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Research papers

Long-term water-sediment multi-objectives regulation of cascade reservoirs: A case study in the Upper Yellow River, China

Wenting Jin, Jianxia Chang*, Yimin Wang, Tao Bai

State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China (Xi'an University of Technology), Xi'an 710048, China

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ABSTRACT

Water-sediment regulation (WSR) is an effective non-engineering measure to alleviate the problem of suspended river and bring benefit to flood control security in sediment-laden river. However, WSR may decrease the socio-economic benefit of reservoirs, for example, reduction of hydropower production and water supply. In order to satisfy the practical requirement of WSR and other utilization objectives, this paper presents a multi-objective operation model for a cascade reservoirs simultaneously considering the maximization water volume for WSR and power generation and water supply, as well as various complex constraints. Then, the Non-dominated Sorting Genetic Algorithm (NSGA-II) is improved to solve the aforementioned model and key control indicators of WSR are analyzed. Meanwhile, a sediment transport model has been introduced to quantify the effect of WSR. The models are applied to the cascade reservoirs in the Upper Yellow River. The following conclusion can be drawn from results (1) Pareto fronts of the model solution demonstrate a strong competition between WSR and water supply, water supply and power generation, a low sensitivity between WSR and power generation; (2) the ability of WSR in Upper Yellow River is 6 times in 24 years, which means the frequency of WSR is four years averagely; (3) 233.77 million tons of sediments are transported by long-term WSR in the Ningxia-Inner Mongolia reaches, account for 19.10% of sediment deposition; (4) the risk-free conditions of LYX and LJX reservoirs' water volume for WSR are $137.42 \times 10^8\,m^3$ and $41.08 \times 10^8\,m^3$, respectively, which could be used as a reference in actual operation. The research results have an important practical significance and application for sediment control and governance of suspended river, and the multi-objective operation model of WSR proposed in this study can be effectively and suitably used in sediment regulation with similar conditions.

1. Introduction

At the time being, developing countries are facing a serious situation with mounting demand of water supply caused by high population growth and worsening river ecological health (Ren et al., 2019). The problem gets even worse in sediment-laden river basin and has become a major bottleneck inhibiting sustainable economic and social developments (Ching and Mukherjee, 2015). Sediment deposition is an internal problem for sediment-laden river that cause various negative problems, for instance, reduce channel discharge capacity, decrease the available storage volume in reservoirs, induce downstream morphological changes, shrink the river channel, raise the riverbed and form perched river which exacerbate the possibility of severe flooding greatly (Miao et al., 2016;Hauer et al., 2018; Tang et al., 2019). Undoubtedly, the control and management of sediment deposition in rivers is a worldwide issue, and increasingly seen as an important environmental challenge for the sustainable development of water resources (Nittrouer and Viparelli, 2014; Hauer, et al, 2018).

In fact, many river basins around the world have to face the problems of sedimentation caused by anthropogenic activities. The Nile River Basin could be a useful case study of the potential negative downstream impacts of a large dam. The construction of the Aswan High Dam has trapped virtually all the sediment previously transported downstream, resulting in channel degradation downstream and disruption of downstream ecosystems and activities (fishing and agriculture) (Liu et al., 2018). Strategies for sediment management include land management (afforestation, promotion of minimum-till agricultural practices and erosion control programs), dredging, and 'flushing sediment' through of dams are propose in Nile River (Garazanti et al., 2015; Ebabu et al., 2019). Moreover, the Mississippi River Basin (Julien and Vensel, 2005; Remo et al., 2018) is a highly managed major river system with many large dams and reservoirs, numerous river training works, extensive levee systems and control structures for flood control. The impact of the decline in downstream

* Corresponding author.
E-mail address: chxiang@xaut.edu.cn (J. Chang).

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sediment supply, e.g. coastal wetland degradation, is especially severe in the marshes and estuaries of the Mississippi River Delta, and the authorities are working towards improving the situation (Maloney et al., 2018). Soil erosion and sediment delivery in the Volga Basin, in central Russia (Golosov and Belyaev, 2009), have undergone significant increases due to human activities and land clearing, and constitute a serious risk to its sustainable management. Sediment management within the Volga River Basin is largely focused on improving land management and agricultural practices to reduce soil erosion (Gusarov et al., 2018). The Yellow River Basin in China is well known for its very high sediment load, and probably the highest rates of soil erosion and sediment yield in the world within the Loess Plateau (Shi et al., 2017; Tian et al., 2019). Widespread land management has been implemented in the Yellow River Basin including major dam construction, afforestation, terracing, construction of check dams, and planting of trees and grasses on former crop land in the past several decades (Shi et al., 2019). Overall, it is thus evident that comprehensive control of sediment in watershed is a common challenge for sediment managers all over the world.

In general, the comprehensive control of sediment deposition in river is a complicated system need concerning reduction of sediment input (e.g. soil erosion, land-use change), sediment retaining, water-sediment regulation (hereafter, WSR), sediment transportation and artificial sand excavation (Li and Sheng, 2011; Kondolf et al., 2014; Maechi et al., 2019). One of them, WSR (as shown in Fig. 1), which is less investment, faster effect and easier to implement, release Controlled-flood from reservoirs to scour downstream riverbed which have raised gradually over past several decades owing to changes in river flow and sediment accumulation (Kong et al.,2015a; Liu et al, 2019). WSR is an effective non-engineering measure to alleviate the problem of perched river and bring benefit to flood control security. Meanwhile, we are aware that reservoirs play a significant role in regulating the fluctuant surface runoff to stably supply water for human needs and providing clean and renewable energy (Feng et al., 2017). Apparently WSR must inevitably lead to a more competitive relationship among multi-objectives of water resource utilization, and may threaten the safety of water supply and energy output. In view of this, the design and optimization of reservoirs for WSR must achieve a balance between sediment control and water resources development, hydropower production, flood control, and so on.

In previous studies about WSR, many researchers focused most of their attentions on operation of single reservoir and fewer objectives. Much more studies were related with the XiaoLangdi (hereafter, XLD, a yearly reservoir) located in the lower Yellow River, which had carried out the WSR annually since 2002, in order to scour the elevated riverbed downstream, and increased the bank-full discharge from 3700 $m^3 s^{-1}$ in 2000 to 6900 $m^3 s^{-1}$ in 2012 (Xia et al., 2014). The effects of WSR by XLD reservoir had been reported in many studies, such as the widening in main river channels (Ma et al., 2012; Fan et al., 2018), changes in hydrological characteristics (Xia et al., 2014; Dong et al., 2015; Wang et al., 2017a,b), as well as improvements in sedimentation features (Kong et al., 2015b; Yang et al., 2017; Bi et al., 2019). As outline above, the theories and practice of WSR had been widely applied for managing single reservoir operations. However, a multi-reservoir system with multi-tasking (e.g. WSR, water supply, power output, ice and flood control), especially the joint operation of multi-yearly reservoir and yearly reservoir, have complex structures of more than single reservoir in constraint conditions and numerous parameter variables. The multi-objectives optimal operation of WSR by multi-reservoir is a challenging work to be solved. Additionally, it is necessary to consider multi-objective evolutionary algorithms (MOEAs) to solve multi-objective problems. Undoubtedly, the non-dominated sorting genetic algorithm II (NSGA-II) has shown excellent performance in solving multi-objective reservoir operation models (Chang et al., 2014; Uen et al., 2018). Actually, the traditional NSGA-II algorithm is searching optimal results based on randomly generated initial population in the entire search space, and it is useful for short-term (e.g., one year) regulation of single reservoir or parallel reservoirs. However, for long-term operation of cascade reservoirs with interconnected and fixed regulation rules, the entire space is too large to search optimal results, and random generation of initial populations is no longer efficient and appropriate due to a large number of initial populations that do not conform to the regulation rules will reduce the maneuverability of the final optimal results. For purpose of improving the efficiency and suitability of the algorithm, the traditional NSGA-II has been improved in this paper, by shrinking feasible search space and generating initial population according to operation rules of cascade reservoirs, to support the model solution.

Overall, how to guide the joint operation of multi-reservoir based on improving the disharmonious relationship between water and sediment, give full play to the positive role of multi-reservoir in sediment control, realize the dynamic balance between WSR and reservoirs utilizable benefit, change the inappropriate operation modes of reservoirs which excessive pursuit of human benefits while neglect sediment

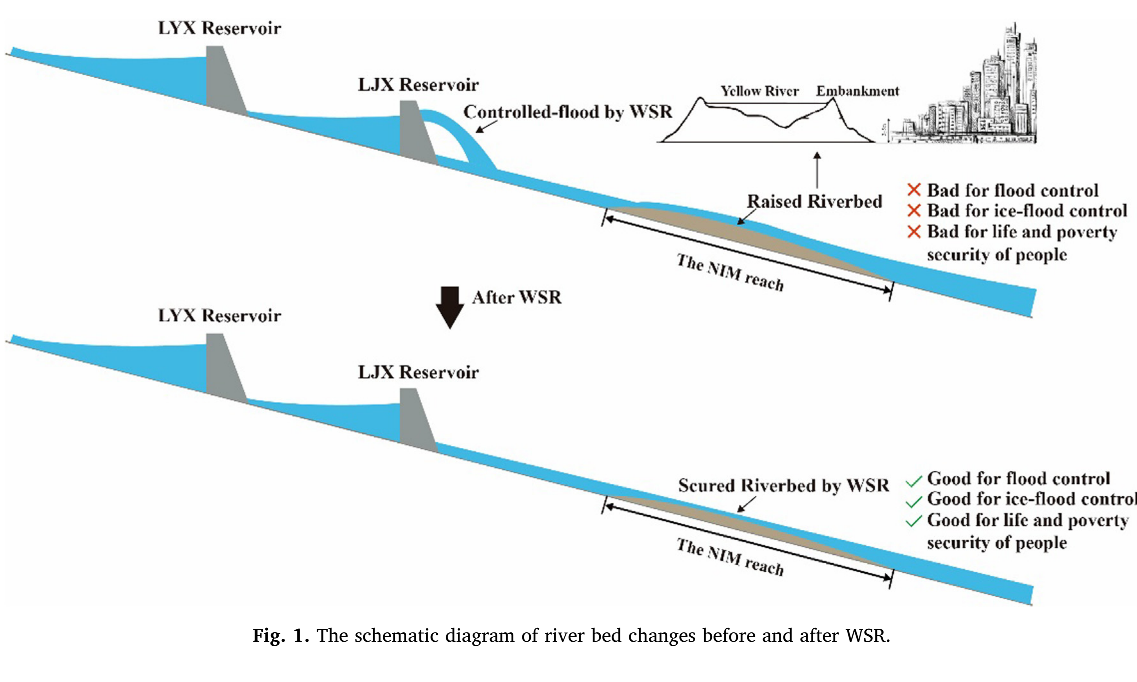


Fig. 1. The schematic diagram of river bed changes before and after WSR.

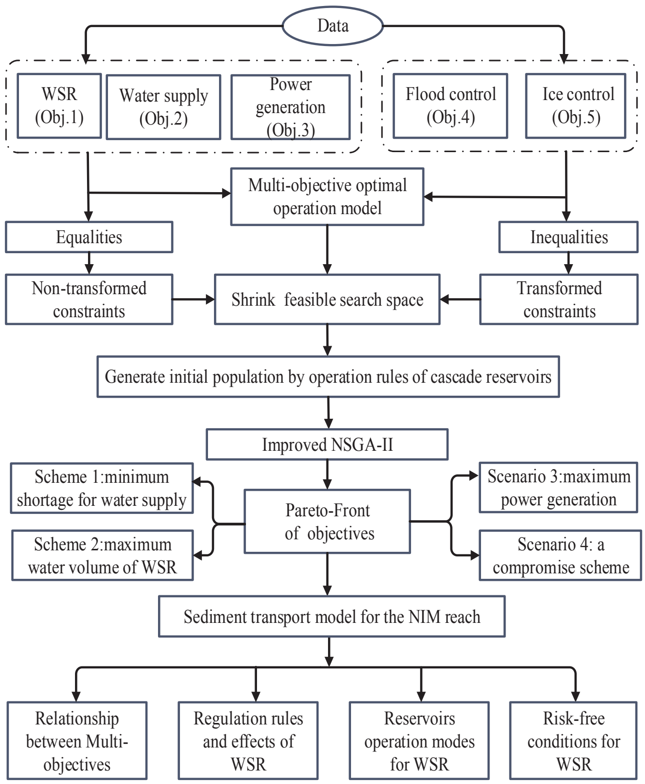


Fig. 2. The research flow chart of this article.

problem at present, provide decision-making basis for risk-free WSR in the actual operation of multi-reservoir, have become frontier problems of sediment management in sediment-laden river. Therefore, the present study is conducted to establish a multi-objectives model of WSR by multi-reservoir and solve it by improved NSGA-II algorithm, and also establish a sediment transport model to quantify sediment transport in WSR period. Then, the relationships between multi-objectives are revealed according to the Pareto fronts, the regulation rules and effects of WSR are obtained through the analysis of the frequency and sediment sluicing of WSR in the study area, the dynamic balance between multi-objectives are achieved by analysis of typical schemes, lastly the operation modes and risk-free conditions of cascade reservoirs for WSR are illustrated to guide the actual operation. The research route of this article is shown in Fig. 2.

2. Study area

2.1. Description of the Yellow River

The Yellow River is the second longest river in China, originates from the Bayan Har Mountains in the Qinghai-Tibet Plateau, flows through nine provinces with a length of 5464 km and a basin area of 0.75 million km^2, finally import into Bohai (Fig. 3) (Wang et al., 2019; Xu et al., 2019). The Yellow River is a major source of freshwater for approximately 8.7% of the total population in China, and water supply include municipal use, industrial use, irrigation, and ecological use (Chang et al., 2014). The monthly water supply demand of Lanzhou (hereafter, LZ) section in upper stream are shown in Table 1. The Yellow River is also a famous sediment-laden river in the world that has hyper-concentration flow with the characteristics of less water and more sediment obviously (Miao et al., 2010; Wang et al., 2017a,b). The recent data (2010–2013) shows the annual sediment load is approximately 1.5×10^8tons while the annual average runoff only $2.2 \times 10^{10}\,m^3$ (Xu et al., 2016). With the high speed development of social economy along the river and the reduction of upstream runoff, there has a sharp contradictory between water-supply and demand, which impair the relationship between runoff and sediment.

The Upper Yellow River is also one of the thirteen major hydropower bases in China, 25 reservoirs have been built or planned in this area with 16.3483 GW of total installed capacity, undertake the important task of transporting clean energy to the north-west electricity network (Li et al., 2018). Thus, water supply and power generation are the two main benefit objectives for water utilization. Additionally, flood control and ice control are the two major objectives for abolishing harmful in the Upper Yellow River. The Ningxia-Inner Mongolia reach (hereafter, the NIM reach) enters the ice control period from November to March of the following year. In this period, the days with an average daily temperature below 0 °C can last 4–5 months, and the coldest temperatures in the winter can reach −35 °C. Because the river flows from a low latitude to a high latitude, the freeze-up occurs from downstream to upstream in the winter, and break-up occurs from upstream to downstream in the spring, which may lead to ice jams or ice dams due to the quick increase of the ice-melt flood (Yang et al., 2004, Chang et al., 2014). In view of this, it is necessary to control ice disaster by limiting the discharge of upstream reservoir during the ice control period and maintaining the discharge within a stable and suitable range. The upper limit discharge of upstream reservoir during ice control period are shown in Table 2. In addition, to analyze multi-objectives regulation, long and extensive runoff data are collected from Yellow River Conservancy Commission (hereafter, YRCC), which consisted of monthly runoff series of 24 years for cascade reservoirs in the Upper Yellow River (1987–2010, monthly, Fig. 4).

2.2. Overview of sediment deposition in the NIM reach

The NIM reach in the Upper Yellow River flows through four deserts, they are the Tengri Desert, the east sandy land of Yellow River in Ningxia, the Ulanbuh Desert and the Kubuqi Desert (shown in Fig. 3). Ten primary tributaries of Yellow River in this reach originate from the Ordos Plateau and flow through the hilly and gully region of the northern Loess Plateau and the hinterland of the Kubuqi Desert, finally import into the Yellow River in the north of Ordos, Inner Mongolia (shown in Fig. 5). The precipitation is concentrated in flood season in the Ordos Plateau, although the annual precipitation is small, and usually in form of rainstorm in July and August. Thus, high peak discharge and high sediment concentration are the main characteristics of flood in the ten tributaries. Among the measured data of a hydrological station in one of the tributaries, the measured maximum peak discharge was 6940 m^3/s, the measured maximum sediment content was 1550 kg/m^3, the maximum sand transporting quantity of a flood was 47.4 million t, and the sediment transport modulus was above 40,000 t/km^2.

The river channel of NIM reach had been shrunk and sediment deposited seriously over the past three decades, as a sharp cut in runoff caused by construction of upstream dams had combined with high sediment concentration of ten tributaries inflow (Yao and Liu, 2018). Finally, a suspended river of 268 km has formed in the reach and the riverbed elevation is 3–5 m higher than cities along the river (shown in Fig. 6). This suspended river not only cause frequent flood and ice disasters, but also seriously affect the layout and implementation of major water conservancy projects and the utilization and development of water resources in the whole basin. Even more serious is that it endanger the safety of downstream river channel and life and poverty security of people (Chu, 2014). Given this circumstances, it is urgent to carry out WSR in the Upper Yellow River.

2.3. Cascade reservoirs in the Upper Yellow River

2.3.1. Overview of cascade reservoirs

There are two pivotal reservoirs bear the responsibility of WSR, water supply, power generation, ice and flood control in the upper

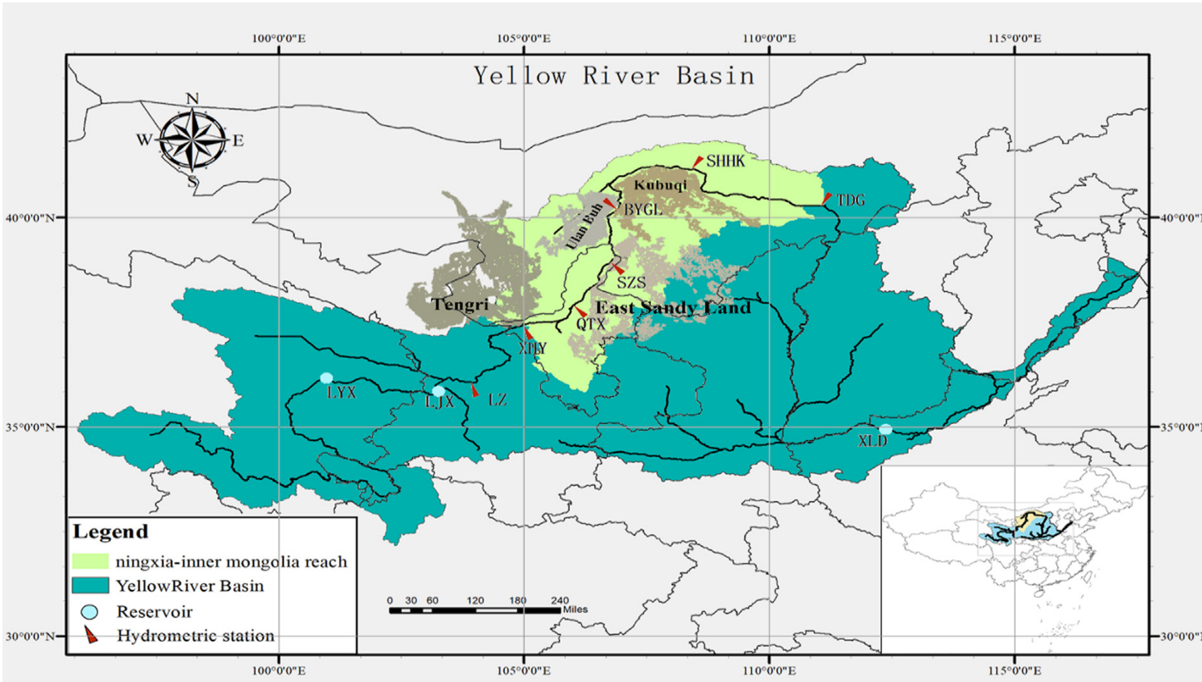


Fig. 3. Study area of the Yellow River.

Yellow River: Longyangxia (LYX), a multi-yearly reservoir and Liujiaxia (LJX), a yearly reservoir. In addition, taking power generation or agricultural irrigation as main task, thirteen run-off reservoirs have been constructed in the river reach from LYX to LZ hydrological section: (i) Laxiwa, (ii) Nina, (iii) Lijiaxia, (iv) Jishixia, (v) Zhiganglaka, (vi) Kangyang, (vii) Gongboxia, (viii) Shuzhi, (ix) Yanguoxia, (x) Bapanxia, (xi) Xiaoxia, (xii) Daxia, and (xiii) Qingtongxia. The annual average power generating capacity of the multi-reservoir system is 462.17×10^8 kW·h. Fig. 7 is the layout of the multi-reservoir system. The primary statistics of the two pivotal reservoirs are listed in Table 3.

2.3.2. Regulation rules of cascade reservoirs

In order to meet the requirements of comprehensive utilization of water resources, LYX and LJX have formed unique regulation rules in different periods (ice prevention period, irrigation period, flood control period) gradually in practical joint operation, which are used to guide the operation of cascade reservoirs. The regulation rules are described as follows, and shown in Fig. 8.

(1) Ice control period (November to March of the following year). In this period, outflow of LJX are limited strictly below upper discharge (shown in Table 2) to ensure the ice control safety of the NIM reach downstream, which escalate the conflict between prevention of ice disaster and power generation. As an effective measure to alleviate this contradiction, increasing the outflow of LJX in October and maintaining a reserve storage volume at the end of October, before the ice control period, is necessary to store the upstream generating flow of the LYX reservoir during ice control period. Thus the regulation rule of cascade reservoir in this period is that water level of LYX decrease continuously, and water level of LJX rise constantly, which can rise to the normal water level under ideal conditions. The mathematical expression of the rules of this period are described as formula (1).

(2) WSR period and irrigation period (April to June). There is an overlap, April, in this two periods that undertake the important task of sediment regulation and agricultural irrigation. To meet the large water demand in this period, the cascade reservoirs need to increase outflow capacity. Thus the regulation rule of cascade reservoir in this two periods is that water level of LYX and LJX decrease continuously. The mathematical expression of this rule are described as formula (2).

(3) Flood control period (July to October). The main task of cascade reservoirs during this period is to store water as much as possible under the premise of ensuring the safety of flood control. The water level of LYX reservoir cannot exceed the flood limit water level in the main flood season (July to September), but it can rise to the normal water level at the end of October. Different from LYX reservoir, the water level of LJX reservoir must be lowered at the end of October to reserve enough storage capacity for ice control period. Thus the regulation rule of cascade reservoir in this period is that water level of LYX and LJX rise constantly, and water level of LJX decrease in October. The mathematical expression of this rule are described as formula (3).

Table 2
Upper limit discharge of upstream reservoir during ice control period Unit: m^3/s.

Month	November	December	January	February	March
discharge	723	480	439	383	421

Table1
Monthly flow for water demand in the LZ section Unit: m^3/s.

Month	1	2	3	4	5	6	7	8	9	10	11	12
discharge	650	600	500	750	1100	900	800	750	750	800	750	700

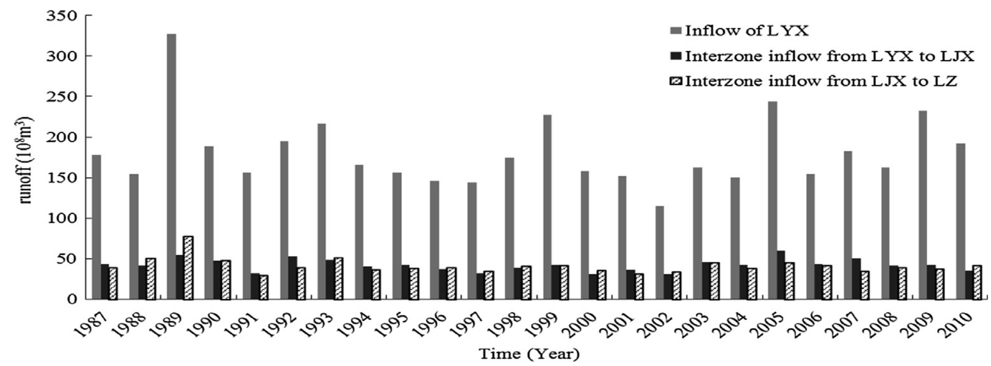


Fig. 4. Runoff process of the multi-reservoir system.

$$\begin{cases} Z_{\mathrm{LYX}}(i,j) \leqslant Z_{\mathrm{LYX}}(i-1,j) \\ Z_{\mathrm{LJX}}(i,j) \geqslant Z_{\mathrm{LJX}}(i-1,j) \end{cases} \quad i = 1, 2, 3, 11, 12; j = 1, \ldots, J \tag{1}$$

$$\begin{cases} Z_{\mathrm{LYX}}(i,j) \leqslant Z_{\mathrm{LYX}}(i-1,j) \\ Z_{\mathrm{LJX}}(i,j) \leqslant Z_{\mathrm{LJX}}(i-1,j) \end{cases} \quad i = 4, 5, 6; j = 1, \ldots, J \tag{2}$$

$$\begin{cases} Z_{\mathrm{LYX}}(i,j) \geqslant Z_{\mathrm{LYX}}(i-1,j) & i = 7, 8, 9; j = 1, \ldots, J \\ Z_{\mathrm{LJX}}(i,j) \geqslant Z_{\mathrm{LJX}}(i-1,j) & i = 7, 8, 9; j = 1, \ldots, J \\ Z_{\mathrm{LJX}}(i,j) \leqslant Z_{\mathrm{LJX}}(i-1,j) & i = 10; j = 1, \ldots, J \end{cases} \tag{3}$$

where $Z_{\mathrm{LYX}}(i, j)$ and $Z_{\mathrm{LYX}}(i-1, j)$ are the water level of LYX reservoir at end of i month and $i-1$ month in j year, respectively, m; $Z_{\mathrm{LJX}}(i, j)$ and $Z_{\mathrm{LJX}}(i-1, j)$ are the water level of LJX reservoir at end of i month and $i-1$ month in j year, respectively, m;

2.3.3. The role of cascade reservoirs for WSR

In consideration of the huge amount of water needed for WSR, how to distribute the WSR water in cascade reservoirs is an important issue of great concern to sustainability and economic feasibility of long-term WSR. Among the cascade reservoirs in the upper Yellow River, only the LYX reservoir is able to bear such a huge amount of water alone, but this will lead to large amount of abandonment water by LYX and its downstream power stations, further exacerbate the contradiction between power generation and sediment regulation. Therefore, the amount of sediment regulation water should be shared by LYX and LJX reservoir. For the regulation discharge of WSR, the LYX reservoir provide 1200 m^3/s (i.e. discharge for maximum power generation) to avoid large amount of hydropower be discarded by LYX reservoir and eight run-off reservoirs from LYX to LJX. Naturally, the rest of the regulation discharge of WSR released from LJX reservoir.

2.4. Key control indicators of WSR in the Upper Yellow River

Regulation discharge, regulation time and duration time of WSR are the three key control indicators which must be determined at first. The regulation discharge should be determined in conjunction with the relationship between runoff and sediment in the study area. The determination of regulation time and duration time of WSR should consider the multi-utilization of water resources in each month and the safety of downstream channel. For the Upper Yellow River, the three key control indicators have been determined as follows.

2.4.1. Regulation discharge

The regulation discharge of WSR is depended on the critical discharge of sediment transporting under different conditions of sediment concentration. Meanwhile, for different intervals, the critical discharge of WSR are inconsistent due to the disparities in geographical location, geology, landform, river morphology, and sediment conditions. When the regulation discharge reach to the critical discharge at a certain sediment concentration, the main channel sediment of the interval changes from siltation to scouring. Necessarily, the NIM reach has been divided into five intervals (as shown in Fig. 3): Xiaheyan (XHY) to Qingtongxia (QTX), Qingtongxia (QTX) to Shizuishan (SZS), Shizuishan

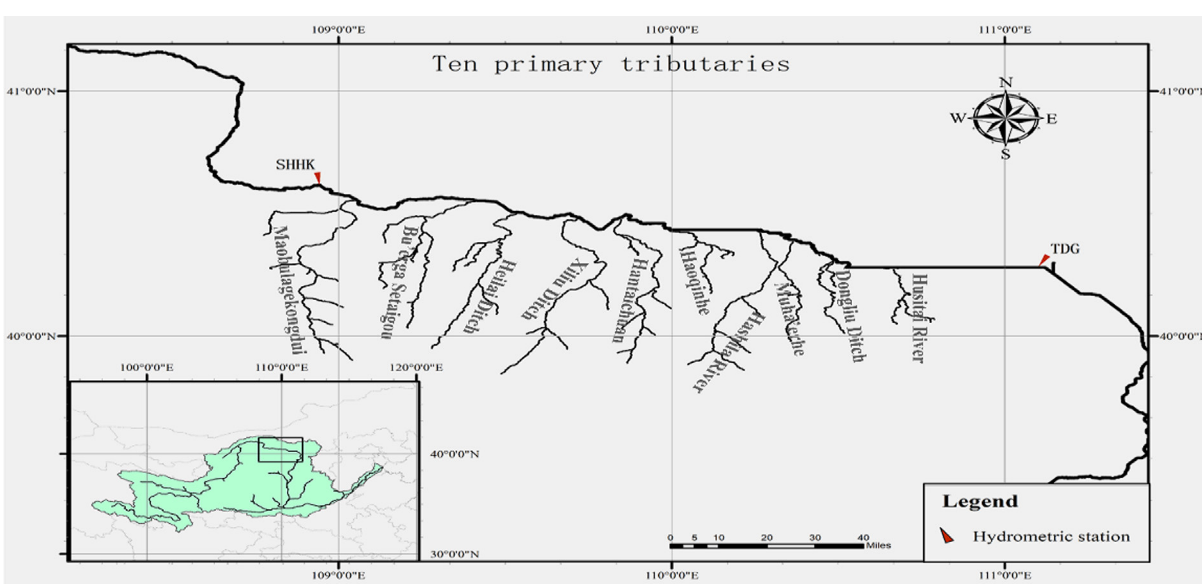


Fig. 5. Ten primary tributaries in the NIM reach.

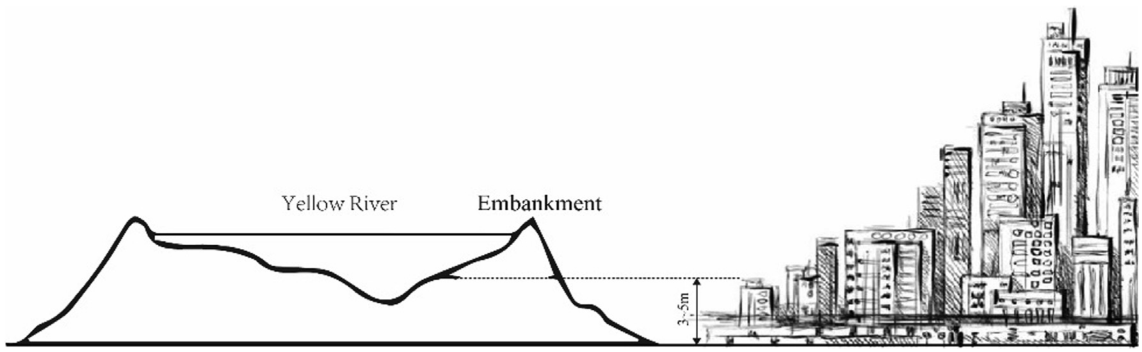


Fig. 6. Sketch map of suspended river in the NIM reach.

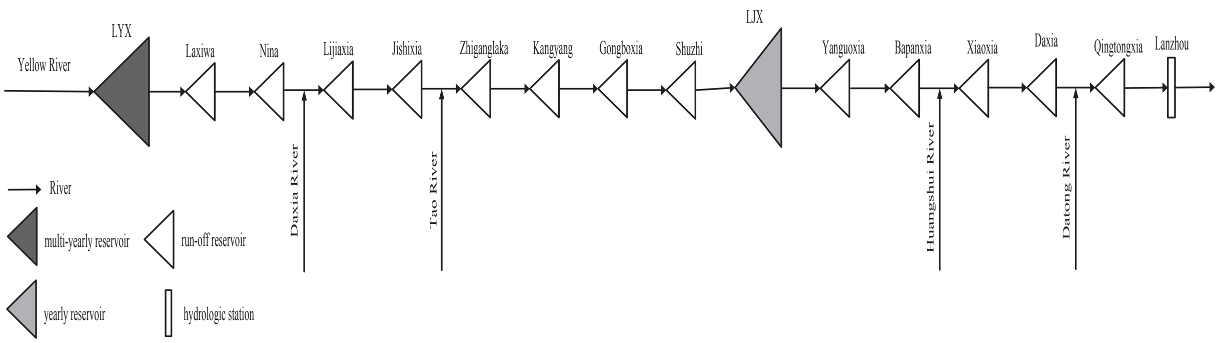


Fig. 7. The layout of the multi-reservoirs system.

Table 3
Major parameters of the LYX and LJX reservoirs.

Pivotal Reservoir	Normal water level/(m)	Flood control level/(m)	Dead water level/(m)	Total capacity/(10^8m^3)	Beneficial capacity/(10^8m^3)	Dead capacity/(10^8m^3)	Installed capacity/(10^5 kW)	Average annual output/(10^8kW·h)
LYX	2600	2594	2530	247	193.6	53.4	128.0	59.24
LJX	1735	1726	1694	57.0	41.5	15.5	135.0	57.60

(SZS) to Bayangaole (BYGL), Bayangaole (BYGL) to Sanhuhekou (SHHK), and Sanhuhekou (SHHK) to Toudaoguai (TDG). The sediment concentration is divided into four sections, they are 0–3 kg/m^3, 3–7 kg/m^3, 7–15 kg/m^3, above 15 kg/m^3, respectively. Critical discharge series of WSR in different sediment concentration of each interval can be obtained by analyzing the relationship between the average discharge during flood period and the sediment scouring or siltation amount of each interval based on historical data, as shown in Table 4 (Bai, 2014).

As can be seen from Table 4, the critical discharge has grown with increasing of sediment concentration in each interval which reflect the characteristic of large discharge bring large sediment transport in the NIM reach, while WSR is un-applicable for sediment concentration exceeded 15 kg/m^3. Thus, the maximum critical discharge is 2580 m^3/s when the sediment concentration between 7 and 15 kg/m^3 in BYGL-SHHK interval. In other word, the suspense sediment, which's sediment concentration is less than 15 kg/m^3, will be scoured in every interval of NIM reach by the discharge of 2580 m^3/s. At the same time, to alleviate the contradiction between WSR and other water use objectives, the second largest critical discharge of 2470 m^3/s is chosen as the lower limit of controlling discharge. At discharge of 2470 m^3/s, except the BYGL-SHHK interval with sediment concentration between 7 and 15 kg/m^3, the river bed can be scour in most intervals of the NIM reach. Thus, in this paper, the regulation discharge range of each section during WSR period is 2470–2580 m^3/s, recorded as $Q_R \in (2470, 2580)$.

2.4.2. Regulation time of WSR

According to the spatial and temporal distribution of water and sediment in upper Yellow River. The NIM reach enter ice period from November to March, and enter flood period from July to October. Obviously, the time of WSR must avoid these two periods while should been selected either follow the end of the ice control period (April) or before the flood control period (June). It is noteworthy that the XLD reservoir in lower Yellow River take WSR for 9–23 days in June every year (Dong et al., 2018). In order to avoid the superposition of upstream flow and downstream flow what will lead flood disaster in regulating period, the time of WSR in the Upper Yellow River could be April and choose 30 days as the duration of WSR.

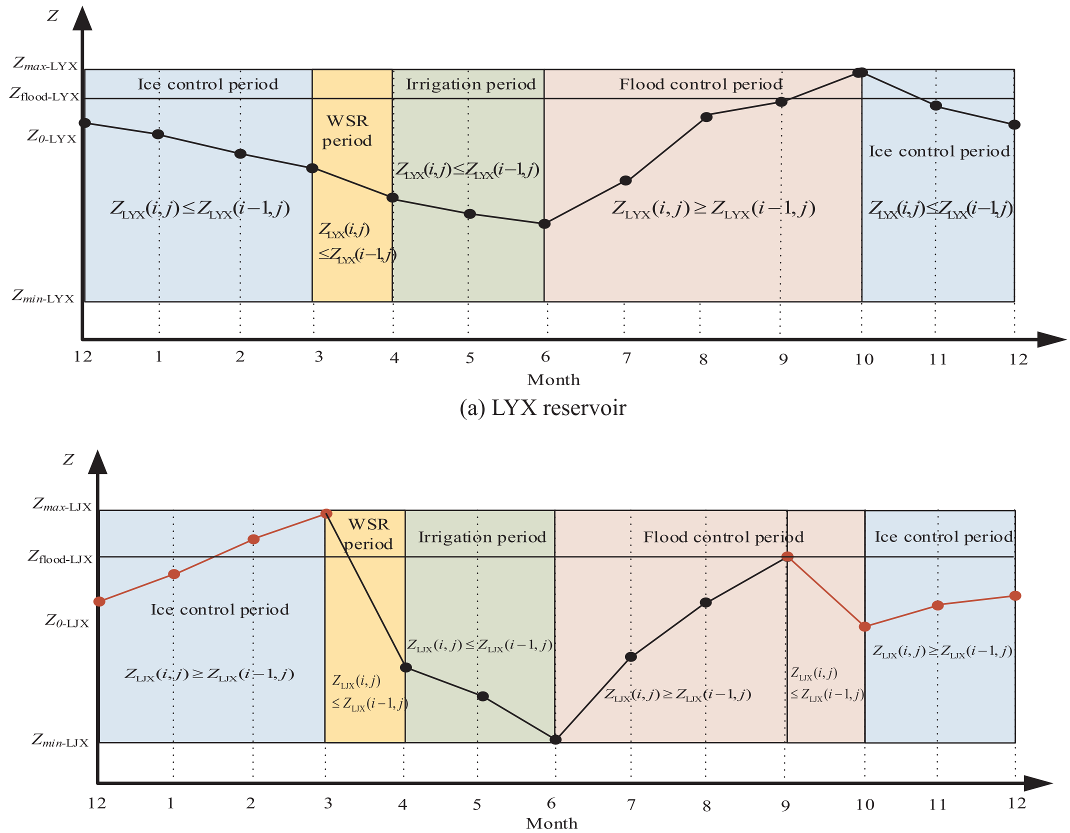
3. Methods

3.1. Model objectives

Five objectives, which include requirement for WSR, water supply, hydropower generation, ice and flood control, are considered in the model, and multi-objective optimal operation model of cascade reservoirs are established. It should be specially explained that cascade reservoirs in this model refer to reservoirs LYX and LJX, the thirteen run-off reservoirs are only used to count their electricity generation and not involved in optimal regulation. The formulations of multiple objectives and related constraints are presented as follows.

3.1.1. Objective 1: Water and sediment regulation (WSR)

In order to decrease the sediment deposition in the suspended river, WSR is urgent to implement effectively. It is necessary to clearly



(a) LYX reservoir

(b) LJX reservoir

Fig. 8. The annual regulation rules of cascade reservoirs.

Table 4
Critical discharge series of the Ningxia-Inner Mongolia reach Unit: m^3/s.

Interval of reach	Sediment Concentration/($kg{\cdot}m^{-3}$)			
	0–3	3–7	7–15	≥15
XHY—QTX	1150	2134	2180	—
QTX—SZS	623	1630	2130	—
SZS—BYGL	921	1720	2010	—
BYGL—SHHK	769	1430	**2580**	—
SHHK—TDG	780	2240	**2470**	—

Note: "—" means WSR is useless, bold fonts are the two largest numbers.

recognize that, for the upper Yellow River, normal and dry years are unsuitable for implementing WSR because of the heavy tasks of water supply and power generation of cascade reservoirs, and WSR will increase the risk of insufficient water supply in these years. While the years of high and partial high flow year are considered as the right time to carry out WSR. Therefore, in the operation model, some judgment conditions were set to judge WSR could be carried out or not in a given year. The judgment conditions include that 1) whether the given year is a wet year with a water coming frequency of less than 40%; 2) whether if the WSR carried out in the given year will lead a successive water-deficiency of water supply in the rest of regulating period. Finally, take the maximum total water volume used for WSR as object, shown as follows.

$$\begin{cases} W_s = \max \sum_{j=1}^{J} (Q_{LJX\mathrm{out}}(4, j) \times \Delta t) \\ s.\ t. \begin{cases} Q_{LJX\mathrm{out}}(4, j) = 1 \times Q_{LJX\mathrm{out}}(4, j) & Q_{LJX\mathrm{out}}(4, j) \geqslant Q_R \\ Q_{LJX\mathrm{out}}(4, j) = 0 \times Q_{LJX\mathrm{out}}(4, j) & Q_{LJX\mathrm{out}}(4, j) << Q_R \end{cases} \end{cases} \tag{4}$$

where$W_s$is the total water volume used for WSR, m^3; $j$is the number of year, $j = 1, 2, \cdots, 24$; $Q_{LJX\mathrm{out}}(4, j)$ is the outflow discharge of LJX reservoir at the fourth month (i.e., April) in j year, m^3/s; $Q_R$is the regulation discharge of WSR (see Section 2.4.1); Δt is the duration, s.

3.1.2. Objective 2: water supply

The YRCC has carried out the Integrated Planning of Water Resources on the Yellow River aid to satisfy water demand of the whole watershed. Thus, LZ is selected as the control section of water supply. Take the minimum water shortage for supply as object, shown as follows.

$$\begin{cases} W_d = \min \sum_j^J \sum_i^I (Q_d(i, j) - Q_g(i, j)) \times \Delta t \\ Q_g(i, j) = Q_{LJXout}(i, j) + Q_{LJX-LZ}(i, j) \end{cases} \tag{5}$$

where W_d is the total water shortage for supply, m^3; $Q_d(i, j)$ is the discharge demand in LZ section at $i$month in$j$ year, m^3/s; $Q_g(i, j)$ is the regulating flow in LZ section, m^3/s. $Q_{LJXout}(i, j)$ is the actual outflow of the LJX reservoir, m^3/s; $Q_{LJX-LZ}(i, j)$ is the inter-zone inflow of LJX to LZ interval reach, m^3/s. It's worth noting that according to the design planning of water supply in the Upper Yellow River, the design guaranteed rate is 75% for long-term water-supply.

3.1.3. Objective 3: hydropower generation

The original intention of building cascade reservoirs in the Upper Yellow River is improving the ability of meeting the demand of electric power with the development of economy. Thus, hydropower generation defined as follows is one of the most important objectives for the cascade reservoirs.

$$E = \max \sum_{j=1}^{J} \sum_{i-1}^{I} \sum_{m=1}^{M} N^m(i, j) \times \Delta t \tag{6}$$

where$E$ is the total generated energy of the cascade reservoirs in j year, kWh; $N^m(i, j)$ is the power output of m reservoir at i month in j year, kW. It is noteworthy that according to the design planning of hydropower generation in the Upper Yellow River, the design guaranteed rate is 90% for long-term power generation.

3.1.4. Objective 4: flood control

In flood period, flood control level of each reservoir must be controlled strictly to ensure the safety of dam and downstream areas, shown as follows.

$$Z^m_{\min}(i, j) \leqslant Z^m(i, j) \leqslant Z^m_{\max}(i, j) \tag{7}$$

where m is the number of reservoir; $Z^m(i, j)$ is the water level of m reservoir at end of i month in j year, m; $Z^m_{\min}(i, j)$ and $Z^m_{\max}(i, j)$ are the minimum and maximum allowable water level of m reservoir at end of i month in j year, respectively, m. In general, $Z^m_{\min}(i, j)$ is the dead water level, $Z^m_{\max}(i, j)$ is the flood control level.

3.1.5. Objective 5: ice control

In ice control period (November to next March), the main channel of Ningxia-Inner Mongolia reaches would be frozen when temperature dips below freezing. The stream discharge during ice control period must be descended into a low and safe magnitude determined by YRCC to maintain the safety of the Ningxia-Inner Mongolia reaches. LJX is the nearest reservoir upper the Ningxia-Inner Mongolia reaches, can control the discharge in ice control period. The formula is described as follow.

$$Q_{LJXout}(i, j) \leqslant Q_{ice-control}(i, j) \tag{8}$$

where $Q_{LJXout}(i, j)$is the actual outflow of the LJX reservoir, m^3/s; $Q_{ice-control}(i, j)$ is the upper limit of outflow during ice period, m^3/s. (Table 2).

The conflict of interests among the five objectives mentioned above is a challenge for the joint optimal operation of cascade reservoirs and the efficient utilization of water resources. More specifically, the implementation of WSR (Obj.1) will cause abandon electricity that reduce the ability of power output (Obj.3), and reduce the reservoirs' storage that may cause insufficient water supply (Obj.2) in the subsequent time period. In addition, in ice control period, the safe discharge of NIM reach (Obj.5) are too little to meet the demand of water supply (Obj.2) and the guaranteed output of LJX reservoir (Obj.3). Moreover, the Obj.3 needs to optimize both the outflow and water level of cascade reservoirs. In order to maximize the hydropower generation, it is necessary to reduce the outflow of reservoirs to raise the power water head sometimes. This would also contradict the Obj.2, as it could lead to a failure to meet the water supply.

3.2. Constraints

3.2.1. Water balance of single reservoir

$$V^m(i, j+1) = V^m(i, j) + [Q^m_{in}(i, j) - Q^m_{out}(i, j)] \times \Delta t \tag{9}$$

where $Q^m_{in}(i, j)$and$Q^m_{out}(i, j)$are the inflow and outflow of m reservoir at i month in j year, m^3/s; $V^m(i, j)$ and $V^m(i, j+1)$ are the initial and end storage capacity at i month in j year, respectively, m^3.

3.2.2. Water balance between reservoirs

$$Q_{LZ}(i, j) = Q_{LYXin}(i, j) + \Delta Q_{LYX}(i, j) + Q_{LYX-LJX}(i, j) + \Delta Q_{LJX}(i, j) + Q_{LJX-LZ}(i, j) \tag{10}$$

where $Q_{LYXin}(i, j)$ is the inflow of LYX reservoir at i month in j year, m^3/s; $\Delta Q_{LYX}(i, j)$ and $\Delta Q_{LJX}(i, j)$ are the discharge equated with storage or supply water quantity of LYX and LJX reservoir, respectively, m^3/s; $Q_{LYX-LJX}(i, j)$ and $Q_{LJX-LZ}(i, j)$ are the inter-zone inflow of LYX to LJX interval and LJX to LZ interval reach, respectively, m^3/s.

3.2.3. Water level

$$Z^m_{\min}(i, j) \leqslant Z^m(i, j) \leqslant Z^m_{\max}(i, j) \tag{11}$$

where $Z^m_{\min}(i, j)$ and $Z^m_{\max}(i, j)$ are the dead level and the maximum water level of m reservoir at end of i month in j year, respectively, m.

3.2.4. Outflow

$$Q^m_{\min}(i, j) \leqslant Q^m(i, j) \leqslant Q^m_{\max}(i, j) \tag{12}$$

where $Q^m_{\min}(i, j)$and $Q^m_{\max}(i, j)$ are the minimum and maximum allowable outflow of m reservoir at i month in j year, respectively, m^3/s. In general, the minimum outflow of reservoir is ecology base runoff of 300 m^3/s.

3.2.5. Power generation output

$$N^m_{\min}(i, j) \leqslant N^m(i, j) \leqslant N^m_{\max}(i, j) \tag{13}$$

where$N^m_{\min}(i, j)$and$N^m_{\max}(i, j)$ are minimum output and maximum output of m reservoir at i month in j year, respectively, kW. In general, $N_{\min}(i, j)$ is the guaranteed output and $N_{\max}(i, j)$ is the installed capacity.

3.3. Model solution by using improved NSGA-II

To dumb down the difficulty of solving the model, we reduce the dimension of multi-objectives, some of the objectives in Section 3.1 can be transformed into constraints which expressed in form of inequality (Obj.4 and Obj.5). So that the multi-objective problem is changed into a three-dimensional problem. It's important to note that, in order to facilitate model solving, we converted the formula of obj.2 from looking for minima to seeking maximum value through adding minus in front.

The NSGA-II is one of the most efficient and steady population-based MOEAs and has been widely used for the multi-objective analysis of multi-reservoir systems (Chang and Chang, 2009; Kumphon, 2013; Uen et al., 2018). The NSGA-II is proposed in 2000 based on NSGA which was proposed by Srinivas and Deb in 1990 (Deb et al., 2000), and it can efficiently solve optimization problems existing mutual restriction and influence among objectives. Obviously, in this study, relationships between power generation, water supply and WSR are considered be counter-balance. In view of this, we improve the NSGA-II algorithm to solve the multi-objective operation model and the detailed description of the improve methods are addressed as follows.

3.3.1. The shrinkage of feasible search space

In view of the special requirement on reservoirs operation in flood period and ice prevention period, and the limitation of inflow and maximum or minimum outflow discharge, the feasible search space must be smaller than that generated by initial constraints. Then, the feasible search space could be extracted from initial search region though removing unfeasible solutions. This action includes three steps: (1) firstly, all constraints are classified into three kinds: water level, outflow and power output, while constraints include the same elements in the same category. (2) Secondly, the intersection of the same kind of constraints are taken as a feasible region which means polymerization of constraints. (3) Lastly, reclassified the three kinds of constraints into two types: transformable constraints and un-transformable constraints. Transformable constraints mean that constraints of water level and outflow can be transformed into optimization variables directly. Un-transformable constraints mean that constraints of power output can't be transformed into optimal variables and shown as implicit function of optimal variables. For un-transformable constraints, we control operators of NSGA-II by judging whether the decision variable (power output) meets requirement. For transformable constraints, we reject infeasible solution and punish infeasible operators to shrink and optimize feasible search space before the initial population of swarm intelligence algorithm. Flow chart of shrinking the feasible search space is

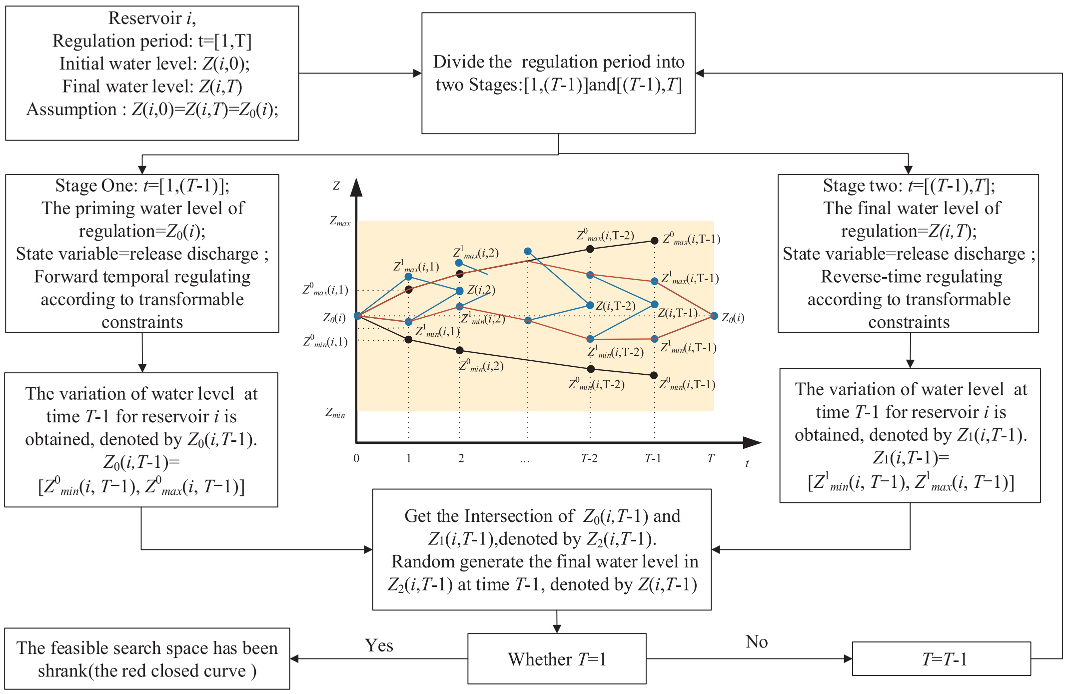


Fig. 9. Flow chart of shrinking the feasible search space.

shown in Fig. 9.

3.3.2. The generation of initial population according to regulation rules

After shrinking the feasible search space, generation of initial population is a key step for optimization and generated randomly in the traditional NSGA-II algorithm. When applied to the optimal operation of cascade reservoirs, water level is usually taken as state variable for initial individual. However, the water level process which randomly generated time interval by time interval in procedure of initial population generation must have contained state variables that do not conform to the regulation rules of cascade reservoirs, and this will be unfavorable to obtain more realistic optimization results. Therefore, generating initial population follow the regulation rules is an effective and practical improvement measure to enhance the adaptability of NSGA-II algorithm in optimal operation of cascade reservoirs. Different from the operation rule of single reservoir, the cascade reservoirs are often needed to cooperate with each other in joint operation to produce more comprehensive benefits. Thus the regulation rules of cascade reservoirs are more complicated, and the upstream and downstream reservoirs have fixed operation rules in different periods. If the initial population can be generated according to this rules, more realistic optimization results will be got. For the study area in this paper, the regulation rules of LYX and LJX cascade reservoirs have been described in detail in Section 2.3.2. In step of initial population generation, the water level variation processes of cascade reservoirs for each initial individual are generated according to formula (1), formula (2) and formula (3).

Given the above, Fig. 10 shows the flowchart of applying the improved NSGA-II to derive a non-inferior set of operation processes for multi-objectives regulation by cascade reservoirs.

3.4. Sediment transport model for the NIM reach

The sediment transporting quantity is an important physical value and useful engineering parameter to reflect the transportability of sediments of river channel. Establishing the conversion relationship between regulation discharge of WSR and sediment transporting quantity of the NIM reach is an important link to evaluate the effect of long-term WSR. In fact, Bai (2014) had established a sediment transport model which reflect the correlation formulas between sediment transport rate and section discharge and sediment content of each section reach based on the measured data of 65 historical floods in NIM, and the errors between calculated values and measured values were less than 10%. In this paper, the model shown as follows were employed to calculate the transported sediment quantity.

$$\text{QTX section:} R_{QTX}(i,j) = 0.011702 \times Q_{QTX}^{0.705}(i,j) \times S_{XHY}^{0.794}(i,j) \tag{14}$$

$$\text{SZS section:} R_{SZS}(i,j) = 0.000424 \times Q_{SZS}^{1.242}(i,j) \times S_{QTX}^{0.412}(i,j) \tag{15}$$

$$\text{BYGL section:} R_{BYGL}(i,j) = 0.000164 \times Q_{BYGL}^{1.240}(i,j) \times S_{SZS}^{1.083}(i,j) \tag{16}$$

$$\text{SHHK section:} R_{SHHK}(i,j) = 0.000159 \times Q_{SHHK}^{1.377}(i,j) \times S_{BYGL}^{0.489}(i,j) \tag{17}$$

$$\text{TDG section:} R_{TDG}(i,j) = 0.000064 \times Q_{TDG}^{1.482}(i,j) \times S_{SHHK}^{0.609}(i,j) \tag{18}$$

$$Q_n(i,j) = Q_{n-1}(i,j) + Q_n^{In}(i,j) - Q_n^{out}(i,j) \tag{19}$$

where $R(i,j)$ is the sediment transport rate in one section, kg/s; $Q_n(i,j)$ is the average discharge in n section, m^3/s; $n = 0, 1, 2, 3, \ldots, 6$ represent the LJX, XHY, QTX, SZS, BYGL, SHHK, TDG section, respectively; $Q_n^{In}(i,j)$ and $Q_n^{out}(i,j)$ are the inter-zone inflow and outflow of interval reach from $n-1$ section to n section, respectively, m^3/s; $S(i,j)$ is the sediment content of upper stream section, kg/m^3.

The sediment transport model given above is benefit to calculate the scouring sediment amount of NIM reach, and the Fig. 11 shows the calculating process of sediment transport in WSR period. It's important to note that it is impossible to obtain the measured value of sediment content during WSR period in each section needed in formulas (14)–(18) because WSR have not yet been carried out in the NIM reach in reality. Fortunately, artificial floods caused by WSR in April should have similar characteristics of sediment transport with natural floods in flood season. Therefore, the values of sediment content of each section during WSR period could be replaced by the measured data of a historical flood which's peak flow of maximal month flood discharge is closest to the controlling discharge of WSR.

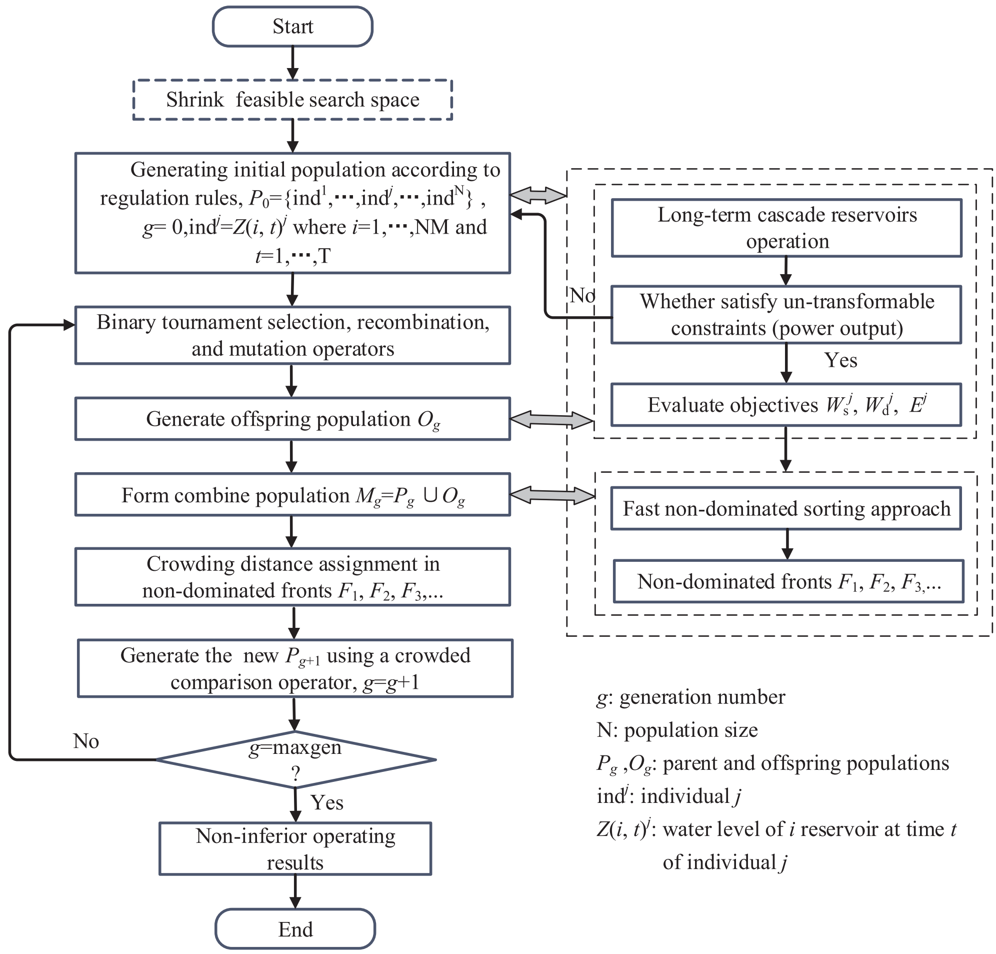


Fig. 10. Flow chart to optimize multi-objectives regulation of cascade reservoirs using the improved NSGA-II.

4. Results and discussion

Usually, for evolutionary algorithms in engineering applications, multiple trials are needed depending on two aspects: (1) the randomness which may largely influence the performance of evolutionary algorithms, and (2) the complexity of the optimization problem. Thus, we choose and analyze a relatively superior trial among many tries. The main parameters of the improved NSGA-II algorithm as

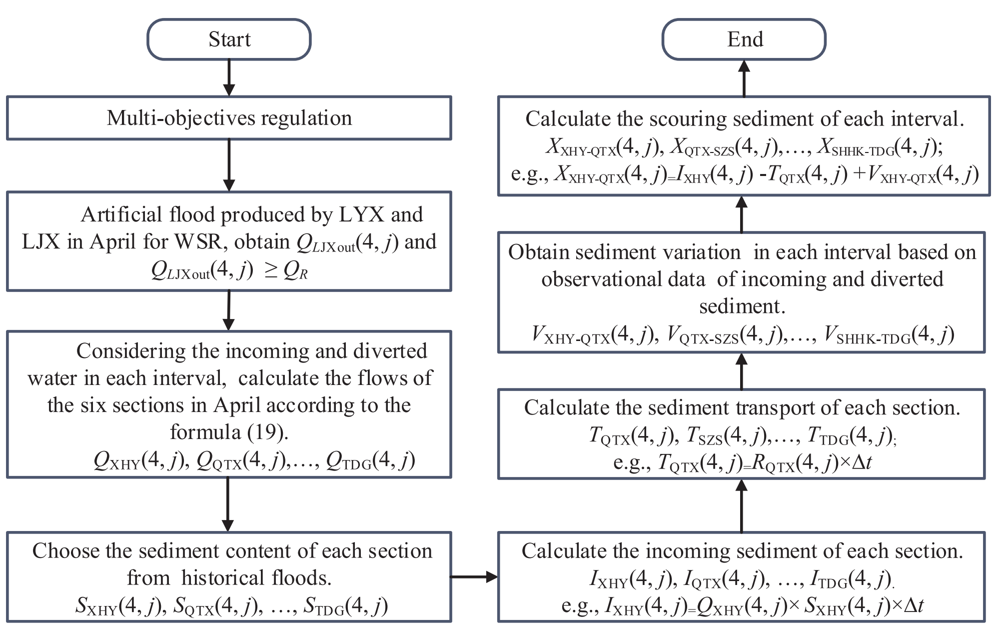


Fig. 11. Process of calculating the scouring sediment of each interval in the NIM reach.

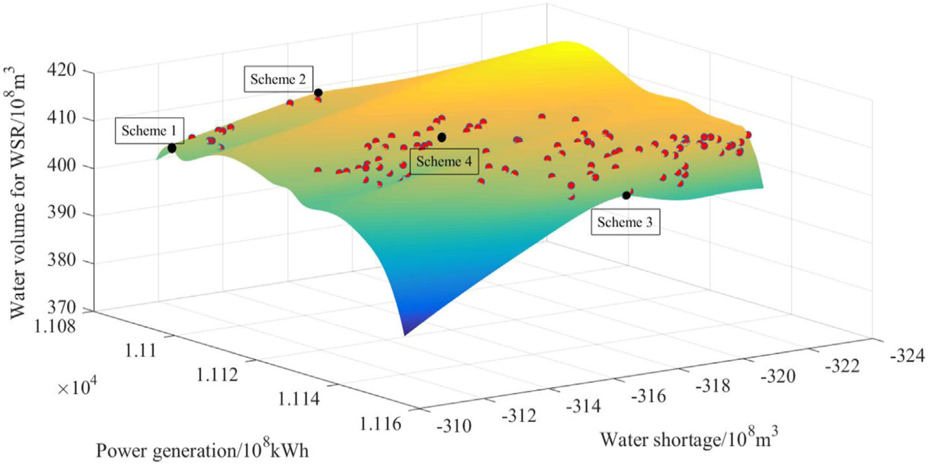


Fig. 12. Pareto-Front of three objectives by NSGA-II.

population size, number of generation, crossover ratio and mutation ratio, are 100, 3000, 0.8 and 0.3–0.01, respectively.

4.1. Competitive relationships between multi-objectives

The Pareto front or the decision space contains 100 feasible design alternatives, derived by improved NSGA-II algorithm, has been shown in Fig. 12. Meanwhile, the Pareto front has been projected into 2D space, as shown in Fig. 13.

Fig. 12 show that the Pareto-front of three objectives are well-distributed in a curved surface from 13840.67×10^8 kW·h to 13901.74×10^8 kW·h for the total generation, from $311.83 \times 10^8\,m^3$ to $322.93 \times 10^8\,m^3$ for the total shortage for water supply, and $375.68 \times 10^8\,m^3$ to $414.92 \times 10^8\,m^3$ for the total water volume of WSR. In addition, the transformation law between the three objectives had be revealed: when one objective increases, at least one of the other two objects decreases, which demonstrate apparent contradiction between the three objectives. Furthermore, Fig. 13 shows the relationship and sensitivity of every pair of objectives through two-dimensional planes. Subfigure (a) shows that the power generation is decreasing while the shortage of water supply is decreasing, i.e., the water supply is increasing, which proves that there is an obvious competitive relationship between the two optimization objectives. It can be observed from Subfigure (b) that the competitive relationship is still clear between the water volume of WSR and the shortage of water supply. However, the competitive relationship is less clear between the water volume of WSR and the power generation in subfigure (c), demonstrate that the power generation is less sensitive to the increase of the water volume of WSR. This may be due to two reasons, (1) the operation policy of cascade reservoirs during the period of WSR, the outflow of LYX reservoir is only $1200\,m^3/s$ (maximum power generating flow) to avoid a great loss of hydropower for eight runoff reservoirs from LYX to LJX, and minimize the losses of hydropower; (2) in periods of WSR which is in a minority, the water volume for WSR is far greater than the maximal usable water for power generation cause the power generation is low insensitive to a spot of increasing or decreasing of WSR water.

In general, the relationship between the three objectives can be described that, as shown in Fig. 14, the Obj.1 has an intense competition with Obj.2 owing to the water supply capacity of cascade reservoirs is restricted in several months after WSR. Similarly, the Obj.2 has an intense competition with Obj.3 because of the relatively stable process of water supply leading the cascade reservoirs reduce the power water head considerably. Whereas the Obj.3 is insensitive to Obj.1.

4.2. Multi-objective analysis of typical schemes

4.2.1. The comprehensive efficiencies for multi-objectives

Four typical schemes were chosen from among 100 alternatives to further analyze the relationships between the three objectives, they are scheme 1 (minimum shortage for water supply), scheme 2 (maximum

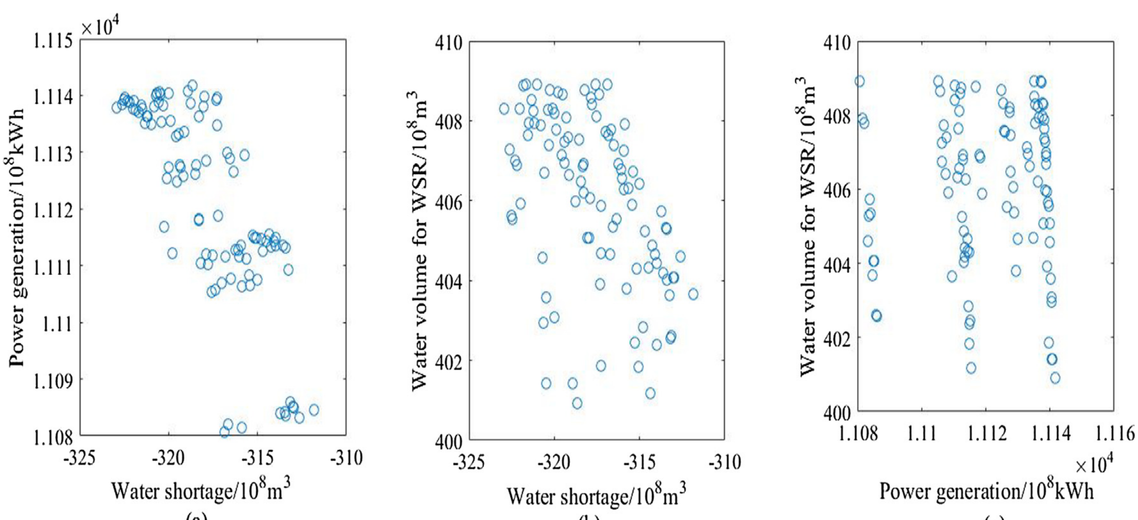


Fig. 13. 2D projections of Pareto-Front.

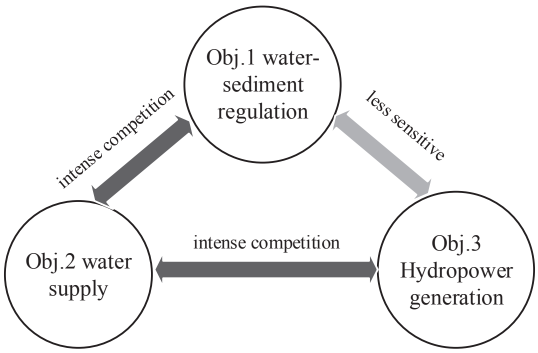


Fig. 14. Relationships between the three objectives.

water volume of WSR), scheme 3 (maximum generation) and scheme 4 (a compromise scheme), as shown in Fig. 12. The comprehensive efficiencies for multi-objectives of four schemes are listed in Table 6.

Table 6 shows some indicators related to the three objectives, such as the times of WSR, the average water volume of once WSR, the annual cascade power generation and power generating guarantee rate, annual shortage for water supply and water supply guarantee rate. It can be seen in Table 6 that:

(1) WSR has been carried out 6 times for the long-term operation that means WSR should be taken once every four years averagely. The maximal water volume of WSR is $408.92 \times 10^8\,m^3$, and the average water volume of WSR is $68.15 \times 10^8\,m^3$ in scheme 2. While the minimal water volume of WSR is $400.92 \times 10^8\,m^3$ and the average water volume of WSR is $66.82 \times 10^8\,m^3$ in scheme 3.
(2) The requirement of power generation has been reached in all schemes, the power generating guarantee rates of four schemes are 92.36%, 91.67%, 92.81%, 92.79%, respectively, which are all above the design guaranteed rate. The annual cascade power generation of four schemes are 576.86×10^8 kW·h, 576.69×10^8 kW·h, 579.24×10^8 kW·h and 578.74×10^8 kW·h, respectively, higher than the design cascade power generation of 565×10^8 kW·h.
(3) The guarantee rates of water supply of four schemes are 79.33%, 77.07%, 76.14%, 78.65%, respectively, higher than the design guaranteed rate of 75%, and meet the requirement of water supply upper the Yellow River. Meanwhile, the maximal annual shortage for water supply is $13.27 \times 10^8\,m^3$ in scheme 3 (scheme of maximum generation), reflect a strong competition between water supply and power generation.

4.2.2. Water demand and sediment sluicing for WSR

Table 7 gives the water volume and discharge for WSR during the long-term optimal operation of four schemes. It is clearly seen that WSR could been carried out in six years according to the long-term operation, i.e. 1989, 1992, 1993, 1999, 2005 and 2009, and the water coming frequency of the six years are all less than 25%. This shows that the suitable years for WSR are the high and partial high flow years. The difference of outflow of LJX reservoir in April for WSR among the four schemes are small, and the outflow values range from 2541 m^3/s to 2682 m^3/s with an average of 2601 m^3/s. Particularly, the outflow of LJX reservoir in four schemes are identical in 1992, 1999, 2009, respectively, while for the rest years, the outflow values of LJX reservoir in scheme 2 are the maximum of four schemes.

Taking the sediment regulation in 1989 of scheme 4 as an example, the incoming sediment and sediment transport of each section and the scouring sediment amount of five intervals of NIM reach are calculated based on the sediment transport model. The calculation results are shown in Table 8.

As shown in Table 8, considering the influence of tributaries and diversion, in the condition that the outflow of LJX Reservoir is 2682 m^3/s, the discharge values of each section in NIM reach can meet the requirements of WSR controlling discharge in Table 4, i.e., $Q_R \in (2470, 2580)$. It is worth noting that the discharge values of sections XHY and SZS shown in Table 8 are outside of the regulation discharge range. Because of water diversion for agricultural irrigation in XHY-QTX and SZS-BYGL intervals in April, the discharge values of sections QTX and BYGL has reduced obviously during WSR period, and the discharge of section BYGL is 2485 m^3/s which only slightly above the minimum limit discharge for WSR (i.e., 2470 m^3/s). In view of this, to ensure that the discharge of each section is greater than the minimum limit discharge for WSR, the discharge of sections XHY and SZS are higher than 2580 m^3/s.

The result of sediment deposition or sluicing of intervals in Table 8 shows that the first interval riverbed (XHY to QTX) is silted with 2.9 million t sand and the other four intervals are all scoured during WSR period, which shows an increasing trend along the river, and the total amount of sluicing sand of riverbed in the NIM reach is 39.3 million t. Among the four scoured intervals, the amount of sluicing sand in SHHK~TDG interval is the largest, accounting for 39.95% of the total sluicing sand. As the last section of NIM reach, the TDG section has transport sand of 61.2 million t during WSR period. The above data only reflect the effect of one times of WSR. In order to reflect the sluicing effect of long-term WSR in the NIM reach intuitively, the sediment sluicing results of 6 years of four schemes are listed in Table 9.

As shown in Table 9, there are 233.6 million tons of riverbed sediments of NIM reach have been sluicing by long-term sediment regulation in scheme 1, 234.5 million tons in scheme 2, 233.2 million tons in scheme 3 and 233.8 million tons in scheme 4. The average value of total sluicing sand by WSR of four schemes is 233.78 million tons. According to the research about sediment deposition volume of recent 50 years in NIM reach, which pointed out that the rate of sediment deposition is 0.51billion t/a approximately, thus the total sediment deposition amount in the riverbed of NIM reach from 1987 to 2010 is 1224 million tons (Shi, 2010). As a consequence, the total amount of sand sluicing by long-term WSR account for 19.10% of the sediment deposition from 1987 to 2010. It is an undeniable fact that the ability of mitigating sedimentation by WSR is limited, due to the contradiction of limited water quantity and multi-utilization. Nonetheless, WSR is useful and necessary for the upper Yellow River to mitigate the increasingly serious problem of sediment deposition and riverbed siltation.

4.2.3. Water supply and hydropower generation considering WSR

Taking the scheme 4 as an example, Fig. 15 shows the annual water shortage and power generation processes of scheme 4. It can be

Table 6
Comprehensive efficiencies for multi-objectives of four schemes.

Sche-me	Times of WSR	Total water volume of WSR/(10^8m^3)	Average water volume of WSR/(10^8m^3)	Total cascade power generation/ (10^8kW·h)	Annual cascade power generation/ (10^8kW·h)	Power generating guarantee rate/ (%)	Total shortage for water supply/(10^8m^3)	Annual shortage for water supply/(10^8m^3)	water supply guarantee rate/ (%)
1	6	403.67	67.28	11084.60	461.86	92.36	311.83	12.99	79.33
2	6	408.92	68.15	11080.67	461.69	91.67	316.86	13.20	77.07
3	6	400.92	66.82	11141.74	464.24	92.81	318.66	13.27	76.14
4	6	404.66	67.44	11129.93	463.74	92.79	316.71	13.19	78.65

Table 7
Water volume and discharge for WSR of four schemes.

Year	Water coming frequency/(%)	Water volume for WSR/($10^8 m^3$)				Outflow of LJX reservoir in April/(m^3/s)			
		Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 1	Scheme 2	Scheme 3	Scheme 4
1989	4	69.54	69.54	65.88	69.54	2682	2682	2541	2682
1992	24	67.52	67.52	67.52	67.52	2604	2604	2604	2604
1993	20	65.97	68.53	67.13	66.81	2544	2643	2590	2577
1999	16	66.48	66.48	66.48	66.48	2564	2564	2564	2564
2005	8	65.92	68.61	65.91	66.07	2543	2646	2542	2548
2009	12	68.24	68.24	68.24	68.24	2632	2632	2632	2632

Table 8
The sluicing and transporting sand results of WSR in April 1989 of scheme 4. If the value of sediment variation of interval (V) is positive, it means that the sediment inflow is greater than the sediment diversion, and the negative number means the opposite situation. The value of sediment deposition or sluicing of interval (X) is positive means the interval river is silting, and the negative number means the interval river is scouring.

Section	XHY	QTX	SZS	BYGL	SHHK	TDG
Q: Discharge (m^3/s)	2740	2532	2671	2485	2580	2570
S: Sediment content (kg/m^3)	3.940	3.890	3.530	4.890	6.960	8.340
I: Incoming sediment ($10^8 t$)	0.280	0.255	0.244	0.315	0.465	0.556
T: Sediment transport ($10^8 t$)	0.231	0.226	0.347	0.270	0.447	0.612
V: Sediment variation of interval ($10^8 t$)	−0.024	0.002	−0.022	0.004	−0.011	
X: Sediment deposition or sluicing of interval ($10^8 t$)	0.029	−0.089	−0.048	−0.128	−0.157	

observed that the shortage volume of water supply increase sharply in years with the implementation of WSR, such as 1989, 1992, 1993, 2009, reflect the negative impact of WSR on the water supply. The year of maximal water shortage is 1992 with shortage volume of 30.03×10^8 m^3, and the year of minimal shortage is 2008 with shortage volume of 8.56×10^8 m^3. In most of the years, the volume of annual water shortage are within the range from 10.95×10^8 m^3 to 15.42×10^8 m^3, which are mainly caused by the contradiction between the limit discharge of LJX reservoir and the LZ section water demand during ice control period. The annual power generation process shows that the year of maximal energy output is 1990 with output of 508.84×10^8 kW·h, which is 46.67×10^8 kW·h higher than the annual average power generating capacity of cascade reservoirs. The year of minimal output is 2002 with output of 439.98×10^8 kW·h, 22.19×10^8 kW·h less than the annual average power generating capacity.

Based on the above analysis of results in Section 4.2, it can be concluded that dynamic balance between WSR and other multi-objectives can be achieved. For the cascade reservoirs in the upper Yellow River, WSR is feasible and sustainable which can mitigate sediment deposition and alleviate the problem of suspended river to a certain extent. Although long-term WSR will bring some negative effects on power generation and water supply, it will not break the design indexes of these two objectives, and will be able to perform the tasks of flood control, ice-flood control and ecological base flow in the upper Yellow River.

4.3. Operation modes and risk-free conditions of cascade reservoirs for WSR

Taking the scheme four as an example as well, this paper analyzes the changing process of inflow and outflow of cascade reservoirs to reflect the joint operation modes of them, as shown in Fig. 16. To reflect the change of operation modes of cascade reservoirs by long-term WSR, the multi-objective operation model has been modified by removing the object 1, and solve the model once again. The Pareto solution set without WSR are obtained and one of the non-inferior solutions is selected. Then the monthly water level changing process of cascade reservoirs of the non-inferior solution without WSR is compared with that of scheme 4, as shown in Fig. 17.

It is can be observed from Subfigure (a) of Fig. 16 that the LYX reservoir takes full advantage of huge regulating storage to regulate the natural runoff in the upper Yellow River, and greatly changes the natural runoff process, especially reduces the flood peak discharge in flood season and increases the downstream runoff in dry season. In the long-term regulation, the abandoned water quantity of LYX reservoir is 0 m^3, and the maximum outflow discharge is 1200 m^3/s which are all occurred in the WSR period. As the anti-regulating reservoir of LYX, the inflow and outflow of LJX reservoir are closely related to the outflow of LYX reservoir to meet the comprehensive water requirement in downstream. The Subfigure (b) of Fig. 16 shows that the LJX reservoir has anti-regulated the outflow of LYX as follows: 1) reducing the water of entering the downstream channel and strictly observing the upper limit outflow discharge during the ice control period; 2) the outflow discharge of LJX reservoir is larger than the inflow during the irrigation period, especially in the WSR period, the outflow increases to more than 2500 m^3/s; 3) in the main flood season, a part of the outflow of LYX reservoir is properly stored under the premise of ensuring the safety of flood control, and the outflow discharge of LJX reservoir in October is increased obviously.

The Subfigure (a) of Fig. 17 shows the difference between the water level process of LYX reservoir with or without WSR. From 1987 to

Table 9
The long-term sediment sluicing results of four schemes (10^8 t).

Year	1989	1992	1993	1999	2005	2009	Total sluicing sand by WSR	Total sand deposition for 24 years	Percent of sluicing sand/(%)
Scheme 1	0.393	0.390	0.387	0.388	0.387	0.391	2.336	12.240	19.083
Scheme 2	0.393	0.390	0.391	0.388	0.392	0.391	2.345	12.240	19.157
Scheme 3	0.386	0.390	0.390	0.388	0.386	0.391	2.332	12.240	19.049
Scheme 4	0.393	0.390	0.388	0.388	0.387	0.391	2.338	12.240	19.097

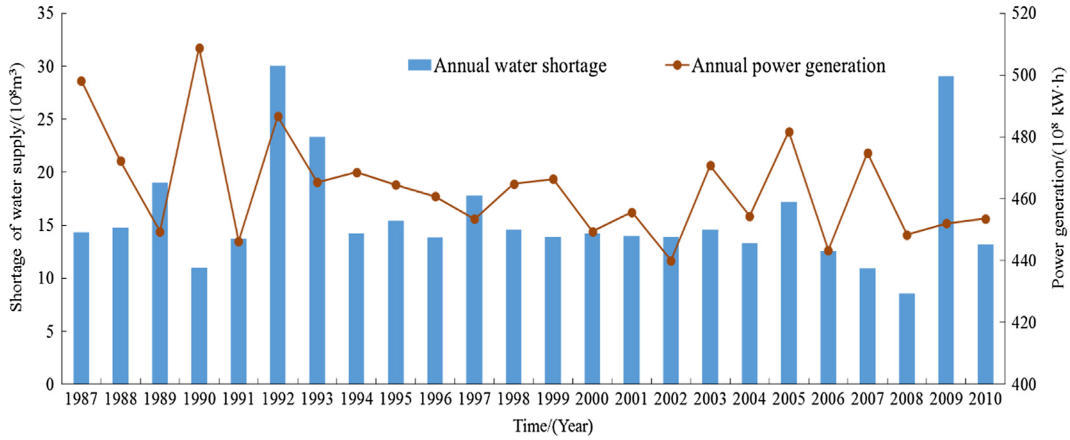


Fig. 15. The annual water shortage and power generation processes of scheme 4.

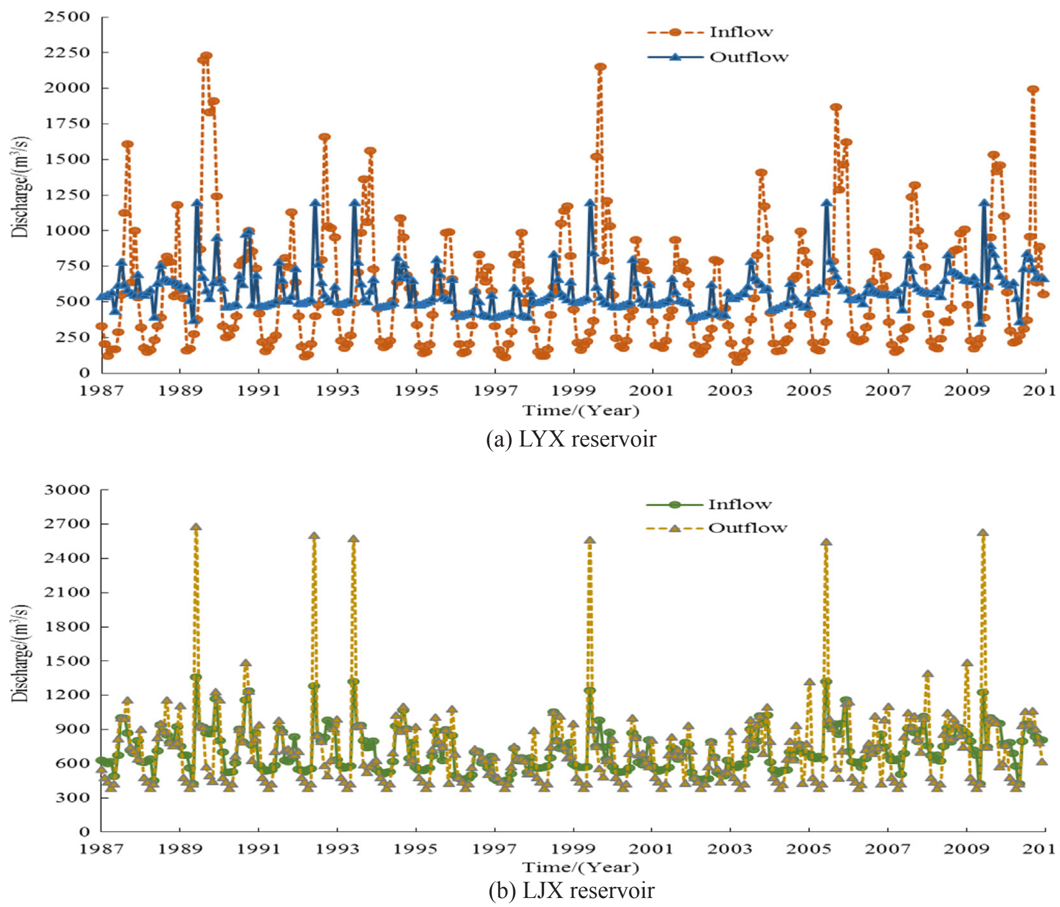
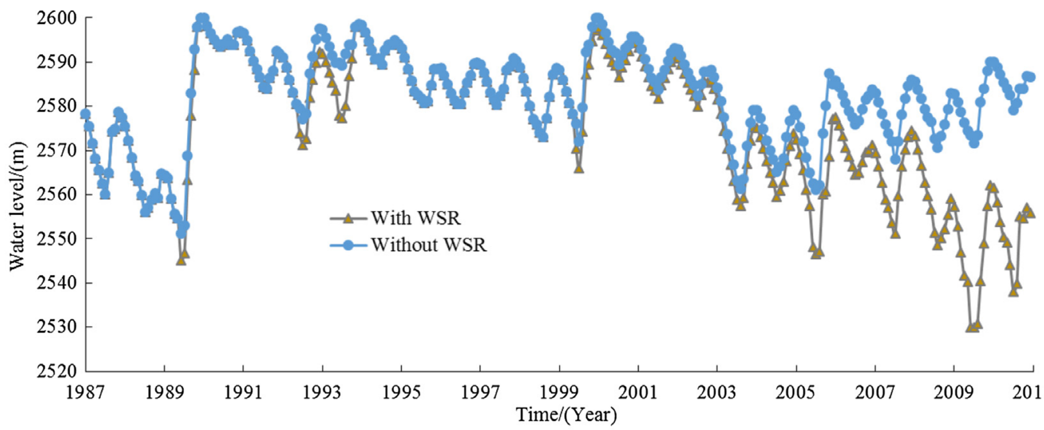


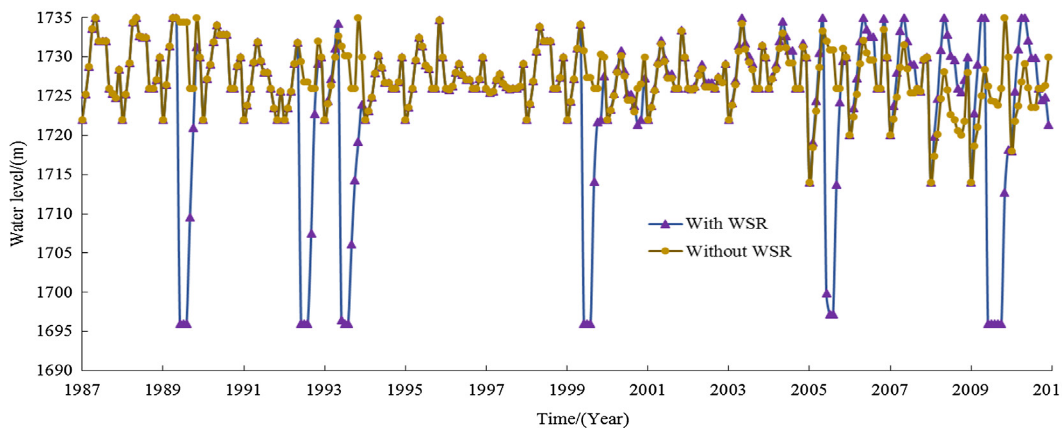
Fig. 16. Monthly inflow and outflow changing process of cascade reservoirs of scheme 4.

2003, the water level process of LYX reservoir is less affected by WSR because of the supplement of abundant runoff in flood season that make the water level could rise rapidly. However, from 2004 to 2010, the water level process of LYX reservoir is great changed by WSR which is manifested by dropping to the dead water level and unable to recover to high water level. The reason is the decrease of runoff (3 dry years in this period) and the LYX reservoir has to lower the water level and increase the discharge to meet the comprehensive water demand. It is noticeable that the water level of LYX reservoir had dropped to the dead water level in the end of April in 2009 what represent the capability of long-term WSR has been fully exploited. Finally, the water level of LYX reservoir with WSR drop to 2557.0 m at the end of the operation period, which is 29.68 m lower than that in the scheme without WSR, and the storage capacity is reduced by 68.83×10^8 m^3. It can be seen from the Subfigure (b) of Fig. 17 that the change of water level of LJX reservoir caused by WSR is temporary. In the years when WSR has been taken, the water level of LJX drop to the dead level in April, due to the small storage capacity of LJX and the water compensation of LYX reservoir in flood season, the water level of LJX rises gradually from July to September. At last the water level of LJX reservoir with WSR rise to 1721.37 m at the end of the operation period, which is 8.63 m lower than that in the scheme without WSR, and the storage capacity was decreased by 10.45×10^8 m^3.

Actually, the optimal operation for cascade reservoirs in this paper



(a) LYX reservoir



(b) LJX reservoir

Fig. 17. Monthly water level changing process of cascade reservoirs with or without WSR.

Table 10
The necessary conditions of the cascade reservoirs for WSR.

Reservoir		Water level before WSR/(m)	Capacity before WSR/ ($10^8 m^3$)	Lowering of water level by once WSR/(m)	Lowering of capacity by once WSR/ ($10^8 m^3$)
LYX	Maximum	2583.56	187.79	10.22	23.95
	Minimum	2540.22	72.58	5.71	18.60
	Average	2565.79	137.42	8.21	21.11
LJX	Maximum	1735.00	42.10	39.00	34.34
	Minimum	1731.87	38.00	35.07	30.24
	Average	1734.22	41.08	37.48	32.94

is based on historical runoff data. However, in the actual reservoir operation, due to the short forecast period of hydrological forecasting technology, it is often impossible to accurately know the long-term runoff in the future. Especially in April, it is impossible to judge whether the runoff in flood season is abundant or not, so it is more difficult to select the right time to carry out WSR. In order to guide the cascade reservoirs to carry out risk-free WSR effectively in practice, it is absolutely essential to make clear the risk-free conditions of the cascade reservoirs for WSR. Table 10 gives the information of water level and capacity before taking WSR for LYX and LJX reservoir, which is used as a reference in actual operation.

It can be observed from Table 10 that (1) for LYX reservoir, the average water level before WSR is 2565.79 m, and the corresponding capacity is $137.42 \times 10^8\, m^3$, the average lowering of water level by once WSR is 8.21 m, and the average lowering of capacity by once WSR is $21.11 \times 10^8\, m^3$; (2) for LJX reservoir, the average water level before WSR is 1734.22 m, and the corresponding capacity is $41.08 \times 10^8\, m^3$, the average lowering of water level is 37.48 m, and the average lowering of capacity is $32.94 \times 10^8\, m^3$. This indicate that, in the actual operation, if the runoff in the future flood season is uncertain, when the water level and capacity of the cascade reservoirs reach those above average values before April, the WSR can be carry out without risk.

4.4. Discussion about ecological impact of WSR and countermeasures

WSR is a non-engineering measure to reduce the sediment deposition in the downstream riverbed through artificial flood regulated by reservoirs. As an effective means of river sediment management, WSR bring some expected benefits of reducing river bed elevation, alleviating suspended river, enhancing flood and ice-flood discharge capacity of the river courses. However, WSR is a double-edged sword for river ecological system. Although WSR has not been carried out in the upper Yellow River in reality, and it is impossible to accurately quantify the ecological impact of WSR. Fortunately, by consulting the literatures on the ecological effects of WSR regulated by the XLD Reservoir in the lower Yellow River, we can get some qualitative conclusions of the ecological impact of WSR.

The ecological benefit of WSR is water supplement for wetlands (Liu et al., 2016). In the past 20 years, affected by climate change and human activities, the areas of wetland in Ningxia Plain and Inner Mongolia Plain in the Yellow River Basin have decreased by 20.48 km^2 and 49.41 km^2, respectively (Zheng et al., 2016; Wang et al., 2018). In addition to scouring sediment, a month-long artificial flood caused by WSR in the NIM reach can also raise groundwater level of river wetlands by seepage supply. It is conceivable that WSR in the NIM reach can benefit to vegetation growth, increase the biodiversity, improve the ecology function, increase the bird population and prevent the shrinkage of wetland area.

The adverse impact of WSR is mainly reflected on fish and ecologically sensitive areas (Zhu et al, 2012). Affected by artificial floods released by cascade reservoirs in WSR period, the fish resources in the reservoirs area and the LYX-LJX reach will be reduced and the diversity of aquatic species will be decreased. The sharp decline in water level of reservoirs in WSR period will also lead to the loss of ecological function of the spawning ground, feeding ground, and wintering ground of fish. Moreover, impacted by WSR, the sediment content of the NIM reach will increases greatly in WSR period which will lead to the rapid increase of ammonia-nitrogen content and the decrease of oxygen content in the river, and may lead to the death of a number of fish. To mitigate this negative impact, countermeasures including establishment of fish resources protected areas, fishery stock enhancement and releasing, fish breeding sites downstream of the tributaries in NIM reach as temporary shelter for fish are necessary.

5. Conclusion

WSR, water supply and hydropower generation are the most three important objectives for the utilization of water resources in sediment laden river under serious circumstance of suspended river and runoff decrease. However, the competitive relationships between the three objectives are uncovered and the effect and necessary conditions of WSR are indefinite which have bring obstacles to sediment management in sediment-laden river. Additionally, whether dynamic balance between long-term WSR and other objectives could be achieved is an important issue related to the sustainability of WSR. Moreover, the traditional NSGA-II algorithm is inefficient and unsuitable to solve multi-objective model for cascade reservoirs with interconnected and fixed regulation rules, thus it is necessary to improve the algorithm.

Different from other similar studies about WSR that focused on operation of single reservoir and fewer objectives, this paper present a multi-objective operation model for cascade reservoirs where five conflicting objectives and a set of complicated operational constrains are all considered simultaneously, and also a sediment transport model was introduced to quantify the effect of WSR. Then, the NSGA-II algorithm was improved through shrinking feasible search space and generating initial population follow regulation rules to effectively solve the operation model, and key control indicators of WSR, i.e. the regulation discharge and regulating time, were analyzed. Methodology mentioned above are applied in the Upper Yellow River basin. The results show that WSR could be carried out every four years averagely in the study area, and 233.78 million tons of sediments can be sluicing by long-term WSR, which account for 19.10% of the downstream sediment deposition in the operation period. Water supply has a strong competition with power generation, an intensified competition with WSR as well. Meanwhile the competition between WSR and power generation is seen as secondary, which means that, in order to mitigate the sediment deposition problem, it is essential to compromise on water supply benefit appropriately. For actual operation that limited by existing hydrological forecasting technology, the necessary conditions of LYX and LJX reservoirs' water volume are $137.42 \times 10^8\,\mathrm{m}^3$ and $41.08 \times 10^8\,\mathrm{m}^3$, respectively, which are a reference for taking WSR without risk. The ecological benefits of WSR include reducing river bed elevation, alleviating suspended river and water supplement for wetlands, while adverse impact on fish and ecologically sensitive areas cannot be ignored and some countermeasures such as establishment of fish resources protected areas and fish breeding sites are suggested.

In this study, through the optimization operation model, dynamic balance between long-term WSR and water supply, power generation, flood control, ice-flood control and ecology base runoff in sediment-laden river have been achieved for the first time via the cooperation of cascade reservoirs. More importantly, the competitive relationships between WSR and other objectives have been revealed, the ability and effect of long-term WSR have been obtained, and the operation modes and risk-free conditions of cascade reservoirs for WSR have been put forward to guide actual operation which expand the theoretical system and technical method of WSR. Although the models and methods have only been applied to the upper Yellow River in this paper, its generic formulation allows its application to a broad range of rivers over the world.

Admittedly, some inadequacies of this work are expected to be improved. The values of key control indicators of WSR are static rather than dynamic in WSR period, and have no function of optimizing with the response of channel morphology and river bed evolution. The improvement suggestion for this problem is to shorten the calculation interval into day or ten days during WSR period, and establish the relationship between the evolution of river bed and the regulation discharge of WSR in the NIM reach. In this way, the dynamic coupling between cascade reservoirs and river channel can be realized by feeding back the response results of river morphology to the water-sediment multi-objectives regulation model. Sediment management is a global and complex problem for sediment-laden rivers like the Yellow River, how to realize the combination of WSR and multi-objective utilization of water resources in the whole river, and study the high-efficiency sediment transport mode of cascade reservoirs under the common action of various sediment control measures, such as sediment retaining, sediment transportation and artificial sand excavation, are the future directions.

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.

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