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MULTI-OBJECTIVE OPTIMIZATION OF TRANSFERABLE WATER FOR CASCADE RESERVOIRS IN THE UPPER YELLOW RIVER

Tao Bai*, Ming Zhang, Xia Liu, and Qiang Huang

Key words: transferable water, multi-objective optimal operation, FSSO-PSO, potential of water and sediment regulation.

ABSTRACT

Artificially controlled floods generated by cascade reservoirs upstream have been applied to regulate the suspended river formed in the main stream of Ningxia–Inner Mongolia reach, China. The presence of sufficient transferable water in reservoirs is the most important limiting factor for the successful implementation of water and sediment regulation schemes. In this study, the conception and four modes of transferable water are proposed. Taking Longyangxia (LYX) and Liujiaxia (LJX) upper the Yellow River for example, a multi-objective optimal operation model of cascade reservoirs is established and solved by Feasible Search Space Optimal Particle Swarm Optimization (FSSO-PSO). Based on long-term time series of transferable water results from the four modes, the most appropriate transferable water mode is recommended and the potential of water and sediment regulation by LYX and LJX is illustrated. The research findings have important practical significance for guiding the implementation of water and sediment regulation and provision of a scientific basis for decision makers

I. INTRODUCTION

In recent years, under rapid socio-economic development, frequent extreme climatic conditions, fragile ecological environment and the increasing mismatch between water supply and demand, the relations between water and sediment of rivers have deteriorated. For example, a 268km suspended river have been formed in the main stream of the Ningxia-Inner Mongolia reach in the Upper Yellow River, causing flow capacity decreased, frequent flood and ice disasters, which severely threatening lives and property downstream. Hence, implementation of water and sediment regulation in the Ningxia-Inner Mongolia reach is urgently required. However, as the foundation of water and sediment regulation, the presence of sufficient transferable water in reservoirs is the most important factor governing the successful implementation of water and sediment regulation schemes.

There have been many studies on transferable water (Anik and Edward, 2011; Tadanobu and David, 2013; Keighobad et al., 2014). In the study of Reza et al. (2012), a inter-basin water transfer project was considered to evaluate the efficiency of three different protocols in the long term series. Take water transfer from the Karoon River basin to the Rafsanjan plain in the central part of Iran for example, a comprehensive scenarios of criteria were proposed to determine the power of water users in a quantitative way (Armaghan and Reza, 2014). In other studies, a simulation model coupled surface water with groundwater was developed to assess the impact of a trans-basin water diversion project on the groundwater (Jia et al., 2015). Zeng et al. (2014) proposed a new water transfer triggering mechanism for multi-reservoir system to divert water from abundant to scarce regions with a constant diversion flow in an inter-basin water transfer-supply project. Ahmadi et al. (2019) investigated the conflict resolution among different stakeholders in a water transfer project. Focus on precipitation, a copula-based approach was proposed to quantify the synchrony and asynchrony of precipitation for the middle route of South-to-North water transfer project in China (Yan and Chen, 2013). Previous studies on transferable water have mostly focused on inter-basin water transfer works (Wu et al., 2006; Zhang et al., 2012; Gu et al., 2017). There are few studies on transferable water in its own basin and concentrated in water and sediment regulation objective. Therefore, this paper focus on transferable water stored in reservoirs upper the Yellow River.

Moreover, with the rapid increase in water demand, the operation and management of reservoirs have changed, not only for power generation but also for water supply, flood and ice control. Therefore, transferable water in the Upper Yellow River will be involved into multi-objective problem by cascade reservoirs optimal operation, which with challenges both in water re-allocation with limited water resources and

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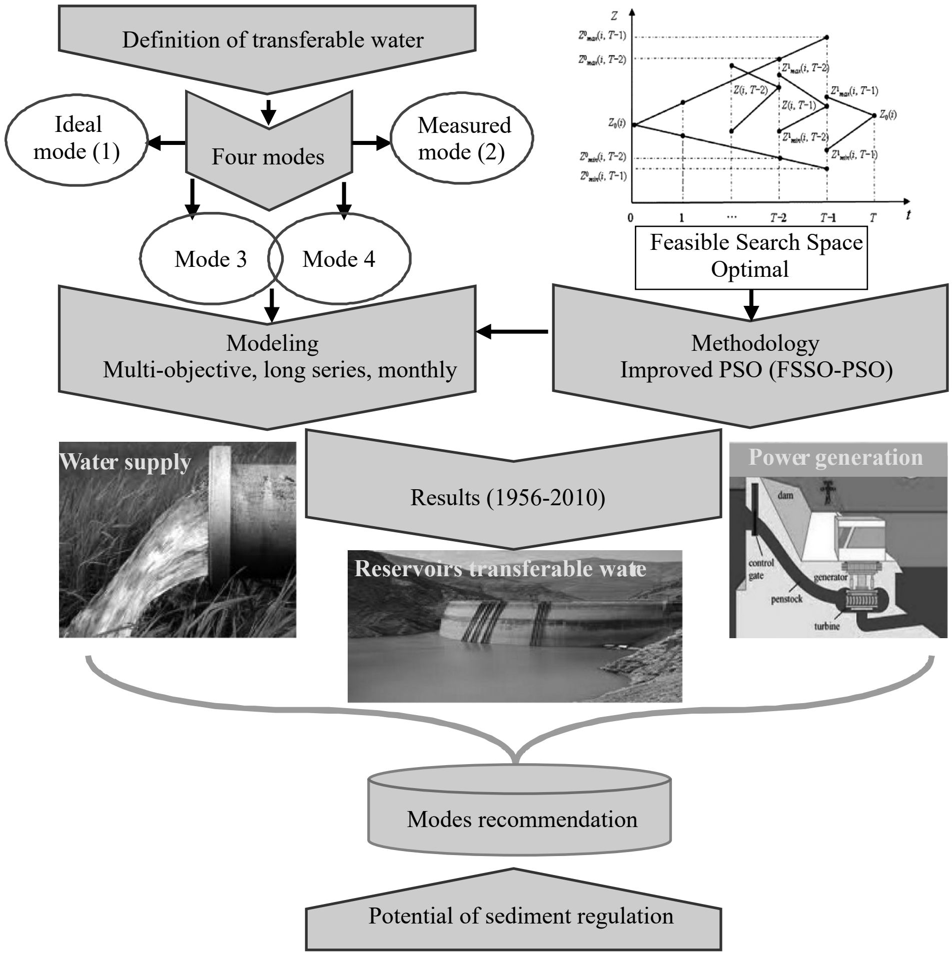

Fig. 1. The flowchart and key technique of the paper.

increasing water demands, and traditional optimal operation algorithms (Kalyanmoy and Abhishek, 2007)

As shown in Fig. 1, quantifying the transferable water and revealing the potential of water and sediment regulation in cascade reservoirs is the purpose of this paper. The Longyangxia (LYX) and Liujiaxia (LJX) cascade reservoirs, the two most important comprehensive regulation reservoirs in the Upper Yellow River, in northwest of China, are taken for example (Fig. 2).

The structure of this paper is as follows. Firstly, the concept of reservoirs transferable water is proposed and four modes of transferable water are defined, which include: ideal mode, measured mode, power generation based on water supply mode and combined power generation and water supply mode. Secondly, multi-objective optimal operation model of LYX and LJX is established by considering flood and ice control, water supply, and power generation as regulation targets. Thirdly, based on constraints and objectives handling techniques, the search space of the initial population is optimized and an improved particle swarm optimization (PSO) algorithm is proposed to solve the multi-objective optimal operation model. Fourthly, long-term time series transferable water results are assessed based on transferable water, power generation, water supply in the four modes. Finally, a suitable transferable water mode is recommended and the potential of water and sediment regulations is illustrated. The research findings have important practical significance for guiding the implementation of water and sediment regulation and providing a scientific basis for decision makers.

II. TRANSFERABLE WATER

Transferable water, first used in inter-basin water transfer projects as a comprehensive indicator to reflect the effort of water resources optimal allocation after inter-basin water diversion, refers to the available water transferred from one watershed to another (Zhang et al., 2010). However, reservoir transferable water refers to available stored water in reservoirs by the end of year after annual regulation, which could also be called adjustable water (Huanghe Hydropower Development Co., Ltd, 2003). In other words, transferable water represents the water stored in reservoirs after deducting the comprehensive utilization water demands for one year. However, for multi-year regulation reservoir, much more storage water must

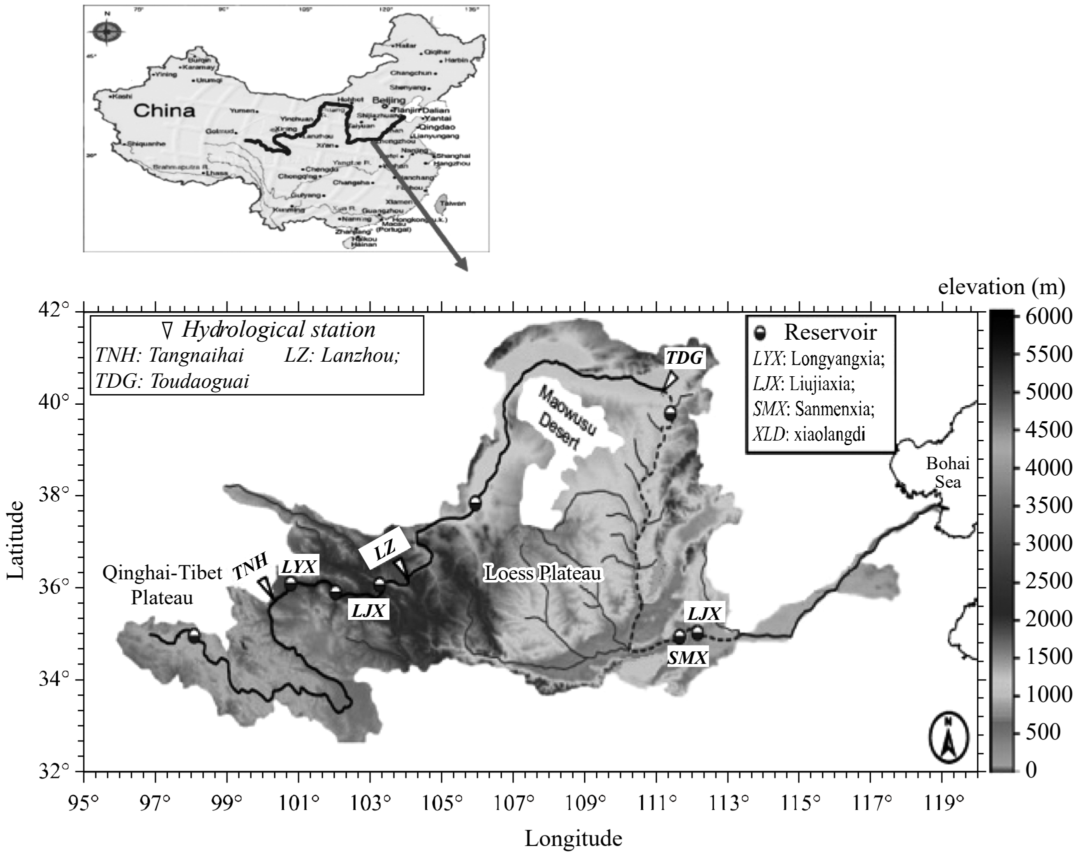

Fig. 2. Drainage basin map of the Yellow River, with locations of major hydrological stations and reservoirs. The dotted line represents the Middle Yellow River and apart the Yellow River into the Upper Yellow River (upper TDG station) and the Lower Yellow River.

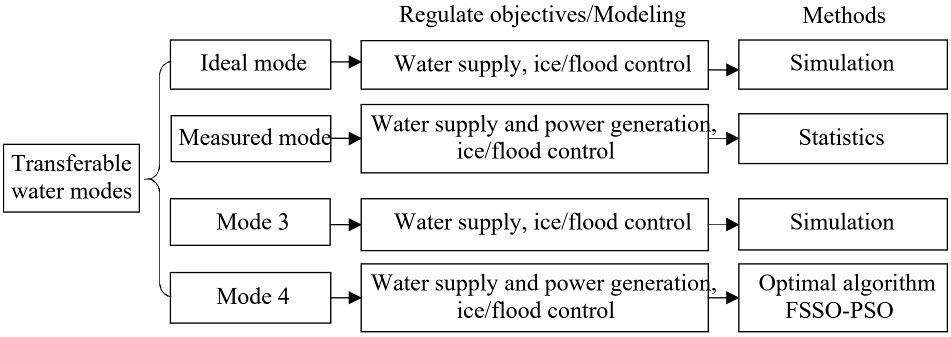

Fig. 3. Transferable water modes.

be reserved for use in dry years, and the amount of transferable water is affected by inflow, supply water, water storage, and the year-end water level, causing moisture change of transferable water over many years.

In this study, transferable water in the Upper Yellow River is defined as follows: according to the natural inflow of LYX, under the premise of ensuring flood and ice control safety of Ningxia-Inner Mongolia in the Upper Yellow River, water excluding from the storage water reserved in advance used to meet multi-years comprehensive utilization water demands in dry years, the remaining adjustable storage water in reservoirs and abandoned water, are defined as transferable water. This transferable water can be used to increase the water of power generation, or to supply water, or to water and sediment regulation. Thus, factors relating to transferable water include inflow, supply water, storage water, abandoned water, reserved water, and the year-end water level of multi-year regulation reservoir.

Transferable water has close ties to operation modes of cascade reservoirs. With references to operation modes of cascade reservoirs and based on the premise of ensuring flood and ice control safety, four modes of transferable water as a novelty achievement are proposed in this paper (Fig. 3).

Table 1. Characteristics of LYX and LJX reservoir/hydropower station.

Name	Normal Water level (m)	Dead water level (m)	Total storage capacity (10^8m^3)	Guaranteed output (10^4 kW)	Installed capacity (10^4 kW)	Average annual output (10^8 kW·h)	Time of start to run (year)
LYX	2600	2530	247	60.0	128.0	59.24	1987
LJX	1735	1694	57.00	40.0	135.0	57.60	1969

Table 2. Monthly minimum flow of comprehensive water supply in LZ section.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Flow/(m^3/s)	650	600	500	750	1100	900	800	750	750	800	750	700

1. Ideal mode

The theoretical maximum value of transferable water can be obtained from this mode, which is the upper limit value of transferable water. It is supposed innovatively that the storage capacities of the LYX and LJX reservoirs are infinitely large and have a completely regulated capacity for inflow over multiple years. Then, under the premise of ensuring flood and ice control safety and meeting comprehensive utilization water demands of the Yellow River, much more water can be stored in the infinitely large reservoir without abandoned water. And the ideal cumulative water process of reservoirs is gained based on long-term data (1956-2010). Based on the reserved water and maximum accumulated value in the final year, the multi-year average value of transferable water can be obtained from these ideal conditions.

2. Measured mode

The value of transferable water in actual operation can be obtained from the measured mode. Measured data for the joint operation of LYX and LJX from 1987-2010 are collected and sorted out by actual operational data, including inflow, water level, storage, abandoned water, discharge, and supply water in the Lanzhou (LZ) section. The measured storage capacity at the end of each year, interval inflow between LYX and LJX, and abandoned water are included in transferable water of the measured mode. Accumulated water processes of transferable water are thus obtained from a long-term data series (1987-2010). Considering the reserved water, maximum accumulated value in the end year and the multi-year average value of transferable water can be obtained from the measured mode.

3. Power generation based on water supply mode (Mode 3)

The value of transferable water that focuses on water supply can be obtained from Mode 3. Power generation based on water supply, which is one of the common operation mode for cascade reservoirs in actual operation, means that the water demands of the Yellow River must be satisfied priority to maintain the balance between water supply and demand, then power generation discharge flow is subsequently decided by supply water flow. In this study, LZ was selected as the controlled station for supply water demand. The storage capacities of reservoirs at the end of each year and the abandoned water are composed for transferable water of Mode 3. The accumulated water process and multi-year average value of transferable water in Mode 3 are obtained based on a long data series (1956-2010).

4. Combined water supply and power generation mode (Mode 4)

The value of transferable water considering water supply and power generation can be obtained from Mode 4. As another common operation mode of cascade reservoirs in actual operation, the combined water supply and power generation mode means that the water demands of the Yellow River must be satisfied first and the guaranteed output of cascade hydropower stations must be satisfied as a second priority. Same as in Mode 3, the accumulated water process and multi-years average of transferable water in Mode 3 are obtained by a long-term data series (1956-2010) either.

III. MODELING

1. The available data

In this study, LYX and LJX reservoirs are regulated subjects of transferable water and the characteristics of the LYX and LJX reservoir and hydropower stations are listed in Table 1.

There are two important hydrological stations in the upper reaches of the Yellow River. The first one is LZ, which control the water supply demand of the whole Yellow River. In order to reflect water resource utilization of the Yellow River Basin accurately, monthly control flow data of comprehensive water in LZ section are used (Table 2). The second important hydrological station is Toudaoguai (TNH), which is the inflow control station of LYX. So the monthly inflow data from year 1956-2010 are collected in this section. Moreover, measured data of joint operation of LYX and LJX (1987-2010) are collected to describe the current operation conditions in this paper. Limit flow data of LJX in the ice control and flood control periods are also collected. More than 3000 collected data points are considered in this study (Table 3).

Table 3. The characteristics of collected data.

Data name/unit	Length	Timescales	Position	Data number
Water level/m	1987-2010	monthly	LYX, LJX	576
Inflow/flow/(m^3/s)	1956-2010	monthly	THN, *LZ*	1320
Discharge/(m^3/s)	1987-2010	monthly	LYX, LJX	576
Power generation/(kW·h)	1987-2010	monthly	LYX, LJX	576
Minimum supply water flow/(m^3/s)		monthly	*LZ*	12
Ice control discharge (Nov-next March)/(m^3/s)	2000-2010	5 month	LJX, *LZ*	110
Control discharge in flood season (Jul-Oct) (m^3/s)		4 month	LYX, LJX	8

Note: data numbers are obtained by data length, timescales and the number of stations. E.g. 576 = 24 (1987-2010) × 12 (month) × 2 (LYX, LJX).

2. The multi-objective model

To analyze transferable water in the four modes, the multi-objective optimal operation model of cascade reservoirs is established. The model considers four objectives (ice control, flood control, power generation and water supply) and five types of constraints (water balance, water balance between reservoirs, water level, outflow and generation output), which are addressed as follows.

(1) Objective 1: ice control

Owing to its location in a high-altitude area with a low temperature in winter, the main channel of the Ningxia-Inner Mongolia reaches would be frozen when the temperature dipped below freezing from the end of November to the following March, which is defined as the ice control operation period. LJX is the last regulated reservoir in Ningxia–Inner Mongolia reaches, and its outflow is controlled by the Yellow River Conservancy Commission (YRCC) to ensure the safety of the Yellow River. Therefore, the ice control objective is to minimize the maximum absolute difference between the reservoir actual outflow and the controlled flow, described as follows.

$$\min(\max\left|Q(Liu,t)-Q_o(t)\right|) \tag{1}$$

where $Q(Liu,t)$ is the outflow of the LJX reservoir; $Q_o(t)$ is the threshold of outflow, which meets the ice control requirement given by YRCC.

(2) Objective 2: flood control

To ensure the safety of dam and downstream area in the flood season (July to August), the water level and outflow of each reservoir should be controlled within certain ranges, described as follows.

$$\mathrm{Z}_{\min}(i,t) \le \mathrm{Z}(i,t) \le \mathrm{Z}_{\max}(i,t) \tag{2}$$

$$Q_{o\min}(i,t) \le Q(i,t) \le Q_{o\max}(i,t) \tag{3}$$

where $Z(i,t)$, $Q(i,t)$ are the water level and outflow of *i* reservoir at time *t*, respectively; $Z_{min}(i,t)$, $Z_{max}(i,t)$ are the minimum and maximum allowable water levels of *i* reservoir at time *t*, respectively; Generally, $Z_{min}(i,t)$ is the dead water level and $Z_{max}(i,t)$ is the flood control water level of *i* reservoir at time *t*; $Q_{0\,min}(i,t)$, $Q_{0\,max}(i,t)$ are the minimum and maximum allowable outflow of *i* reservoir at time *t*, respectively.

(3) Objective 3: power generation

Power generation is one of the most important objectives, which is the initial goal before construction in the Yellow River to gain more power generation benefits. Power generation is calculated based on their outputs in different periods.

$$E = \max\sum_{i=1}^{M}\sum_{i=1}^{T} N(i,t)\times\Delta t \quad \forall i\in \mathrm{M}, t\in \mathrm{T} \tag{4}$$

where *E* is the total power generation of cascade in a given operation period; $N(i,t)$ is the output of reservoir *i* at time *t*; Δt is the duration; *M* is the number of hydropower stations; and *T* is the operation period.

(4) Objective 4: water supplement

To maintain the balance between supply and demand of water resources in the whole Yellow River, according to Water Supplement Planning (WSP) published in 1987, LZ is selected as control section of water supplement. The minimum flow of LZ section must be ensured in different time, which is shown as follows.

$$Q(LZ\ ,t) \ge Q\ \mathrm{min}\ (t) \tag{5}$$

where $Q(LZ\ ,t)$ is the inflow in LZ section at time *t*; $Q\ \mathrm{min}\ (t)$, a known parameter shown in WSP, is the minimum flow in the section required to maintain the balance between supply and demand of water resources.

Constraints, corresponding with the objectives above, are shown as follows.

Water balance:

$$Q(i,t) = Q(i-1,t) + [Q_I(i,t) - Q_W(i,t) - Q_L(i,t) + Q_B(i,t)] \tag{6}$$

Water balance between reservoirs:

$$V(i,t+1) = V(i,t) + [Q_{IN}(i,t) - Q_{OUT}(i,t)] \times \Delta T(t) \quad (7)$$

Water level:

$$Z_{\min}(i,t) \le Z(i,t) \le Z_{\max}(i,t) \quad (8)$$

Outflow:

$$Q_{o\min}(i,t) \le Q_o(i,t) \le Q_{o\max}(i,t) \quad (9)$$

Generation output:

$$N_{\min}(i,t) \le N(i,t) \le N_{\max}(i,t) \quad (10)$$

where $Q_I(i,t)$, $Q_W(i,t)$, $Q_L(i,t)$ and $Q_B(i,t)$ are the interval inflow, water supply flow, lost flow (such as evaporation and leakage), and recession flow from irrigation area, between nodes $i-1$ and node i at time t, respectively; $Q(i-1,t)$ is the flow of node $i-1$ at time t; $V(i,t+1)$ and $V(i,t)$ are the initial storage of reservoir i at times $t+1$ and t; $Q_{IN}(i,t)$ and $Q_{OUT}(i,t)$ are the inflow and outflow of reservoir i at time t, respectively; $\Delta T(t)$ is the duration; $Z_{\min}(i,t)$ is the dead level; $Z_{\max}(i,t)$ is the maximum water level of reservoir i at time t; $N_{\min}(i,t)$ and $N_{\max}(i,t)$ are the minimum output and maximum output of reservoir i at time t, respectively.

The importance of the four objectives in various periods could be very different. For example, in the ice control period, other objectives must make a concession to ice control safety target, that is to say, the flow in the LZ section and the outflow of LJX must be controlled by ice control safety flow but not water supply flow or power generation flow. However, in the flood control period, reservoirs must prioritize flood control. Then, the value of power generation is calculated using the flood outflow. Furthermore, the consideration of four objectives in different modes are also different (Table 4 and Table 5).

In Table4, ice control, flood control and water supplement are considered in Mode 1 and Mode 3. Then, a multi-objective model of cascade reservoirs considering three objectives is established and power generation is calculated using only the reservoir outflow. In Table5, ice control, flood control, power generation and water supplement are considered in Mode 4. Then, a multi-objective model of cascade reservoirs considering four objectives is established.

3. Initial and constraints parameters

The beginning water levels of LYX and LJX are 2580 and 1735 m, respectively. The constraint parameters are listed in Table 5. Guaranteed rate of power generation of LYX and LJX are 90% and 95%, respectively. The guaranteed rate of water supply at LZ is 75%.

Table 4. Objectives considered and its order in multi-objective model of Mode1and Mode 3.

Month	Operation periods	Objectives and its order
11, 12,1,2,3	Ice control period	LYX:Obj.4> (Obj.1, Obj.2) LJX: Obj.1> (Obj.2, Obj.4)
7, 8	Flood control period	LYX:Obj.2> Obj.4 LJX: Obj.2> Obj.4
Others	Water supply period	LYX:Obj.4> Obj.2 LJX: Obj.4> Obj.2

Table 5. Objectives considered and its order in multi-objective model of Mode 4.

Month	Operation periods	Objectives and its order
11, 12,1,2,3	Ice control period	LYX:Obj.3> (Obj.1, Obj.4) LJX: Obj.1> (Obj.2, Obj.3)
4, 5	Water supply period	LYX:Obj.4> Obj.3 LJX: Obj.4> Obj.3
7, 8	Flood control period	LYX:Obj.2> (Obj.3, Obj.4) LJX: Obj.2> (Obj.3, Obj.4)
Others		LYX:Obj.3> (Obj.2, Obj.4) LJX: Obj.3> (Obj.2, Obj.4)

IV. METHODOLOGY

With the rapid development of reservoirs optimal operation, optimization models and various search tools, ranging from linear programming and dynamic programming to a variety of nonlinear methods, have been introduced for the allocation of water resources (Chang and Chang, 2006), drought early warning (Huang and Yuan, 2004), reservoir optimization operations (Pereira and Pinto, 1985; Karamouz and Vasiliadis, 1992; Mousavi et al., 2004; Chang et al., 2010) and optimal basin-scale water allocation (Nabinejad et al., 2017). In recent decades, swarm intelligence algorithms, such as genetic algorithms (Cai et al., 2001; Chang, 2008) and the PSO algorithm (Massimiliano, 2013; Yu et al., 2014), have become popular in optimization application of reservoir planning and management in science and engineering (Huang et al., 2002; Kerachian and Karamouz, 2007; Chen and Chang, 2009).

Since J. Kennedy and R. C. Eberhart proposed the PSO algorithm (Kennedy and Eberhar), as an optimization technique, swarm intelligence algorithms, including PSO, GA (genetic algorithm), and ACA (adaptive genetic algorithm) have become very popular and been successfully used in optimal operation of cascade reservoirs. PSO has been widely used due to its simple principle, few parameters and easy implementation. However, the PSO algorithm also has its own defects, such as fall into a local optimal solution, early maturity, slow convergence rate and difficult to handle constraint optimization. Thus, many improved algorithms have been proposed. For instance, the linear decreasing inertia weight was proposed to accelerate the convergence rate of PSO (Feng et al., 2008). A

Table 6. Constraints parameters of models.

Constraints		Ice season (Nov-next March)	Water supply (April-May)	Flood season (July-August)	Others
Max water level/(m)	LJX	1728	1735	1726	1735
	LYX	2594	2600	2594	2600
Min water level/(m)	LJX	1694	1694	1694	1694
	LYX	2530	2530	2530	2530
Max discharge/(m^3/s)	LJX	740, 490,460, 380, 450	1552	5048	1552
	LYX	2500	1200	4500	1200
Min discharge/(m^3/s)	LJX	740, 490,460, 380, 450	Table.2	Table.2	Table.2
	LYX	552	552	552	552
Max output/(10^4 kW)	LJX	128	128	128	128
	LYX	135	135	135	135
Min output/(10^4 kW)	LJX	60	60	60	60
	LYX	40	40	40	40

new dynamic adaptive inertia weight was proposed to avoid falling into local optimal solution (Zhang et al., 2007). Furthermore, most improved PSO algorithms were combined with progressive optimization algorithm (Wan et al., 2018), simulated annealing algorithm (Wang et al., 2008) and some new hybrid algorithms (Chang et al., 2013).

However, these improved PSO studies have focused on the design of the algorithms, such as inertia weight, optimization capability, and operators. In this paper, we consider a new way to optimal the search space of initial population by constraints handling techniques and a new PSO algorithm: feasible search space optimal PSO (FSSO-PSO). The core of FSSO-PSO includes constraints on handing and feasible search space optimization.

1. Constraints handing

According to equations of objectives and constraints, the optimal targets and constraints can be classified into two groups: equalities and inequalities. Inequality objectives are transformed into constraint conditions. Then constraints are classified into two groups based on their features: transformed constraints, which can be directly converted to optimization variables (e.g. water level and discharge); and non-transformed constraints, which are the implicit function of optimization variables after several transformations, and indicates that those constraints cannot be converted to optimization variables.

2. Feasible search space optimization

For transformed constraints, we assume that the initial and final water level of reservoir i have the same value ($Z_0(i)$) in operation period, then the operation period can be divided into two stages: $1 \sim (T-1)$ and $(T-1) \sim T$ (Fig. 4). Details of the feasible search space optimization are as follows.

Step 1: The first stage begins with $Z_0(i)$. According to the transformed constraints, range of the final water level in first stage can be gained and denoted as Z_0.

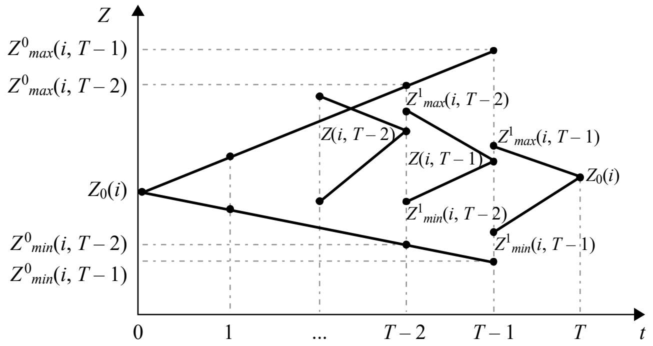

Fig. 4. Optimization of feasible search spaces in different time.

$$Z_0 = [Z^0_{\min}(i, T-1), Z^0_{\max}(i, T-1)] \tag{11}$$

Step 2: Note the final water level of second stage as $Z_0(i)$. As shown in *Step 1*, it can obtain the optimized range of the initial water level in second stage and show as follows.

$$Z_1 = [Z^1_{\min}(i, T-1), Z^1_{\max}(i, T-1)] \tag{12}$$

Then, the intersection of Z_0 and Z_1 is shown as *Z*, which is $Z = [Z^1_{\min}(i, T-1), Z^1_{\max}(i, T-1)]$. Next, the final water level of the $(T-1)$ period is generated by a stochastic approach within *Z*, which is written as $Z(i, T-1)$. The search spaces of initial solutions are optimized twice.

Step 3: The next period can be divided into two stages: $1 \sim (T-2)$ and $(T-2) \sim (T-1)$. As shown in *Step 2*, the final water level in the $(T-2)$ period is generated and described as $Z(i, T-2)$. The cycle continues until all dispatch periods are completed and then the water level range in whole operation period of reservoir i can be obtained and written as $Z = [Z(i,1), \ldots, Z(i,T)]$, which satisfies all the transformed constraints and the search space of initial solution are optimized in each period. The details of the FSSO-PSO algorithm

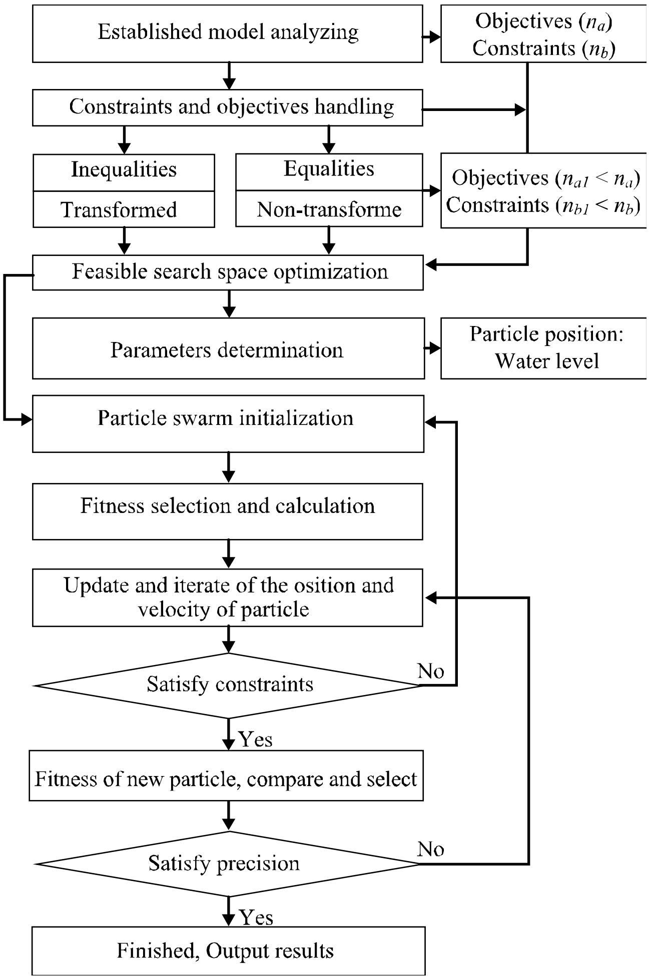

Fig. 5. Steps of FSSO-PSO applied in optimal operation of cascade reservoirs.

steps are shown in Fig. 5.

V. RESULTS AND DISCUSSION

1. Transferable water

(1) Ideal transferable water

Figure 6 shows that based on ensuring flood and ice control safety and satisfying water demand, the cumulative storage capacity of reservoirs in the ideal mode have a sustained upward trend, with the rate of increase slowing considerably after 1987. By the end of 2010, total storage capacity is 286.09 billion m^3 and adjustable storage capacity is 279.20 billion m^3. The maximum complementary water is 3.81 billion m^3 occurred in 2002. In the ideal mode, there is no abandoned water because of the infinitely large storage capacity. So, cumulative transferable water in the ideal mode is 275.39 billion m^3 and the value of average annual is 5.01 billion m^3 without abandoned water. This shows that the theoretical maximum value of cumulative transferable water is 275.39 billion.

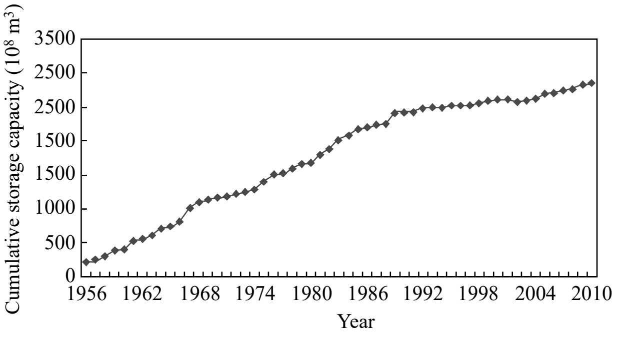

Fig. 6. Cumulative storage capacity of reservoirs transferable water in ideal mode.

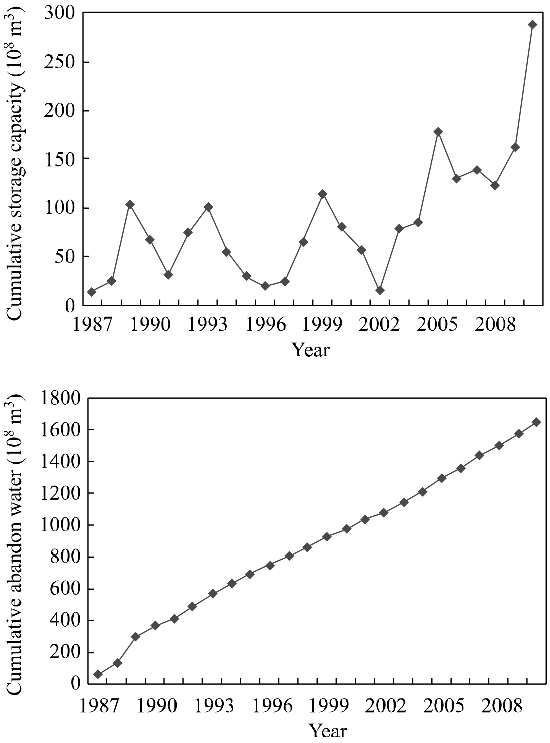

Fig. 7. Cumulative storage capacity and abandon water in measured mode.

(2) Measured transferable water

The measured data of cumulative storage capacity process of transferable water (Fig. 7) show that by the end of 2010, total storage capacity is 28.77 billion m^3 and adjustable storage capacity is 21.88 billion m^3. The maximum complementary water is 9.91 billion m^3 occurred in 2000-2002. Hence, the cumulative water storage in the measured mode is 11.97 billion m^3 and the value of average annual is 0.22 billion m^3. The cumulative abandoned water is 164.62 billion m^3 and the average annual is 3.00 billion m^3. So, the total cumulative transferable water in the measured mode is 186.95 billion m^3 and the average annual is 3.22 billion m^3.

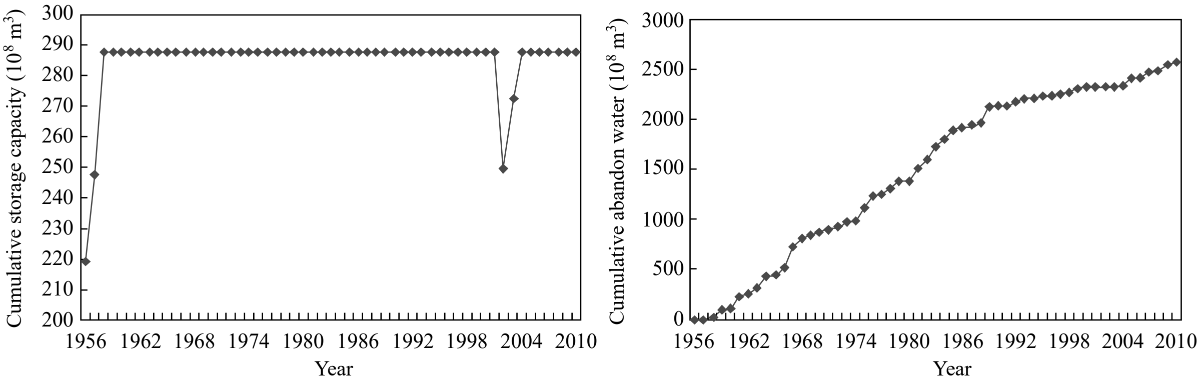

Fig. 8. Cumulative storage capacity and abandon water in Mode 3.

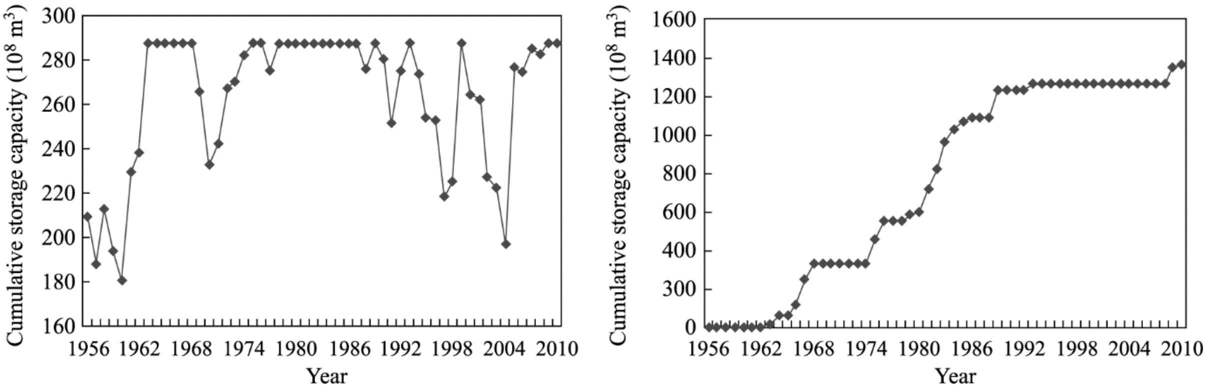

Fig.9. Cumulative storage capacity and abandon water in Mode 4.

(3) Transferable water in Mode 3

Based on ensuring flood and ice control safety and satisfying water supply demand, the storage capacity of reservoirs is used in the first 3 years and then close to normal water level, except in 2002-2003. Limited by the designed storage capacity or normal water level, most water could not be impounded in reservoirs and abandoned.

By the end of 2010, cumulative storage capacity is 28.77 billion m^3 and adjustable storage water is 21.88 billion m^3. The cumulative storage water of Mode 3 is 18.06 billion m^3 and the average annual is 0.33 billion m^3. The cumulative abandoned water is 257.32 billion m^3 and the value of average annual is 4.68 billion m^3. The total cumulative transferable water of Mode 3 is 275.38 billion m^3 and the value of average annual is 5.01 billion m^3.

(4) Transferable water in Mode 4

Fig.9 shows the process of cumulative storage water and abandoned water of Mode 4. By the end of 2010, cumulative storage capacity is 28.77 billion m^3 and adjustable storage capacity is 21.88 billion m^3. The cumulative storage water in Mode 4 is 18.06 billion m^3 and the value of average annual is 0.33 billion m^3. The abandoned water is 136.95 billion m^3 and the value of average annual is 2.49 billion m^3. The total cumulative transferable water in Mode 4 is 155.01 billion m^3 and the value of average annual is 2.82 billion m^3.

Overall, the values of maximum cumulative and average annual of transferable water of the four modes are Mode 1 and Mode3, then is Mode 2, and the minimum is Mode 4 (Fig. 10).

2. Water supplement

The process and average annual supply water of LZ, and annual guaranteed water supply objective of the four modes are shown in Fig. 11.

All modes are satisfied the water demand and guaranteed water supply. The average annual water supply and water annual guaranteed water supply of Mode 1 and Mode 3 only meet the design requirements. This is because Mode 1 and Mode 3 focus on water supply and store more water in the reservoirs. Therefore, the reservoirs operate under the water supply design values in Mode 1 and Mode 3. The average annual water supply and water annual guaranteed water supply of Mode 2 is the maximum in the four modes, and then is Mode 3.

3. Power generation

The average annual output and annual guaranteed output of LYX and LJX of the four modes are shown in Fig. 12.

Because power generation is not considered in the objectives of Mode 1, the value of power generation is calculated only for water supply flow, flood control flow, and ice control

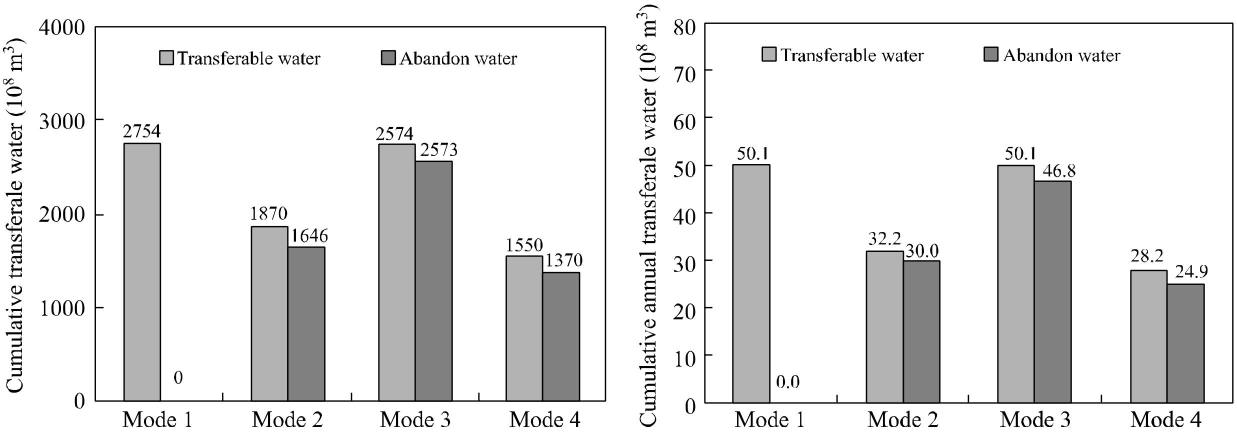

Fig. 10. Cumulative and average transferable water of each mode.

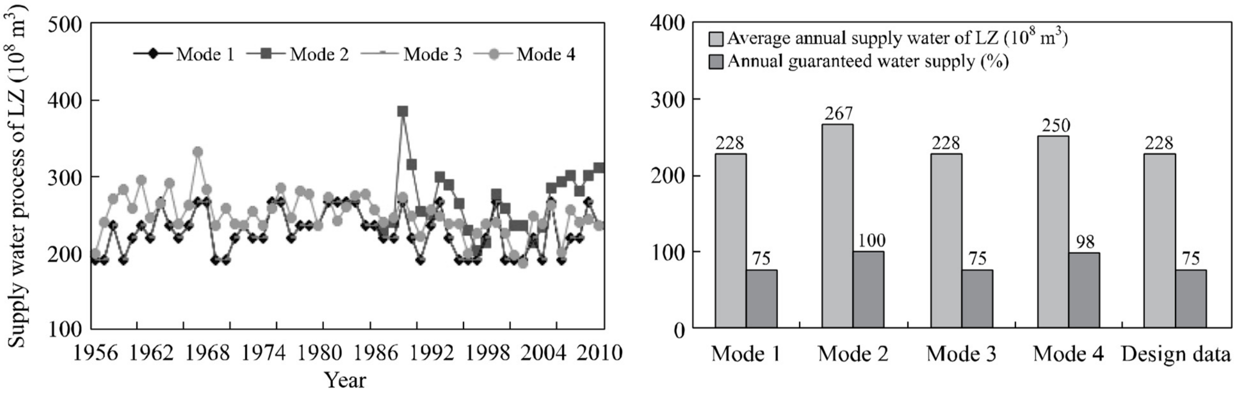

Fig. 11. Process and average account of supply water of each mode.

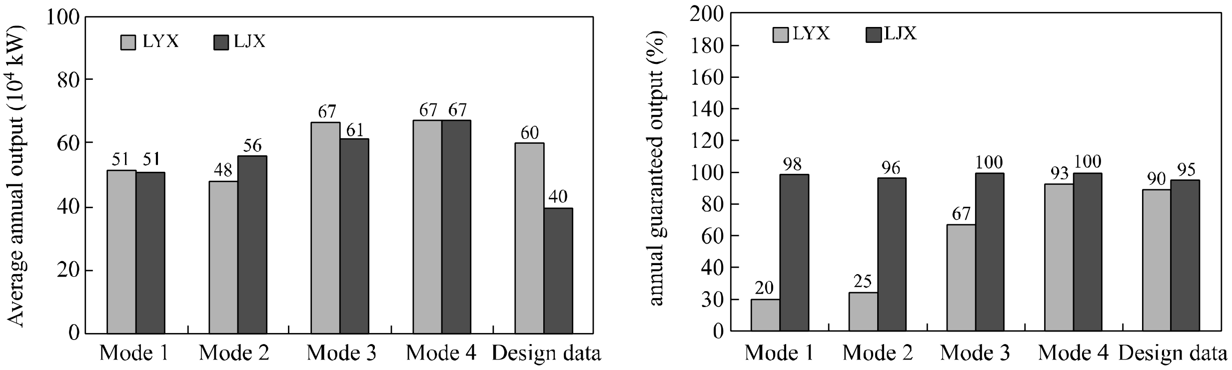

Fig. 12. Average annual output and annual guaranteed output of LYX and LJX of each mode.

flow. Average annual output and annual guaranteed output of Mode 1 are lower than the design values, and thus cannot satisfy the power generation demands. Different with Mode 1, average annual output of Mode 3 reaches the design value due to abandoned water. However, the annual guaranteed output of Mode 3 cannot satisfy the design values. In Mode 2, average annual output and annual guaranteed output of LYX are both lower than the design values. In Mode 4, both average annual output and annual guaranteed output of LYX and LJX meet the design requirements values, since power generation is considered as the objectives in Mode 4.

4. Water and sediment regulation potential

According to the relationship between flood duration and siltation amount in Ningxia–Inner Mongolia reaches, the scouring flow of sediment regulation cannot be less than 2580

m^3/s and lasted more than 14 days (Chang et al., 2009). For monthly optimal operation of cascade reservoirs, water and sediment regulation would last at least 30 days and scouring flow would be 6.69 billion m^3. This shows that at least 6.69 billion m^3 of transferable water is required for water and sediment regulation. The average annual of transferable water of Mode 1 and Mode 3 is 5.01 billion m^3, Mode 2 is 3.22 billion m^3, and Mode 4 is 2.82 billion m^3. For Mode 1 and Mode 3, water and sediment regulation can be implemented once every 2 years, Mode 2 and Mode 4 are once every 3 years. Adequate transferable water can be used to implement water and sediment regulation in four modes. Each mode has sufficient potential for water and sediment regulation.

5. Modes recommendation

Mode 1 is the idea mode for the theoretical maximum limit of transferable water. Mode 1 cannot be achieved in practice as it is based on the assumption of infinite large storage capacity of LYX and LJX reservoir.

Mode 2 is the measured mode for analyzing the actual operational results of the cascade reservoirs. Mode 2 meets the demand for water supply, but does not meet the power generation requirement of LYX. Therefore, cascade reservoirs benefits cannot be fully utilized.

Transferable water of Mode 3 meets the theoretical maximum, but annual guaranteed output of LYX is lower than the design value. Furthermore, only water supply objective can meet the design requirements. Therefore, the benefits of cascade reservoirs are also not fully utilized neither.

Mode 4 is the mode combined water supply and power generation. In Mode 4, under the premise of ensuring flood and ice control safety, objectives of water supply and power generation are all satisfied by multi-objective model establishment and solution. The highest value of transferable water in the four modes is not in Mode 4, but the transferable water in Mode 4 is sufficient for water and sediment regulation. This shows that the comprehensive benefits of cascade reservoirs can be effectively utilized. Based on the increasing water requirements in the future, the operation mode is likely to be transferred to satisfy water supply firstly and power generation secondly. So, the results of Mode 4 are reasonable to recommend as the best mode in this paper.

VI. CONCLUSION

(1) The conception of transferable water is proposed in this study and include two parts: the remaining adjustable storage water in reservoirs and the abandoned water, which can be used for increasing power generation, or supply water, or water and sediment regulation.

(2) Four modes of transferable water are constructed and the suitability of each mode is analyzed. Mode 4, including both water supply and power generation objectives, is recommended as the best mode in this paper. The total cumulative transferable water is 155.01 billion m^3 and the value of average annual is 2.82 billion m^3.

(3) With the scouring flow 2580 m^3/s and sediment regulation lasted 30 days, Mode 4 has sufficient transferable water for water and sediment regulation once every 3 years. This indicates the great sediment regulation potential of the LYX and LJX reservoirs.

(4) The research findings, which provide scientific foundations for water and sediment regulation in this region, have important practical significance for guiding the implementation of water and sediment regulation schemes and providing a scientific basis for decision makers.

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