Exploration and attribution of synergistic gains from joint optimal operation of downstream Jinsha River cascade and Three Gorges cascade reservoirs for hydropower generation

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ABSTRACT

Joint operation for multi-reservoir systems leads to synergistic gains. This study aims to explore and attribute the driven mechanism of synergism from joint operation of a multi-hydropower system. It quantified synergistic gains in spatial, temporal, and interannual scales by establishing and solving an individual and a joint reservoir operation model. It then proposed an attribution method for identifying the contribution of water released and water head to synergistic gains using total differential equation. Results of the case study of the downstream Jinsha River cascade and Three Gorges cascade reservoirs during the drawdown season show that: (1) synergistic gains generally occur in May and are mostly generated in Xiangjiaba and Gezhouba; (2) joint reservoir operation is driven by the rapid drawdown policy of Xiluodu and the Three Gorges in early May, which lowers down their water head and gains for most cases; (3) the main contribution factor to synergistic gains of Xiangjiaba and Gezhouba are water released and water head, respectively; and (4) the influence mechanisms of synergistic gains of Xiangjiaba and Gezhouba are jointly determined by their storage and power release capacity conditions. The study provides new insights for analyzing synergism of joint hydropower operations.

Key words | attribution analysis, cascade reservoir system, reservoir operation, synergistic gains, total differential equation

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INTRODUCTION

In the past two decades, China has accelerated its development of reservoirs and hydropower stations for alleviating energy shortages and environmental pollution caused by fossil energy consumption (Zhang *et al.* 2017). In 2015, the hydropower installations in China reached 319 GW, which was the highest in the world and accounted for 26% of global installed capacity (Zhang *et al.* 2017). Hydropower energy delivered in 2015 reached 996 TWh, which comprised approximately 18% of the total energy consumption in China. According to previous studies (Lazarova *et al.* 2012; Li *et al.* 2014), the fast development of the hydropower industry has greatly reduced CO_2 emissions. Using optimal reservoir operation techniques to improve hydropower generation efficiency generates significant benefits, especially for multiple hydropower systems in which synergistic gains can be explored by joint operations because of the abundance of hydropower energy sources (Cheng *et al.* 2012). However, a gap (Yeh 1985; Labadie 2004) separates

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mathematical models and real-world implementations involved in reservoir operations. Thus, joint optimal operation techniques remain in the preliminary stage of application in practice. The lack of systematic evaluations and attributions on synergistic gains is one of the factors that limit the use of joint optimal operation models.

Synergistic gains were commonly defined as the gains in benefits from the joint operation of a system of reservoirs in excess of the benefits from optimal individual operation. This definition provided the estimations of synergistic gains on the basis of the differences in gains between joint and individual operations for reservoir systems. Following this concept, Hirsch *et al.* (1977) verified the effectiveness of synergism in saving costs in designing optimal reservoir sizes via a hypothetical case with a water supply reservoir system. Bai *et al.* (2015) investigated the synergistic gains from the optimal joint operations of the Longyangxia and Liujiaxia reservoirs at the Yellow River. By comparing model results with historical operation data, they validated that energy production and water supply can be significantly increased by joint operations. Harboe *et al.* (1994) extended the concept to explore synergistic gains from the conjunctive operation of hydropower and thermal power stations. Synergistic gains are highly influenced by streamflow variability. Therefore, systematic simulations should investigate the temporal, spatial, and interannual results of synergistic gains. Although these studies assessed the value of synergistic gains for different systems and objectives, the influence of driven factors and the mechanisms of determining synergistic gains have not been thoroughly discussed.

The synergism of joint reservoir operation (Zhu *et al.* 2016) originates from inhomogeneous conditions of streamflow and reservoir characteristics in multi-reservoir systems. Under inhomogeneous conditions, systems with joint reservoir operations can complement one another via reservoir regulations on streamflows to improve the efficiency of the entire system. Increasing the benefits of energy production (Chen *et al.* 2015; Xu *et al.* 2015a, 2015b; Feng *et al.* 2017; Zhu *et al.* 2017) from joint reservoir operations is mainly influenced by increases in water head and decreases in spillage. As regard to guiding joint reservoir operation for energy production, various operation rules were developed in extensive studies (Xu *et al.* 2017a, 2017b). Lund & Guzman (1999) introduced the hydropower production rule for maximizing hydropower production subjected to a given total water storage in a single period. Zhao *et al.* (2015) studied the optimal condition for maximizing the total energy production of a single reservoir over sequences of time periods, and concluded that the reservoir should store more water than that released from current energy delivery and increase the total water head under dry hydrology conditions. However, the regulations for balancing water released and water head under other hydrology conditions have not been elaborated upon. Zeng *et al.* (2014) proposed chance-constrained hedging rules for cascade hydropower reservoirs and investigated the complementarity of reservoir operations under dry hydrology conditions in which hedging has proceeded. Variations in water head and water released in power generation are critical in generating synergism via joint reservoir operation for all types of hydrology conditions. However, these studies do not discuss how variations in these two factors affect synergism.

The purpose of the study includes two fields: (1) to evaluate the synergistic gains of the joint operation of the mega cascade reservoir system that comprises the downstream Jinsha River and Three Gorges cascade reservoirs in China; and (2) to explore and attribute the driven mechanism of synergism as regard to the changes in water released for energy production and water head via joint operation. This paper is organized as follows. The methodologies of evaluating the synergistic gains are introduced by establishing an individual reservoir operation model and a joint reservoir operation model. Moreover, we propose an attribution method that is based on the total differential equation for calculating the contribution percentage of water released for energy production and water head in determining the synergistic gains. Thereafter, the methodology is applied to the downstream Jinsha River cascade and Three Gorges cascade reservoir system and the specific results and mechanism of synergistic gains are analyzed.

METHODS

Synergistic gains of reservoir joint operation

Synergistic gains are gains from joint reservoir operations in excess of the total gains obtained from individual operations, which can be characterized as follows:

$$\Delta B = \sum_{i=1}^{n}\sum_{t=1}^{T}\Delta B_{i,t} = \sum_{i=1}^{n}\sum_{t=1}^{T}(B_{i,t}^{(1)} - B_{i,t}^{(0)}), \tag{1}$$

where n and T are the total numbers of reservoirs and time periods, respectively, $B_{i,t}^{(1)}$ and $B_{i,t}^{(0)}$ are the gains from energy production from reservoir i during time period t under the joint and individual operation models (CNY), respectively, $\Delta B_{i,t}$ is the synergistic gains of reservoir i during time period t (CNY), and ΔB is the total synergistic gains of the reservoir system during the planning horizon (CNY).

Equation (1) indicates that the total synergistic gains are determined by the result differences between the joint and individual operation models for each reservoir in each time period. Therefore, the mechanism of synergistic gains of joint operations is investigated by establishing a joint optimal operation model that aims to maximize the total revenue of the reservoir system and an individual optimal operation model that aims to maximize the revenue for each reservoir.

Optimal reservoir operation models

Individual optimal operation model

In this model, each reservoir is assumed to operate separately to maximize revenue from energy production. Assuming that the information is perfectly foresighted, the downstream reservoir delivers the best response according to the optimal release policy of its upstream reservoir. Accordingly, the operation policy of the reservoirs is sequentially optimized from upstream to downstream. The objective function is provided by:

$$Max\ B_i^{(0)} = \sum_{t=1}^{T} N_{i,t}^{(0)} \cdot \Delta_t \cdot P_i,\ i = 1, 2, \ldots, n, \tag{2}$$

where $N_{i,t}^{(0)}$ is the power output of reservoir i during time period t in the individual operation model (kW), Δ_t is the duration of time period t (h), and P_i is the energy price of reservoir i (CNY/kWh).

Joint optimal operation model

In the model, all the reservoirs are jointly operated by an operating center that aims to maximize the total benefit of the entire reservoir system. The objective function is provided by:

$$Max\ B^{(1)} = \sum_{i=1}^{n}\sum_{t=1}^{T} N_{i,t}^{(1)} \cdot \Delta_t \cdot P_i, \tag{3}$$

where $N_{i,t}^{(1)}$ is the power output of reservoir i during time period t in the joint operation model (kW).

The following constraints are addressed in both models.

Mass balance equation:

$$\begin{aligned} &V_{i,t+1}^{(j)} = V_{i,t}^{(j)} + (Q_{i,t}^{(j)} - q_{i,t}^{(j)} - J_{i,t}^{(j)} - S_{i,t}^{(j)}) \cdot \Delta_t,\ i = 1, j = 0, 1 \\ &V_{i,t+1}^{(j)} = V_{i,t}^{(j)} + (Qu_{i,t} + q_{i-1,t}^{(j)} + J_{i-1,t}^{(j)} - q_{i,t}^{(j)} - J_{i,t}^{(j)} - S_{i,t}^{(j)}) \\ &\quad \cdot \Delta_t,\ i = 2, \ldots, n,\ j = 0, 1 \end{aligned} \tag{4}$$

where $V_{i,t}^{(j)}$ and $V_{i,t+1}^{(j)}$ denote the storage of reservoir i at the beginning and ending of time period t in the optimization model j (individual operation models $j = 0$; joint operation model $j = 1$) (m^3), respectively, and $Q_{i,t}^{(j)}$, $q_{i,t}^{(j)}$, $J_{i,t}^{(j)}$, $S_{i,t}^{(j)}$, and $Qu_{i,t}$ are the inflow, power release, non-power release (spill), water loss rate, and lateral inflow, respectively, of reservoir i during time period t (m^3/s). $Q_{1,t}^{(j)} = Qu_{1,t}$ for most of the upstream reservoir. When solving the joint operation model, all the variables of $Q_{i,t}^{(1)}$, $q_{i,t}^{(1)}$, $J_{i,t}^{(1)}$, $S_{i,t}^{(1)}$, $i = 1, \ldots, n, t = 1, \ldots, T$ are decision variables and optimized simultaneously. By contrast, the individual operation models are solved sequentially with the variables of $q_{i,t}^{(0)}, J_{i,t}^{(0)}, S_{i,t}^{(0)}, t = 1, \ldots, T$ for a specific reservoir i determined each time.

Storage limits:

$$\underline{V_{i,t+1}} \le V_{i,t+1}^{(j)} \le \overline{V_{i,t+1}}, \tag{5}$$

where $\overline{V_{i,t+1}}$ and $\underline{V_{i,t+1}}$ are the upper and lower bounds, respectively, on storage at the end of time period t for reservoir i (m^3).

Outflow limits:

$$\underline{O_{i,t}} \le q_{i,t}^{(j)} + J_{i,t}^{(j)} \le \overline{O_{i,t}}, \tag{6}$$

where $\underline{O_{i,t}}$ is minimum limit of outflow considering ecological downstream water use and shipping requirement (m^3/s) and $\overline{O_{i,t}}$ is the maximum limit of outflow that can be released to the downstream river when the available spillways and turbine units reach their discharge capacities (m^3/s).

Power output:

$$N_{i,t}^{(j)} = 3600q_{i,t}^{(j)}/k_i(H_{i,t}^{(j)}), \tag{7}$$

$$H_{i,t}^{(j)} = f_1((V_{i,t+1}^{(j)} + V_{i,t}^{(j)})/2) - f_2(q_{i,t}^{(j)} + J_{i,t}^{(j)}), \tag{8}$$

where $H_{i,t}^{(j)}$ is the gross water head of reservoir i during time period t (m), which is the difference between average forebay water level and tailrace water level; f_1 and f_2 are functions that specify the forebay water level and tailrace water level (m), respectively; and $k_i(\cdot)$ is the water release rate for per unit energy production (m^3/kWh).

Power output limit:

$$N_{i,t}^{(j)} \leq NH_{i,t}, \tag{9}$$

where $NH_{i,t}$ is the power output limit of reservoir i during time period t (kW).

Boundary condition:

$$V_{i,T+1}^{(j)} = VE_i, \tag{10}$$

where VE_i is the ending storage of reservoir i (m^3).

Water level variation limits:

The forebay water level should not fluctuate rapidly to ensure the safety of the riverbank upstream of the dam. The difference in water level between two adjacent time periods varies within a given range according to the fluctuation rate requirement, which can be characterized as:

$$|Z_{i,t+1}^{(j)} - Z_{i,t}^{(j)}| \leq \Delta Z_{i,t}, \tag{11}$$

where $Z_{i,t+1}^{(j)}$ and $Z_{i,t}^{(j)}$ denote the water level of reservoir i at the ending and beginning of time period t, respectively, and $\Delta Z_{i,t}$ is the maximum allowable water level variation rate [m/d].

Attribution on the influencing factors of synergistic gains

Joint reservoir operation seeks the optimal complementarity mechanism of water released and water head to increase the total benefit for the entire system. Synergistic gains are generated from benefit-increasing reservoirs, in which the power release and water head are increased more than those in individual operation models because of joint operation. Meanwhile, the benefits from the energy production of the benefit-decreasing reservoirs, which help enhance the benefits of benefit-increasing reservoirs, can be reduced because the joint operation strategies of benefit-decreasing reservoirs deviate from their individual optimal strategies that maximize their own benefit.

Because hydropower operations are also involved in reallocating water released during multiple time periods, the temporal complementarity of water released and water head could also affect energy production and benefit, which enhances the difficulty in identifying synergism from joint operations. The temporal complementarity is generated from optimal regulations on the total inflow volume such that the total energy production (or gains) during the multiple time periods is maximized. Consequently, this could result in heterogeneous outflow processes over different time periods, during which water is mostly released when the productivity is the highest or the released water yields an equalized marginal utility. Therefore, for minimizing the influence of temporal complementarity on exploring synergism from joint operations, we examine the contribution on synergism from joint operations over a sequence of time periods (a sub-time span) rather than each single time period. Specifically, the paper introduces a method that uses the total differential equation to identify the contribution percentage of water released to energy production and water head in influencing synergistic gains. The steps are as follows.

Step I: The synergistic gains of each reservoir during the considered sub-time span ($t \in [ts, te]$) are determined. ts and te are the starting and ending time period, respectively, of the considered sub-time span. The synergistic gain of joint reservoir operation is the increased benefit of each reservoir during joint operation, which can be calculated by using

Equations (1)–(3).

$$\begin{aligned}\sum_{t=ts}^{te}\Delta B_{i,t} &= \sum_{t=ts}^{te}(B_{i,t}^{(1)} - B_{i,t}^{(0)}) \\ &= \sum_{t=ts}^{te}(N_{i,t}^{(1)}\cdot\Delta_t\cdot P_i - N_{i,t}^{(0)}\cdot\Delta_t\cdot P_i) \\ &= \sum_{t=ts}^{te}(N_{i,t}^{(1)} - N_{i,t}^{(0)})\cdot\Delta_t\cdot P_i \\ &= \sum_{t=ts}^{te}\Delta N_{i,t}\cdot\Delta_t\cdot P_i,\end{aligned}\tag{12}$$

where $\Delta N_{i,t}$ is the difference in the power outputs under joint and individual operation models for reservoir i during time period t (kW).

Step II: The contribution percentage of water released and water head are quantified. According to Equation (12), synergistic gains are affected only by the difference in power output. Let $\overline{\Delta N_i}$ (kW) as the average value of the changed power output during the sub-time span and ΔT (h) is the total time interval of the sub-time span, such that:

$$\overline{\Delta N_i}\cdot\Delta T = (\overline{N_i^{(1)}} - \overline{N_i^{(0)}})\cdot\Delta T = \sum_{t=ts}^{te}\Delta N_{i,t}\cdot\Delta_t,\tag{13}$$

where $\overline{N_i^{(j)}}$ is the average value of power output during the sub-time span under the operation model j (kW). According to Equation (7), the output difference $\overline{\Delta N_i}$ is jointly determined by the difference in power release $\overline{\Delta q_i} = [\sum_{t=ts}^{te}(q_{i,t}^{(1)} - q_{i,t}^{(0)})\cdot\Delta_t]/\sum_{t=ts}^{te}\Delta_t = \overline{q_i^{(1)}} - \overline{q_i^{(0)}}$ (m^3/s) and the difference in water head $\overline{\Delta H_i} = \overline{H_i^{(1)}} - \overline{H_i^{(0)}}$ (m) under the two models. $\overline{q_i^{(j)}}$ (m^3/s) is the average value of power release during the sub-time span under the operation model j. $\overline{H_i^{(j)}}, j = 1, 2$ (m) is the synthesized water head which represents the equivalent 'average' water head during the sub-time span (m). It should be noted that $\overline{H_i^{(j)}}$ is not the arithmetic mean value of the water head during each time period of the sub-time span, but the equivalent of the 'average' water head under which the calculus of total benefit from energy production is the same with the summation of benefit from energy production during each single time period, which satisfies the following equation:

$$\overline{q_i^{(j)}}\cdot\Delta T/k_i(\overline{H_i^{(j)}}) = \sum_{t=ts}^{te}N_{i,t}^{(j)}\cdot\Delta_t,\tag{14}$$

Therefore, $\overline{H_i^{(j)}}$ can be derived from Equation (14):

$$\overline{H_i^{(j)}} = k_i^{-1}(\overline{q_i^{(j)}}\cdot\Delta T/\sum_{t=ts}^{te}N_{i,t}^{(j)}\cdot\Delta_t),\tag{15}$$

Accordingly, Equation (13) can be expanded using the total differential equation, which can be characterized as:

$$\overline{\Delta N_i} = \overline{\Delta q_i}\cdot\frac{\partial\overline{N_i^{(0)}}}{\partial\overline{q_i^{(0)}}} + \overline{\Delta H_i}\cdot\frac{\partial\overline{N_i^{(0)}}}{\partial\overline{H_i^{(0)}}},\tag{16}$$

where the two terms on the right-hand side of the equation are the influence values caused by variations in power release $(\overline{\Delta q_i}\cdot(\partial\overline{N_i^{(0)}})/(\partial\overline{q_i^{(0)}}))$ and synthesized water head $(\overline{\Delta H_i}\cdot(\partial\overline{N_i^{(0)}})/(\partial\overline{H_i^{(0)}}))$, respectively. The two terms are calculated as follows:

$$\begin{aligned}\frac{\partial\overline{N_i^{(0)}}}{\partial\overline{q_i^{(0)}}} &= 3600\cdot\frac{1}{k_i(\overline{H_i^{(0)}})}\frac{\partial\overline{N_i^{(0)}}}{\partial\overline{H_i^{(0)}}} = \frac{\partial\overline{N_i^{(0)}}}{\partial k_i(\overline{H_i^{(0)}})}\cdot\frac{\partial k_i(\overline{H_i^{(0)}})}{\partial\overline{H_i^{(0)}}} \\ &= (-1)\cdot 3600\cdot q_i^{(0)}\cdot\frac{1}{k_i^2(\overline{H_i^{(0)}})}\cdot k'_i(\overline{H_i^{(0)}}),\end{aligned}\tag{17}$$

where $k'_i\overline{H_i^{(0)}} = (dk_i(H_{i,t})/dH_{i,t})|_{H_{i,t}=\overline{H_i^{(0)}}}$ is the derivative of water release rate for energy production on synthesized water head $\overline{H_i^{(0)}}$.

Therefore, the contribution percentages of water released and water head to the synergistic gains of reservoir i during the sub-time span can be quantified as follows:

$$\begin{aligned}\eta_i &= \left(\overline{\Delta q_i}\cdot\frac{\partial\overline{N_i^{(0)}}}{\partial\overline{q_i^{(0)}}}/\overline{\Delta N_i}\right)\cdot 100\% \\ \upsilon_i &= \left(\overline{\Delta H_i}\cdot\frac{\partial\overline{N_i^{(0)}}}{\partial\overline{H_i^{(0)}}}/\overline{\Delta N_i}\right)\cdot 100\%,\end{aligned}\tag{18}$$

where η_i and υ_i are the contribution percentages of power release and water head, respectively, to the synergistic gains. A positive value of contribution percentage denotes a positive contribution of the considering factor to the synergistic gains of reservoir i while a negative value of contribution percentage represents an opposite direction in synergistic gains contribution.

RESULTS AND DISCUSSION

The area that stretches from downstream Jinsha River to the middle reaches of the Yangtze River is one of the most prominent hydropower energy sources in China. After the construction of the Xiluodu and Xiangjiaba dams on the Jinsha River, which are the two representative megaprojects of China's West–East Electricity Transfer Project Plan, Xiluodu, Xiangjiaba, the Three Gorges project, and Gezhouba began to constitute a cascade reservoir system that greatly enhances the flood control capacity in the Yangtze River and regional water and energy supply to recipients. A map of the considered system is shown in Figure 1.

The entire cascade reservoir system, which aims to maximize system benefit from energy production, is owned by China Yangtze Power Corporation and operated by the Three Gorges Cascade Dispatching and Communication Center (TGCDCC). Considerable effort has been devoted to the research and application of basin-wide precipitation and streamflow forecasts and joint operation of the system. However, research achievements (Zeng *et al.* 2014) and related decision-supporting tools remain in the preliminary stage of application in the system. Decision-makers in TGCDCC wish to identify the specific level of the synergistic gains and the mechanism of synergism because of the large potential synergistic benefit that can be explored through the joint operation of the four reservoirs.

The drawdown season of the reservoir system is from December 1st to June 30th. For considering the high streamflow variations' situations in the late drawdown season and addressing the influences of spillage on energy production, the intervals of time periods are heterogeneous during the planning horizon. Monthly time periods are used from December 1st to April 30th, and 5-day time periods are used from May 1st to June 11th, while daily time periods are used in the remaining time span. The operation objectives during the drawdown season involve shipping, water supply, ecological water use, and hydropower production. Furthermore, the objective of total benefit from energy production is to be optimized, whereas the other objectives are treated as constraints that should be strictly satisfied. The reservoirs are assumed to be in full storage at the beginning of the drawdown season and have ending water levels that are depleted to the flood-limited water level such that sufficient reservoir storage can be reserved for flood control. Table 1 lists the parameters and operation conditions used

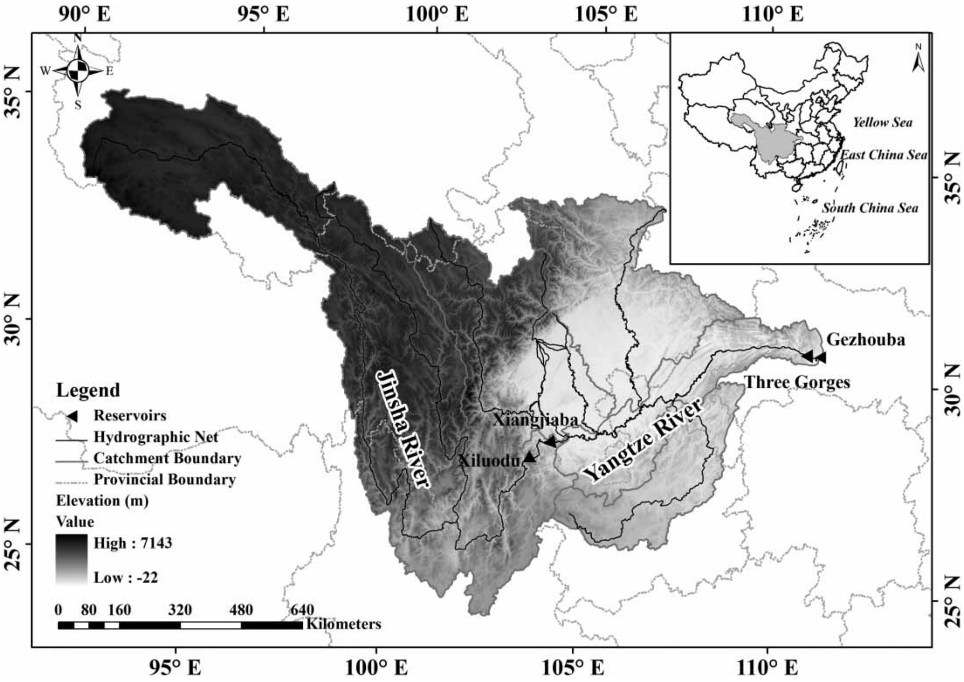


Figure 1 | Location sketch map of the downstream Jinsha River cascade and Three Gorges cascade reservoirs system.

Table 1 | Reservoir parameters during the drawdown season

Reservoir	Upper bound of water level (m)	Lower bound of water level (m)	Installed capacity (MW)	Maximum allowable water level variation rate (m/d)	Minimum limit of outflow (m^3/s)	Energy price (CNY/kwh)
Xiluodu	600	560	12,600	2.0	1,600	0.34
Xiangjiaba	380	370	6,000	1.0	1,600	0.34
Three Gorges	175	146.5	22,500	0.6	6,000/5,700	0.25
Gezhouba	66		2,950	3.0	6,000/5,700	0.2

for modeling. For investigating the influence of hydrology year pattern on the results of the joint operation, a 74-year observed streamflow sequence covering 1940 to 2013 is divided into three groups, namely, wet, normal, and dry hydrology years, based on the total value of water that entered the Three Gorges project during the drawdown season. The benefit from energy production of each reservoir is calculated for each year.

The two optimization models are solved under given parameters and streamflow conditions by a nonlinear programming software, LINGO (http://www.lindo.com/downloads/LINGO-WINDOWS-64×86-17.0.zip), and the results are statistically analyzed over the covered 74 years.

Temporal results of synergistic gains

Table 2 lists the statistical results of system benefit from power generation under the individual and joint operation models. The results show that joint optimal operation can increase the efficiency of energy production under different hydrology conditions. The mean value of the synergistic gains under multiple years is CNY 0.103 billion, which is nearly 0.44% of the total system gains of joint operation. The mean value of the synergistic gains under the wet, normal, and dry years are CNY 0.107, 0.098, and 0.104 billion, respectively. On average, the synergistic gains under the wet years is the highest among the sequence groups.

Table 2 | Gain results of the cascade reservoir system under two operation models

	Multi-year average (billion CNY)	Wet years (billion CNY)	Normal years (billion CNY)	Dry years (billion CNY)
Individual operation	23.277	24.966	23.374	21.492
Joint operation	23.380	25.073	23.472	21.596
Total synergistic gains	0.103	0.107	0.098	0.104

Figure 2 plots the temporal results of the synergistic gains in different months and hydrology years ($\sum_{i=1}^{n} \Delta B_{i,t} = \sum_{i=1}^{n} (B_{i,t}^{(1)} - B_{i,t}^{(0)}), t = 1, 2, \ldots, T$).

This figure indicates that the synergistic gains of the drawdown season are produced mostly in May. The total system benefit from December to April is nearly the same under the joint and individual operation models. The total system benefit from energy production in June under the joint operation model is lower than that under the individual operation model, thereby demonstrating that the temporal complementarity mechanism increases system benefit in May at the expense of a benefit reduction in June.

For analyzing the reasons for the temporal distributions of synergistic gains, Figure 3 plots the monthly water released sequences of Xiluodu and the Three Gorges under the normal-year scenario. It is evident from both parts of the figure that the water released strategies obtained by the individual operation model and the joint operation model are nearly identical from December to April. Specifically, the water released during January to April is binding by the constraint of minimum limit of water released while the reservoir storages are binding by the constraint of upper storage limit in December. As a result, the energy production as well as gains of the entire system are nearly the same during these time periods. This phenomenon can be explained by the optimality conditions when constraints of lower limits of outflow are binding (Zhao *et al.* 2011), which helps reserve the most water to the very last time periods and generate a high water head for energy production. However, this strategy could also face a high risk of spillage when the inflows in the late time periods are

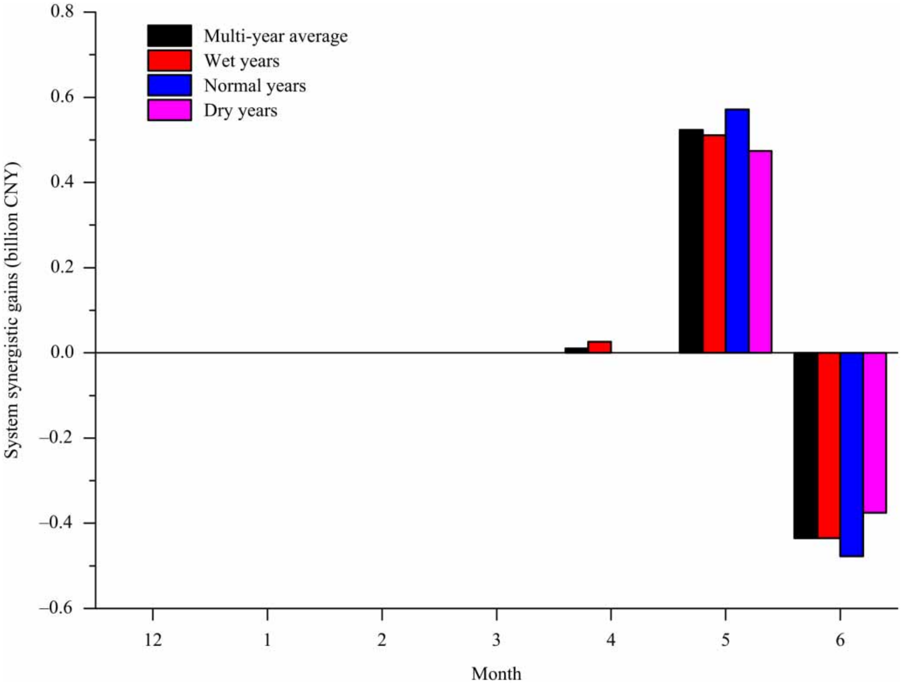


Figure 2 | Temporal distribution of synergistic gains from the joint operation of the cascade reservoirs.

also high. In this system, inflows during May and June are much greater than the minimum limit of water released due to the monsoon climate, thereby the outflow sequences during the two months are unbinding and synergistic gains are primarily produced at the same time.

Statistical results of synergistic gains from reservoirs

Figure 4 shows the total synergistic gains from each reservoir under different hydrology years ($\Delta B_{i,t} = \sum_{i=1}^{T} (B_{i,t}^{(1)} - B_{i,t}^{(0)})$, $i = 1, 2, 3, 4$). Table 3 lists the monthly synergistic gains in May and June, which are the major time periods for producing synergistic gains.

Figure 4 and Table 3 show the following:

1. The average synergistic gains from Xiluodu, Xiangjiaba, the Three Gorges project, and Gezhouba under all hydrology years are CNY −0.107, 0.149, −0.001, and 0.062 billion, respectively. These results show that synergistic gains are generally produced from Xiangjiaba and Gezhouba at the expense of gains deterioration in Xiluodu and the Three Gorges project. As the most upstream reservoir, Xiluodu provides the optimal release schedule to the downstream reservoirs, such as Xiangjiaba and Gezhouba, for improving their water head and water released conditions through joint operations. This schedule helps increase the benefits at these downstream reservoirs. In addition, the complementarity mechanism provided by the Three Gorges project can enhance the power generation efficiency of Gezhouba in normal and dry hydrology years.
2. The synergistic gains differ across different hydrology years and reservoirs. The synergistic gains from Xiluodu and Gezhouba increase as streamflow decreases, whereas those of the Three Gorges project and Xiangjiaba decrease as streamflow decreases. Under wet hydrology years, joint optimal operation can increase the benefit from power generation of the Three Gorges project by CNY 0.014 billion compared with that under the individual operation mode. Under other hydrology years, the benefit from power generation of the Three Gorges project decreases as a trade-off of the increase in benefit of Gezhouba through joint optimal operation.

For identifying the regulations of synergistic gains of the reservoir system provided by Table 3, the stack plots of

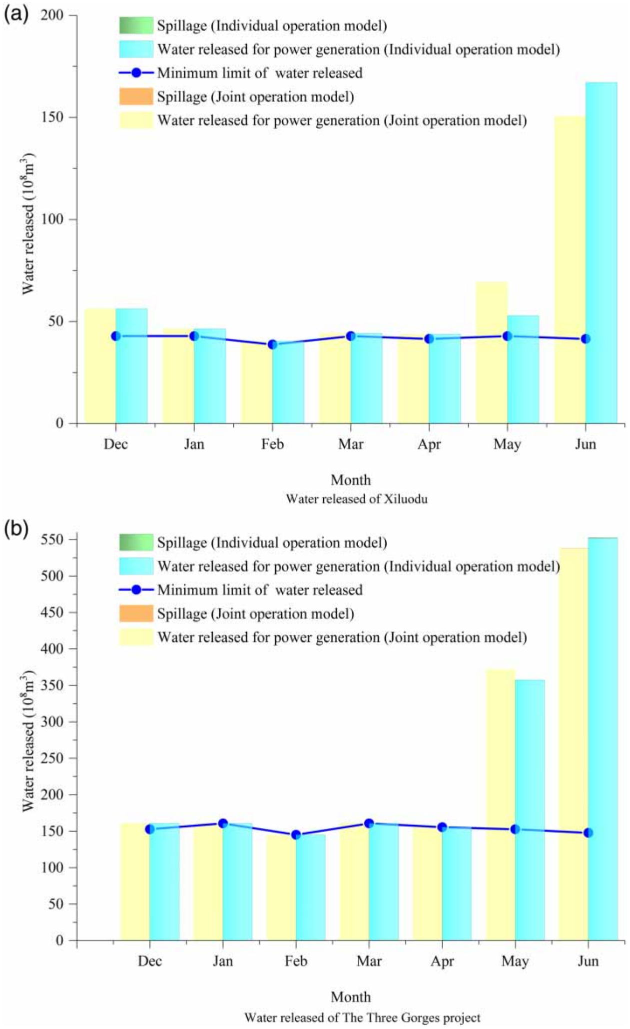


Figure 3 | Water released trajectories of the storage reservoirs obtained by the two models under the normal hydrology year scenario.

water released processed during May and June obtained by the two different models under different hydrology years are drawn in Figure 5.

Figure 5 shows that joint reservoir operations homogenize water released results in May and June, compared to the results under individual operations. Therefore, water released during May under joint operations is greater than water released during May under individual operations (a positive increment in water released), while water released during June is less (a negative increment in water released) than that under individual operations for all reservoirs. Accordingly, synergistic gains of storage reservoirs (Xiluodu and the Three Gorges) are positive in May but negative in June due to these changes. Meanwhile, synergistic gains of run-of-river reservoirs (Xiangjiaba and Gezhouba) are both positive in May and June, since water released during May is increased and spillage, as well as water head, are improved during June. Due to the limited storage capacity to regulate inflow, Xiangjiaba and Gezhouba (the benefit-increasing reservoirs) can only produce energy surplus from coordinated regulations from upstream storage reservoirs through synergism. To the contrary, Xiluodu and the Three Gorges will face reductions in total gains due to deviations from individual optimal strategies under most hydrology years, as the homogenization in outflows could cause a rapid drawdown in reservoir water level for increased release during May, which reduces the average water head during the two months.

For analyzing the relationship between synergistic gains and hydrology conditions, Figure 6 plots the influenced value of water released and water head on synergistic gains of each reservoir under different hydrology years. Figure 6 shows that the synergistic mechanisms of reservoirs are different from each other, and they are jointly determined by the complicated relationship among power output, water head, and release. The primary factor (water head or release) that affects synergism can be identified from the figure, indicating the following:

1. Synergistic gains of storage reservoirs are mostly determined by variations in water head that is affected by streamflow changes. However, the driven mechanisms between Xiluodu and the Three Gorges are different. Water head is the only factor that determines the synergistic gains of Xiluodu. As shown in Figure 6(a), the reduction in streamflow would lower down the effect of water head reduction in Xiluodu, thus synergistic gains of Xiluodu would increase as streamflow decreases. The synergistic gains of the Three Gorges are mutually determined by water head and water released in wet and normal years. In wet years and normal years, joint reservoir operations could reduce spillage of the Three Gorges through the regulation from Xiluodu, thus water released could cause positive synergistic gains. Additionally, water head of the Three Gorges is also improved in wet years, which results in positive synergistic gains in total. In normal and dry years, the Three Gorges

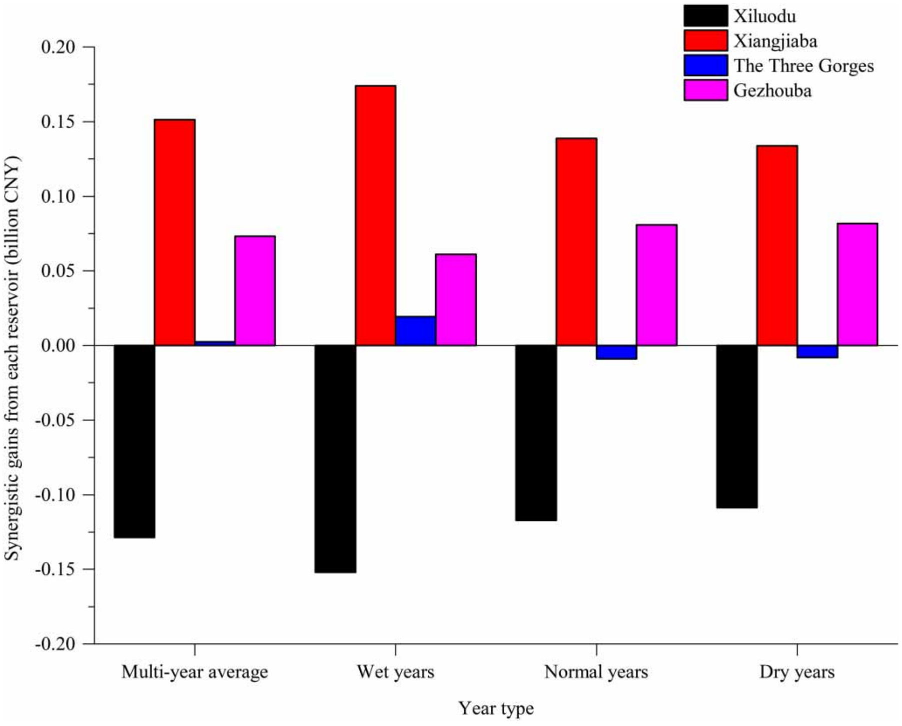


Figure 4 | Synergistic gains from each reservoir in different hydrology years.

Table 3 | Synergistic gains from different reservoirs during May and June

	May				**June**			
Synergistic gains (billion CNY)	**Multi-year average**	**Wet years**	**Normal years**	**Dry years**	**Multi-year average**	**Wet years**	**Normal years**	**Dry years**
Xiluodu	0.211	0.21	0.248	0.158	−0.318	−0.336	−0.349	−0.246
Xiangjiaba	0.117	0.137	0.122	0.08	0.032	0.031	0.02	0.049
Three Gorges	0.049	0.063	0.049	0.025	−0.051	−0.053	−0.059	−0.037
Gezhouba	0.057	0.049	0.063	0.061	0.005	0.001	0.004	0.013
The entire system	0.434	0.46	0.482	0.325	−0.332	−0.358	−0.383	−0.22

regulates inflows for the Gezhouba in the downstream at the expense of sacrificing its head benefits. Therefore, negative synergistic gains of the Three Gorges are encountered then.

2. Synergistic gains of run-of-river reservoirs are jointly determined by variations in water head and water released via joint operations, and the results vary case by case. Synergistic gains of Xiangjiaba are primarily contributed by water released. Therefore, as streamflow decreases, synergistic gains produced from reducing spillage from Xiangjiaba would decrease, which results in total synergistic gains reduction correspondingly. Different from Xiangjiaba, synergistic gains of Gezhouba are generally determined by increases in water head. This is because the turbine discharge capacity of Gezhouba is relatively small compared to its inflow discharge, thereby causing high chance of spillage. Additionally, reducing spillage helps increase water head as it lowers down tailrace water level. Since the decrease in streamflow not only reduces the spillage of Gezhouba but also increases its water head, synergistic gains of Gezhouba will increase as streamflow decreases.

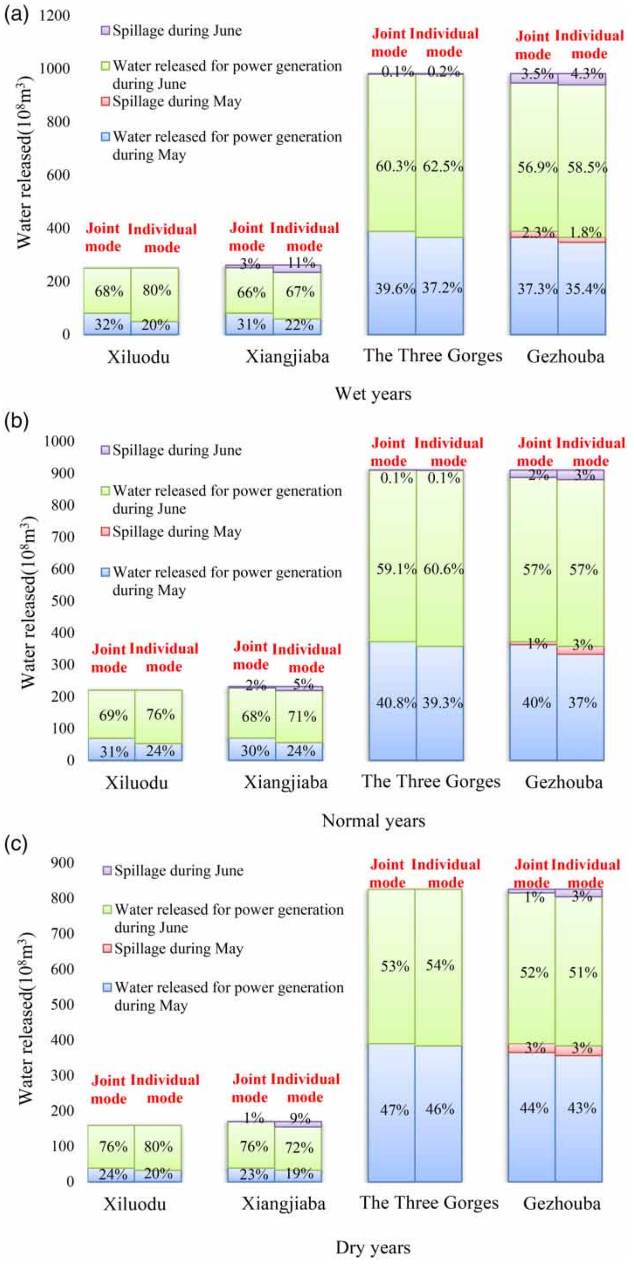


Figure 5 | Stack plots of water released during May and June obtained by the two different models.

Contribution percentages of influencing factors to synergistic gains

According to Equation (16), the synergistic gains are jointly determined by power release and water head. The differences in operation policies under the individual and joint operation models are emphasized to determine how the operation policies of reservoirs affect the mechanism of synergism. The mean trajectories of water head, and power release, over normal years under the two operation models are shown in Figure 7. Table 4 lists the contribution factors of the reservoirs to the synergistic gains produced in May and June.

The results indicate the following:

1. Compared with the reservoir operation policy from the individual operation model, the joint operation of the reservoir system is driven by a rapid drawdown policy from Xiluodu and the Three Gorges project in early May. The rapid drawdown policy of Xiluodu and the Three Gorges project cause reductions in their water head and energy production. The water head of Xiluodu and the Three Gorges project decreases by 7.3 and 1.31 m, respectively, and the loss in benefits is CNY 0.101 and 0.011 billion, respectively. The loss in benefits of the two reservoirs in the joint operation model is primarily determined by water head reduction.
2. The benefits and power generation of Xiangjiaba and Gezhouba are increased by joint operation due to the complementarity of release policy from Xiluodu and the Three Gorges project. As observed, their major contribution factors differ.

For analyzing the mechanism of influencing factors in determining the contribution, Figure 8 plots the contribution percentages of power release in Xiangjiaba's synergistic gains and Gezhouba's synergistic gains under different inflow conditions, respectively.

These figures show that variations in reservoir inflow greatly affects the variation range of the contribution percentages of the factors for both reservoirs. In general, the variation range of the contribution percentage of power release in Gezhouba is higher than that of power release in Xiangjiaba. These results may be explained by the differences in the value of the reservoir relative capacity index, which equals the value of reservoir storage capacity divided by the value of total inflows. The indexes of Xiangjiaba and Gezhouba are 0.63% and 0.019%, respectively, thereby showing that Xiangjiaba has a higher value of relative reservoir capacity than Gezhouba. Therefore, the influence of inflow variations on the complementarity mechanism of synergistic gains can be decreased. Accordingly, the

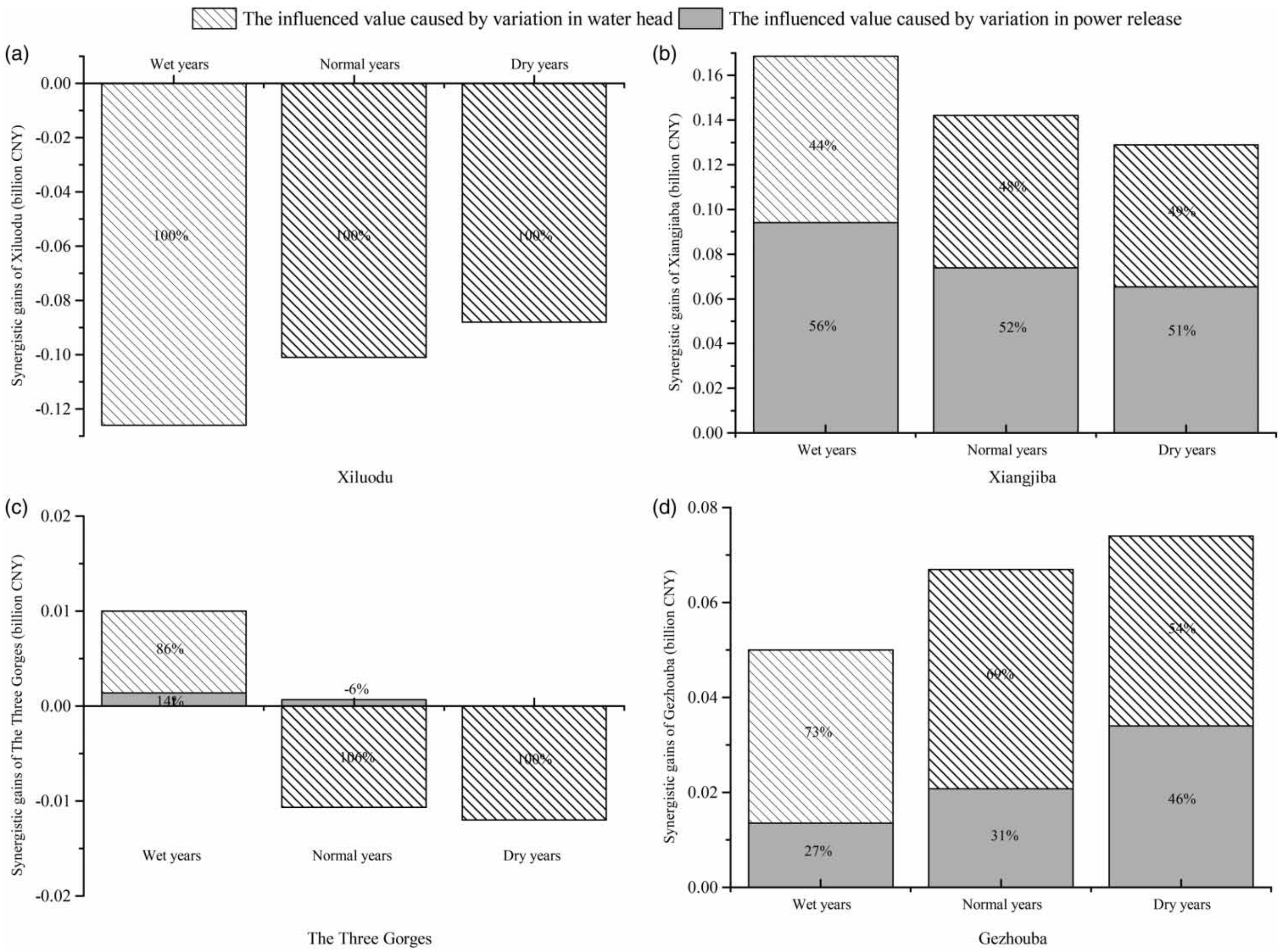


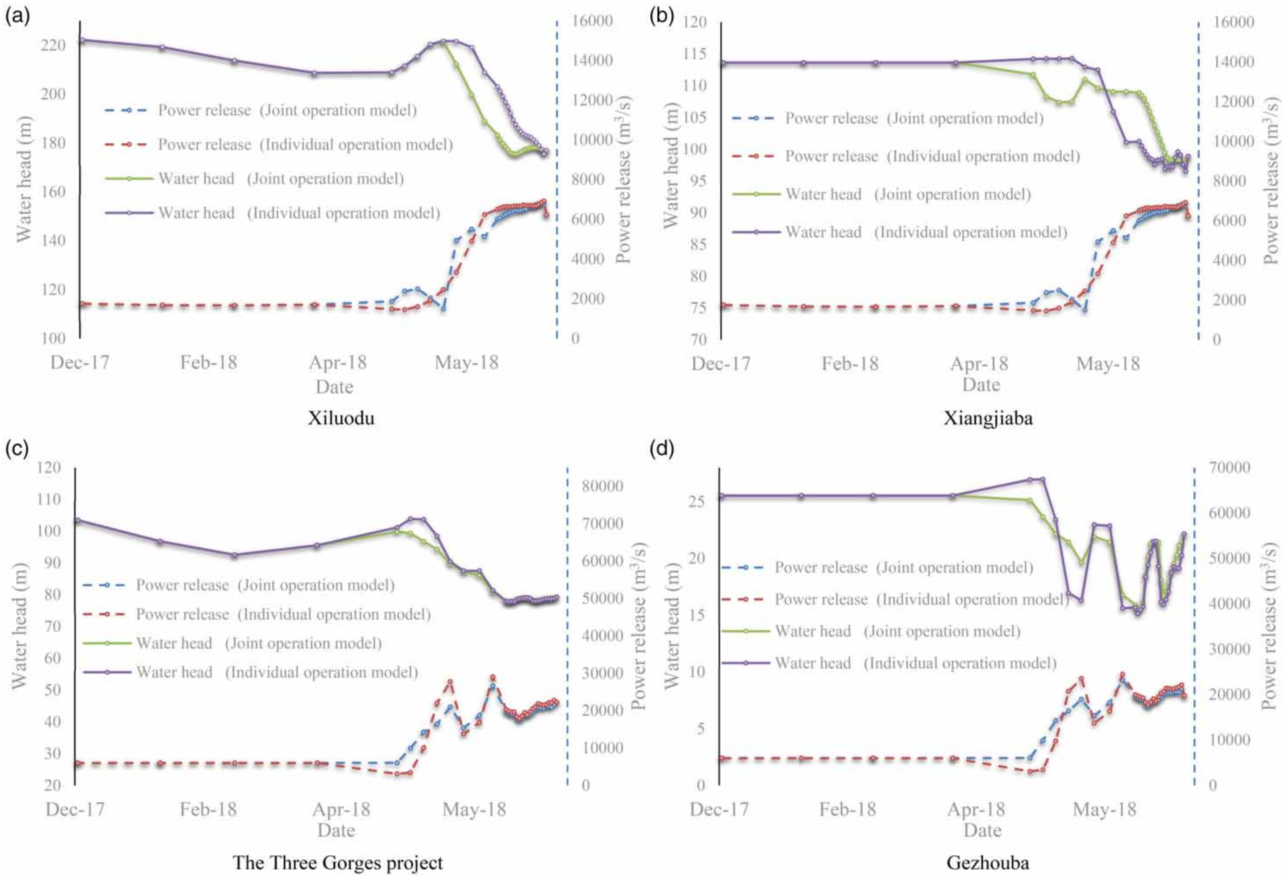
Figure 6 | Stack plots of synergistic gains caused by water head and power release variations under the two models.

variation range of the percentages of power release of Xiangjiaba is smaller than that of Gezhouba.

Moreover, there is a positive correlation between inflow of Xiangjiaba with contribution percentage of power release but a negative correlation between inflow of Gezhouba with contribution percentage of power release. The phenomenon can be explained by analyzing the results of the reservoir relative capacity index and power release capacity. The power release capacity of Xiangjiaba is 7,500 m^3/s, which is greater than the maximum value of Xiangjiaba's historical inflow samples (the average inflow during May and June). The power release capacity of Gezhouba is 18,000 m^3/s, which is greater than the 35% percentile historical inflow value of Gezhouba. With a low storage to regulate inflow and a low power release capacity to use water for generating energy, the likelihood and quantity of spillage would increase with inflow to Gezhouba. Consequently, the influence of power release in affecting synergistic gains from energy production reduces gradually with the increase in inflow of Gezhouba. In contrast, synergistic gains from energy production of Xiangjiaba could still be increased as inflow increases, due to its high power release capacity. Therefore, the influence of power release in affecting synergistic gains from energy production increases gradually with the increase in inflow of Xiangjiaba.

CONCLUSIONS

This paper analyzes the results and the complementarity mechanism of synergistic gains from the joint operation of



Xiluodu

Xiangjiaba

The Three Gorges project

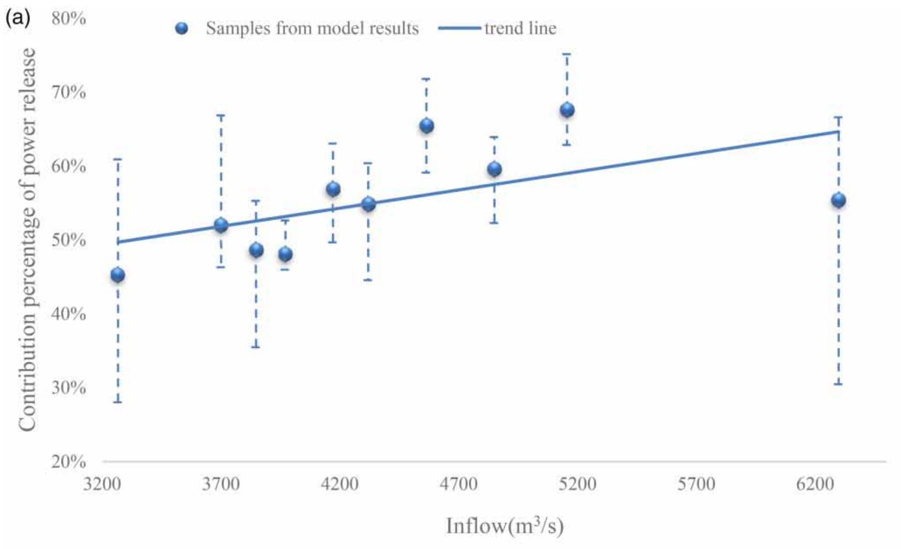
Gezhouba

Figure 7 | Water head and power release trajectories of all reservoirs under the two models.

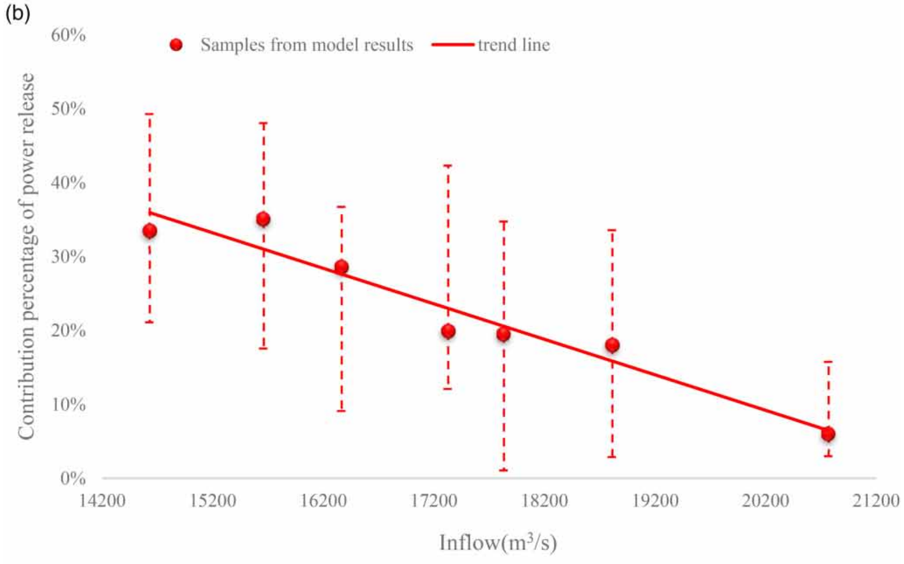
Table 4 | Contributions of power release and water head to synergistic gains from energy production under the two models in normal years

Reservoir	**Difference in water from power release $\overline{\Delta q_i}\cdot\Delta T$ (10^8 m^3)**	**Difference in water head $\overline{\Delta H_i}$ (m)**	**Synergistic gains (billion CNY)**	**The influenced value caused by variation in power release $\overline{\Delta q_i}\cdot\overline{\frac{\partial N_i^{(0)}}{\partial q_i^{(0)}}}$ (billion CNY)**	**The influenced value caused by variation in water head $\overline{\Delta H_i}\cdot\overline{\frac{\partial N_i^{(0)}}{\partial H_i^{(0)}}}$ (billion CNY)**	**Contribution percentage of power release η_i (%)**	**Contribution percentage of water head υ_i (%)**
Xiluodu	0.00	−7.30	−0.101	0.000	−0.101	0%	100%
Xiangjiaba	8.63	0.54	0.142	0.074	0.068	52%	48%
Three Gorges	0.69	−1.31	−0.010	0.001	−0.011	−6%	106%
Gezhouba	22.38	0.15	0.067	0.021	0.046	31%	69%

the reservoir system that comprises the downstream Jinsha River and Three Gorges cascade reservoirs. Individual reservoir operation models and a joint operation model are established for simulating the results of synergistic gains through joint operations for all streamflow sequences. Thereafter, the temporal and spatial statistical results of synergistic gains are investigated over all hydrology years. Moreover, this paper proposes a method for calculating the contribution percentage of each factor using the total differential equation for revealing the driven factors and their contributions to the synergistic gains of joint operation. The following conclusions are drawn:



Xiangjiaba



Gezhouba

Figure 8 | Contribution percentage of power release in Xiangjiaba and Gezhouba's synergistic gains under different inflow conditions.

1. Joint reservoir operation can generate significant synergistic gains from energy production. Compared to the gains from energy production under individual operation, the synergistic gains during the drawdown season can reach a multi-year average of CNY 0.103 billion. Synergistic gains are generally produced from Xiangjiaba and Gezhouba in May.
2. The synergistic gains of joint operation are driven by a rapid storage depletion of Xiluodu in early May and the corresponding regulation on the streamflow by the Three Gorges project. The fast storage depletion policy of Xiluodu reduces its water head, thereby resulting in deterioration in its gains from energy production. However, this policy can reduce spillage and increase the water head to the downstream reservoirs of Xiangjiaba and Gezhouba, thereby serving as a trade-off for increasing the gains from energy production at these reservoirs.

3. Synergistic gains in Xiangjiaba are equally and proportionally determined by increases in water released for energy production and water head through joint reservoir operation. Synergistic gains in Gezhouba are mainly determined by increase in water head. The reduction in the gains of Xiluodu and the Three Gorges project is affected primarily by reduced water head through joint operation.
4. Regulations of synergistic gains contribution of Xiangjiaba and Gezhouba associated with their inflows differ. Due to a low reservoir storage and power release capacity of Gezhouba, influence of power release in Gezhouba's synergistic gains weakens as spillage would increase with inflow. To contrast, influence of power release in Xiangjiaba's synergistic gains enhances with inflow, attributing to its high power release capacity.

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