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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: 247×10^8 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