Research on the multi-objective optimal operation of cascade reservoirs in the upper and middle Yellow River basin

Jia-qi Bian, Zeng-chuan Dong, Yi-fei Jia and Dun-yu Zhong

ABSTRACT

The reservoirs (hydro plants) along the upper Yellow River are typical cascade reservoirs, with multiple objectives regarding flood control, ice control, water supply, power generation, and ecological security. The competition among these multiple objectives reflects the competition among various agencies with different interests. There has been a certain degree of conflict between 'power scheduling', which aims at obtaining greater power generation from the cascade reservoirs, and 'water regulation', which is currently being implemented. Questions of how to reasonably use the comprehensive regulation capacity of the cascade reservoirs, in order to relieve the conflicts among multiple objectives, and understand the nature of the competition between 'power scheduling' and 'water regulation', require urgent research and solutions. Based on an analysis of the current situation regarding water supply, electricity demand, flood control, ice control, and ecology, a multi-objective optimal operation model for the cascade reservoirs in the upper and middle reaches of the Yellow River has been constructed to reveal the relationships between power generation and other objectives. This study provides theoretical evidence for the informed operation of the cascade reservoirs and will be of great significance for coordinating the relationship between power generation and water regulation.

Key words | Modified Progressive Optimality Algorithm, multi-objective optimal operation, power generation, water regulation, Yellow River

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INTRODUCTION

Water is an important natural resource that is essential for human life and society. Since the 1980s, the water crisis has become a global problem. It is recognized that the shortage of water resources will bring negative impacts to economic, social and ecological sustainable development. Research on water conservation has gradually moved from focusing on reservoirs' construction to their operation and management. How to maximize the regulation and storage capacity of various types of water conservancy projects, and obtain the greatest benefits for life, production and ecology given limited water resources, has become the focus of current research. At present, the focus of research into optimal reservoir operation is gradually shifting from single reservoirs to multi-objective joint operation of cascade reservoirs. Traditional optimization algorithms have been improved accordingly, and a large number of modern optimal operation methods have been introduced (Kirkpatrick *et al.* 1983; Esat & Hall 1994; Kennedy & Eberhart 1995; Dorigo *et al.* 1999; Deb *et al.* 2002). These algorithms are often used to solve complex optimization problems in many different domains (Cimorelli *et al.* 2015; Zheng *et al.* 2017) and are constantly being improved (Qin *et al.* 2010;

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Zheng *et al.* 2016). Such problems involving multiple objectives and decision variables are often referred to as 'multi-objective optimization problems' (Reddy & Kumar 2006, 2007). At present, research on multi-objective optimization theories and decision-making methods (Reed *et al.* 2013; Xu *et al.* 2015) for cascade reservoirs mainly focuses on the analysis of competitiveness and coordination among objectives, to determine a compromise scheme which can resolve the contradictions between them (Bai *et al.* 2015; Tsai *et al.* 2015). However, there is little research on the mechanisms behind these conflicts and the relationships between objectives (Zeff *et al.* 2014; Smith *et al.* 2016; Xu *et al.* 2017; Zhang *et al.* 2017). Competition among multiple objectives reflects the competition among various agencies with different interests, such as water supply departments, flood control departments, hydropower development departments and so on. However, there are always some discrepancies between the theoretical and actual multi-objective operation of reservoirs. For the decision-making department, the relationships among the multiple objectives are most often understood intuitively. Therefore, it is of value for operational decision-making regarding these reservoirs to quantify the trade-offs among the objectives appropriately. The study area chosen in this paper, the Yellow River, is a typical case. There is a certain degree of competition between the 'power generating' aim, which consists of obtaining greater power generation, and the 'water regulation' aims that are currently being implemented for the whole river, which emphasize water supply, flood control, ice control and ecological safety, and this contradiction needs to be solved urgently. This paper aims to identify the trade-offs among these multiple objectives, and provide a theoretical basis for better decision-making in the management of the Yellow River.

STUDY AREA

The upper and middle reaches of the Yellow River are characterized by unique topography and changeable flow directions, and are influenced by variable climates. Tasks such as flood control, ice control, power generation, water supply and ecological protection are undertaken in these areas. Firstly, two pivotal reservoirs, Longyangxia (built in 1987, storage capacity: $247 \times 10^8\,\mathrm{m}^3$) with multi-year regulation storage, and Liujiaxia (built in 1968, storage capacity: $57 \times 10^8\,\mathrm{m}^3$) with annual regulation storage, are arranged to supply water for the five provinces (autonomous regions) of Qinghai, Sichuan, Gansu, Ningxia and Inner Mongolia (Figure 1). Secondly, the upper reaches of the Yellow River (especially the section from Longyangxia Reservoir to Qingtongxia Reservoir) have become one of the major hydropower development bases in China due to their abundant water resources, stable runoff and huge fall head. The water dispatching plan for Longyangxia and Liujiaxia determines the power generation benefits of the cascade reservoirs. Thirdly, ice disasters are one of the major ecological problems that are unique to the Yellow River, mainly occurring in areas from Shizuishan to Toudaoguai Hydrological Station in Ningxia and Inner Mongolia. Water in this area flows from southwest to northeast, and serious ice disasters are possible due to inconsistencies in thawing times and freezing times between the upper and lower sections of the river. It is thus essential to strictly control runoff in the river during the 'ice period' from December to March. Fourthly, the Yellow River's ecological safety has become one of the most important objectives in the scheduling process, due to the impact of the frequent drying up of the river before the 1990s. The 'discontinuous flow prevention and control' task for the management of the Yellow River puts forward strict requirements for annual water dispatching. At present, the early warning discharges of Xiaheyan, Shizuishan and Toudaoguai Hydrological Stations have been set. The water scheduling rules implemented since December 1998 ensure the reasonable and healthy operation of the Yellow River, but there is an issue of energy wastage due to not fully utilizing the reservoirs' scheduling capability. In this paper, two major reservoirs, Longyangxia and Liujiaxia, and eight other hydropower stations in the upper and middle reaches of the Yellow River are taken as the research objects, and a multi-objective optimal scheduling model for the cascade reservoirs is established. The contradiction between power generation and water regulation is analysed, and the relationships between power generation, water supply, flood control, and ice control are established. This research will have a certain reference value for decision-making in the dispatching of water from the reservoirs.

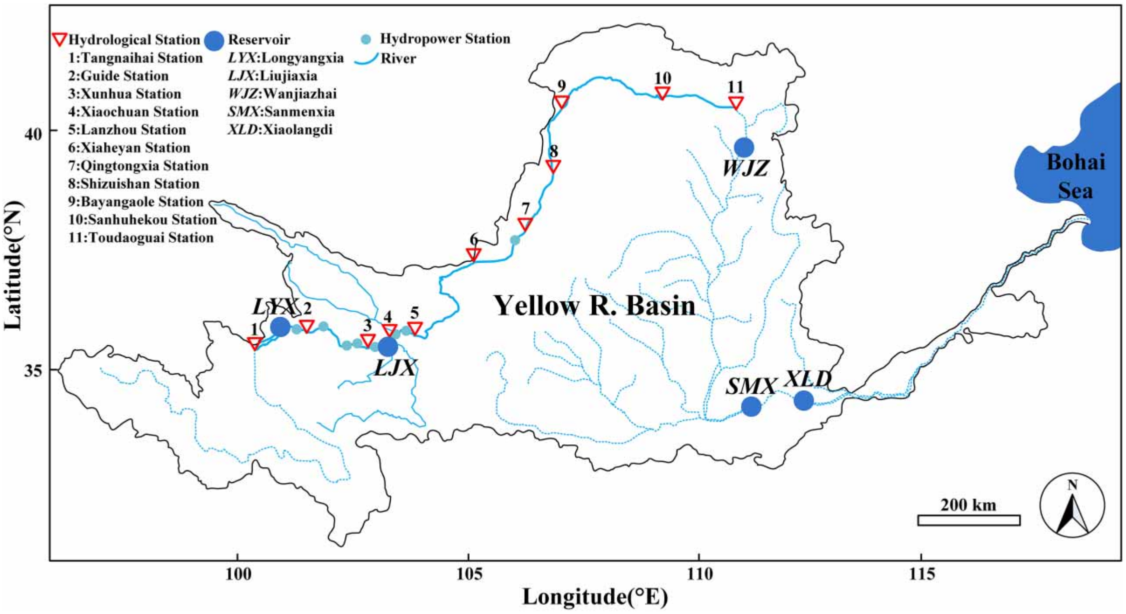

Figure 1 | Location of the study region (Yellow River Basin), reservoirs, hydropower stations, and main hydrological gauging stations.

METHODOLOGY

Data setting

In this paper, the upper and middle reaches of the Yellow River, from Tangnaihai to Toudaoguai Hydrological Stations, are selected as the study area. The locations of the study region, reservoirs, hydropower stations and main hydrological gauging stations are shown in Figure 1. The water demand data for each province (autonomous region) are provided by the Yellow River Conservancy Commission (YRCC), and the hydrological data from each hydrological station are provided by the Hydrology Bureau of the YRCC. There are two major reservoirs with regulation and storage capacity in the study area: Longyangxia and Liujiaxia. The parameters of Longyangxia and eight hydropower stations were provided by the Yellow River Hydropower Development Co., Ltd and the parameters of Liujiaxia were provided by the YRCC.

Model construction

With the successive operation of several large-scale water conservancy projects, the operation of cascade reservoirs along the upper and middle reaches of the Yellow River has gradually transformed from a single-objective into a multi-objective optimization problem, in which the aim is to maximize the benefits of flood control, ice control, water supply, power generation, etc. The formulas for these multiple objectives and constraints are presented as follows.

Objective functions

Flood control objective

To ensure the safety of upstream areas, downstream areas and dams during the flood season, the water level and outflow of reservoirs should be controlled according to the constraints described as follows:

$$Q(i,t) \leq Q_{\max}(i,t) \tag{1}$$

$$Z(i,t) \leq Z_{\max}(i,t) \tag{2}$$

where $Q(i,t)$, $Z(i,t)$, $Q_{\max}(i,t)$, $Z_{\max}(i,t)$ are the average outflow, average water level, maximum allowable outflow and maximum allowable water level of the ith reservoir during the tth scheduling period, respectively.

Ice control objective

The mainstream reaches of Ningxia and Inner Mongolia are frozen from December to March each year. During this period, the river flow should be strictly controlled within a certain range to avoid ice disasters in the frozen reaches. According to the relevant research, the safety of the river during the ice season can be ensured by controlling the outflow of the Shizuishan Hydrological Station. In this study, the outflow of the Shizuishan Hydrological Station during the ice season is controlled within the range of $[Q^*_{jt,\min}, Q^*_{jt,\max}]$. The function is expressed as follows:

$$Q^*_{jt,\min} \leq Q(j,t) \leq Q^*_{jt,\max} \tag{3}$$

where $Q(j,t)$, $Q^*_{jt,\min}$ and $Q^*_{jt,\max}$ are the average outflow, minimum allowable outflow and maximum allowable outflow of the jth hydrological station during the tth scheduling period, respectively.

Water supply objective

$$Q_{j,t} \geq \varepsilon \cdot D_{j,t} \tag{4}$$

where j is the river reach number; t is the scheduling period number; ε is the minimum water supply rate per scheduling period; and $D_{j,t}$ and $Q_{j,t}$ are the water demand and the water supply of the jth reach during the tth period, respectively.

Power generation objective

$$\begin{aligned} f_{\mathrm{p}} &= \max E = \max\left(\sum_{i=1}^{I}\sum_{t=1}^{T} K_i Q_{i,t} H_{i,t} \Delta t\right) \\ &= \max\left(\sum_{i=1}^{I}\sum_{t=1}^{T} N_{i,t} \Delta t\right) \end{aligned} \tag{5}$$

where E is the total power generation of the reservoirs; i is the reservoir serial number; Δt is the time step, I and T are the number of reservoirs and periods during the dispatch period, respectively; K_i is the integrated output coefficient of the ith reservoir; and $Q_{i,t}$ and $H_{i,t}$ are the discharge of water flows through the turbine, and the net water head of the ith reservoir during the tth period, respectively. $N_{i,t}$ is the amount of hydropower generated by the ith hydropower station during the tth period.

Constraints

Ecological flow

The outflow from hydrological stations should not be lower than their minimum outflow limit.

$$QA_{j,t} \geq QA_{j,t,\min} \tag{6}$$

where $QA_{j,t}$ and $QA_{j,t,\min}$ are the average and minimum allowable outflow of the jth hydrological station during the tth period, respectively.

Reservoir constraints

During the operation of the reservoirs, the water level, outflow and output of each reservoir should be within certain ranges, and the principle of water balance should be met.

$$Z_{it,\min} \leq Z_{i,t} \leq Z_{it,\max} \quad t = (1, 2, 3, \cdots\cdots, T) \tag{7}$$

where $Z_{i,t}$, $Z_{it,\min}$ and $Z_{it,\max}$ are the average, lowest and highest dam water level of the ith reservoir during the tth period, respectively.

$$Q_{i,t,\min} \leq Q_{i,t} \leq Q_{i,t,\max} \tag{8}$$

where $Q_{i,t}$, $Q_{i,t,\min}$ and $Q_{i,t,\max}$ are the average, minimum allowable and maximum allowable outflow of the ith reservoir during the tth period, respectively.

$$V_{i,t} = V_{i,t-1} + (I_{i,t} - Q_{i,t} - E_{i,t}) \cdot \Delta t \tag{9}$$

where $V_{i,t}$ is the capacity of the ith reservoir at the end of the tth period; $I_{i,t}$, $Q_{i,t}$ and $E_{i,t}$ are the inflow, outflow and lossflow of the ith reservoir during the tth period, respectively.

$$N_{i,t} \leq N_{i,t,\max} \tag{10}$$

where $N_{i,t}$ and $N_{i,t,\max}$ are the actual output and the installed capacity of the ith reservoir during the tth period, respectively.

Water supply constraint

Water supply should not exceed the limit of demand and the principle of water balance should be met at each node.

$$Q_{j,t} \leq D_{j,t} \tag{11}$$

$$I_{j,t} - Q_{j,t} = QA_{j,t} \tag{12}$$

where $Q_{j,t}$, $D_{j,t}$, $I_{j,t}$ and $QA_{j,t}$ are the diversion flow, demand flow, inflow and outflow of the jth node during the tth period, respectively.

Water balance between nodes

The flow equation between the upper and lower nodes of the river section shows the water balance between nodes. Because the water flow details become blurred when time steps of a month or 10 days are used, the water balance between nodes is described on the basis of the Muskingum method as follows:

$$\begin{aligned} QA_{j,t} = {} & \frac{\tau_{j,t}}{\Delta t} QA_{j-1,t-1} + \frac{\Delta t - \tau_{j,t}}{\Delta t} (QA_{j-1,t} - QT_{j,t}) \\ & + QI_{j,t} + QR_{j,t} - QL_{j,t} \end{aligned} \tag{13}$$

This is transformed into a reverse calculus formula:

$$\begin{aligned} QA_{j-1,t} = {} & \frac{\Delta t}{\Delta t - \tau_{j,t}} QA_{j,t} - \frac{\tau_{j,t}}{\Delta t - \tau_{j,t}} QA_{j-1,t-1} + QT_{j,t} \\ & - \frac{\Delta t}{\Delta t - \tau_{j,t}} (QI_{j,t} + QR_{j,t} - QL_{j,t}) \end{aligned} \tag{14}$$

where $QA_{j,t}$ is the average flow of the jth node during the tth period; $QT_{j,t}$, $QI_{j,t}$, $QR_{j,t}$ and $QL_{j,t}$ are the diversion flow, local inflow, return flow and loss flow from the (j-1)th node to the jth node during the tth period; $\tau_{j,t}$ is the time of the stream runs from the (j-1)th node to the jth node during the tth period; and Δt is the time step, which is selected as one month in this study.

Optimization method

The abovementioned model was applied to optimize the long series over the past 59 years (1957–2016), to study the trade-offs between power generation and water supply, flood control and ice control in the research area. Since power generation is the only target that needs to be optimized in the model, owing to the other objectives having been converted into constraints, the Modified (Wang *et al.* 2017) Progressive Optimality Algorithm (POA) (Howson & Sancho 1975) was used to solve the model. The Modified POA solves the problem of the 'curse of dimensionality' in dynamic programming, and has the advantage of global convergence under certain conditions. A great quantity of research has been conducted in an effort to improve the traditional POA algorithm with regard to the initial feasible solution and optimization method (Zhang *et al.* 2016). When solving the model, different constraint values for water supply, flood control and ice control are set, and these are transformed into the constraint for the reservoirs' outflow through the streamway reverse calculus formula. Thus, the optimal solution for power generation is calculated based on different constraint scenarios regarding flood control, ice control and water supply.

The initial water level of Longyangxia is set to 2,570 m, and the actual water level on July 1, 2016, is used as the final state. The average value of 1,722.30 m on July 1 is used as the initial and final state of Liujiaxia. When optimizing this model, the regulation capacities of Longyangxia and Liujiaxia are taken into account, and their scheduling is a typical multi-stage decision-making process. The total period is divided into T stages in monthly steps, with t representing the variable and $t = 0, 1, \ldots, T$, and $t - 1$ to t the current period and t to T the remaining period. The reservoir water level Z is selected as the state variable, and Z_t, Z_{t+1} are the initial and final states respectively at time t. The gross generation E is taken as the decision variable. The optimization steps are shown in Figure 2.

RESULTS AND DISCUSSION

The purpose of this section is to analyse the trade-offs between power generation and flood control, ice control, and water supply.

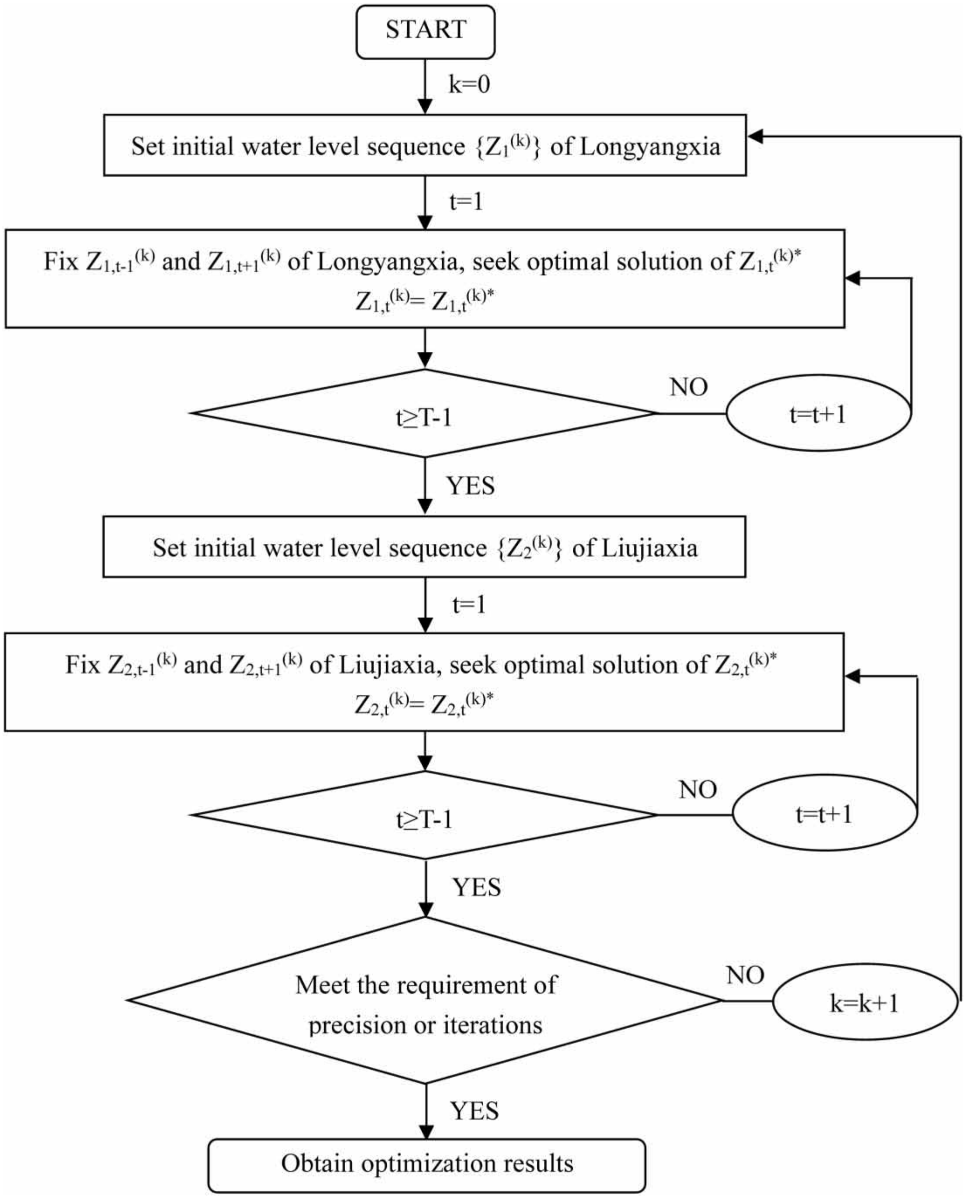

Figure 2 | Implementation steps for the model.

Trade-offs between objectives

Figure 3(a)–(c) show the competitive relationship between flood control, ice control, water supply and power generation. In Figure 3(a), the *x*-, *y*-, and *z*-axes represent the maximum water level of Longyangxia Reservoir during the flood season (LHWL), the water supply ratio (WSR) and the total power generation (TPG), respectively. The colour of the scattered dots represents the outflow values at Shizuishan hydrological station, from 550 to 750 m^3/s, during the ice season (ICOF). The arrows represent the optimization directions of the corresponding objectives. It can be seen that the ideal solution for power generation is in the upper corner of the plot, and the ideal solutions for water supply and flood control are located toward the rear left corner. However, there is no definite optimization direction for ice control. As can be seen from Figure 3(a), there are some complex relationships between the

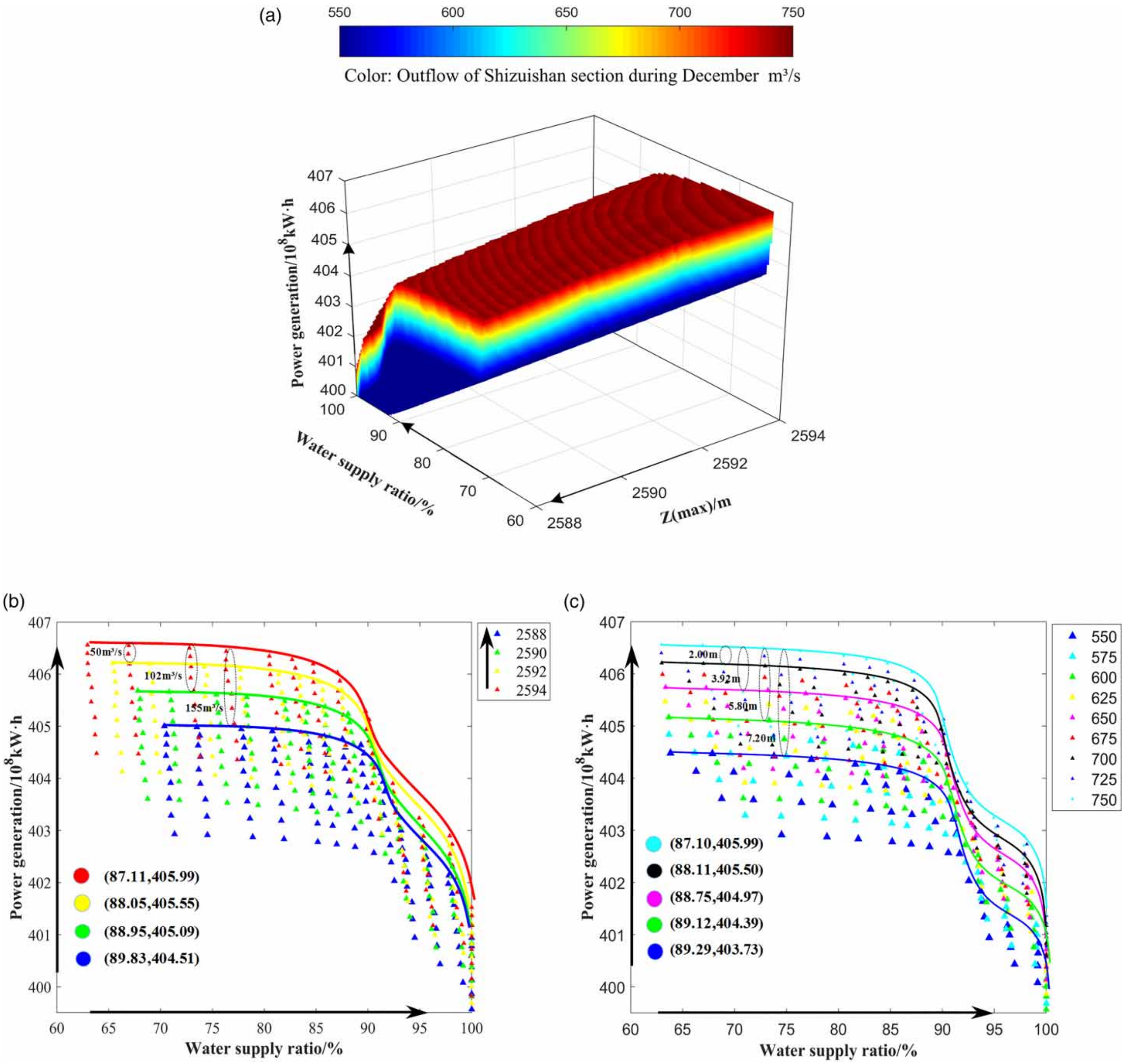

Figure 3 | Relationships among flood control, ice control, water supply, and power generation.

objectives. (1) WSR has a complex negative relationship with TPG (i.e. the former increases as the latter decreases) because an increase in WSR will affect the water head of the hydropower station. (2) LHWL has a positive relationship with TPG (i.e. the power generation shows an increasing trend with the rise of the maximum water level during the flood season). Therefore, effective utilization of the flood is of great value for improving power generation. (3) Increasing LHWL has no significant effect on alleviating the contradiction between WSR and TPG (i.e. the rate of reduction in TPG caused by increasing WSR is not affected by LHWL because the main period of conflict between power generation and water supply does not coincide with the flood season), which weakens the impact of flood control on the competition relationship between water supply and power generation. (4) TPG shows an increasing trend as ICOF increases from 550 to 750 m^3/s. Therefore, raising the outflow of Shizuishan hydrological station has a significant positive effect on power generation.

Impact of water supply on power generation

To analyse the relationship between water supply and power generation, the ideal solutions of TPG with different WSRs are obtained by setting different values of LHWL and ICOF, as shown in Figure 3(b) and 3(c). In Figure 3(b) and 3(c), the *x*- and *y*-axes represent the values of the water supply ratio (WSR) and total power generation (TPG), respectively. The arrows represent the optimization direction of corresponding objectives. The following can be seen:

1. Figure 3(b) shows the trade-off between TPG and WSR under different LHWLs without considering the value of ICOF. The scatter-points in different colours represent the ideal solutions under different LHWLs. It can be seen that when LHWL is kept at a certain value, the change rate of TPG shows a complex decreasing trend with the increase of WSR, and a point with the largest gradient can be found, which corresponds to the WSR and TPG values, as shown in the figure. When WSR is higher than the value of this point, power generation has to be sacrificed to obtain greater water supply. When WSR is less than this value, power generation will be low even if a great amount of water supply is sacrificed. Therefore, taking the two objectives of WSR and TPG into account, the ideal solution is found at this point.
2. Figure 3(c) shows the trade-off between TPG and WSR under different ICOFs without considering the value of LHWL. The scatter-points in different colours represent the ideal solutions under different ICOFs. It can be seen that when the ICOF is kept at a certain value, the rate of change in TPG shows a complex decreasing trend with increasing WSR. A point with the largest gradient can be found, which is the ideal solution, corresponding to the WSR and TPG values, as shown in the figure.
3. The rate of reduction in TPG caused by increasing WSR is basically not affected by LHWL or ICOF. This is because the water demand of the reservoirs is low during the flood and ice seasons, and the contradiction between water supply and power generation does not coincide with flood control and ice control objectives in the time domain. Therefore, changes in flood control and ice control objectives have no significant effect on the relationship between water supply and power generation.

The impact of maximum water level at Longyangxia Reservoir on power generation during the flood season

Due to the limitations of the initial operating conditions of Longyangxia Reservoir, the maximum water level in July and August has not reached the design standard of 2,594 m. In recent years, improvements to the project have made it possible to change the maximum water level during the flood season. Figure 3(b) shows the effect of adjusting LHWL on TPG. The following can be seen:

1. As LHWL is adjusted from 2,588 m to 2,594 m, the TPG of the ideal solution increases by 148 million kW h, with an average increment speed of 25 million kW h m^{-1}. Therefore, it is of great value to raise the maximum water level, or to use dynamic control technology at Longyangxia Reservoir, to enhance the utilization of the flood water resource for improved power generation in the flood season.
2. As LHWL is adjusted from 2,588 m to 2,590 m, 2,590 m to 2,592 m, and 2,592 m to 2,594 m, the TPG of the ideal solution increases by 58, 46 and 44 million kW h, with average increment speeds of 29, 23 and 22 million kW h m^{-1}, respectively. The result shows that with the increase of LHWL, the increase rate of TPG gradually slows down; i.e. TPG increases less and less for every 2 metres of LHWL elevation.

The impact of the outflow at Shizuishan Station on power generation during the ice control season

In the model established in this paper, the safety of ice control can be guaranteed by controlling the outflow within a certain range, and there is no definite optimization direction of outflow during the ice control season. However, the control flow value of Shizuishan Hydrological Station during December determines the control flow value from January to March of the following year, which will have a great impact on power generation from the cascade reservoirs. Figure 3(c) shows the effect of adjusting ICOF on TPG. The following can be seen:

(1) As ICOF is adjusted from 550 to 750 m^3/s, the TPG of the ideal solution increases by 226 million kW h, with an average increment speed of 113 million kW h/(100 m^3/s). Therefore, power generation from the cascade reservoirs can be improved by increasing the outflow during the ice control season, while ensuring the safety of the ice control, so as to make full use of the water resources.

(2) When ICOF increases from 550 to 750 m^3/s with a step size of 50, the TPG of the ideal solution increases by 49, 53, 58 and 66 million kW h, with average increment speeds of 98, 106, 116 and 132 million kW h/(100 m^3/s), respectively. This shows that with the increase of ICOF, the rate of increase of TPG gradually decreases; i.e. the additional TPG that can be obtained by increasing ICOF decreases.

(3) When ICOF increases from 550 to 750 m^3/s with a step size of 50, the WSP of the ideal solution decreases by 0.17%, 0.37%, 0.64% and 1.11%, with average increment speeds of −0.34%, −0.74%, −1.28% and −2.02%/(100 m^3/s), respectively. This shows that with increasing ICOF, WSP decreases more and more, and the decrease of ice control outflow has a more significant effect on the water supply rate.

(4) Relationships between the ideal solutions under different LHWLs and ICOFs can be analysed from Figure 3(b) and 3(c). Taking the ideal solutions under four values of LHWL and five values of ICOF as examples (the curves shown in the figure), the reduced values of TPG caused by ICOF decreases of 50, 100, 150 and 200 m^3/s on the basis of 750 m^3/s are almost the same as the reduced values of TPG caused by LHWL decreases of 2.00, 3.92, 5.80 and 7.20 m on the basis of 2,594 m, respectively. The result shows that the impact of the maximum water level (which has not reached the design standard) on power generation during the flood season can be compensated by increasing the outflow during the ice season. On the other hand, the impact on power generation caused by reducing the outflow during the ice season can be compensated by raising or dynamically controlling the maximum water level of Longyangxia Reservoir during the flood season, so as to raise the water supply rate indirectly while ensuring power generation.

CONCLUSIONS

In this paper, the multi-goal optimization scheduling of power generation, water supply, flood control and ice control of cascade reservoirs in the upper and middle reaches of the Yellow River has been studied. The trade-offs between power generation and other objectives are currently controversial with regard to the Yellow River. In view of this, a multi-objective optimal scheduling model of the cascade reservoirs on the upper and middle Yellow River was established, using the power generation from the reservoirs, the water supply rate, the maximum water level of Longyangxia Reservoir during the flood season, and the outflow of Shizuishan Hydrological Station during the ice season as the objectives. The Modified Progressive Optimality Algorithm (POA) was used to solve the model, and finally the relationships between power generation and water supply, flood control, and ice control were identified. This work has a certain reference value for multi-objective decision-making, and could allow for more informed decision-making for reservoir operation. The results obtained demonstrate the following:

(1) The conflict between power generation and water supply in the upper and middle reaches of the Yellow River is obvious. Increasing the water supply rate will affect the water head at the hydropower station, and the power generation from the cascade reservoirs shows a more and more obvious decreasing trend as the water supply rate increases. The point with the largest gradient change in the relationship between power generation and water supply is the optimal solution when weighing the two objectives. Changing the maximum water level of Longyangxia Reservoir in the flood season, and the outflow of Shizuishan Hydrological Station during the ice season, cannot alleviate the conflict between power generation and water supply.

(2) With increasing maximum water level in Longyangxia Reservoir, power generation shows an increasing trend, but with a gradually lessening rate of increase. Therefore, properly raising or dynamically controlling the maximum water level of Longyangxia Reservoir

during the flood season is of great value for increasing power generation.

(3) Changing the outflow at Shizuishan Hydrological Station during the ice season has an impact on power generation and water supply rate. Power generation increases significantly with increasing outflow during the ice season, but with the increment rate gradually slowing down. Increasing outflow during the ice season will reduce the water supply rate, with the reduction of water supply rate gradually increasing.

In this paper, we have taken the upper and middle reaches of the Yellow River as the study area, and analysed the trade-offs between power generation and other objectives using a visual analysis method. However, identifying the optimum process for coordination among multiple objectives is challenging and needs further study.

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