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Synergistic gains from the multi-objective optimal operation of cascade reservoirs in the Upper Yellow River basin

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SUMMARY

The Yellow River, known as China's "mother river", originates from the Qinghai–Tibet Plateau and flows through nine provinces with a basin area of 0.75 million km^2 and an annual runoff of 53.5 billion m^3. In the last decades, a series of reservoirs have been constructed and operated along the Upper Yellow River for hydropower generation, flood and ice control, and water resources management. However, these reservoirs are managed by different institutions, and the gains owing to the joint operation of reservoirs are neither clear nor recognized, which prohibits the applicability of reservoir joint operation. To inspire the incentive of joint operation, the contribution of reservoirs to joint operation needs to be quantified. This study investigates the synergistic gains from the optimal joint operation of two pivotal reservoirs (i.e., Longyangxia and Liujiaxia) along the Upper Yellow River. Synergistic gains of optimal joint operation are analyzed based on three scenarios: (1) neither reservoir participates in flow regulation; (2) one reservoir (i.e., Liujiaxia) participates in flow regulation; and (3) both reservoirs participate in flow regulation. We develop a multi-objective optimal operation model of cascade reservoirs by implementing the Progressive Optimality Algorithm-Dynamic Programming Successive Approximation (POA–DPSA) method for estimating the gains of reservoirs based on long series data (1987–2010). The results demonstrate that the optimal joint operation of both reservoirs can increase the amount of hydropower generation to 1.307 billion kW h/year (about 594 million USD) and increase the amount of water supply to 36.57 billion m^3/year (about 15% improvement). Furthermore both pivotal reservoirs play an extremely essential role to ensure the safety of downstream regions for ice and flood management, and to significantly increase the minimum flow in the Upper Yellow River during dry periods. Therefore, the synergistic gains of both reservoirs can be suitably quantified under the three scenarios. The proposed optimization methodology provides an effective way to analyze synergistic gains, and the analyzed results provide an important reference guideline for sustainable allocation of water resources in the Yellow River basin.

1. Introduction

Human societies and economic entities are seriously threatened by diverse factors, such as water and energy shortages, environmental degradation and global climate change. Therefore, there are urgent needs for sustainable water resources development and implementation of renewable energy strategies (Chinedu et al., 2014; Henrik, 2007). Hydropower is one of the most effective and mature forms of clean and renewable energy. 1 kW h of hydropower generation can replace approximately 0.5 kg of coal burning for thermal power generation, and thus reduces CO_2 emissions by 0.8 kg (Lazarova et al., 2012; Wang et al., 2011). Therefore, hydropower generation plays a major role in renewable energy supply. In China, the total hydropower potential is estimated at approximately 6.94 million kW, while the installed capacity of hydropower plants is technically available at about 5.40 million kW. Moreover, China's annual power generation reaches about 2.5 trillion kW h, which is the highest in the world (Noam et al., 2011; Zhang et al., 2009). To make sustainable use of water resources, improve resources utilization and efficiency, and increase power generation efficiency, it is important and crucial to investigate the optimal joint operation of cascade reservoirs in consideration of multiple stakeholders.

The study of optimal reservoir operation has been conducted for decades, which made abundant research achievements, such as theoretical findings (Gene and Cheng, 2013), and model and method development (Chang et al., 2010, 2013; Guo et al., 2010; Leila et al., 2012). Various search methods, such as the improved non-dominated sorting particle swarm optimization (I-NSPSO)

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(Guo et al., 2013), genetic algorithm (GA) (Bungon, 2013; Chen and Chang, 2009; Chang et al., 2010) and artificial bee colony algorithm (Choong and El-Shafie, 2014; Hossain and El-Shafie, 2014), have been used for tackling multi-objective optimization problems. However, there is always a gap between theoretical and actual joint operation of reservoirs, and the decisive factor for implementing reservoir joint operation mainly depends on appropriate estimation of synergistic gains. If synergistic gains cannot be properly quantified, the incentive of joint operation will be low, which could significantly prohibit the applicability of joint operation.

Synergistic gain has been commonly defined as the gain in benefits acquired from the joint operation of reservoirs in excess of the benefits acquired from the operation of individual reservoir, and such acquisition can also be introduced by the alteration of operation objectives, the orders of regulations and/or control targets, or the interests of stakeholders (Robert et al., 1977). The studies on synergistic gains relevant to the joint operation of reservoirs can be traced back to 1950s. In China, "Reservoirs benefit compensation and payment management regulations among cascade reservoirs of the river basin in Sichuan Province" was announced by the People's Government of Sichuan Province in 1997, which were the first laws and regulations pertaining to the compensation for reservoir benefits of cascade reservoirs (Huang, 2002). In recent years, ecological compensation has been reported (Ana and Jordi, 2010; Carly and Stuart, 2012; Marie et al., 2013; Xu et al., 2014). Compensations of cascade hydropower stations along the Yellow River and the Yangtze River were investigated (Du and Zhang, 2012; Guo et al., 2011). Previous studies mainly focused on the synergistic gain obtained from single-objective reservoir operation, such as power generation or flood control. For the sustainable development of river basins, the operation of cascade reservoirs would involve not only the pursuit of the maximum hydropower generation but also the fulfillment of other objectives, such as water supply and flood control. In this study, various synergistic gains obtained from the joint operation of cascade reservoirs are systematically analyzed.

There are a number of ways to evaluate synergistic gains and/or compensation. For instance, "willingness to accept" was established to analyze the accounting system of ecological compensation (Xu et al., 2014), and a cost-benefit analysis was applied to evaluating ecological compensation (Sun et al., 2013). To better describe "synergistic gains" of reservoir operation, three issues should be clarified. First, which reservoirs are the gainers of synergistic gains, and which are the contributors? Second, what are the objectives and their measuring units, such as the amount of water, or the quantity of hydropower? Third, what institutions are responsible for carrying out the allocation of synergistic gains? The purpose of this study is to provide a sound scientific approach to optimizing the operation of cascade reservoirs under multiple objectives and quantifying synergistic gains for sustainable allocation of water resources. We propose three operational strategies of cascade reservoirs to quantify synergistic gains and/or compensation for restoring flows within the Upper Yellow River basin. The overall intention is to motivate the joint operation of cascade reservoirs through suitably identifying the contribution of multi-objective optimal operation for the two pivotal reservoirs, *Longyangxia* and *Liujiaxia* (Fig. 1).

2. Materials and methodology

2.1. Data setting

The Yellow River with a length of 5464 km is the second longest river in China, and it flows through nine provinces across North China. There are two pivotal reservoirs, *Longyangxia* (*LYX*, R1, built in 1987, storage capacity: $247 \times 10^8\ m^3$) and *Liujiaxia* (*LJX*, R2, built in 1968, storage capacity: 57×10^8 m), and 16 runoff reservoirs (hydropower stations; R11–R19 and R21–R27) in the study area (Table 1, Fig. 2). Nevertheless, these reservoirs are managed by different institutions, which raises the difficulty in reservoir joint operation mainly due to unclear synergistic gains in response to operational objectives. To analyze synergistic gains, long and extensive data were collected from the Huanghe Hydropower Development Co., Ltd and the Yellow River Conservancy Commission, which consisted of long term reservoir inflow (1987–2010), water demands of various sectors, reservoirs' water levels and discharge in ice and flood control periods, and the amount of power generation at hydropower stations. *Lanzhou* is the key hydrological control section, which determines both the satisfaction degree of water supply and the safety requirements for ice and flood control in downstream regions. The flow of *Lanzhou* is mainly controlled by R2. The primary statistics of reservoirs and hydropower stations in the basin are listed in Tables 1 and 2. A total of 3274 data sets are used to establish a multi-objective optimal reservoir operation model, and then the applicability and reliability of the constructed model is verified in this study.

2.2. Model construction

Five objectives, which include requirements for hydropower generation, water supply, flood and ice control and ecosystem sustainability, are considered as regulation objectives for reservoirs, and their synergistic gains are evaluated in this study. The formulations of multiple objectives and related constraints are presented as follows.

2.2.1. Objectives

2.2.1.1. Objective 1 (Obj-1): Hydropower generation. Hydropower generation is one of the most important objectives in this study. The power generation amount of the hydropower stations built in the Upper Yellow River basin is calculated as follow.

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

where E is the total amount of hydropower generated in a given period; $N(i,t)$ is the amount of hydropower generated by the ith hydropower station at time t, Δt is the duration, M is the number of hydropower stations, and T is the number of operation periods.

2.2.1.2. Objective 2 (Obj-2): Water supply. The balance between water supply and demand is essential for the Yellow River basin. According to the Water Supplement Planning of China (WSP), *Lanzhou* is selected as the control section of water supply, where a certain (minimum) flow in the outlet of the *Lanzhou* section must be preserved.

$$Q(Lanzhou,\ t) \geqslant Q\min(t) \tag{2}$$

where $Q(Lanzhou, t)$ is the flow in the *Lanzhou* section at time t; and $Q\min(t)$, a known parameter shown in WSP, is the minimum flow required for maintaining the balance between water supply and demand.

2.2.1.3. Objective 3 (Obj-3): Ice control. The main channel of Ningxia–Inner Mongolia reaches would freeze when temperature dips below freezing during the end of November and the next coming March. Ice control operation during this period is crucial for maintaining the safety of Mongolia reaches. Being the nearest regulation reservoir to the upper Mongolia, *Liujiaxia* reservoir (*LJX*, R2) is controlled by the Yellow River Conservancy Commission (YRCC) to make sure the reservoir outflow will not endanger the safety of

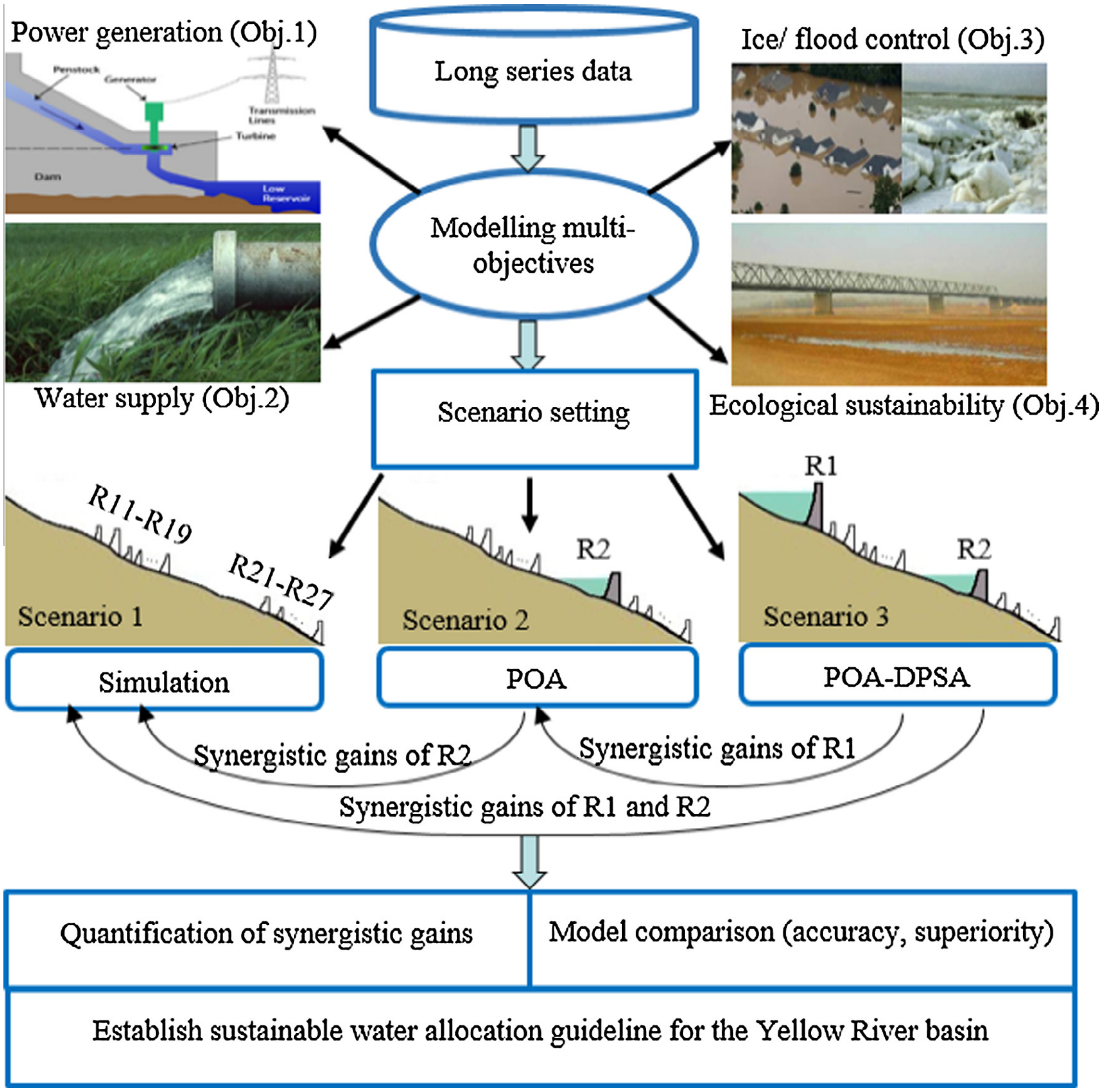

Fig. 1. Research flowchart (R1: Longyangxia (LYX); R2: Liujiaxia (LJX); R_{ij}: runoff reservoirs; Obj.: objective).

Table 1
Parameters of reservoirs (R1, R2) and hydropower stations (R11–R19 and R21–R27) in the Yellow River basin.

No	Normal water level (m.a.s.l.[a])	Dead water level (m.a.s.l.)	Total storage capacity (10^8 m^3)	Installed capacity (10^4 kW)	Average annual power generation (10^8 kW h)	Regulation ability	Run time (year)
R1[b]	2600	2530	247.00	128.0	59.24	Multi-year	1987
R11	2236	2232	0.26	16.0	7.63	Runoff	2003
R12	2180	2178	16.48	200.0	59.00	Runoff	1996
R13	2050	2048	0.15	19.2	7.01	Runoff	2005
R14	2033	2031	0.29	28.4	9.92	Runoff	2007
R15	2005	2002	5.50	150.0	51.40	Runoff	2004
R16	1900	1989	0.46	22.5	9.10	Runoff	2005
R17	1881	1879	0.60	24.8	9.27	Runoff	2010
R18	1856	1854	2.64	102.0	33.63	Runoff	2010
R19	1748	1747	0.48	24.0	9.74	Runoff	2008
R2[c]	1735	1694	57.00	135.0	57.60	Annual	1968
R21	1619	1618	2.70	41.7	22.80	Runoff	1990
R22	1578	1576	0.49	19.9	10.46	Runoff	1980
R23	1558	1557	0.12	7.8	4.55	Runoff	2010
R24	1550	1549	0.16	9.6	4.94	Runoff	2008
R25	1480	1479	0.90	30.0	14.56	Runoff	1999
R26	1241	1240	0.26	12.5	6.06	Runoff	2004
R27	1156	1153	5.56	30.2	10.51	Runoff	1967

[a] Meters above sea level.
[b] *Longyangxia.*
[c] *Liujiaxia.*

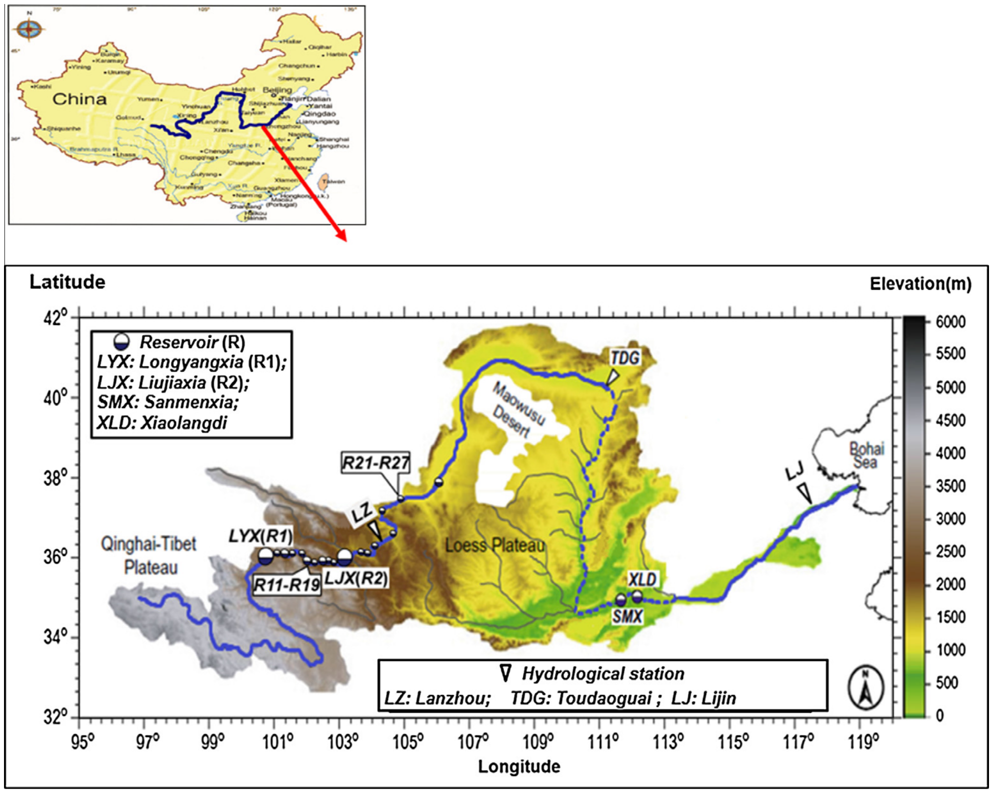

Fig. 2. Locations of Yellow River basin, reservoirs and hydropower stations. The dotted line represents the Middle Yellow River that divides the Yellow River into the Upper Yellow River and the Lower Yellow River. R11–R19 are runoff reservoirs between LYX and LJX, and R21–R27 are runoff reservoirs downstream LJX.

Table 2
Statistics of collected data.

Data type (unit)	Data length	Time scale	Data collection sites	Number of data[a]
Water level (m)	1987–2010	Month	R1, R2, *LZ*	864
Inflow/flow (m^3/s)	1987–2010	Month	R1, R2, *LZ*	864
Discharge (m^3/s)	1987–2010	Month	R1, R2	576
Power generation (kW h)	1987–2010	Month	R1, R2	576
Minimum supply_water flow (m^3/s)		Month	LZ	12
Ice control_discharge (Nov–next March) (m^3/s)	2000–2010	5 months	R2, *LZ*	110
Ice control_water level (Nov–next March) (m)	2000–2010	5 months	R2, *LZ*	110
Control discharge in flood season (Jul–Oct) (m^3/s)		4 months	R1, R2, *LZ*	12
Control water level in flood season (Jul–Oct) (m)		4 months	R1, R2, *LZ*	12
Ice disaster	1951–2010	Year	TDG	120
Price of power generation (USD/kW h)		Year	Provinces	9[b]
Price of irrigation water (USD/m^3)		Year	Provinces	9[b]

[a] Obtained by data length, time scales and the number of sites. E.g., 864 = 24 (years) X 12 (months) X 3 sites (R1, R2, *LZ*).
[b] Nine provinces along the Yellow River.

the Yellow River (Chang et al., 2014). Therefore, the objective of ice control is to minimize the maximum absolute difference between the actual outflow and the controlled outflow of the reservoir, described as follows.

$$\min(\max|Q(Liu,t) - Q_o(t)|) \tag{3}$$

where $Q(Liu, t)$ is the outflow of R2, $Q_o(t)$ is the threshold of outflow subject to the ice control requirement given by the YRCC. In fact, $Q(Liu, t)$ must strictly comply with $Q_o(t)$, which means the outflow of R2 should be very close (or equal) to $Q_o(t)$ during this period.

2.2.1.4. Objective 4 (Obj-4): Flood control. To ensure the safety of dams and downstream areas in flood seasons (July–August), the water level and outflow of each reservoir should be controlled within certain ranges, shown as follows.

$$Z_{\min}(i,t) \leqslant Z(i,t) \leqslant Z_{\max}(i,t) \tag{4}$$

$$Q_{o\,\min} \leqslant Q(i,t) \leqslant Q_{o\,\max}(i,t) \tag{5}$$

where $Z(i, t)$, $Q(i, t)$ are the water level and the outflow of the *i*th reservoir at time *t*, respectively; $Z_{\min}(i, t)$ and $Z_{\max}(i, t)$ are the minimum and maximum allowable water levels of the *i*th reservoir at time *t*, respectively; and $Q_{o\,\min}(i, t)$ and $Q_{o\,\max}(i, t)$ are the minimum and maximum allowable outflows of the *i*th reservoir at time *t*, respectively. In general, $Z_{\min}(i, t)$ is the dead water level, whereas $Z_{\max}(i, t)$ is the water level for flood control in the *i*th reservoir at time *t*.

2.2.1.5. Objective5 (Obj-5): Ecological flow. In order to avoid zero-flow problems and ensure enough water for flushing sands, a certain amount of flow in each river section must be preserved to maintain the ecological balance of the Yellow River.

$$Q(Lijin, t) \geqslant Q_{\min}(Lijin, t) \tag{6}$$

where $Q(Lijin, t)$ is the flow of the *Lijin* section at time t, and $Q_{\min}(Linin, t)$ is the minimum flow in this section preserved to avoid drying up the river.

2.2.2. Constraints

2.2.2.1. Water balance.

$$Q(i,t) = Q(i-1,t) + [Q_I(i,t) - Q_W(i,t) - Q_L(i,t) + Q_B(i,t)] \tag{7}$$

where $Q(i, t)$ and $Q(i-1, t)$ are the flow of sections i and $i-1$ at time t, respectively; and $Q_I(i, t)$, $Q_W(i, t)$, $Q_L(i, t)$ and $Q_B(i, t)$ are interval inflow, water supply flow, lost flow (such as evaporation and leakage), and backwater flow from irrigation area at time t, respectively.

2.2.2.2. Water balance between reservoirs.

$$V(i,t+1) = V(i,t) + (Q_I(i,t) - Q_O(i,t)) \times \Delta T(t) \tag{8}$$

where $V(i, t+1)$ and $V(i, t)$ are the initial storages of the ith reservoir at times $t+1$ and t, respectively; $Q_I(i, t)$ and $Q_O(i, t)$ are the inflow and outflow of the ith reservoir at time t, respectively; and $\Delta T(t)$ is the duration.

2.2.2.3. Water level.

$$Z_{\min}(i,t) \leqslant Z(i,t) \leqslant Z_{\max}(i,t) \tag{9}$$

where $Z_{\min}(i, t)$ and $Z_{\max}(i, t)$ are the dead level and the maximum water level of the ith reservoir at time t, respectively.

2.2.2.4. Outflow.

$$Q_{O\min}(i,t) \leqslant Q_O(i,t) \leqslant Q_{O\max}(i,t) \tag{10}$$

where $Q_{O\min}(i,t)$ and $Q_{O\max}(i,t)$ are the minimum and maximum allowable outflow of the ith reservoir at time t, respectively.

2.2.2.5. Hydropower generation.

$$N_{\min}(i,t) \leqslant N(i,t) \leqslant N_{\max}(i,t) \tag{11}$$

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

We would like to note that the importance and operational regulation of these five objectives in various periods could be very different. For example, in ice control periods, the other objectives must make a concession to the safety requirement for ice control, i.e., the flow in the *Lanzhou* section and the discharge of R2 must be fully confirmed. The implementation priority of objectives in each period is shown in Table 3.

Table 3
Implementation priority of objectives in each period for the multi-objective optimization model.

Month	Operation period	Implementation priority[a]
11, 12, 1, 2, 3	Ice control period	R1: Obj.1 > Obj.3 > Obj.4 R2: Obj.3 > Obj.4 > Obj.1
4, 5	Water supply period	R1: Obj.1 > Obj.2 > Obj.5 R2: Obj.2 > Obj.1 > Obj.5
6	Power generation period 1	R1: Obj.1 > Obj.2 > Obj.5 R2: Obj.1 > Obj.2 > Obj.5
7, 8	Flood control period	R1: Obj.4 > Obj.1 > Obj.2 R2: Obj.4 > Obj.1 > Obj.2
9, 10	Power generation period 2	R1: Obj.1 > Obj.4 > Obj.5 R2: Obj.1 > Obj.4 > Obj.5

[a] Obj.1 is hydropower generation; Obj.2 is water supply; Obj.3 is ice control; Obj.4 is flood control; Obj.5 is ecological flow.

2.3. Search methods

In general, there are two main approaches to handling the multi-objective optimal operation of cascade reservoirs: one approach aims to transform multiple objectives into one single main objective through identifying the most important objective and then setting the remaining sub-goals as constraints (e.g., Deb, 2014); and the other approach aims to combine all the sub-goals as an overall objective, where the weight coefficients of sub-goals are commonly adopted. There are a number of methods that solve the weight values of sub-goals. For instance, the analytic hierarchy process (Mohammad et al., 2013; Thomas, 2008) and the interactive multi-objective decision method (Ankur et al., 2014; Deb and Kumar, 2007).

In the abovementioned multi-objective optimization model, the outflow of R2 in Eq. (3) is simply set equal to the enacted flow by the YRCC during ice control periods, and Obj.3 can be transformed into the outflow constraint of R2. Consequently, there is only one equality objective function (Obj.1), and the others (Obj.2, 4, 5) are inequality objectives. In other words, except Obj.1 and Obj.3, the other objectives are constraints exactly. It appears that the transformation approach is more applicable than the other approach. Therefore, the multi-objective operation problem is thus transformed into one single objective problem, in which power generation is the only objective that needs to be optimized while the other objectives are expressed by inequality constraints. The constraints can be classified into three categories: water level, outflow, and output of R1 and R2.

There are a number of optimization algorithms that have been adopted for solving various water management problems, such as the large-scale system decomposition-coordination technique (Cheng et al., 2012) and the non-dominated sorting genetic algorithm (NSGA-II) (Chang and Chang, 2009).

In the aforementioned multi-objective optimization model of cascade reservoirs, there are 576 decision variables (=24 years $\times$ 12 months $\times$ 2 reservoirs (R1, R2)) and 1728 constraints (=24 years $\times$ 12 months $\times$ 3 equations $\times$ 2 reservoirs). Thus, it is extremely difficult to handle such a high-dimensional complex system due to the curse of dimensionality. The Progressive Optimality Algorithm–Dynamic Programming Successive Approximation (POA–DPSA) has been promisingly used for searching optimal solutions (Mohammed et al., 2013; Liu, 2008). In this hybrid algorithm, the Dynamic Programming Successive Approximation (DPSA) is used to conduct dimension reduction that converts an m-dimensional dynamic programming problem into m one-dimensional sub-problems based on the idea of successive iterative approximation while the Progressive Optimality Algorithm (POA) is used to solve one-dimensional sub-problems. Therefore, the number of calculations made by the POA–DPSA would grow only linearly, not exponentially, which greatly reduces computation time and is easier to implement. Details of the POA–DPSA can be found in Li et al. (2005) and Ma et al. (2012).

In order to effectively quantify the synergistic gains of R1 and R2, long term time series are first divided in an annual scale. The multi-year calculation for the optimal joint operation of R1 and R2 during 1987 and 2010 is sequentially conducted year by year. The water levels of reservoirs in the end of the current year are set as the initial water levels of reservoirs for the next consecutive year. Then the optimal monthly operation of the two reservoirs based on one single objective (hydropower generation) can be much easily solved by the POA–DPSA, in which the DPSA is used

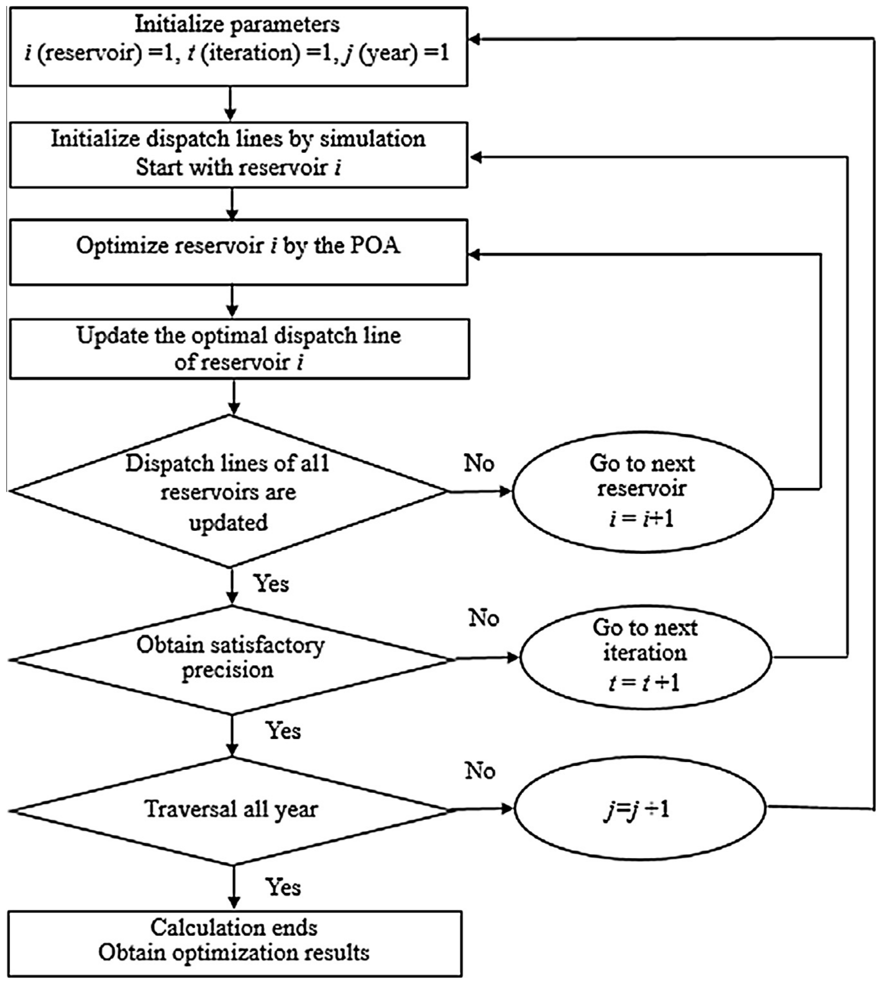

Fig. 3. Implementation steps of the POA–DPSA.

for dimension reduction while the POA is used to optimize the operation of each reservoir. Moreover, inflow data are given and thus the optimal operation can be described as a deterministic problem. The implementation process of the POA–DPSA is shown in Fig. 3, and the implementation details are introduced step by step, shown as follows. Variables of the multi-objective optimization model are listed in Table 4, while the parameter setting of the POA–DPSA can be found in Table 5.

Step 1: Initialize parameters

Table 4
Variables of the multi-objective optimization model.

Type	Item
Decision variable	Power generation of two cascade reservoirs
State variable	Water level
Input variables	Inflow of R1
	Interval inflow between R1 and R2
	Water level and storage capacity of R1 and R2
	Discharge and water level relationship of R1 and R2
	Initial parameters (such as: water level, output coefficient of R1 and R2)
	Constraint parameters (such as: water level, discharge, output of R1 and R2)
Output variables	Power generation of cascade reservoirs
	Discharge of R1 and R2
	Flow of LZ

In this study, flow data were collected monthly between 1987 and 2010. The initial water levels (1987) and the final water levels (2010) of reservoirs R1 and R2 are set the same as historical data, which are 2580 m for R1 and 1735 m for R2, respectively. For ensuring the reservoir capacity required for flood and ice control operations, the water level of R2 must be reduced to 1726 m and 1728 m prior to the flood control period (the end of June) and the ice control period (the end of November), respectively, whereas the water level of R1 must be reduced to 2594 m prior to the flood control period. The monthly controlled outflow of R2 during the ice control period (November–next March) is set as 740, 490, 462, 385 and 458 m^3/s, respectively. Table 6 shows the minimum monthly flow in the *Lanzhou* section required for maintaining the minimum requirement of the water supply objective over the whole watershed. The ecological flow of the *Lijin* section should exceed 300 m^3/s. The minimum amounts of hydropower produced from R1 and R2 are 60×10^4 kW and 40×10^4 kW, respectively.

In this study, water level and water release are selected as a state variable and a decision variable, respectively, and both

Table 5
Parameters of the POA–DPSA.

Parameter	Setting value
Calculation step of POA	0.01
Termination accuracy of POA	0.001
Convergence discrimination of DPSA	0.0005

Table 6
Minimum monthly flow for water supply in the Lanzhou 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

variables can be calculated based on initial conditions. As shown in Table 3, calculation starts from November.

Step 2: Obtain the initial dispatch lines of R1 and R2 based on initial setting or simulation results

Based on the initialized parameters set in *Step* 1, the initial dispatch lines of R1 and R2 can be obtained by simulation.

Step 3: Optimize reservoir R1 in a year by the POA

The monthly water discharge of R1 in a year is optimized by the POA, and related variables, including storage capacity and water level of R1, are updated by the optimization results. The amount of hydropower produced from R1 is calculated and denoted as E_1.

Step 4: Update the optimal operation status of R1, and then optimize the operation of R2 by the POA

Based on the DPSA, the two-dimensional dynamic programming problem can be converted into two one-dimensional subproblems that can be iteratively solved. Then the optimal operation of two cascade reservoirs (R1&R2) can be iteratively solved by the POA. The initial dispatch line of R1 is updated according to the solution obtained from the previous step. Then the monthly water discharge of R2 in a year is also optimized by the POA, and thus the related variables (storage capacity and water level) of R2 can then be updated. The amount of hydropower produced from R2 is calculated and denoted as E_2. At last, the total amount of hydropower produced from R1 and R2, denoted as E ($E = E_1 + E_2$), can be obtained.

Step 5: Go to *Step* 2 for the next iteration

Update R1 and R2 accordingly, and re-calculate the total amount of hydropower, denoted as E'. If the difference between E and E' is greater than the designed (satisfactory) precision, then go to *Step* 2 for conducting the next iteration, otherwise go to the next step for obtaining the optimal results of R1 and R2 in a year.

Step 6: Go to *Step* 1 for the next iteration (year) until the optimal results of R1 and R2 in all years (1987–2010) are obtained.

3. Results and discussion

In this study, the established optimization model is solved by the POA–DPSA to quantify the synergistic gains of reservoirs R1 and R2. Then the individual synergistic gains of R1 and R2 are clarified based on three designed scenarios shown as follows.

3.1. Scenario setting

3.1.1. Scenario 1 (S1, 1987–2010): neither R1 nor R2 participate in flow regulation

In S1 (under un-controlled conditions), it is assumed that neither R1 nor R2 participate in flow regulation. It means that only 16 runoff reservoirs (R11–R19 and R21–R27) participate in flow regulation under natural runoff conditions, and their operations in response to five objectives are not influenced by R1 or R2 at all. Therefore, S1 is a perfect contrasting scenario to both separate operation and joint operation. Because no optimal search process is applied to S1, the amount of hydropower generation can be obtained simply by simulation.

3.1.2. Scenario 2 (S2, 1987–2010): only R2 participates in flow regulation

R2 was built in 1968, which was much earlier than R1 was built (1987). Therefore in S2, only R2 participates in flow regulation and the optimal results of S2 is obtained from the POA. The synergistic gains of R2 can be quantified clearly by comparing the results of S1 and S2.

3.1.3. Scenario 3 (S3, 1987–2010): both R1 and R2 participate in flow regulation

S3 deals with the synergistic gains from the joint operation of R1 and R2. The synergistic gains can be calculated by the POA–DPSA. The synergistic gains of joint operation can be quantified by subtracting the results of S1 from those of S3, and the synergistic gains of R1 can be quantified by deducting the results of S2 from those of S3.

The design of S1–S3 and related methods for reservoir operation can be briefly addressed as follows.

S1 (without R1, without R2) involves the simulation of 16 runoff reservoirs;
S2 (separate operation of R2 only) involves the optimization of reservoir operation by the POA; and
S3 (joint operation of R1 and R2) involves the optimization of reservoir joint operation by the POA–PSDA.

Consequently, the synergistic gains of joint operation and separate operation can be obtained. It is noticed that the joint operation of R1 and R2 has been actually implemented since 2001. The comparison between the obtained optimization results and historical operation is also conducted.

3.2. Results and analyses

The inputs of the established optimization model consist of monthly inflow data sets, initial parameters and constraints, and the annual results of Scenarios 1, 2 and 3 can be obtained from simulation, the POA, the POA–DPSA, respectively. For the years of 1987–2010, and the average annual results of each objective are analyzed. Synergistic gains with respect to hydropower generation, water supply, ice/flood control, and ecological sustainability under the three scenarios are summarized below.

3.2.1. Hydropower generation

According to the optimal monthly discharge of R1 and R2, which is regarded as outflow, the amounts of average annual hydropower produced from 16 runoff reservoirs (hydropower stations) can be calculated in consideration of the designed water heads and output coefficients. The power generation results under three scenarios and scenarios comparison are listed in Table 7, in which the synergistic gains of R1, R2 and both R1&R2 are quantified, respectively. Fig. 4 illustrates the synergistic gains of sixteen hydropower stations in power generation with respect to R1 (S3 vs. S2), R2 (S2 vs. S1) and R1&R2 (S3 vs. S1). Results of S2 vs. S1

Table 7
Comparison of synergistic gains in average annual hydropower generation (1987–2010).

Reservoirs	Power generation[a]			Synergistic gains[a]		
	S1	S2	S3	S2 vs. S1	S3 vs. S1	S3 vs. S2
R1	–	–	50.02		–	–
R11	7.15	7.15	7.57	0	0.42	0.42
R12	59.16	59.16	61.42	0	2.26	2.26
R13	6.53	6.53	6.68	0	0.15	0.15
R14	9.50	9.50	9.69	0	0.19	0.19
R15	56.46	56.46	58.75	0	2.29	2.29
R16	8.43	8.43	8.77	0	0.34	0.34
R17	9.39	9.39	9.79	0	0.40	0.40
R18	33.87	33.87	34.55	0	0.68	0.68
R19	9.41	9.41	9.79	0	0.38	0.38
R2	–	52.56	55.74	–	–	3.18
R21	20.27	21.30	22.04	1.03	1.77	0.74
R22	10.06	10.64	10.95	0.58	0.89	0.31
R23	4.20	4.52	4.65	0.32	0.45	0.13
R24	4.68	5.01	5.15	0.33	0.47	0.14
R25	15.32	16.23	16.57	0.91	1.25	0.34
R26	5.12	5.41	5.53	0.29	0.41	0.12
R27	9.42	9.63	10.14	0.21	0.72	0.51
Total	268.97	325.20	387.80	3.67	13.07	12.58
Subtotal of runoff reservoirs	268.97	272.64	282.04	3.67	13.07	9.40

[a] Units-10^8 kW h/year.

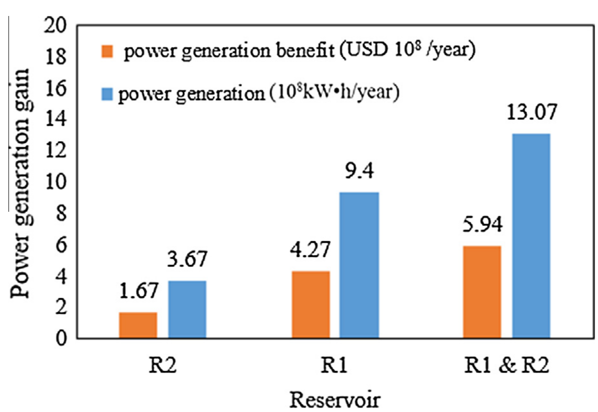

Fig. 4. Synergistic gains of sixteen hydropower stations in hydropower generation with respect to R1, R2, and R1&R2 (joint operation).

indicate that the participation of R2 in flow regulation increases the annual power generation of seven hydropower stations (R21–R27) by 0.367 billion kW h/year (167 million USD), which represents the synergistic gains from R2 (*LJX*). Results of S3 vs. S1 indicate that the participation of both R1&R2 in flow regulation increases the annual power generation of sixteen hydropower stations by 1.307 billion kW h/year (594 million USD), which represents the synergistic gains from the optimal joint operation of R1 and R2. The comparison of S3 and S2 can quantify the synergistic gains from R1, which shows the participation of both R1&R2 in flow regulation increases the annual power generation of R2 and sixteen hydropower stations by 0.318 billion kW h/year (15 million USD) and 0.94 billion kW h/year (427 million USD), respectively. That is to say, the participation of R1 in this joint operation is also beneficial to R2.

Table 8 shows the amount of annual average hydropower produced from S3 and historical operation. Because the joint operation has been actually implemented since 2001, the comparison is divided into two parts according to two different periods (before and after the year of 2001). Results indicate that the amount of annual average hydropower generation in S3 is 20.2% more than that of historical operation in the period without joint operation

Table 8
Comparison of average annual hydropower generation between Scenario 3 and historical operation (Units-10^8 kW h/year).

Averaging period	1987–2000		2001–2010	
Item	Historical separation operation	Scenario 3[a]	Historical joint operation	Scenario 3
R1	40.52[b]	50.10	46.88	49.91
R2	46.88	55.87	51.28	55.56
R11–R19, R21–R27	235.80	282.50	264.10	281.40
Total	323.20	388.47	362.26	386.87
Improvement rate		20.2%		6.79%

[a] Optimal joint operation of R1 and R2.
[b] Units-10^8 kW h/year.

(1987–2000) while 6.79% more in the period with joint operation (2001–2010). The results clearly demonstrate that (1) the optimal joint operation does make much more hydropower generation than historical separate operation and (2) the multi-objective optimization model searched by the POA–DPSA is suitable and superior to historical operation.

3.2.2. Water supply

The average annual flow in the *Lanzhou* section during 1987 and 2010 is obtained from the established optimization model. Water discharged from the *Lanzhou* section to downstream areas is allocated to nine provinces along the Yellow River according to the water supply requirement approved by the YRCC, which is published annually in the Yellow River Water Resources Bulletin (YRWRB).

Table 9 shows the synergistic gains in water supply to each province along the Yellow River. Results of S2 vs. S1 demonstrate that the average annual amount of water supply to the nine province increases by 0.930 billion m^3 (4%), which can be attributed to the participation of R2. Results of S3 vs. S2 demonstrate that the average annual amount of water supply increases by 2.727 billion m^3 (11%), which can be attributed to the participation of R1. Results of S3 vs. S1 demonstrate that the average annual amount of water supply increases by 3.657 billion m^3 (15%), which can be attributed to the optimal joint operation of R1 and R2. In brief, the optimal

Table 9
Average annual amount of water supplied to each province during 1987–2010 for Scenarios 1–3.

	P1[a,b]	P2	P3	P4	P5	P6	P7	P8	P9	Total
S1	11.78	0.00	33.68	59.17	68.28	25.63	18.28	23.69	10.10	250.61
S2	12.51	0.00	33.87	59.96	69.37	30.01	21.30	23.03	9.86	259.91
S3	14.63	0.00	39.22	69.40	77.38	31.52	22.85	22.67	9.51	287.18

[a] Units-10^8 kW h/year.
[b] P1–P9 represent nine provinces (P) along the Yellow River by the order of: Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, He'nan and Shandong.

joint operation of R1 and R2 (S3) produces the maximum percentage (15%) of synergistic gains for water supply.

We notice that the amounts of water supply to He'nan and Shandong provinces decrease in Scenarios 2 and 3 (Table 9). It is mainly because water supply to both provinces was re-regulated and re-allocated by the *Xiaolangdi* (*XLD*) reservoir, which is the closest reservoir to both provinces. Even though the flow regulation of *XLD* is ignored in this study, the water demand of He'nan and Shandong provinces can still be practically satisfied by incorporating the synergistic gains from the *XLD* reservoir.

3.2.3. Flood and ice control

As compared with hydropower generation and water supply, the synergistic gains of flood and ice control are more complex and difficult to quantify because monthly results cannot suitably reflect a flooding or icing process in a daily time scale. Thus, different from three scenarios designed above, the designed data of R1 and R2 were collected to analyze the synergistic gains of flood and ice control.For flood control, the analyses are divided according to three periods: neither R1 nor R2 participate in flood control (Scheme 1: 1919–1968; before R1&R2 were built), only R2 participate in flood control through separate operation (Scheme 2: 1968–1987; only R2 was built), and both R1 and R2 participate in flood control through joint operation (Scheme 3: 1987–2010). For simplicity, the synergistic gains from flood control are reflected mainly by flood peak clipping, shown in Fig. 5. Under the natural condition (Scheme 1), there are no hydraulic facilities installed in the Yellow River for flood control, and the probable maximum flood (PMF) in the dam sites of R1 and R2 are 10,500 m^3/s and 13,000 m^3/s (Fig. 5), respectively. In Scheme 2, the PMF in the dam sites of R1 and R2 reduce to 6000 m^3/s and 7500 m^3/s, respectively, which can be attributed to the participation of R2 in flow regulation. Furthermore, after the joint operation of R1 and R2 started (Scheme 3), the PMF in the dam sites of R1 and R2 decrease further to 4500 m^3/s and 5048 m^3/s, with peak-clipping rates of 57.1% and 61.2%, respectively, which can be attributed to the joint operation of R1 and R2. In addition, the joint operation of R1 and R2 also reduces the discharge from 4770 m^3/s to 4290 m^3/s for a 100-year recurrence flood, which greatly improves the reliability of flood control for the *Lanzhou* city.

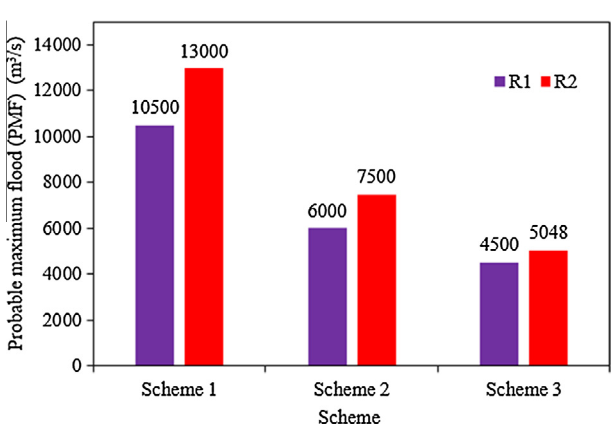

Fig. 5. Synergistic gains of flood peak clipping in flood control with respect to Scheme 1–3.

Table 10
Comparison of synergistic gains of R1 and R2 for ice control.

Items	Neither R1 nor R2 participate in ice control (1951–1968)[a]	R1 and R2 participate in ice control (1968–2010)[a]
Number of years	18	42
Number of years with ice disasters occurred	13	17
Occurrence probability of ice disaster (%)	72.22	40.47
Return period of ice disaster (year)	1.46	2.53

[a] Chang et al., 2014.

The spatial and temporal data of ice disasters are different from those of flood control. Besides, the water releases of R1 and R2 are mainly based on the regulation, as mentioned above. Consequently, historical data of ice disasters (1951–2010) are selected and analyzed for obtaining the synergistic gains of ice control in two periods: neither R1 nor R2 participate in ice control (1951–1968); and R1 and R2 participate in ice control (1968–2010), in which all data were measured in the past. By comparing ice disasters happened in two different time periods (Chang et al., 2014), Table 10 shows the synergistic gains of R1 and R2 for ice control. The outflow of R2 is well controlled during ice control periods and is regarded as a strong constraint that may reduce the occurrence interval of ice disasters. Based on the historical data of ice disasters, the occurrence probability of ice disasters reduces from 72.22% to 40.47% (31.74% decreasing) after both R1 and R2 participate in joint operation for ice control, which demonstrates the significant synergistic gains of R1 and R2 regarding ice control. However, ice disasters are very complicated and cannot be entirely avoided by reservoir regulation.

3.2.4. Ecological sustainability

Before commencing the joint operation of R1 and R2 in 2001, zero-flow conditions in the Yellow River occurred more than 20 times before the year of 2000 and the most serious case happened in 1997, which lasted for 226 days. After the year of 2000, the unified allocation of water resources has been adopted by R1 and R2, and ecological base flow has been proposed to avoid zero-flow conditions in the whole Yellow River. Based on the joint operation of R1 and R2, the minimum ecological base flow of the *Lijin* section is set as 200 m^3/s, which can both meet ecological demands and avoid drying up the Yellow River. Before the year of 2000, the average annual natural flow of the *Lanzhou* section was small (less than 300 m^3/s) in dry periods (November–April) of drought years. After commencing the joint operation of R1 and R2, the observed average annual flow of the *Lanzhou* section exceeded 520 m^3/s in dry periods during 2001 and 2010, which greatly improved the water quality of the *Lanzhou* section.

4. Conclusions

In this study, the synergistic gains of two pivotal reservoirs along the Upper Yellow River are explored by implementing a multi-objective optimal operation model of cascade reservoirs, which is constructed by the POA–DPSA method based on long series data (1987–2010). The synergistic gains relevant to hydropower generation, water supply, ice control and flood control, and ecological sustainability are analyzed, and the results are summarized as follows.

(1) Compare the optimal joint operation with historical operations: (i) the amount of annual average hydropower generation increases by 7%; (ii) the average annual power generation of the sixteen runoff reservoirs in the Upper Yellow River increases by USD 0.594 billion/year; and (iii) the average water supply to nine provinces along the Yellow River increases by 36.57 billion m^3/year (15%). It appears that a great contribution in hydropower generation and water supply could be made by the optimal joint operation of the two pivotal reservoirs.

(2) The safety requirements for ice and flood control in the downstream regions can be suitably satisfied by the joint operation of the two pivotal reservoirs. The joint operation would also avoid drying up the Yellow River and increase the minimum flow of the *Lanzhou* section during dry periods, which significantly improves river water quality as well as ecosystem sustainability.

With the quantified synergistic gains, the optimal joint operation of cascade reservoirs could be greatly inspired. This study makes a great progress in the unity of theory and practice by quantifying synergistic gains, which provides important recommendations on sustainable management and unified allocation of water resources over the Yellow River basin and a sound scientific basis for optimizing the operation of cascade reservoirs.

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