactly equal to the selected safe level is obtained. The results of different schemes and corresponding extreme risk rates are displayed in Table 3.

Figure 3 presents the relationship curve between different FLWLs Z_i and the corresponding extreme risk rate P_{lim}.

5.3.2 Benefit Analysis

XHD reservoir supplies water mainly including industrial water, agricultural water, domestic water and ecological water, of which 70% is used for agricultural water. According to relevant research, the reservoir water supply benefit generated by per cubic metre water is 35.40 yuan (Zheng 2020). The hydropower generation operation is subject to the flood control and irrigation operation. According to the actual operation data of the hydropower station (Yu 2010), the average water consumption rate per unit electric energy was 9.786 m^3.

In the pre-flood season, to meet the storage requirements of the incoming flood, the reservoir needs to empty its water in advance. The benefit of raising the FLWL only considers the hydropower generation, which positively influenced by the increase of average water head. Equation (14) is used to calculate the increased hydropower generation benefit.

In the post-flood season, the reservoir begins to store water to improve the utilization benefit. Therefore, the benefits include not only the hydropower generation benefit caused by increased water head and volume, but also the water supply benefit. According to the

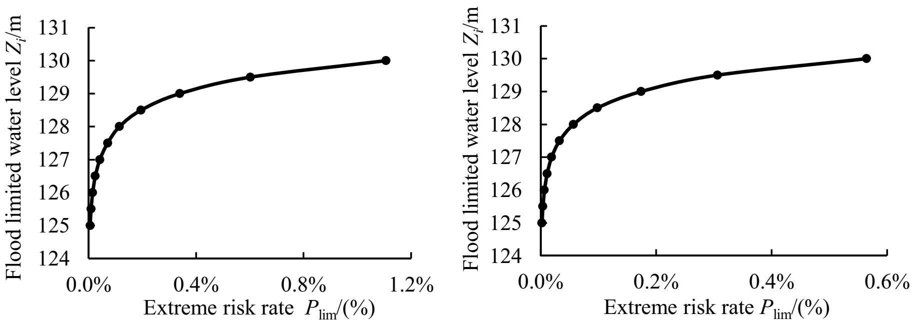
Table 3 Extreme risk rate under different flood limited water levels in the flood season

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

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. Next, Using Eqs. (13) and (14), the hydropower generation benefit caused by increased water head and volume can be calculated. Table 4 presents the benefit results in the pre-flood season and the post-flood season, respectively.

5.4 Nash Negotiation Solution

The value of each index is standardized by Eqs. (16) and (17). Considering that the reservoir focuses on flood control and water supply, supplemented by hydropower generation, the weight of the two benefit indexes, namely water supply and hydropower generation, is (0.6, 0.4). The utility payoff function values u_1 and u_2 are calculated by Eqs. (21) and (22). Table 5 shows the solution of payoff function values of each scheme.



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

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

Fig. 3 Extreme risk rate under different flood limited water levels

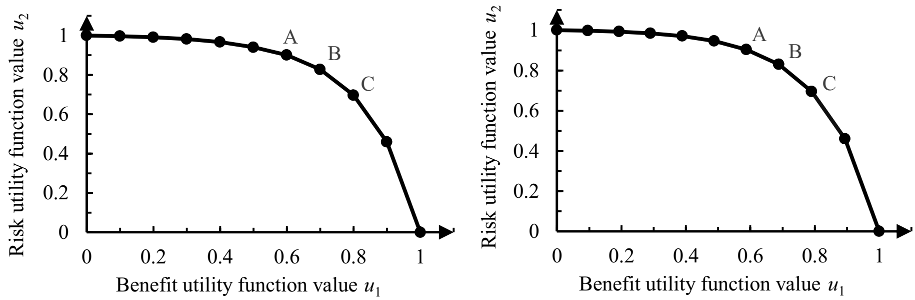
Table 4 Hydropower generation benefit and water supply benefit of different schemes in the pre-flood season and post-flood season

Water level (m)	Pre-flood season	Post-flood season		
	Hydropower generation benefit (10^4 kW·h)	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	0.000
125.5	96.052	8.031	231.839	87.675
126.0	192.104	16.129	465.593	175.350
126.5	288.157	24.307	701.647	263.025
127.0	384.209	32.577	940.384	350.700
127.5	480.261	40.874	1179.886	438.375
128.0	576.313	49.237	1421.305	526.051
128.5	672.365	57.680	1665.023	613.726
129.0	768.418	66.229	1911.807	701.401
129.5	864.470	74.937	2163.189	789.076
130.0	960.522	83.879	2421.315	876.751

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. 4 below. For u_1 and u_2, the maximum value of the product should appear in the range where the values of the two variables are closest, corresponding to the lines of AB and BC in Fig. 4. Then the problem of Nash negotiation is transformed into the following nonlinear programming problems. The product value is optimized during the two lines respectively, and the objective function is as follows.

Table 5 DM_1 and DM_2 payoff function values of each FLWL scheme

Water level /m	payoff function value			
	Pre-flood season		Post-flood season	
	u_1	u_2	u_1	u_2
125.0	0	1	0	1
125.5	0.1	0.997	0.096	0.997
126.0	0.2	0.991	0.193	0.992
126.5	0.3	0.982	0.291	0.984
127.0	0.4	0.967	0.39	0.97
127.5	0.5	0.941	0.489	0.946
128.0	0.6	0.901	0.588	0.903
128.5	0.7	0.828	0.689	0.829
129.0	0.8	0.697	0.791	0.695
129.5	0.9	0.459	0.894	0.459
130.0	1	0	1	0



(a) Joint reachable utility set of risk-benefit collaborative decision in pre-flood season

(b) Joint reachable utility set of risk-benefit collaborative decision in post-flood season

Fig. 4 Joint reachable utility set in pre-flood season and post-flood season

For pre-flood season:

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

For post-flood season:

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

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 6 presents the membership degree of each scheme, and then the optimal water level can be determined.

The membership degree is the largest when the water level in the pre-flood season is 129.0 m and in the post-flood season is 128.5 m. When $d=(0,0)$, the FLWLs of the optimal scheme are 129.0 m and 128.5 m for the pre-flood season and the post-flood season, respectively.

The water level at different sub-seasons of the flood season should be considered for specific situations. The flood control safety is mainly considered in the pre-flood season,

Table 6 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

Table 7 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

so that the decision preference is targeting on risk assessment. In the post-flood season, to ensure water supply, decision preference will focus on benefit assessment. A decision-maker would change the preference by changing the current point. Table 7 presents the specific results. It can be deduced 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.

6 Conclusions

1. We use the circular distribution method and relative frequency method to calculate the flood segmentation. The main flood season of XHD reservoir is gained as June 10—August 17. The results of circular distribution method are verified by relative frequency method, and the verification results are consistent.
2. We establish the index sets of risk and benefit respectively and use the Nash negotiation theorem to solve the utility payoff function of the two index sets, and, based on the game theory, we establish a multi-objective cooperative decision-making model.
3. Taking XHD reservoir as an example, we obtain an optimal FLWL control scheme for sub-seasons. The resulting FLWLs of the optimal scheme are 129.0 m, and 128.5 m in the pre-flood season and the post-flood season, respectively in the condition that the risk and benefit are equally valued. By adjusting the current point to reflect decision-makers' preference, the decision-makers' expectations for risk and benefit in different sub-seasons can be realized through this study.

In the future, we should deeply analyze the characteristics of rainstorm and flood in combination with the hydrological and meteorological characteristics of the basin where the reservoir is located. Based on the real-time rainfall and flow data, the FLWL of each stage more in line with the reality could be achieved.

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

Declarations

Ethics Approval All authors kept to the Ethical Responsibilities of Authors.

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.

Competing Interests The authors declare that they have no confict of interest.

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