Optimal selection of joint impoundment schemes of Xiluodu–Xiangjiaba–Three Gorges cascade reservoirs at the end of flood season

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Abstract: To address conflicts between flood control and utilisation benefits in reservoir operation, this study takes Xiluodu–Xiangjiaba–Three Gorges cascade reservoirs as an example and selects their optimal impoundment schemes at the end of flood season by means of multi-objective assessment and decision making. Firstly, on the basis of analysing the cascade reservoirs’ impoundment situation, this study sets an impounding operation target and draws up preliminary impoundment schemes. Then each scheme is operated with typical flood data and a long series of runoff data. Secondly, based on the operation results, structural equation model is used to analyse flood control and benefit objectives, among which the mutual feedback relationship is revealed. Finally, given the correlation among different objectives and indexes, grey target model with positive and negative bull’s-eyes based on Mahalanobis distance is applied to assess each scheme, obtaining satisfactory solutions and thus picking out the optimal scheme, which can provide scientific reference for the actual operation of cascade reservoirs at the end of flood season.

1 Introduction

The Yangtze River is China’s largest river. With the vigorous development of China’s water conservancy cause, hydropower is continually being harnessed in the Yangtze River basin. Preliminary statistics show that reservoirs on the Yangtze River upstream have a total storage capacity of 57.291 billion cubic metres. Reservoir regulation has remarkably changed the law of flow in natural waterways. Impoundment of upstream reservoirs inevitably leads to decrease in inflow of downstream reservoirs, affecting the latter’s impoundment process. Water storage of the Yangtze River upstream reservoir group at the end of flood period is up to 35.812 billion cubic metres, and for these reservoirs, impoundment mostly begins between August and October, thus there is serious conflict between different reservoirs’ impoundment. Xiluodu–Xiangjiaba–Three Gorges cascade reservoirs is a backbone engineering project on the Yangtze River mainstream. Scientific coordination of the three reservoirs’ impounding time and process can not only reduce their impoundment pressure at the end of flood season, but is also of great significance to optimal allocation of water resources in the Yangtze River basin.

So far there has been plenty of research on the Three Gorges reservoir’s impounding mode at the end of flood season. Jiali and Shenglian [1] established a hydrological flood risk analysis model based on Bayesian method. After calculation of the proposed impoundment scheme for the Three Gorges reservoir, results showed that the flood control risk of the Jingjiang River reach would not increase. Yang and Yitian [2] developed a water-sediment operation model for the Three Gorges reservoir by studying the relationship among flood control, power generation and navigation during the operation process, and multi-objective decision making is applied to different impounding schemes. Compared to research on a single reservoir, a smaller quantity of research has been conducted on joint impoundment of cascade reservoirs. Yanlai and Shenglian [3] calculated the risks and benefits of joint impoundment schemes of Xiluodu–Xiangjiaba–Three Gorges cascade reservoirs, and used projection pursuit method for multi-objective decision making to obtain the optimal non-inferior scheme. While impoundment time is indeed important, the influence of controlled water levels at key moments (i.e. the impoundment process) cannot be neglected. In the above methods that only focus on impoundment time and do not take impoundment process into account, scheme settings are incomprehensive and only a few indices are used in scheme assessment, which is not representative enough.

To overcome the deficiency in existing research, this paper takes Xiluodu–Xiangjiaba–Three Gorges cascade reservoirs (hereinafter referred to as the cascade reservoirs) as an example and studies their joint impoundment at the end of flood season. When formulating an impoundment scheme, a breakthrough has been made based on existing research that only focuses on impoundment time, to consider impoundment process as an additional factor and make more comprehensive schemes. When building the index system, this paper selects a number of representative indices to reflect such objectives as flood control, water storage and power generation, whose mutual feedback relationships are revealed by applying structural equation model. Furthermore, grey target model with positive and negative bull’s-eyes based on Mahalanobis distance is used to assess the proposed schemes and determine their rankings, which can provide a reference for selecting optimal joint impoundment scheme at the end of flood season.

2 Analysis of the cascade reservoirs’ impoundment situation

According to statistics, the combined water storage of Xiluodu, Xiangjiaba and Three Gorges reservoirs is 27.703 billion cubic metres, accounting for 77.4% of that of the Yangtze River upstream reservoir group. Hence, reasonable arrangements for joint impoundment of the cascade reservoirs are of crucial importance to relieving impoundment pressure on all reservoirs in the Yangtze River basin.

Fig. 1 illustrates the layout of the Yangtze River upstream reservoirs. It shows that Xiluodu and Xiangjiaba reservoirs are located in...
the Jinsha River downstream, with the Jinsha River midstream and the Yalong River cascade reservoirs in the upstream. The Three Gorges reservoir is situated in the downstream of Xiluodu and Xiangjiaba reservoirs, with the Minjiang River, the Jialing River and the Wujiang River cascade reservoirs in between. Operation of upstream reservoirs has a significant impact on the inflow of the cascade reservoirs. According to runoff data and runoff regulation results from 1959 to 2010, we draw three diagrams contrasting natural flow and Xiluodu reservoir inflow.

As can be seen from Figs. 2–4, due to the effect of upstream reservoirs’ impoundment, inflow of the cascade reservoirs in flood season is generally smaller than natural flow. In June and July, as the upstream reservoirs fill their utilizable capacity, inflow of the cascade reservoirs decreases compared to natural flow. As Xiluodu reservoir starts to undertake the task of flood control in July, its water level must drop to the flood control level by the end of June. Consequently, in the late June, inflow of both Xiangjiaba and the Three Gorges reservoirs increases in contrast to natural flow. From August onwards, the Jinsha River upstream and the Yalong River cascade reservoirs start impounding water, and as their flood control capacity gradually releases, inflow of the cascade reservoirs all declines sharply. In September, Xiluodu and Xiangjiaba reservoirs begin impoundment, leading to a considerable reduction in inflow of Xiangjiaba and the Three Gorges reservoirs.

3 Joint impoundment schemes at the end of flood season

3.1 Scheme proposition

According to planning and design, both Xiluodu and Xiangjiaba reservoirs begin impounding water from 560 and 370 m on 11 September, not exceeding 600 and 380 m, respectively on 20 September. Impoundment of the Three Gorges reservoir is scheduled to start on October 1. Since operation and years of experimental practice, improvement has been made on the original impoundment scheme. It is approved by the State Flood Control and Drought Relief Headquarters that the Three Gorges reservoir can be operated at 150–155 m in early September and that impoundment can begin as early as 10 September. The above scheme (Scheme 1) is set as the original scheme, and another 15 different schemes (Schemes 2–16) are set up and calculated for comparison. In these 15 schemes, Xiluodu and Xiangjiaba reservoirs begin impounding water 10–20 days earlier than the original time. Additionally, their controlled water levels on 10 September are adjusted, with specific settings of each scheme shown in Table 1.

3.2 Scheme calculation

Calculation of joint impoundment operation of the above schemes is mainly divided into the following two parts.(i) Calculate flood control risk. According to data of typical flood processes, we conduct a stochastic simulation of Xiluodu reservoir’s flood

| Scheme | Impounding time | Controlled water level, m |
|--------|----------------|---------------------------|
|        | XLD | XJB | XLD | XJB | XLD | XJB | TTG |
| 1      | 9/11 | 9/11 | 560 | 370 | 600 | 380 | 162 |
| 2      | 9/1  | 9/11 | 570 | 370 | 590 | 380 | 162 |
| 3      | 9/11 | 9/1  | 560 | 380 | 590 | 380 | 162 |
| 4      | 9/1  | 9/1  | 570 | 380 | 590 | 380 | 162 |
| 5      | 8/21 | 9/1  | 570 | 380 | 590 | 380 | 162 |
| 6      | 9/1  | 8/21 | 570 | 380 | 590 | 380 | 162 |
| 7      | 8/21 | 8/21 | 570 | 380 | 590 | 380 | 162 |
| 8      | 9/1  | 9/1  | 580 | 380 | 590 | 380 | 162 |
| 9      | 9/1  | 9/1  | 590 | 380 | 590 | 380 | 162 |
| 10     | 9/1  | 9/1  | 570 | 375 | 590 | 380 | 162 |
| 11     | 9/1  | 9/1  | 570 | 380 | 570 | 380 | 162 |
| 12     | 9/1  | 9/1  | 570 | 380 | 580 | 380 | 162 |
| 13     | 9/1  | 9/1  | 570 | 380 | 600 | 380 | 162 |
| 14     | 9/1  | 9/1  | 570 | 380 | 590 | 380 | 162 |
| 15     | 9/1  | 9/1  | 570 | 380 | 590 | 380 | 165 |
| 16     | 9/1  | 9/1  | 570 | 380 | 590 | 380 | 168 |

XLD: Xiluodu; XJB: Xiangjiaba; TTG: the Three Gorges.
Table 2 Calculation result of each scheme

| Scheme | S1, % | S2, % | R1, % | R2, % | Es | (10^3 kWh) | E5 | (10^3 kWh) |
|--------|-------|-------|-------|-------|----|------------|----|------------|
| 1      | 92.31 | 98.32 | 0     | 0     | 1753 | 168.2      |
| 2      | 94.23 | 98.36 | 0     | 0     | 1759.6 | 162.2     |
| 3      | 94.23 | 98.36 | 0     | 0     | 1755.4 | 167.3     |
| 4      | 94.23 | 98.47 | 0     | 0     | 1760.9 | 162.4     |
| 5      | 94.23 | 98.51 | 2.31  | 16.53 | 1764.2 | 161.3     |
| 6      | 94.23 | 98.51 | 0.98  | 6.43  | 1762.8 | 162.2     |
| 7      | 94.23 | 98.57 | 3.25  | 25.69 | 1765.7 | 159.4     |
| 8      | 94.23 | 98.47 | 0     | 0     | 1762.4 | 163.0     |
| 9      | 94.23 | 98.46 | 0.66  | 2.12  | 1761.7 | 165.2     |
| 10     | 94.23 | 98.44 | 0     | 0     | 1760.6 | 161.9     |
| 11     | 90.38 | 98.32 | 0     | 0     | 1750.9 | 167.9     |
| 12     | 92.31 | 98.43 | 0     | 0     | 1757.3 | 163.8     |
| 13     | 92.31 | 98.44 | 0     | 0     | 1759.2 | 162.3     |
| 14     | 94.23 | 98.47 | 0     | 0     | 1763.2 | 162.5     |
| 15     | 94.23 | 98.47 | 1.35  | 13.11 | 1765.2 | 162.6     |

inflow and interval flood from Xiangjiaba reservoir to the Three Gorges reservoir (no interval flood between Xiluodu and Xiangjiaba reservoirs). Then the derived flood processes of the cascade reservoirs are used as input into the joint impoundment operation model to work out flood control risk. We take the flood control risk rate ($R_1$) and the loss from flood control risk ($R_2$) as assessment indices of flood control. The latter is characterised by the risk loss rate [4]. (ii) Calculate utilisation benefit. According to the long series of runoff data from 1959 to 2010, we calculate benefits of water storage and power generation of the cascade reservoirs operated under each scheme. Water storage indices include the full storage rate ($S_1$) and the average annual water storage rate ($S_2$), while power generation indices include the average annual generated energy ($E_s$) and the opportunity loss from abandoning water ($E_5$) [5]. Results are shown in Table 2.

4 Multi-objective decision making on joint impoundment operation

Xiluodu, Xiangjiaba and the Three Gorges are all reservoirs of comprehensive utilisation. For the cascade reservoirs at the end of flood season, research about their joint impoundment needs to consider multiple objectives. Therefore, it is a typical multi-objective problem.

4.1 Research on the mutual feedback relationship among multiple objectives

In general, there is conflict between flood control and utilisation benefits, and there are also complicated relations between different benefit objectives. Clarifying the mutual feedback relationship among objectives can make the multi-objective assessment results more in line with reality. However, flood control, water storage, power generation and other objectives usually cannot be measured directly but can only be reflected indirectly by corresponding indices. We call these objectives latent variables. Traditional methods of correlation analysis cannot deal with latent variables, and their way of processing multivariate relationships is not mature enough as well. As a multivariate data analysis model, structural equation model can solve such problems very well. Structural equation model is a statistical model to analyse the relationship between variables, commonly consisting of a measurement model and a structural model. The former reflects the relationship between observational variables and latent variables while the latter reveals the structural relationship between latent variables. Observational variables are directly measurable variables, such as those indices that can be obtained by calculation like $R_1$ and $E_s$ in this paper. Latent variables cannot be directly observed or measured, and need to be indirectly reflected by designing certain observational variables. In the structural equation model, it is assumed that there is a relationship between latent variables which are indicated by observational variables. This model calculates the covariance of observational variables, estimates the linear regression coefficients, and then examines how well the covariance matrix of observational variables fits with the covariance matrix of the model.

Apart from mathematical expressions, structural equation model can also be constructed in the form of path diagram. With the advantages of being simple, clear and easy to understand, path diagram has been widely used in constructing structural equation model. So in this paper path diagram is adopted to describe the mutual feedback relationship between different objectives of the cascade reservoirs, in the following four steps:

1) Model construction: Draw the variables in a path diagram where a circle represents a latent variable, a rectangle an observational variable and arrows the relationship between variables. This paper mainly studies the influence of water storage on flood control and power generation. Therefore, water storage, flood control and power generation are taken as latent variables, and their corresponding indices are used as observational variables. An initial model is established, as shown in Fig. 5.

2) Convert the index set obtained from Section 3 into the model’s input: First, the original index set $A(a_{ij})_{p×q}$ in which $a_{ij}$ represents the original index $j$ in scheme $i$, $p$ the number of schemes and $q$ the number of indices, is standardised with the following formula:

$$profit\ index_{ij} = \frac{a_{ij} - \min\{a_{ij}\}}{\max\{a_{ij}\} - \min\{a_{ij}\}}$$

$$cost\ index_{ij} = \frac{\max\{a_{ij}\} - a_{ij}}{\max\{a_{ij}\} - \min\{a_{ij}\}}$$

After getting the standardised index set $B(b_{ij})_{p×q}$, the standardised indices are graded according to the ranking function $f$ defined as follows:

$$f(x) = \begin{cases} \
1, & x \in [0, 0.25] \\
2, & x \in (0.25, 0.5) \\
3, & x \in [0.5, 0.75] \\
4, & x \in (0.75, 1]
\end{cases}$$

Let $c_{ij} = f(b_{ij})$ and obtain the graded index set $C(c_{ij})_{p×q}$ that is used as input of the structural equation model.

3) Carry out model fitting calculation and work out the estimated values of the model’s parameters: In this paper, the AMOS software is applied to conduct fitting calculation of the model and
estimation is done using the method of scale-free least squares. The result is shown in Fig. 6.

4.2 Multi-objective assessment method based on improved grey target model

The grey target model is one of the approaches in the grey system theory to solving multi-objective assessment problems. Its core idea is that without a standard mode, a grey target is set up with the ideal scheme to the bull’s-eye (hereinafter referred to as off-target distance) determines the scheme’s ranking.

According to the research results in Section 4.1, there is a certain degree of correlation among flood control, water storage and power generation. These objectives are reflected by corresponding indices, so that there is a certain relationship among indices. The traditional grey target model calculates off-target distance by using the Euclidean distance, failing to consider the correlation between indices, which can lead to distortion of the assessment result and influence the final decision. Therefore, this paper introduces the Mahalanobis distance to improve the traditional grey target model. The Mahalanobis distance uses covariance distance as the Euclidean distance between two points and takes the correlation between indices into account, which can more accurately reflect the relationship between the scheme point and the target. For a multivariate vector \( x = (x_1, x_2, \ldots, x_m)^T \) whose mean vector is \( \mu = (\mu_1, \mu_2, \ldots, \mu_m)^T \) and covariance matrix is \( \Sigma \), its Mahalanobis distance is defined as follows:

\[
d_M = \sqrt{(x - \mu)^T \Sigma^{-1} (x - \mu)}
\]

In addition, the traditional grey target model chooses the ideal optimal scheme as the bull’s-eye and ignores the effect of the ideal worst scheme, bringing about one-sidedness to assessment results. Therefore, this paper introduces the positive and negative bull’s-eyes [6] and defines integrated off-target distance. Positive bull’s-eye (\( b^+ \)) is the ideal optimal scheme point and the distance from scheme \( x_t \) to \( b^+ \) is positive off-target distance (\( d^+_t \)). Similarly, negative bull’s-eye (\( b^- \)) is the ideal worst scheme point and the distance from scheme \( x_t \) to \( b^- \) is negative off-target distance (\( d^-_t \)). The distance between \( b^+ \) and \( b^- \) is defined as positive-to-negative distance (\( d_0 \)). In Fig. 7, \( x_s \), \( b^+ \) and \( b^- \) are three spatial points, forming a triangle, and \( d^+_s \), \( d^-_s \) and \( d_0 \) are all vectors. The length of projection of \( d^-_s \) on the line between \( b^+ \) and \( b^- \) is defined as the integrated off-target distance \( d_i \). The greater the integrated off-target distance is, the better a scheme is.

Combining the Mahalanobis distance with the positive and negative bull’s-eyes, this paper proposes the grey target model with positive and negative bull’s-eyes based on the Mahalanobis distance, and its calculation process is as follows:

1. Establish the index set: The standardised index set \( B(b_{ij})_{p \times q} \) can be obtained by the standardisation of the original index set \( A(d_{ij})_{p \times q} \) with the same method in Section 4.1.
2. Determine the positive and negative bull’s-eyes: Let \( b^+_j = \max \{ b_{ij} | 1 \leq i \leq p \} \), \( b^-_j = \min \{ b_{ij} | 1 \leq i \leq p \} \), then positive and negative bull’s-eyes are expressed as follows:

\[
\begin{align*}
\{ b^+_j \} &= (b^+_1, b^+_2, \ldots, b^+_q) \\
\{ b^-_j \} &= (b^-_1, b^-_2, \ldots, b^-_q)
\end{align*}
\] (4)

3. Determine the weight of index: The weight vector of index \( W \) can be obtained by subjective or objective weighting methods

\[
W = (w_1, w_2, \ldots, w_q)
\] (5)

4. Calculate \( d^{++} \), \( d^+ \) and \( d^- \): Let \( v = (v_1, v_2, \ldots, v_q)^T \), and then \( d^{++} \) can be expressed as follows:

\[
d^{++} = \sqrt{V^T \Sigma^{-1} V}
\] (6)

For scheme \( x_s \), let \( u^+_s = w_j (b^+_j - b^-_j) \), \( U^+_s = (u^+_1, u^+_2, \ldots, u^+_q)^T \), \( U^-_s = (u^-_1, u^-_2, \ldots, u^-_q)^T \) then \( d^+_s \) and \( d^-_s \) are calculated as follows:

\[
\begin{align*}
\{ d^+_s \} &= \sqrt{(U^+_s)^T \Sigma^{-1} U^+_s} \\
\{ d^-_s \} &= \sqrt{(U^-_s)^T \Sigma^{-1} U^-_s}
\end{align*}
\] (7)

5. Calculate the integrated Mahalanobis off-target distance \( d_i \) to assess each scheme

\[
d_i = \frac{\left( d^+_s \right)^2 + (d^{++})^2 - (d^-_s)^2}{2d_0^2}
\] (8)
4.3 Analysis of multi-objective decision making

Analysis of Schemes 1–7 demonstrates that with the advance of impoundment time of Xiluodu and Xiangjiaba, both water storage and power generation indices for the cascade reservoirs rise as a whole. Since it is still in the main flood season for the Yangtze River in the late August, advancing both reservoirs’ impoundment time will trigger some flood control risk. Therefore, it is suggested that the impounding time of Xiluodu and Xiangjiaba reservoirs at the end of flood season should not be earlier than 1 September.

Analysis of Schemes 4, 8 and 9 reveals that when controlled water level of Xiluodu reservoir is raised from 570 to 580 m on 10 September, indices of flood control and water storage of the cascade reservoirs remain basically unchanged while \( E_a \) grows. When controlled water level is raised to 590 m, however, both \( S_m \) and \( E_a \) of the cascade reservoirs decline, and \( R_f \) no longer remains at zero. Thus it is recommended that controlled water level of Xiluodu reservoir should not exceed 580 m on 10 September.

By analysing Schemes 4 and 11–13, it can be learnt that as a controlled water level of Xiluodu reservoir is raised higher and higher on 20 September, flood control risk of the cascade reservoirs remains at zero while water storage indices keep rising. When controlled water level is raised from 570 to 590 m, there is a significant growth in \( E_a \). Nevertheless as controlled water level continues to rise, energy output of the cascade reservoirs falls due to declining water utilisation rate. So it is suggested that controlled water level of Xiluodu reservoir should not exceed 590 m on 20 September.

We learn from analysing Schemes 4 and 10 that as controlled water level of Xiangjiaba reservoir is raised from 375 to 380 m on 10 September, both \( S_m \) and \( E_a \) increase to some extent. Therefore, it is proposed that Xiangjiaba reservoir can impound water up to the normal water level of 380 m on 10 September.

It is learnt from analysing Schemes 4, 14–16 that with controlled water level of the Three Gorges reservoir raised higher and higher on 30 September, \( R_f \) of the cascade reservoirs remains at 0 at the beginning but it is no longer the case when controlled water level reaches 168 m. Water storage indices grow initially, but when controlled level is above 162 m, \( S_m \) and \( E_a \) remain constant. Although \( E_a \) increases with the rising controlled water level, \( E_a \) still continues growing. Considering all the objectives, it is suggested that controlled water level of the Three Gorges reservoir is 162–165 m on 30 September.

On the basis of the above qualitative analysis, the grey target model with positive and negative bull’s-eyes based on the Mahalanobis distance is applied to assess the schemes. Using the analytic hierarchy process, the weight of each index is determined as 0.253, 0.253, 0.036, 0.216, 0.151 and 0.091, respectively. The final assessment results and rankings of each scheme are shown in Table 3.

Optimal selection of schemes and multi-objective decision-making are conducted based on the integrated Mahalanobis off-target distance. Table 3 shows that the \( d_i \) of Scheme 15 is 1.7848, the maximum among all schemes, making it the optimal satisfactory solution. In contrast to Scheme 1, the impounding time of Xiluodu and Xiangjiaba reservoirs is appropriately advanced in Scheme 15 without increasing the risk of flood control. Besides, the impounding processes of the three reservoirs are reasonably controlled and \( E_c \) is considerably reduced, with an increase of 0.58, 2.08 and 0.15% in \( E_o, S_f \) and \( S_m \), respectively. Further analysis shows that the settings in Scheme 15 are basically consistent with the above suggestions, confirming the scientificity of the improved grey target model. In Schemes 8, 13 and 4, the impounding time of Xiluodu and Xiangjiaba reservoirs is the same as Scheme 15 (1 September). But due to different settings of impounding process, the \( E_o \) of these schemes is less than that of Scheme 15, and thus their values of \( d_i \) are slightly smaller than that of Scheme 15, making them the less satisfactory schemes. In addition, although Schemes 5 and 7 have great advantages in water storage and power generation indices, their impounding time is too early, resulting in greater risk of flood control, so they are inferior schemes. On the contrary, the settings of Schemes 1 and 11 are too conservative. Despite zero risk of flood control, they have a certain gap with other schemes in terms of water storage and power generation indices, ranking at Schemes 15 and 16, respectively, which means they are the least ideal of all schemes.

5 Conclusion

In view of the impoundment conflicts among reservoirs in the Yangtze River upstream at the end of flood season, this paper takes the Xiluodu–Xiangjiaba–Three Gorges cascade reservoirs as an example and studies their joint impounding at the end of flood season. The results are as follows: (i) Water storage of the cascade reservoirs is large at the end of flood season, and their impounding time is close to one another. Impoundment of the upstream reservoirs can reduce inflow of the cascade reservoirs, which are facing huge pressure of impoundment at the end of flood season. Storing water in advance and implementing joint impoundment of the cascade reservoirs can fully utilise water resources at the end of flood season and effectively alleviate the impounding pressure. (ii) Calculation results of the structural equation model indicate that there is some conflict between water storage and flood control of the cascade reservoirs, but properly advancing impoundment does not necessarily increase the risk of flood control. Meanwhile, there is a strong synergistic relationship between water storage and power generation, which means impounding water ahead of schedule can effectively enhance the benefit of power generation. Therefore, it is feasible to impound water ahead of schedule and boost benefits without extra risk of flood control. (iii) While the starting time is indeed important to the flood control of the cascade reservoirs, but properly advancing impoundment does not necessarily increase the risk of flood control. Meanwhile, there is a strong synergistic relationship between water storage and power generation, which means impounding water ahead of schedule can effectively enhance the benefit of power generation. Therefore, it is feasible to impound water ahead of schedule and boost benefits without extra risk of flood control. (iv) For Scheme 15, the impounding time of Xiluodu and Xiangjiaba reservoirs is appropriately advanced by 10 days and the impounding processes of the three reservoirs are reasonably controlled. Benefits are greatly enhanced without increasing the risk of flood control of the cascade reservoirs. According to results of the grey target model with positive and negative bull’s-eyes based on Mahalanobis distance, Scheme 15 is the most satisfactory scheme.

In this paper, however, only the three objectives of flood control, water storage and power generation are considered. For a multi-purpose reservoir such as Xiluodu, Xiangjiaba and the Three Gorges, functions of water supply, ecology protection and navigation also greatly affect its comprehensive utilisation benefits.
Therefore, future research can focus on comprehensive consideration of various functions of the cascade reservoirs and further study their other important objectives.

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7 References

[1] Jiali G., Shenglian G.: ‘Flood control risk analysis model of impounding water in advance for Three Gorges reservoir’, J. Hydroelectr. Eng., 2012, 31, (4), pp. 16–21

[2] Yang P., Yitian L.: ‘Study on the impounding time and objective decision of the Three Gorges project at the end of flood period’, Adv. Water Sci., 2003, 14, (6), pp. 682–689

[3] Yanlai Z., Shenglian G.: ‘Multi-objective decision and joint refill schemes of Xihoudu-Xiangjiaba-Three Gorges cascade reservoirs’, J. Hydraul. Eng., 2015, 46, (10), pp. 1135–1144

[4] Yu L., Shenglian G.: ‘Flood control risk and benefit of impounding water in advance for the Three Gorges Reservoir’, J. Yangtze River Sci. Res. Inst., 2013, 30, (1), pp. 8–14

[5] Changmeng L., Rongbo L.: ‘Assessment index system and decision-making model for load adjustment schemes of cascade hydropower stations’, J. Hydraul. Eng., 2017, 48, (3), pp. 261–269

[6] Luo D., Wang X.: ‘The multi-attribute grey target decision method for attribute value within three-parameter interval grey number’, Appl. Math. Model., 2012, 36, (5), pp. 1957–1963