Research papers

Optimize multi-objective transformation rules of water-sediment regulation for cascade reservoirs in the Upper Yellow River of China

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Abstract

Frequent occurrence of flood and ice disasters caused by river channel sedimentation in the Upper Yellow River of China has seriously threatened the lives and property of downstream residents, which has become the most challenging issues in harnessing the Yellow River. In this paper, we aim at optimizing water-sediment regulation that considers two cascade reservoirs (Longyangxia and Liujiaxia) as the regulatory bodies using one multi-objective model (sediment transport and hydropower generation) and two single-objective models (sediment transport only, and hydropower generation only). We propose an innovative approach (FSS-MOPSO) that hybridizes the Feasible Search Space (FSS) with the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm to search the optimal solutions for the multi-objective joint operation of cascade reservoirs. We analyze the transformation rules of water-sediment regulation among five objectives (hydropower generation, sediment transport, water supply, flood control and ice control) under various optimization schemes. The results indicate that the conflict between the hydropower generation objective and the sediment transport objective is prominent. An extreme case indicates that an increase in hydropower output by 2.31 billion kW·h (17.6% increase) would greatly reduce the amount of sediment transport (73.5% decrease) while only makes little effects on the other three objectives. The results demonstrate that the optimal water-sediment regulation not only can ensure to meet water demands in the future (2030) but can provide an important guideline to safely operate cascade reservoirs during ice and flood periods. The research findings contribute to the identification of the relationship among objectives and strategy recommendations on water-sediment regulation for efficient cascade reservoirs operation in the Upper Yellow River.

1. Introduction

Rivers play a vital role in the transport of water, sediment and nutrients from terrestrial to marine ecosystems (Xia et al., 2016). However, the increasing extents of human activities and climate change have notable effects on river systems (Kiss and Blanka, 2012; Tripathi et al., 2006). As a result of land use changes and other anthropogenic influences, significant quantities of soil have eroded from landscapes, with subsequent transport into rivers, reservoirs or lakes (Alighalehbabakhani et al., 2016), which has caused serious river siltation. River sedimentation has resulted in the emergence of floods and ice disasters, which could seriously affect residents’ lives, property and economic development in basins, especially in the Yellow River Basin of China (Li et al., 2017; Wang et al., 2010; Fan et al., 2017; Wang et al., 2010). With the goal to maintain the health of the Yellow River, the joint reservoir operation technology has been used to establish a harmonious water-sediment relationship under the water-sediment regulation scheme for creating artificial flood peaks to scour river channels (Yang et al., 2017). The water-sediment regulation scheme (WSRS) has been implemented using the Xiaolangdi reservoir to manage the Yellow River since 2002, leading to two main benefits: the main river channel has been fully scoured in the lower reaches, and the reduction in riverbed elevation has slowed down obviously since 2005 (Miao et al., 2016; Wang et al., 2017a,b). Under this background, there is a need to explore multi-objective transformation rules of water-sediment regulation for mitigating disasters and improving the benefits of water conservancy facilities, especially in the Upper Yellow River.

Reservoir operation is a complex task that involves many decision variables, multiple conflicting objectives as well as considerable risk and uncertainty (Chang et al., 2010; Guo et al., 2004; Wang et al., 2010).
Reservoirs operation problems are mostly formulated as multi-objective ones, with many conflicting objectives and constraints. When tackling multi-objective problems, evolutionary algorithms (EAs) are commonly used to generate non-dominated solutions for obtaining the optima from a population of Pareto optimal solutions, rather than from a single solution. These features make EAs attractive for addressing complex water resources problems. The results produced by EAs are useful for decision makers to ensure equitable distribution of resources.

Fig. 1. Research flowchart for optimizing multi-objective cascade reservoirs operation.
among competing users. Nowadays, many Multi-Objective Evolutionary Algorithms (MOEAs) have been developed to solve various water resources problems. For instance, the particle swarm optimization (PSO) (Bai et al., 2015; Delgarm et al., 2016; Fu et al., 2018; Hojjati et al., 2018; Jia et al., 2018; Taormina & Chau, 2015; Ostadrahimi et al., 2012) and the non-dominated sorting genetic algorithm-II (NSGA-II) (Azadeh et al., 2017; Chang et al., 2016; Lei et al., 2018; Sadatsakkak et al., 2015; Tsai et al., 2015; Uen et al., 2018; Zhou et al., 2018a,b, 2019) have been used to optimize multi-objective reservoir operation. Existing multi-objective algorithms, however, have been criticized for lacking efficient and robust generic methods to handle constraints, low computational efficiency and easily falling into local optima. Although various techniques were applied to improving multi-objective evolution efficiency, the study of the relationship among objectives still suffers from a lack of in-depth discussions to clarify the types of relationship, for instance, fierce competition or little connection between each other. Improving the systematic analysis of multi-objective relationship is needed to guide the development of reservoir operation plans.

Sediment transport is one of the most important processes responsible for shaping the Earth’s surface (Elias, 2013; Houssais et al., 2015; Song et al., 2018; Wang et al., 2016). Riverine sediment is becoming a worldwide concern because of its great importance in engineering fields (Dai and Lu, 2014; Gomez, 2018). Dam and reservoir construction since the 1950s has caused an average of 44% decline in sediment supply at 33 major deltas in the world (Kemp et al., 2016). On the other hand, due to long-term coal-based electricity generation, China’s power industry has produced not only heavy burdens on provincial coal supplies but has also caused serious environmental deterioration (Zhao et al., 2014). Being one of the most effective and mature forms of clean and renewable energy, hydropower has attracted more attention since last decades (Bilgili et al., 2018; Ifaei et al., 2018; Tarroja et al., 2019; Zhang et al., 2018). However, sediment transport and hydropower generation constitutes a fuzzy relationship, which will lead to a series of problems like flood disasters if the relationship cannot be recognized.

In this study, cascade reservoirs Longyangxia and Liujiaxia located in the Upper Yellow River Basin of China forms the study case and various optimization models are established upon five important objectives to better manage the cascade reservoirs. A multi-objective Particle Swarm Optimization algorithm equipped with the Feasible Search Space technology is developed to effectively and efficiently obtain the optimal reservoir operation. This study would identify the relationship between various objectives and suggest reservoir operation strategies for sediment reduction, flood control and ice control (Fig. 1). The remainder of the paper is organized as follows. Section 2 briefly introduces the study area and cascade reservoirs. Section 3 establishes a multi-objective operation model involving three parts: objectives based on the functions of cascade reservoirs; related constraints; and the optimization methods. Section 4 presents and discusses the optimal results associated with different scenarios. The conclusions are drawn in Section 5.

2. Research area and data

The Yellow River, known as the “mother river” in China, is the fifth longest river in the world. It is also known as a river with the most massive sediment residing in its middle reach that flows through the Loess Plateau. The desert wide valley sections in the Upper Yellow River across the Tengger Desert, Hedong Sandy, Ulanbuh Desert and Kubuqi Desert extend 1080 km from the Xiheyuan County of the Ningxia to the Tuoketuo County of the Inner Mongolia. The desert wide valley sections have undergone the most dramatic evolution of the river channel and the most complicated interactions between water and sediment. Longyangxia and Liujiaxia reservoirs (Fig. 2) have great capabilities of regulation and storage and play an important role in water supply, irrigation, flood control, ice control and river sediment control for the Upper Yellow River. The values of the characteristic parameters for the cascade reservoirs are given in Table 1. In general, the operations of water-sediment regulation can only be carried out in wet years so that there is enough water to ensure a smooth implementation of water-sediment regulation. The reservoir operation in 2010 was selected as a study case because reservoir water levels were high in this wet year (Bai et al., 2015). Reservoir inflow mainly includes the inflows from the Longyangxia reservoir, the section of Longyangxia – Liujiaxia, and the section of the Liujiaxia – Lanzhou (Table 2). The flood season lasts from July to October whereas the ice season lasts from November to March. The monthly flow limit in the ice season is shown in Table 3.

To meet the balance of water supply and demand in the Yellow River Basin, a certain flow in the Lanzhou section must be guaranteed.

Fig. 2. Locations of the Yellow River Basin, reservoirs and hydropower stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Therefore, this study takes the Lanzhou station as the control station of water resources in the context of water supply and demand for the whole Yellow River Basin. Meanwhile, to investigate the effect of water supply on the Upper Yellow River under different scenarios, the water demands of 2010 and 2030 are selected to measure water supply efficiency, respectively (Du et al., 2013). The water supply efficiency for 2010 and the future (2030) are assessed based on “The Water Distribution Plan in 1987” and “The Comprehensive Planning of the Yellow River Basin (2012–2030)”, respectively (Xue, 2011). The monthly water demand in 2010 and 2030 are shown in Table 4.

The Xiaheyan-Toudaoguai section is the key sediment control section in the Upper Yellow River. Therefore, sediment transport effects in this section are identified. Regulation period and flow rate are two key factors in water-sediment regulation. In this study, the flow rates of the water-sediment regulation are set as 2240 m³/s and 2580 m³/s, respectively, while the duration of the water-sediment regulation is set to be 30 days (Hu et al., 2017). Based on historical flood data, the end of flood season (early April) is selected as the best period for water and sediment transport in this study.

3. Multi-objectives optimization model

With rapid economic development, the role of reservoirs has become substantially important to meet energy and water requirements (Zhou and Guo, 2013; Zhou et al., 2019). Serving as regulation hubs in the Upper Yellow River, Longyangxia and Liujiaxia cascade reservoirs have undertaken comprehensive resource utilization tasks. It not only needs to meet the water demands of different sectors and hydropower generation but also needs to carry out the task of sediment transport in the Yellow River. Moreover, it requires to ensure the safety of lives and property of downstream residents during flood and ice seasons. Therefore, five objectives including requirements for hydropower generation, sediment transport, water supply, flood control and ice control are considered as regulation objectives for Longyangxia and Liujiaxia cascade reservoirs.

3.1. Objective functions

3.1.1. Objective 1: hydropower generation

Hydropower generation is one of the most important objectives in this study. Hydropower outputs associated with hydropower stations built in the Upper Yellow River Basin are calculated as follows.

\[ \text{max}_i f_1 = \text{max} \left( \sum_{n=1}^{m} \sum_{t=1}^{T} (N(i, t) \times \Delta t) \right) \]  

(1)

where \( f_1 \) is the total hydropower output in a given period, \( N(i, t) \) is the average output of the \( i \)th hydropower station at time \( t \), \( \Delta t \) is the time interval, \( m \) is the number of hydropower stations, and \( T \) is the number of operation periods. \( K(i) \) is the output coefficient of the \( i \)th hydropower station.

3.1.2. Objective 2: Sediment transport

Sediment transport is another important objective in this study. The Xiaheyan-Toudaoguai river reach section is the key section with hydrological stations for managing the sediment transport of the desert wide valley reach. Therefore, the sediment transport (maximum) in this section is used as the measure of the effect of sediment transport on the Upper Yellow River, presented as follows.

\[ \text{max}_i f_2 = \text{max} \left( \sum_{n=1}^{m} \sum_{t=1}^{T} \omega(n, t) \Delta t \right) \]  

(3)

\[ \omega(n, t) = kQe^{n}(n, t)S^{n}(n, t) \]  

(4)

where \( f_2 \) is the total amount of sediment transport in a given period, \( Nu \) is the number of sediment transport sections, and \( \omega(n, t) \) is the sediment transport rate of section \( n \) at time \( t \), which refers to the measured data of the Yellow River Conservancy Commission (YRCC). \( Qe(n, t) \) is the sediment transport flow at the outlet (section \( n \)) at time \( t \), which varies from section to section. In this study, the sediment transport flow for the water-sediment regulation is set as 2580 m³/s in the Xiaheyan-Toudaoguai river reach section, which refers to the research finding of the flood sediment transport model in Zhang et al. (2008). \( S(n, t) \) is the sediment concentration of section \( n \) at time \( t \), which refers to the measured data of the YRCC. \( k \), \( a \) and \( b \) are the parameters of sediment transport rate of section \( n \) at time \( t \), which could be determined by the water-sediment relationship of section \( n \) (Zhang et al., 2008).

3.1.3. Objective 3: Water supply

To meet water demands, a certain flow in the Lanzhou section must be guaranteed. Therefore, the water supply objective can be expressed by water shortage (minimum), shown as follows.

\[ \text{min}_i f_3 = \text{min} \left( \sum_{t=1}^{T} [\varphi(t) \times (WQ(t) - QS(t))] \times \Delta t \right) \]  

(5)

\[ \varphi(t) = \begin{cases} 0 & WQ(t) \leq QS(t) \\ 1 & WQ(t) > QS(t) \end{cases} \]  

(6)

\[ QS(t) = QO(LL, t) + QO(LL, t) \]  

(7)

where \( f_3 \) is the total amount of water shortage in a given period, \( \varphi(t) \) is the coefficient of water shortage, and \( WQ(t) \) and \( QS(t) \) are the water demand and water supply of the Lanzhou section at time \( t \), respectively.
QW(t) is a known parameter that meets the water demand of the Lanzhou section, which is given by the YRCC for satisfying the water demand of the whole watershed. QO(LJX, t) is the outflow of the Liujiaxia reservoir at time t, QO(LL, t) is the flow from the Liujiaxia reservoir to the Lanzhou section at time t, which refers to the measured data of the YRCC, and Δt is the time interval.

3.1.4. Objective 4: Ice control

The main channel of the Ningxia–Inner Mongolia reaches would freeze when the temperature dips below freezing during the end of November and the next coming March (Bai et al., 2015). Therefore, the ice control objective is to control the water level (minimum) of the Liujiaxia reservoir at the beginning of the ice season (early November) under the premise of meeting the flow requirements of ice control.

\[ \begin{align*}
\min f_{QI} &= \min (Z(LJX, Nov) - Z_{\text{max}}(LJX, Nov)) \\
\text{QO}(LJX, t) &\leq \text{QO}_{\text{max}}(LJX)
\end{align*} \]  

where \( Z(LJX, Nov) \) and \( Z_{\text{max}}(LJX, Nov) \) are the water level and the upper limit of water level for the Liujiaxia reservoir in early November, respectively, \( \text{QO}(LJX, t) \) is the outflow of the Liujiaxia reservoir at time t during the ice season, \( \text{QO}_{\text{max}}(LJX) \) is the maximum outflow of the Liujiaxia reservoir at time t during the ice season to ensure ice control safety, which is a known parameter. \( \text{QO}_{\text{max}}(LJX) \) is given by the Ice Flood Control Preparedness (IFCP) of the YRCC to ensure ice control safety of the whole Ningxia–Inner Mongolia reaches.

3.1.5. Objective 5: Flood control

In the Yellow River Basin, flood disasters occur frequently each year. In order to meet the water demand for flood control, the flood control objective can be described to control the water level (minimum) of the Liujiaxia reservoir at the beginning of the flood season (early July) under the premise of meeting the requirements of the water level and outflow limit.

\[ \begin{align*}
\max f_{Z} &= \max (Z_{\text{max}}(LJX, July) - Z(LJX, July)) \\
Z_{\text{min}}(LJX, t) &\leq Z(LJX, t) \leq Z_{\text{max}}(LJX, t)
\end{align*} \]  

where \( Z_{\text{max}}(LJX, July) \) and \( Z_{\text{min}}(LJX, July) \) are the maximum allowable water level (i.e. 1728 m, the designed value of water level limit) and the water level of the Liujiaxia reservoir in early July, respectively. \( Z_{\text{min}}(LJX, t) \) and \( Z_{\text{max}}(LJX, t) \) are the minimum and maximum allowable water levels of the Liujiaxia reservoir at time t during the flood season, respectively, which could be determined by the designed values of the dead water level and the flood control water level for the Liujiaxia reservoir, respectively.

3.2. Constraints

3.2.1. Water balance

\[ V(i, t) = V(i, t - 1) + [Q_I(i, t - 1) - \text{QO}(i, t - 1)] \times \Delta t \]  

where \( V(i, t) \) and \( V(i, t - 1) \) are the initial storages of the ith reservoir at times t and t-1, respectively. \( Q_I(i, t - 1) \) and \( \text{QO}(i, t - 1) \) are the inflow and outflow of the ith reservoir at time t-1, respectively. \( \Delta t \) is the time interval.

3.2.2. Water level

\[ Z_{\text{min}}(i, t) \leq Z(i, t) \leq Z_{\text{max}}(i, t) \]  

where \( Z_{\text{min}} \) and \( Z_{\text{max}} \) are the minimum and maximum water levels of the ith reservoir at time t, respectively.

3.2.3. Outflow

\[ \text{QO}_{\text{min}}(i, t) \leq \text{QO}(i, t) \leq \text{QO}_{\text{max}}(i, t) \]  

where \( \text{QO}_{\text{min}}(i, t) \) and \( \text{QO}_{\text{max}}(i, t) \) are the minimum and maximum allowable outflows of the ith reservoir at time t, respectively. \( Q_I(i, t) \) and \( Q_I(t, t) \) are the outflow and inflow of the ith reservoir at time t, respectively. \( V(i, t + 1) \) and \( V(i, t) \) are the initial and final storages of the ith reservoir at times t + 1 and t, respectively.

Table 4

<table>
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<th>Year</th>
<th>Month</th>
<th>1</th>
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<td>754</td>
<td>452</td>
<td>452</td>
<td>650</td>
</tr>
</tbody>
</table>

3.2.4. Hydropower outputs

\[ N_{\text{min}}(i, t) \leq N(i, t) \leq N_{\text{max}}(i, t) \]  

where \( N_{\text{min}}(i, t) \) and \( N_{\text{max}}(i, t) \) are the minimum and maximum hydropower outputs of the ith reservoir at time t, respectively. In general, \( N_{\text{min}} \) is the guaranteed output and \( N_{\text{max}} \) is the installed capacity.

3.3. Search methods

Cascade reservoir operation is a complex problem, and it is a great challenge to make efficient water resources management for cascade reservoirs. The explored multi-objective water resources management model for the Upper Yellow River Basin involves inherent complex and high-dimensional variables with a large number of constraints on cascade reservoir operation. Many optimization algorithms have been applied to reservoir operation (Ahmad et al., 2014; Labadie, 2004; Wurbs, 1993; Yeh, 1985). Among them, EAs like the Multi-Objective Particle Swarm Optimization (MOPSO) and the Non-dominated Genetic Algorithm (NSGA-II) are good prospective tools to deal with nonlinear and multi-objective problems and they become popular in reservoir operation owing to their ability to find optimal solutions within reasonable computation time. As known, every method has its own advantages and disadvantages, depending on the types of problems involved in water resources, especially in reservoir operation (Ahmad et al., 2014). The Particle Swarm Optimization (PSO) proposed by Eberhart and Kennedy (1995) is one of the swarm intelligent methods. The PSO has been applied in many types of optimization problems (Zhang et al., 2014) whereas many researchers have developed various MOPSO for solving multi-purpose reservoir operation problems (Reddy & Nagesh Kumar, 2007; Ostadrahimi et al., 2012; Farshad et al., 2017; Zain et al., 2018; Zhang et al., 2014). Baltar and Fontane (2008) proposed an MOPSO to solve a multi-purpose reservoir operation and indicated that the MOPSO could make obtain better results as compared to the NSGA-II and the Pareto Archived Evolution Strategy (PAES). In this study, we use the PSO to solve the single-objective model while using the MOPSO to solve the multi-objective model.

3.3.1. Optimization procedure for the Feasible Search Space

To effectively solve the high-dimensional multi-objective cascade reservoirs operation problem, we first develop strategies for...
dimensionality-reduction and constraint transformation to obtain a Feasible Search Space (FSS). The core idea is to speed up solution convergence through reducing the search space, which can be achieved by effectively handling constraints. A detailed description of the methods adopted in this study is shown as follows.

Constraints can be divided into two categories: 1) transformable constraints, such as water level and flow constraints, where variables involved can be transformed directly into constraints; and 2) non-transformable constraints, such as outputs, variables involved are mostly associated with implicit functions and cannot be directly transformed into constraints (Bai et al., 2017). For a non-transformable constraint, since the range of its relevant variable cannot be directly converted into constraints, it will be controlled in the algorithm by identifying whether the decision variable satisfies the non-transformable constraint. For transformable constraints, a two-stage simulation method is used to eliminate infeasible solutions step-by-step (Fig. 3).

Implementation steps are addressed as follows.

**Step 1:** Set $i = T - 1$, the water levels of the reservoir at initial and final stages are set as $Z^0(i)$ and $Z^T(i)$, respectively.

**Step 2:** The first stage starts with $Z^0(i)$, and the middle stage is controlled by the transport restriction. The water level range at the end of the first stage is obtained and denoted as $Z^m(i) = [Z^m_{\text{min}}(i), Z^m_{\text{max}}(i)]$.

**Step 3:** Taking $Z^m(i + 1)$ as the final water level at the second stage, this period is controlled according to the transport constraint, where the initial water level that changes the water level range at the second stage is obtained from back-pushing. That is to say, the change in the water level range at the end of the first stage is recorded as $Z^t(i) = [Z^t_{\text{min}}(i), Z^t_{\text{max}}(i)]$.

**Step 4:** Taking the intersection of $Z^m(i)$ and $Z^t(i)$ as the water level range at the end of the $i$th stage $[Z^i_{\text{min}}(i), Z^i_{\text{max}}(i)]$, the water level at the end of the $i$th stage is randomly generated and recorded as $Z(i)$.

Then let $i = i - 1$, $Z(i) = Z(i)$.

**Step 5:** Terminate the judgment. If $i > 0$, go to Step 2, otherwise go to Step 6.

**Step 6:** Output the result.

3.3.2. Implementation procedure of the FSS-MOPSO

To increase computation efficiency, an improved multi-objective algorithm (FSS-MOPSO) that fuses the Feasible Search Space into the MOPSO is proposed in this study. The procedure is described as follows:

**Step 1:** Set the maximum number of iterations ($T$), the size of the population ($n$), and the number of dimensions ($m$). The water level during the scheduled period serves as the decision variable.

**Step 2:** Based on the known initial and final water levels of each reservoir, the initial sequence $Z(1), Z(2), \ldots, Z(i)$ can be randomly assigned within the refined FSS.

**Step 3:** Initialize the population $X^j(j = 1, \ldots, n)$ and the speed $VEL^j = 0(j = 1, \ldots, n)$ for each particle within the FSS. Then evaluate each particle based on Eqs. (1) and (3) and store non-dominated solutions in the archived repository (REP).

**Step 4:** Generate a hypercube.

**Step 5:** Initialize the memory of each particle by storing initial $X^j$ positions as the best positions found (BPF) so far. BPF$^j$ is set as follow.

$$BPF^j = X^j$$

**Step 6:** Compute the speed of each particle, shown below (Coello et al., 2004).

$$VEL^j = W \times VEL^j + R_1 \times (BPF^j - X^j) + R_2 \times (BPF^j - X^j)$$

where $W$ is the inertia weight, $R_1$ and $R_2$ are random numbers falling within the interval of $[0, 1]$.

**Step 7:** Maintain the particles within the search boundaries (Coello et al., 2004). When the value of a decision variable goes beyond its boundaries, then carry out two actions: 1) the decision variable takes the value of its corresponding boundary (either the lower or the upper bound), and 2) its velocity is multiplied by $-1$ so that the search moves toward the opposite direction.

**Step 8:** Evaluate each particle based on Eqs. (1) and (3).

**Step 9:** Apply mutation to each particle (Coello et al., 2004).

**Step 10:** Update the REP and the hypercube by inserting non-dominated solutions into the repository and eliminating dominated solutions from the repository.

**Step 11:** Update each particle memory by replacing the previous best position with the current best position found by each particle.

**Step 12:** If the maximum iteration is achieved, terminate and output multi-objective optimization results for cascade reservoirs (e.g. water level, flood, hydropower output). Otherwise repeat Step 6.

4. Results and discussion

4.1. Model design

In this study, two single-objective models configured by the PSO and one multi-objective model configured by the FSS-MOPSO are established to analyze the transformation rules of water-sediment...
regulation in the Upper Yellow River. Then the transformation rules of water-sediment regulation for cascade reservoirs are clarified based on three designed schemes, shown as follows.

4.1.1. Scheme 1: Hydropower generation maximization model

Scheme 1 assumes that hydropower generation is the only optimization objective in the optimal operation, which does not consider the maximization of sediment transport. The other three objectives (i.e., water supply, flood control and ice control) are converted into constraints.

However, aiming at comparing sediment transport results among different schemes, the sediment transport must be calculated by Eqs. (3) and (4) after obtaining the single objective optimization results associated with hydropower generation maximization. And the other three objectives are converted into water level and outflow constraints (as shown in Eqs. (7), (13) and (14)). The PSO is used to solve this model with data collected in 2010.

4.1.2. Scheme 2: Sediment transport maximization model

Scheme 2 assumes that sediment transport is the only optimization objective in the optimal operation, which does not consider the maximization of hydropower generation. The other three objectives (i.e., water supply, flood control and ice control) are converted into constraints.

Similarly, aiming at comparing hydropower generation results among different schemes, the hydropower generation objective is converted into constraint as shown in Eq. (16). And the other three objectives are converted into water level and outflow constraints (same as the above). The PSO is also used to solve this model with data collected in 2010.

4.1.3. Scheme 3: joint operation model for maximizing hydropower generation and sediment transport

Scheme 3 assumes that hydropower generation and sediment transport are the main objectives in flow regulation. The other three objectives (i.e., water supply, flood control and ice control) are converted into water level and outflow constraints (same as the above). It means that this model needs to consider both objectives for obtaining a set of compromised solutions. The FSS-MOPSO is proposed to solve the model with data collected in 2010.

For the three schemes, the value of the flow rates of the water-sediment regulation is set as 2580 m$^3$/s (Bai et al., 2016). The water level is selected as the decision variable. The parameters of the PSO and the FSS-MOPSO algorithm are shown in Table 5.

4.2. Results and discussion of the single-objective optimization model

The two maximization models associated with sediment transport and hydropower generation, respectively, are solved by the PSO. The optimal results are shown in Tables 6 and 7, respectively. In order to visually analyze the variations in water level and power output, monthly water level and monthly hydropower output obtained from the hydropower generation and sediment transport optimization models for Longyangxia and Liujiaxia cascade reservoirs are shown in Figs. 4–7, respectively.

As shown in Figs. 4–7, the year-initial and year-end water levels of the Longyangxia and the Liujiaxia are the same so that the total amount of water consumption for both optimization models are the same. Compared to that of the hydropower generation maximization model, the hydropower output obtained from the sediment transport maximization model is reduced by 17.6%, which causes a loss of 525 million RMB in power generation benefits. The reason could be that the sediment transport maximization model generated a large flow to “flush” the river in April, which resulted in a large amount of abandoned water. Meanwhile, the hydropower head of the Longyangxia is in a lower position during the late period, resulting in greater power loss.

The water supply amounts of the Lanzhou section obtained from the hydropower generation and sediment transport maximization models (schemes) are 37.3 billion m$^3$ and 36.3 billion m$^3$, respectively, which do not show much difference. It can be because that the two different schemes change the flow process only, without consuming water. The total water supply of the Lanzhou section will not make much difference under the premise of the same amount of outflow in the Longyangxia-Liujiaxia section, which indicates hydropower generation and sediment transport will not cause conflicts in water supply.

The water levels of the Liujiaxia reservoir in early November (early July) are 1725.9 m (1721.7 m) and 1724.7 m (1725.8 m) under the schemes of sediment transport maximization and hydropower generation maximization, respectively. That means the water levels of the Liujiaxia reservoir in early July under both schemes are less than the water level for flood control (1726 m). Meanwhile, the water level of the sediment transport maximization model is lower than that of the hydropower generation maximization model, which means the scheme for sediment transport maximization has a larger flood storage capacity and can be more conducive to flood control. The reason accounting for the phenomenon is that the objectives of flood control and ice control are influenced by the subsequent effects of large flow for channel scouring in April. In other words, the closer the regulation timing (such as July) to April is, the more significant the impact of flow on the objective is.

In addition to the greater negative impact on hydropower generation, the sediment transport maximization model has no significant impacts on water supply and flood control but has a positive impact on flood control. Among them, the effect of sediment transport is related to sediment transport flow, the sediment transport of each section is calculated by Eqs. (3) and (4), and the results are shown in Table 8. As shown in Table 6, the total amount of sediment transport reaches 59.74 million tons for the sediment transport maximization model, although the river sections (Qingtongxia–Shizuishan, Bayangou–Sanhehukou and Sanhehukou–Toudaoguai) shows micro-scouring situations for the hydropower generation maximization model. In contrast, the sediment transport effect for the hydropower generation maximization model is very small, with a total amount of sediment transport reaching 15.83 million tons only. The effect of sediment transport is greatly reduced by the hydropower generation maximization model. For example, the amount of sediment transport in the Sanhehukou–Toudaoguai section is 4.12 million tons, which decreases 18.05 million tons or 81%, as compared to that (22.17 million tons) of the sediment transport maximization model.

The hydropower generation maximization scheme represents the objective of maximizing hydropower generation efficiency for cascade reservoirs whereas the sediment transport maximization scheme

| Table 5 Parameters of the PSO and the FSS-MOPSO. |
|-------------------------|-------------------------|-------------------------|
| Parameter | Preset value | Parameter | Preset value |
| Population size | 200 | Population size | 200 |
| Iterations | 300 | Iterations | 300 |
| $c_1$ | 0.2 | $c_2$ | 0.2 |
| $w$ (inertia weight) | $\frac{2.05 \pm 0.2}{w^*10}$ | $c_1$ (personal learning coefficient) | $w^*0.5$ |
| $c_2$ (global learning coefficient) | $w^*0.5$ | $c_2$ (global learning coefficient) | $w^*0.5$ |
| $u$ (mutation) | 0.5 | $u$ (mutation) | 0.5 |
| $\beta$ (leader selection pressure) | 4 | $\beta$ (leader selection pressure) | 4 |
| $a$ (grid inflation rate) | 0.1 | $a$ (grid inflation rate) | 0.1 |
| $n$ (number of grids per dimension) | 100 | $n$ (number of grids per dimension) | 100 |
| $n_{grid}$ (the number of grids per dimension) | 10 | $n_{grid}$ (the number of grids per dimension) | 10 |
produces the largest sediment transport effect on the Upper Yellow River. If we want to further increase the amount of sediment transport in river sections based on the hydropower generation maximization scheme, the balance between hydropower generation and sediment transport will inevitably be broken, which means Longyangxia and Liujiaxia cascade reservoirs will abandon more water and therefore reduce hydropower outputs. How to find a balance between the two objectives to increase the amount of sediment transport, without significantly increasing the amount of abandoned water and reducing hydropower output, will be analyzed in Section 4.3.

### 4.3. Results and discussion of the multi-objective optimization model

The FSS-MOPSO is used to solve the multi-objective optimization model. The Pareto-Front curve of hydropower generation and sediment transport is shown in Fig. 8. Hydropower generation and sediment transport present a nonlinear contradiction, i.e. an increase in hydropower output will inevitably lead to a decrease in the amount of sediment transport. According to the characteristics of the Pareto-optimal solutions, it can be observed that any point lying on the Pareto-Front curve serves as an optimal solution to the multi-objective problem. Additionally, in order to verify the rationality of the multi-objective optimal solution, the Pareto-Front curve is combined with the solutions associated with the two single-objective optimization models, and the relationship between single- and multi-objective optimization models is compared. That is to say, the distance between a multi-objective extremum solution and the optimal solution of the single-objective optimization model would determine whether the proximity is reasonable. Results show that the optimal solutions associated with the two single-objective optimization models just fall on the endpoints of the Pareto-Front curve, confirming that the results of the three models are reasonable (Fig. 8).

To further analyze the difference between the multi-objective joint operation and the single-objective operation, a joint operation scheme (the black point in Fig. 8.) is selected from the Pareto-Front curve according to the objective weight 1:1. As shown in Table 9, both Longyangxia and Liujiaxia reservoirs have abandoned water, 75 m$^3$/s and 1146 m$^3$/s, respectively, during the operation of water-sediment regulation. Compared with the sediment transport maximization model (Table 6), the flows of abandoned water are reduced by 1500 m$^3$/s and 430 m$^3$/s for Longyangxia and Liujiaxia reservoirs, respectively. The difference between the joint operation scheme and the sediment transport maximization model is that the former not only can make full use of the annually adjusted storage capacity of the Liujiaxia reservoir but also can replenish water during water-sediment regulation. By this way, the Longyangxia reservoir can prevent from being the only hub for sediment scouring and large flow discharging, which may cause a large amount of abandoned water and affect the operation of the hydropower station seriously.

Furthermore, the results associated with the five objectives of the three optimization models are analyzed (Table 10). In order to eliminate the impact of different dimensionality of the five objectives on the

### Table 6
Optimization results of the sediment transport maximization model.

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longyangxia reservoir</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Inflow (m$^3$/s)</td>
<td>216</td>
<td>224</td>
<td>265</td>
<td>310</td>
<td>371</td>
<td>958</td>
<td>1994</td>
<td>888</td>
<td>635</td>
<td>553</td>
<td>378</td>
<td>188</td>
</tr>
<tr>
<td>Outflow (m$^3$/s)</td>
<td>429</td>
<td>392</td>
<td>475</td>
<td>2775</td>
<td>870</td>
<td>854</td>
<td>945</td>
<td>1018</td>
<td>714</td>
<td>561</td>
<td>528</td>
<td>572</td>
</tr>
<tr>
<td>Abandon water (m$^3$/s)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1575</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>Water level (m)</td>
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<td>2589</td>
<td>2587</td>
<td>2566</td>
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<td>2563</td>
<td>2572</td>
<td>2571</td>
<td>2570</td>
<td>2570</td>
<td>2569</td>
<td>2565</td>
</tr>
<tr>
<td>Hydropower output (MW)</td>
<td>523</td>
<td>473</td>
<td>566</td>
<td>1280</td>
<td>838</td>
<td>809</td>
<td>938</td>
<td>1046</td>
<td>735</td>
<td>579</td>
<td>543</td>
<td>574</td>
</tr>
<tr>
<td><strong>Liujiaxia reservoir</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inflow (m$^3$/s)</td>
<td>546</td>
<td>490</td>
<td>548</td>
<td>2835</td>
<td>995</td>
<td>1026</td>
<td>1160</td>
<td>1180</td>
<td>963</td>
<td>647</td>
<td>640</td>
<td>704</td>
</tr>
<tr>
<td>Outflow (m$^3$/s)</td>
<td>462</td>
<td>391</td>
<td>470</td>
<td>3128</td>
<td>1100</td>
<td>1171</td>
<td>1110</td>
<td>1079</td>
<td>775</td>
<td>809</td>
<td>800</td>
<td>491</td>
</tr>
<tr>
<td>Abandon water (m$^3$/s)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1576</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Water level (m)</td>
<td>1730</td>
<td>1732</td>
<td>1734</td>
<td>1728</td>
<td>1725</td>
<td>1722</td>
<td>1723</td>
<td>1725</td>
<td>1729</td>
<td>1726</td>
<td>1722</td>
<td>1727</td>
</tr>
<tr>
<td>Hydropower output (MW)</td>
<td>429</td>
<td>370</td>
<td>451</td>
<td>1350</td>
<td>978</td>
<td>1049</td>
<td>948</td>
<td>939</td>
<td>701</td>
<td>733</td>
<td>700</td>
<td>436</td>
</tr>
<tr>
<td><strong>Lanzhou section</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow (m$^3$/s)</td>
<td>540</td>
<td>472</td>
<td>521</td>
<td>3250</td>
<td>1240</td>
<td>1380</td>
<td>1530</td>
<td>1370</td>
<td>1010</td>
<td>945</td>
<td>938</td>
<td>627</td>
</tr>
</tbody>
</table>
regulation analysis, normalization of objective values is conducted, as shown in Table 11. Meanwhile, the normalized values of objectives for each scheme is plotted in Fig. 9. As shown in Fig. 9, the objectives of hydropower generation and sediment transport show significant differences under different schemes; however, the objectives of ice control, flood control and water supply show less differences. The values of hydropower generation and sediment transport under different schemes (the sediment transport maximization scheme, the hydropower generation maximization scheme, and the joint operation scheme) are 0.851, 1.000, 0.959 (hydropower generation) and 1.000, 0.265, 0.645 (sediment transport), respectively. Taking the two single-objective schemes as an example, when the hydropower output increases from 13.145 billion kW·h to 15.455 billion kW·h, the amount of the corresponding sediment transport decreases from 0.5974 million tons to 0.1583 million tons. This can be described as: an increase in hydropower output by 2.31 billion kW·h (17.6% increase) would greatly reduce the amount of sediment transport (73.5% decrease). At the same time, it also shows that the appropriate reduction of hydropower output can obtain a larger benefit of sediment transport. Water supply, flood control and ice control can meet their requirements, and overall, the values of these three objectives do not change significantly. It means sediment transport has little effect on these three objectives.

4.4. Multi-objective transformation under different scenarios

In order to further analyze the above-mentioned multi-objective transformation rules and investigate the changes of multi-objectives associated with water and sediment over the reaches of the Upper Yellow River in the future, we choose 2030 as the operation year. Therefore, this study designs four scenarios according to the initial water level of the Longyangxia and the flow for sediment regulation with respect to 2010 and 2030, as shown in Table 12. The four scenarios are optimized using the multi-objective model that considers the objectives of hydropower generation and sediment transport. The FSS-MOPSO is used to solve these four multi-objective models. In order to facilitate the comparative analysis of the four scenarios, the joint operation scheme is selected from the Pareto-Front curve according to the objective weight 1:1. The values of objective functions under each scenario are shown in Figs. 10 and 11.

Fig. 10 reveals several findings. With an increase in sediment regulation flow, the loss of hydropower output for the Longyangxia-Liujiaxia cascade reservoirs becomes 400 million kWh, but the amount of water supply from the Liujiaxia reservoir increases such that the reservoir has a lower water level before the flood season, which is more conducive to flood control for the Liujiaxia reservoir. Besides, the water supply in the Lanzhou section is increased by 700 million m³, which is more conducive to the balance between water supply and demand in Yellow River Basin under the premise of satisfying water supply requirements. The amount of sediment transport increases from 25 million tons to 39 million tons in the desert wide valley section, which means the effect of water-sediment regulation is significantly enhanced. The average loss of power generation is 1 kWh, which can increase...
Thereof, in 2010, further increase in water-sediment regulation flow can result in a smaller hydropower loss, in exchange for a larger sediment transport effect. This can be conducive not only to maintaining the relative balance of river channel erosion and siltation in the reaches of the Upper Yellow River but also to the realization of objectives with respect to water supply, flood control and sediment transport.

Fig. 11 illustrates that: (1) considering the water demand of 2030, hydropower output will be increased by 100 million kWh when sediment regulation flow is reduced (Scenario 3). However, the water level of the Lijiaxia before the flood season will be increased by 1 m and the amount of sediment transport will be decreased by 11 million tons while the amount of water supply will be decreased by 800 million tons and the ice control will be the same in Scenario 3 and Scenario 4. (2) Similar to the analysis for Fig. 10, with an increase in the comprehensive water demand over the Upper Yellow River Basin, an appropriate increase in sediment regulation flow will result in a smaller loss of hydropower generation, in exchange for greater sediment transport benefits. Meanwhile, increasing sediment regulation flow also increases the water supply of the Lanzhou section, which will not cause flood disasters in the downstream reaches of the Lijiaxia reservoir.

Above all, as the comprehensive water demand increases, increasing the sediment regulation flow to control water and sediment will result in the loss of hydropower generation. For example, the loss in 2010 under Scenario 2 is 400 million kWh, compared to 2010 under Scenario 1, and the loss in 2030 under Scenario 4 is 100 million kWh, compared to 2030 under Scenario 3. However, the loss of hydropower output will increase the water supply by 700 and 800 million tons for Scenario 2 and Scenario 4, respectively, which will be more conducive to ensuring water supply meets comprehensive water requirements. Therefore, with an increase of the comprehensive water demand in the future, the regulation of water and sediment with appropriately large flow can ensure the dam safety in the upper reaches of the Yellow River during the flood season, which will not aggravate the contradiction between

### Table 8

<table>
<thead>
<tr>
<th>Model</th>
<th>River section</th>
<th>Sediment transport maximization (10^6 t)</th>
<th>Hydropower generation maximization (10^6 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Xiaheyan – Qingtongxia</td>
<td>0.0227</td>
<td>0.0105</td>
</tr>
<tr>
<td></td>
<td>Qingtongxia – Shizuishan</td>
<td>0.0965</td>
<td>0.0571</td>
</tr>
<tr>
<td></td>
<td>Shizuishan – Bayanggole</td>
<td>0.0859</td>
<td>0.0066</td>
</tr>
<tr>
<td></td>
<td>Bayanggole – Sanhehukou</td>
<td>0.1706</td>
<td>0.0429</td>
</tr>
<tr>
<td></td>
<td>Sanhehukou – Toudaoguai</td>
<td>0.2217</td>
<td>0.0412</td>
</tr>
<tr>
<td>Total amount</td>
<td></td>
<td>0.5974</td>
<td>0.1583</td>
</tr>
</tbody>
</table>
Fig. 8. Pareto-Front of sediment transport and hydropower generation.

Table 9
Optimization results of the joint operation model.

<table>
<thead>
<tr>
<th>Month</th>
<th>Longyangxia reservoir</th>
<th>Liujiaxia reservoir</th>
<th>Lanzhou section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inflow (m³/s)</td>
<td>Outflow (m³/s)</td>
<td>Flow (m³/s)</td>
</tr>
<tr>
<td>1</td>
<td>216</td>
<td>469</td>
<td>540</td>
</tr>
<tr>
<td>2</td>
<td>224</td>
<td>451</td>
<td>466</td>
</tr>
<tr>
<td>3</td>
<td>265</td>
<td>429</td>
<td>509</td>
</tr>
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<td>4</td>
<td>310</td>
<td>1275</td>
<td>2820</td>
</tr>
<tr>
<td>5</td>
<td>371</td>
<td>1200</td>
<td>1240</td>
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<tr>
<td>6</td>
<td>958</td>
<td>1200</td>
<td>1465</td>
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<td>7</td>
<td>1994</td>
<td>1200</td>
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<td>8</td>
<td>888</td>
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<td>1570</td>
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<tr>
<td>9</td>
<td>635</td>
<td>1200</td>
<td>1260</td>
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<tr>
<td>10</td>
<td>553</td>
<td>836</td>
<td>945</td>
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<tr>
<td>11</td>
<td>378</td>
<td>691</td>
<td>938</td>
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<tr>
<td>12</td>
<td>188</td>
<td>365</td>
<td>627</td>
</tr>
</tbody>
</table>

Table 10
Values of objective functions under different schemes.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Sediment transport maximization</th>
<th>Hydropower generation maximization</th>
<th>Joint operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydropower generation (10⁸ kWh)</td>
<td>131.45</td>
<td>154.55</td>
<td>148.22</td>
</tr>
<tr>
<td>Sediment transport (10⁸ t)</td>
<td>0.5974</td>
<td>0.1583</td>
<td>0.3851</td>
</tr>
<tr>
<td>Water supply (10⁶ t)</td>
<td>363</td>
<td>373</td>
<td>367</td>
</tr>
<tr>
<td>Flood control (m)</td>
<td>1721.7</td>
<td>1725.8</td>
<td>1723.6</td>
</tr>
<tr>
<td>Ice control (m)</td>
<td>1725.9</td>
<td>1724.7</td>
<td>1725.3</td>
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</table>

Table 11
Normalized values of objective functions under different schemes.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Sediment transport maximization</th>
<th>Hydropower generation maximization</th>
<th>Joint operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydropower generation</td>
<td>0.851</td>
<td>1.000</td>
<td>0.959</td>
</tr>
<tr>
<td>Sediment transport</td>
<td>1.000</td>
<td>0.265</td>
<td>0.645</td>
</tr>
<tr>
<td>Water supply</td>
<td>0.973</td>
<td>1.000</td>
<td>0.984</td>
</tr>
<tr>
<td>Flood control</td>
<td>0.998</td>
<td>1.000</td>
<td>0.999</td>
</tr>
<tr>
<td>Ice control</td>
<td>1.000</td>
<td>0.998</td>
<td>0.999</td>
</tr>
</tbody>
</table>
5. Conclusion

Maintaining a healthy Yellow River through establishing a harmonious water-sediment relationship is a challenging and crucial task. In this study, we optimize multi-objective water-sediment regulation for reducing disasters and improving benefits of water conservancy facilities for two cascade reservoirs (regulatory bodies). The multi-objective cascade reservoir operation model involves inherent complex and high-dimensional variables with a large amounts of constraints. In this study, we establish three optimization models, i.e. the sediment transport maximization model, the hydropower generation maximization model and the joint optimal operation model, for deriving transformation rules of water-sediment regulation for the upper Yellow River. The PSO and the FSS-MOSPO are proposed to cope with the conflicts between five objectives, including sediment transport, flood control, ice control, hydropower generation and water supply. The main findings are drawn as follows.

(1) The Pareto-Front curve of hydropower generation and sediment transport (Fig. 8) obtained from the FSS-MOSPO indicates a non-linear contradiction between these two objectives, where an increase in hydropower output will inevitably result in a decrease in sediment transport. The quantitative transformation rule of these two objectives reveals: an average loss of 1 kWh in power generation would increase 0.039 ton of sediment transport in the case of year 2010. In other words, it’s worthwhile exchanging a small amount (loss) of power generation for a larger sediment transport volume.

(2) When sediment transport is maximized, water requirements associated with the objectives of water supply, flood control and ice control can also be fulfilled. Nevertheless, the changes in the outcomes of the three objectives are not obvious, which discloses sediment transport is related to the three objectives while making little effects on them.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Year</th>
<th>Regulation flow (m³/s)</th>
<th>Initial water level of the Longyangxia (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2010</td>
<td>2240</td>
<td>2591.5</td>
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<tr>
<td>2</td>
<td>2010</td>
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<td>2591.5</td>
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<td>3</td>
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<tr>
<td>4</td>
<td>2030</td>
<td>2580</td>
<td>2580.0</td>
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</tbody>
</table>

Fig. 9. Multi-objective radar chart.

Table 12
Water-sediment regulation scenarios.

Fig. 10. Values of objective functions under Scenarios 1 and 2 in the perspective of 2010.
(3) Expecting an increase of water demand in the future (2030), the derived water-sediment regulation using large flows can ensure the dam safety in the upper reaches of the Yellow River during the flood season. However, competition in water resources between power generation and sediment transport has been significantly mitigated, as compared to scenario 2010. This provides an efficient and sustainable development of water resources management strategies for decision makers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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