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Extraction and application of energy storage operation chart in Yangtze River cascade reservoirs

Zhiqiang Jiang, Hui Qin, Changming Ji and Wenjie Wu

ABSTRACT

Reservoir operation charts have been widely researched and applied to reservoir operation. However, these achievements are generally used for a single reservoir and have rarely been applied to cascade reservoirs. Considering the requirements of flood control and water supply, this paper studied the extraction and application of energy storage operation chart (ESOC) for cascade reservoirs. Steps in the methodology mainly include: (1) model building of cascade reservoirs operation optimization (CROO), (2) extracting ESOC based on discriminant coefficient method (DCM) and CROO model, (3) simulation operation of ESOC based on DCM, (4) choosing the optimal ESOC and verifying its efficiency through the results. Cascade reservoirs in the Yangtze River of China were selected for a case study. Compared with the conventional operation method, the simulation results show that the ESOC presents better performance in terms of power generation, guaranteed output and assurance rate. In detail, the annual power generation of ESOC can be increased by 0.9%, the total guaranteed output can be increased by 3.4% and the assurance rate can be increased by 9.6%, which indicates that the proposed ESOC method can greatly improve the hydropower energy efficiency and reliability of cascade reservoirs' power supply.

Key words | cascade reservoirs, energy storage, hydropower, operation chart, Yangtze River

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INTRODUCTION

As one of the most stable renewable energy, hydropower can be commercially developed and utilized on a large scale (Lu *et al.* 2015). After the reservoir is built, how to exert its function as much as possible, and to improve the efficiency of hydropower generation on the premise of guaranteeing the water supply and flood control requirements (Jiang *et al.* 2015) is the focus of many scholars and managers in the world, which is also the problem that needs to be solved by the reservoir operation optimization (Valipour 2013).

Nowadays, many methods are used to guide the optimal reservoir operation. One kind is the traditional optimization algorithms, such as the linear programming (Li *et al.* 2013), dynamic programming (DP) (Shokri *et al.* 2013), progressive optimality algorithm (Lu *et al.* 2013), and fuzzy theory (Chang *et al.* 2005), etc. Another kind is the intelligent optimization algorithms, such as genetic algorithm (Momtahen & Dariane 2007), particle swarm optimization (Zhang *et al.* 2014), and neural network algorithm (Valipour 2015), etc. However, in the actual reservoir operation, especially in the long or mid-term operation, the established operating rules through the historical data are dependent on the natural uncertainties of inflow in the future.

To obtain the optimal operating rules for reservoirs, large numbers of studies and practices have been developed in recent years (Ma *et al.* 2013), which vary significantly in their extraction methods and applications. For example, in 2007, Chaleeraktrakoon and Kangrang proposed a DP approach for finding the optimal rule curves of single and multi-reservoir systems, compared with the traditional method, results of the case study demonstrated that the

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proposed approach is generally fast and robust (Chaleeraktrakoon & Kangrang 2007). In 2013, Zhou and Guo developed an integrated adaptive optimization model (IAOM) for derivation of multipurpose reservoir operating rule curves (Zhou & Guo 2013); the innovation of this work is that the obtained optimal multipurpose reservoir operating rule curves by IAOM can reflect the hydrologic characteristics of future climate change. In 2014, using a constrained genetic algorithm and a penalty strategy, Trieu *et al.* proposed a methodology for establishing the optimal operation rule curves based on a multi-use reservoir system (Trieu *et al.* 2014). The proposed model was formulated by including various water demands configured into the objective function, and it was demonstrated as an effective and powerful tool for optimal strategy searching for multi-use reservoir operations. In 2015, Afshar *et al.* developed a set of piecewise linear operating rule curves for water supply and hydropower reservoirs by employing an imperialist competitive algorithm (Afshar *et al.* 2015). In 2016, Najl *et al.* provided a simulation optimization model for deriving an operating policy for multi-reservoir systems, and two adjustable monthly rule curves were introduced to each reservoir in the system and a self-adaptive genetic algorithm was developed to maximize the system's hydropower production (Najl *et al.* 2016). To a certain extent, the above research results effectively improved the hydropower generation efficiency of the applied reservoir system, and obtained a considerable economic benefit, and it also effectively promotes the development of reservoir operation around the word.

There are many kinds of operating rules in the actual reservoir operation (Chiamsathit *et al.* 2014), while the reservoir operation chart is the frequently used at present, which is the graphical representation of operating rules, and it consists of several operation curves and zones (Ai & Gao 2011). Through the above review, it can be seen that the research of reservoir operating rule or operation chart has made a great progress, especially in the field of single reservoir operation (Jiang *et al.* 2014). However, previous studies are mostly based on the optimization algorithms, models and the data processing technologies. Although it is simple and easy to get the joint operation chart of cascade reservoirs by optimization algorithms, these methods are usually insufficient in terms of physical significance. Especially for intelligent optimization algorithms, there is a big randomness in their optimization, so the reliability of optimization results is not high enough (Jiang *et al.* 2016). Nowadays, along with the formation of cascade reservoirs systems around the world, the joint operation of cascade reservoirs is becoming very necessary, while it has an output allocation problem. In the actual operation, it is found that discriminant coefficient method (DCM) is a relatively matured output allocation method in guiding the joint operation of cascade reservoirs compared with the other methods. However, through a sufficient literature survey, it is found that the achievements about the joint operation chart research based on DCM are rarely around the world (Liu *et al.* 2011).

Thus, in order to obtain the best way of energy storage operation, so that to improve the water resources utilization efficiency and get the maximum energy using the limited hydropower resources, this paper takes the cascade reservoirs of the upstream reaches of the Yangtze River as an instance, to research the extraction and application of energy storage operation chart (ESOC) considering the requirements of flood control and water supply. Meanwhile, in order to make more reasonable total output distribution for the cascade hydropower stations and avoid the randomness of intelligent optimization algorithms in extracting ESOC, the DCM is coupled in the extraction and application of ESOC in this paper, which can effectively improve and guarantee the output stability and reliability of the obtained ESOC.

FORMULATION OF CROO PROBLEM

The major objective of cascade reservoirs operation is maximizing the water resource benefits which are mainly related to hydroelectric energy. Generally, the objective function of the optimization model can be described as follows:

$$
\begin{gathered}
E = \max \sum_{i=1}^{n} \sum_{t=1}^{T} N_t^i \cdot \Delta t \\
N_t^i = \begin{cases} k^i \cdot q_t^i \cdot H_t^i \text{ when } k_i \cdot q_t^i \cdot H_t^i \leq N_{t,exp}^i \\ N_{t,exp}^i \text{ when } k^i \cdot q_t^i \cdot H_t^i > N_{t,exp}^i \end{cases}
\end{gathered}
\tag{1}
$$

where E is the total power generation over the entire planning horizon; T is the number of stages; N_t^i is the output of

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the ith hydropower station in the tth stage; n is the number of reservoirs; H_t^i is the average water level of the ith hydropower station in the tth stage; Δt is the duration of a stage; q_t^i is the outflow through the turbines of the ith reservoir in the tth stage; k^i is the efficiency coefficient of the ith hydropower station; $N_{t,\exp}^i$ is the expected output, which is the maximum output of the unit under a working water head, and it is usually measured by experiments.

Subject to the following equality and inequality constraints.

(1) Water volume balance:

$$q_t^i = \frac{V_{t-1}^i - V_t^i}{\Delta t} + I_t^i - W_t^i - Ev_t^i \tag{2}$$

where W_t^i is the redundant water outflow through flood outflow gate of the ith reservoir in the tth stage; I_t^i is the inflow of the ith reservoir in the tth stage; Ev_t^i is the evaporation capacity of the ith reservoir in the tth stage; V_t^i is the storage volume of the ith reservoir in the tth stage.

(2) Reservoir volume limits:

$$V_{t,\min}^i \le V_t^i \le V_{t,\max}^i \tag{3}$$

where $V_{t,\min}^i$ is the lower limit of V_t^i, which is corresponding to dead level; $V_{t,\max}^i$ is the upper limit of V_t^i, which is corresponding to flood control level in flood season and normal level in dry season.

(3) Comprehensive utilization of water resources required at downstream reservoir limits:

$$Q_{t,\min}^i \le Q_t^i \le Q_{t,\max}^i \tag{4}$$

where Q_t^i is the total outflow of the ith reservoir in the tth stage, including q_t^i and W_t^i; $Q_{t,\min}^i$ is the lower limit of Q_t^i, which is determined by the ecological flow of downstream; $Q_{t,\max}^i$ is the upper limit of Q_t^i, which is determined by the downstream river channel capacity.

(4) Output limits:

$$N_{t,\min}^i \le N_t^i \le N_{t,\max}^i \tag{5}$$

where $N_{t,\min}^i$ is usually determined by the allowed minimum output; $N_{t,\max}^i$ is usually determined by the installed capacity or expected output.

(5) The assurance rate limit of power generation:

$$P = \frac{\varphi(N_t \ge N_b)}{T} \times 100\% \ge P_{\min}, \quad t = 1, 2, \ldots, T \tag{6}$$

where N_b is the guaranteed output of the cascade system; $\varphi()$ is the statistical function, represents the times that the actual total output of the cascade system is greater than N_b; P is the statistical assurance rate of cascade system in each simulation operation, it means the degree of reliability of the output N_b being satisfied in a long operation period; P_{min} is the lower limit of the assurance rate.

(6) The guaranteed output limit of power generation:

$$N_b > N_{b,min} \tag{7}$$

where $N_{b,min}$ is the lower limit of guaranteed output of cascade system.

ESOC MODEL AND ITS SOLVING

Extraction of ESOC based on DCM

In the single reservoir operation, we usually use the reservoir operation chart to guide the actual operation, which takes the water level as the operation indicator that can fully reflect the current energy state of the reservoir. However, in the joint operation of cascade reservoirs, the same amount of water has different energy in different reservoirs because of the geographical position, so we take a comprehensive indicator which is the total energy storage of cascade system to represent its overall energy state, and use the corresponding ESOC to guide the actual operation. The following section will introduce the extraction process of ESOC based on DCM and the cascade reservoirs joint optimization model described in the previous section.

DCM

After the cascade system's total output determined, there is an allocation problem in the joint operation of cascade reservoirs by ESOC. Only if the total output is allocated to each power station reasonably, the cascade system can get

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a high energy efficiency (Zhu *et al.* 2014). DCM's basic principle is to determine the optimal order of water storage and water supply for cascade reservoirs, so that to maximize the power generation and minimize the energy loss as far as possible. The computational formula of discriminant coefficient for each reservoir in DCM can be simply described as follows, and the detailed derivation can be found in the literature by Jiang *et al.* (2016).

In the water supply operation, due to the water supply of the ith hydropower station, the extra energy loss to unit electricity generation is

$$K_{t,loss}^{i}=\frac{\Delta E_{W-\text{supply}}+\Delta E_{V-\text{supply}}}{\Delta E_{\text{supply}}}=\frac{0.5W_{t}^{i}+\sum V_{\text{avai}}}{F_{t}^{i}\cdot\sum H_{t}^{i}} \tag{8}$$

where $K_{t,\text{loss}}^{i}$ is the extra energy loss to unit electricity generation of the ith hydropower station; $\Delta E_{W\text{-supply}}$ is the extra hydropower loss of the ith reservoir in generating hydroelectric power by the amount of inflow water W_t^i in the ith stage; $\Delta E_{V\text{-supply}}$ is the extra energy decrement of the upstream reservoirs' available storage water $\sum V_{\text{avai}}$ to current reservoir; ΔE_{supply} is the energy provided by the supplied water of the ith reservoir; W_t^i is the amount of inflow water of the ith reservoir in the ith stage; $\sum V_{\text{avai}}$ is the upstream reservoirs' available storage water of current reservoir; F_t^i is the average water surface area of the ith reservoir in the tth stage; $\sum H_t^i$ is the sum of average water head of the ith reservoir and downstream reservoirs in the tth stage.

In the water storage operation, due to the water storage of the ith hydropower station, the extra energy obtainment to unit of stored energy of the ith hydropower station is

$$K_{t,obtain}^{i}=\frac{\Delta E_{W-\text{store}}+\Delta E_{V-\text{store}}}{\Delta E_{\text{store}}}=\frac{0.5W_{t}^{i}+\sum V_{\text{avai}}}{F_{t}^{i}\cdot\sum H_{t}^{i}} \tag{9}$$

where $K_{t,\text{obtain}}^{i}$ is the extra energy obtainment to unit of stored energy of the ith hydropower station; $\Delta E_{W\text{-store}}$ is the extra energy obtainment of the ith reservoir in generating hydroelectric power by the amount of inflow water W_t^i in the tth stage; $\Delta E_{V\text{-store}}$ is the extra energy obtainment of the upstream reservoirs' available storage water $\sum V_{\text{avai}}$ to current reservoir; ΔE_{store} is the energy stored by the ith reservoir.

In general, the value of $K_{t,\text{loss}}^{i}$ or $K_{t,\text{obtain}}^{i}$ of each reservoir is different in a cascade system. When the water need to be stored, the best reservoir for storing water is the one that can maximize the extra energy increment caused by storing unit energy, so the reservoir with the maximum $K_{t,\text{obtain}}^{i}$ value should store water first. Similarly, when the water needs to be supplied, the best reservoir for supplying water is the one that can minimize the energy loss caused by generating unit electrical energy, so the reservoir with the minimum $K_{t,\text{loss}}^{i}$ value should supply water first.

Extraction process of ESOC

In the actual reservoir operation, there are three output situations which are increased output, guaranteed output and reduced output, respectively. So there are three kinds of operation zones and curves in ESOC, correspondingly. The upper boundary and lower boundary of the guaranteed output zone are corresponding to the upper basic operation curve and lower basic operation curve, respectively. The increased output curves are the boundaries of increased output zones, and the reduced output curves are the boundaries of reduced output zones. The ESOC can be obtained by a reverse calculation using the hydrological process of typical years. The specific steps of choosing typical years have been recorded in the literature by Shao *et al.* (2010) and Yu *et al.* (2011). The specific reverse extracting processes for the three main operation curves are shown in Figure 1.

Simulation operation of ESOC based on DCM

Suppose TO_{chart} represents the total output read from ESOC according to the current energy state of cascade system, and TO_{runoff} represents the total output calculated by the runoff of current stage, as shown in Figure 2, where the runoff here means the average input rate of water for the reservoir in a stage, including the runoff generated by the precipitation in the upper reaches of the reservoir and the direct precipitation on the water surface of the reservoir. Then, the specific operation steps by ESOC and DCM are as follows.

Step 1: At the beginning of the current stage, the total energy storage of cascade reservoirs can be calculated by formula (10) according to $V^{i}{}_{\text{avai},t}$ and H_t^i, where e_t is the total energy storage of cascade reservoirs in the tth stage; e_t^i is the energy storage of the ith reservoirs in the tth

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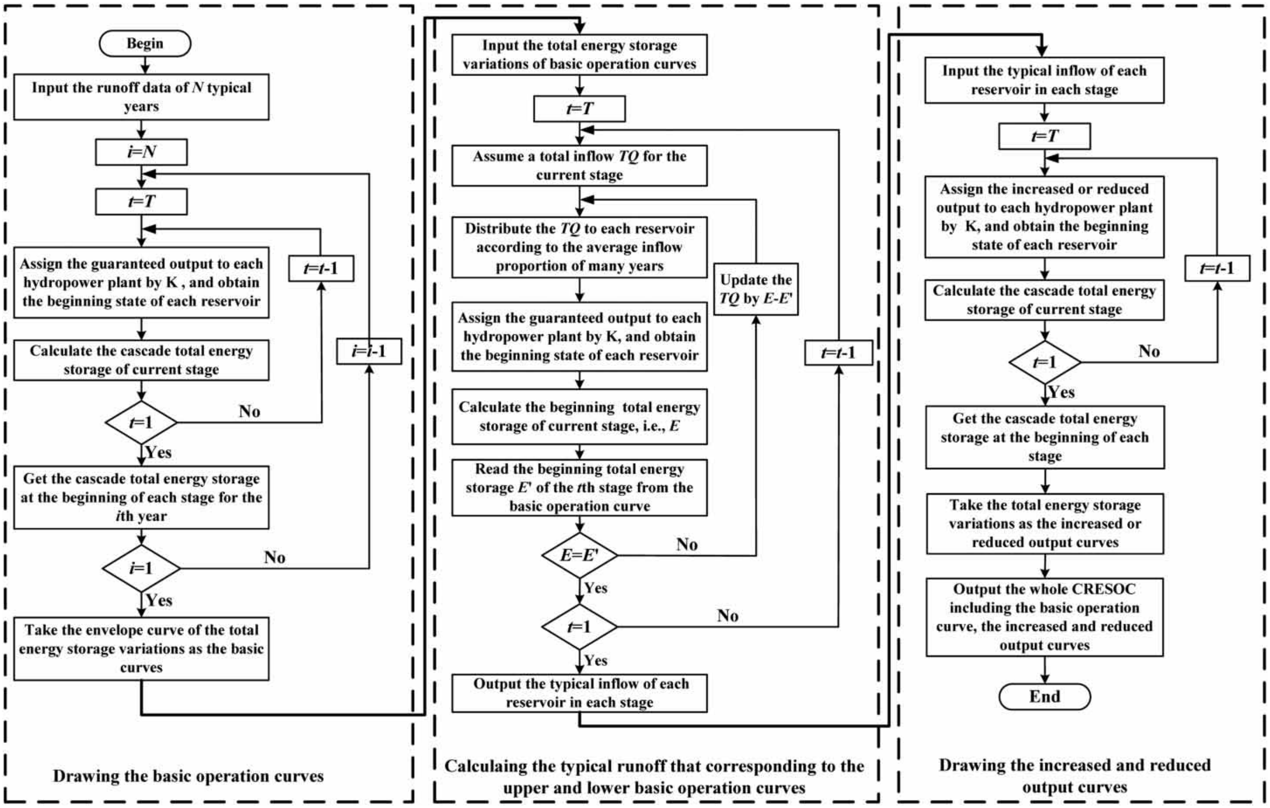

Figure 1 | Flowchart of extracting the operation curves.

stage; ρ is the density of water; g is the acceleration of gravity; $V^i_{\text{avai},t}$ is the available amount of water of the ith reservoir in the tth stage.

$$e_t = \sum_{i=1}^{n} e_t^i = \rho g \sum_{i=1}^{n} \left(V^i_{\text{avai},t} \cdot \sum_{j=i}^{n} H_t^j \right) \tag{10}$$

Step 2: Read a TO_{chart} from ESOC according to e_t, and calculate TO_{runoff} by the runoff of current stage.

Step 3: If $TO_{\text{runoff}} > TO_{\text{chart}}$, the cascade system should store water. We arrange the reservoirs to store water according to the calculated $K^i_{t,\text{obtain}}$ at the beginning of current stage, until the total output calculated by the flow of natural inflow minus the stored flow is equal to TO_{chart}.

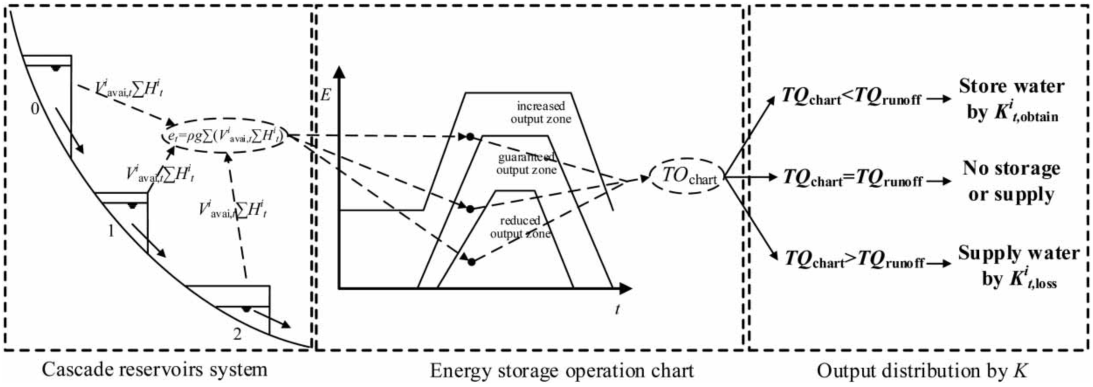

Figure 2 | Simulation process using ESOC in the cascade reservoirs operation.

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Step 4: If $TO_{\text{runoff}} < TO_{\text{chart}}$, the cascade system should supply water. We arrange the reservoirs to supply water for power generation according to the calculated $K^{i}_{t,\text{loss}}$ at the beginning of the current stage, until the total output calculated by natural inflow and supplied flow is equal to TO_{chart}.

Step 5: If $TO_{\text{runoff}} = TO_{\text{chart}}$, there should be no water storage or supply. The cascade system generates the electricity by the natural inflow only.

The simulation process using ESOC to guide the cascade reservoirs operation can be described by Figure 2.

The optimal ESOC confirmation

The design guaranteed output and assurance rate for a reservoir are determined at the design or construction phase, which are relatively fixed values. However, when the cascade reservoirs system formed with multiple reservoirs and implements the joint operation, the total guaranteed output and assurance rate of cascade system will have some changes because of the mutual compensation effect among reservoirs. Therefore, when we determine the optimal ESOC, the effect of the changes of guaranteed output and assurance rate must be taken into consideration. Usually, in order to choose the optimal ESOC reasonably, we need to get the variations of power generation and assurance rate with the changes of guaranteed output, by which we can get the optimal ESOC.

Table 1 | Parameters of the Xi Luodu, Xiang Jiaba and Three Gorges reservoirs

Items	Unit	Xi Luodu	Xiang Jiaba	Three Gorges
Normal level	M	600	380	175
Dead level	m	540	370	145
Regulation performance	None	Annual	Season	Season
Design guaranteed output	MW	3,350	2,009	4,990
Coefficient of output	None	8.5	8.5	8.5
Flood control level	m	560	370	155
Flood season	Month	5–9	5–9	5–9

To achieve the above purpose, we discrete the total guaranteed output in a certain range (for example, the design guaranteed output fluctuation within 20%), and for each discretized guaranteed output, we extracted the corresponding ESOC according to the method in 'Extraction of ESOC based on DCM', and then use the method in 'Simulation operation of ESOC based on DCM' to implement the simulation by the historical runoff data and the obtained ESOC, and get the corresponding statistical assurance rate and power generation. Taking the same calculation for all the discretized guaranteed output, we can finally get the variations of power generation and assurance rate with the changes of guaranteed output.

According to the obtained relation curve of guaranteed output, power generation and assurance rate, we can determine the optimal ESOC corresponding to the maximum

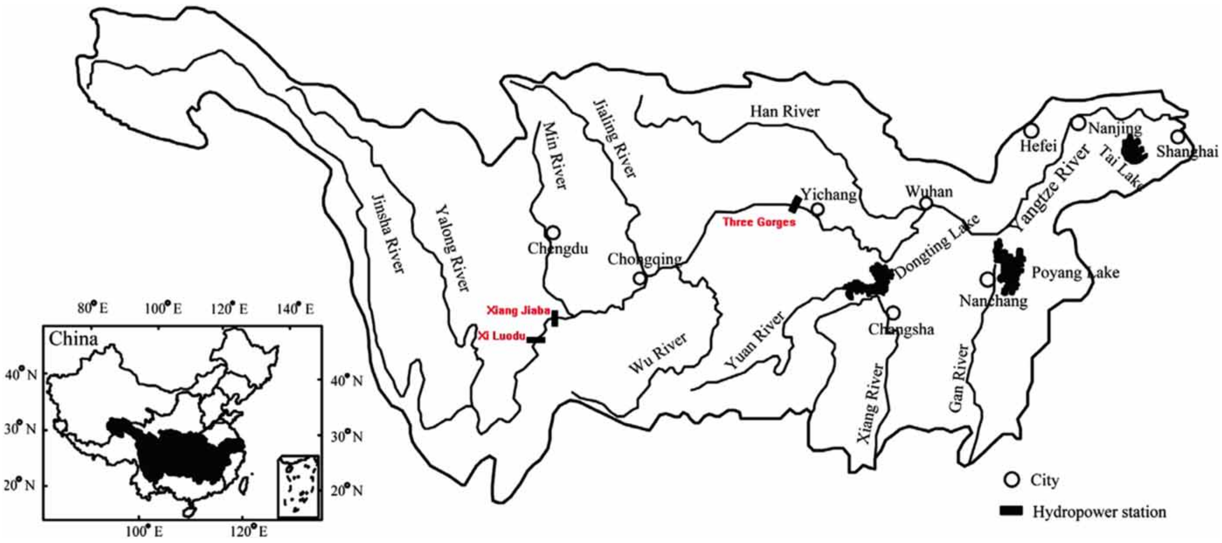

Figure 3 | Plane sketch map of the studied cascade hydropower stations.

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Table 2 | Constraints of water level and outflow in the practical power generation operation

	Xi Loudu Reservoir				**Xiang Jiaba Reservoir**				**Three Gorges Reservoir**			
Name Item	**Max *Z* (m)**	**Min *Z* (m)**	**Max *Q* (m^3/s)**	**Min *Q* (m^3/s)**	**Max *Z* (m)**	**Min *Z* (m)**	**Max *Q* (m^3/s)**	**Min *Q* (m^3/s)**	**Max *Z* (m)**	**Min *Z* (m)**	**Max *Q* (m^3/s)**	**Min *Q* (m^3/s)**
Jan.	600	560	43,700	1,500	380	370	49,800	1,500	175	155	98,800	4,500
Feb.	600	560	43,700	1,500	380	370	49,800	1,500	175	155	98,800	4,500
Mar.	600	560	43,700	1,500	380	370	49,800	1,500	175	145	98,800	4,500
Apr.	600	560	43,700	1,500	380	370	49,800	1,500	175	145	98,800	4,500
May	560	560	43,700	1,500	370	370	49,800	1,500	145	145	98,800	4,500
Jun.	560	560	43,700	1,500	370	370	49,800	1,500	145	145	98,800	4,500
Jul.	560	560	43,700	1,500	370	370	49,800	1,500	145	145	98,800	4,500
Aug.	560	560	43,700	1,500	370	370	49,800	1,500	145	145	98,800	4,500
Sep.	560	560	43,700	1,500	370	370	49,800	1,500	145	145	98,800	4,500
Oct.	600	560	43,700	1,500	380	370	49,800	1,500	175	155	98,800	4,500
Nov.	600	560	43,700	1,500	380	370	49,800	1,500	175	155	98,800	4,500
Dec.	600	560	43,700	1,500	380	370	49,800	1,500	175	155	98,800	4,500

power generation under the actual requirements of guaranteed output and assurance rate.

CASE STUDY

Basic data

The Yangtze and Jinsha River basin is the largest river basin in China. There are two hydropower stations in the upstream of the Yangtze River main stream, which are Three Gorges and Ge Zhouba (Chen *et al.* 2014), and Three Gorges reservoir has a seasonal regulation performance. There are four planned hydropower stations with a good regulation performance in the downstream reaches of Jinsha River, which is Wu Dongde, Bai Hetan, Xi Luodu and Xiang Jiaba, but only Xi Luodu and Xiang Jiaba hydropower stations have been put into operation at present (Xie *et al.* 2015). Considering the reservoir regulation performance and the availability of data, this paper

Table 3 | Runoff data of typical years for each hydropower stations (unit: m^3/s)

Reservoir	**Year**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**
Xi Loudu	1,959	5,116	6,139	9,200	5,434	4,776	3,129	1,817	1,478	1,313	1,351	1,524	2,041
	1,970	3,445	8,365	6,135	5,702	4,678	2,798	1,781	1,832	1,550	1,512	2,329	2,563
	1,976	2,863	7,776	7,245	10,435	5,036	2,720	1,835	1,671	1,412	1,288	1,336	1,310
	1,977	4,325	7,584	8,853	6,983	4,471	2,491	1,745	1,567	1,308	1,253	1,398	2,378
	1,997	6,042	5,988	5,775	6,718	4,420	2,283	1,651	1,647	1,388	1,476	1,855	2,363
Xiang Jiaba	1,959	5,187	6,268	9,375	5,534	4,872	3,192	1,846	1,489	1,324	1,368	1,541	2,068
	1,970	3,473	8,507	6,213	5,761	4,762	2,862	1,815	1,876	1,595	1,533	2,354	2,583
	1,976	2,915	7,909	7,335	10,629	5,140	2,780	1,882	1,727	1,448	1,310	1,352	1,324
	1,977	4,392	7,682	8,943	7,085	4,553	2,539	1,781	1,607	1,338	1,279	1,425	2,427
	1,997	6,128	6,047	5,877	6,764	4,507	2,332	1,684	1,659	1,401	1,504	1,881	2,400
Three Gorges	1,959	17,353	22,595	27,806	13,643	11,966	8,940	5,612	3,987	3,813	5,273	6,649	11,316
	1,970	20,890	29,538	19,286	14,467	16,047	8,227	4,519	4,735	4,279	6,089	10,750	16,706
	1,976	9,635	26,924	19,848	25,250	16,785	10,807	5,079	4,287	3,599	3,467	5,612	7,615
	1,977	17,683	24,180	16,911	17,313	13,539	8,969	4,504	3,915	3,430	4,215	6,832	13,729
	1,997	17,510	20,452	12,095	18,227	17,621	9,117	7,432	4,627	3,531	4,324	8,067	9,032

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takes the Xi Luodu, Xiang Jiaba and Three Gorges reservoirs as a cascade system instance to study the ESOC. The basic parameters of this three hydropower stations are shown in Table 1, and the plane sketch map of the studied cascade hydropower stations is shown in Figure 3.

Considering the flood control requirements of reservoir in flood season, and the water supply requirements of downstream in dry season, the water level and outflow constraints of each reservoir in each stage are shown in Table 2, where Max Z and Min Z respectively represent the allowed maximum and minimum water level in power generation operation, and Max Q and Min Q respectively represent the allowed maximum and minimum outflow.

The long series observed runoff data of this cascade system is available from 1959 to 2000, a total of 42 years. Five hydrological years which are 1959, 1970, 1976, 1977 and 1997 are selected as the typical years. The observed runoff data of these typical years is shown in Table 3.

Results and analysis

According to the ESOC model and its solving method described earlier, we set different discretized guaranteed

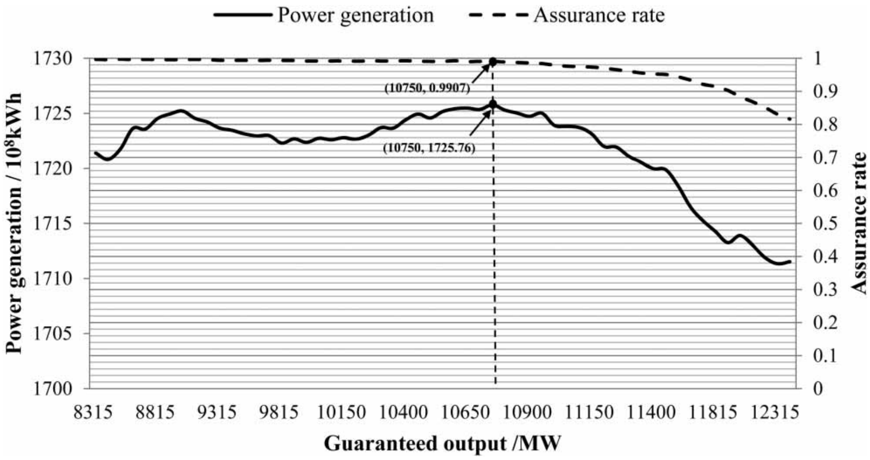

Figure 4 | The relationship curve among guaranteed output, assurance rate and power generation.

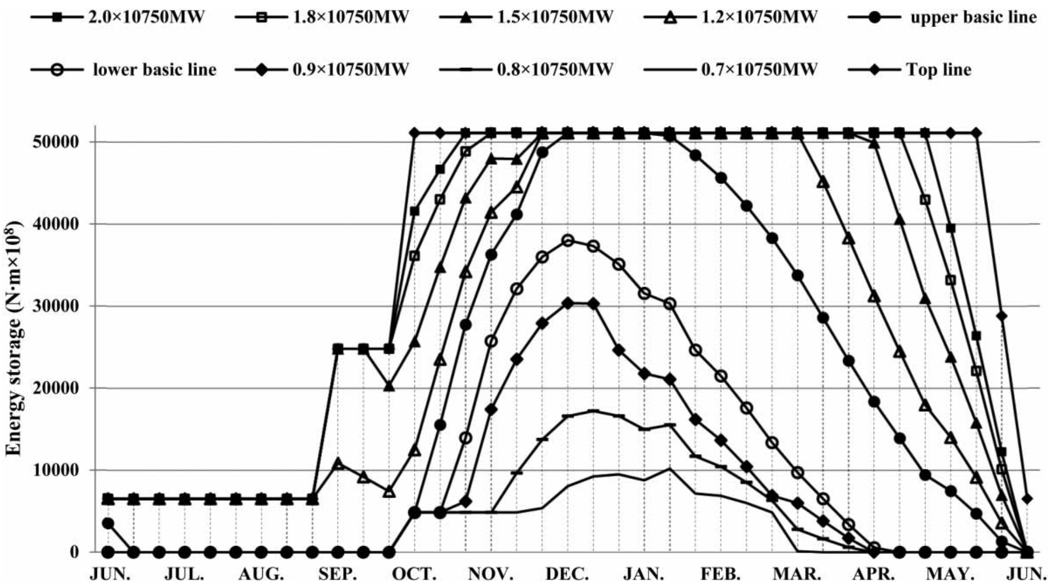

Figure 5 | The optimal energy storage operation chart.

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output in the range of the sum of original design guaranteed output (i.e. 10,394 MW, form Table 1) plus and minus 20%, with 1% discrete interval, then, according to each discretized guaranteed output, we extracted the ESOC and implemented the simulation under the constraints of flood control and water supply; finally, the relation curve of guaranteed output, assurance rate and power generation can be obtained, as shown in Figure 4.

From Figure 4, it can be seen that the assurance rate of ESOC are gradually reduced with the increase of guaranteed

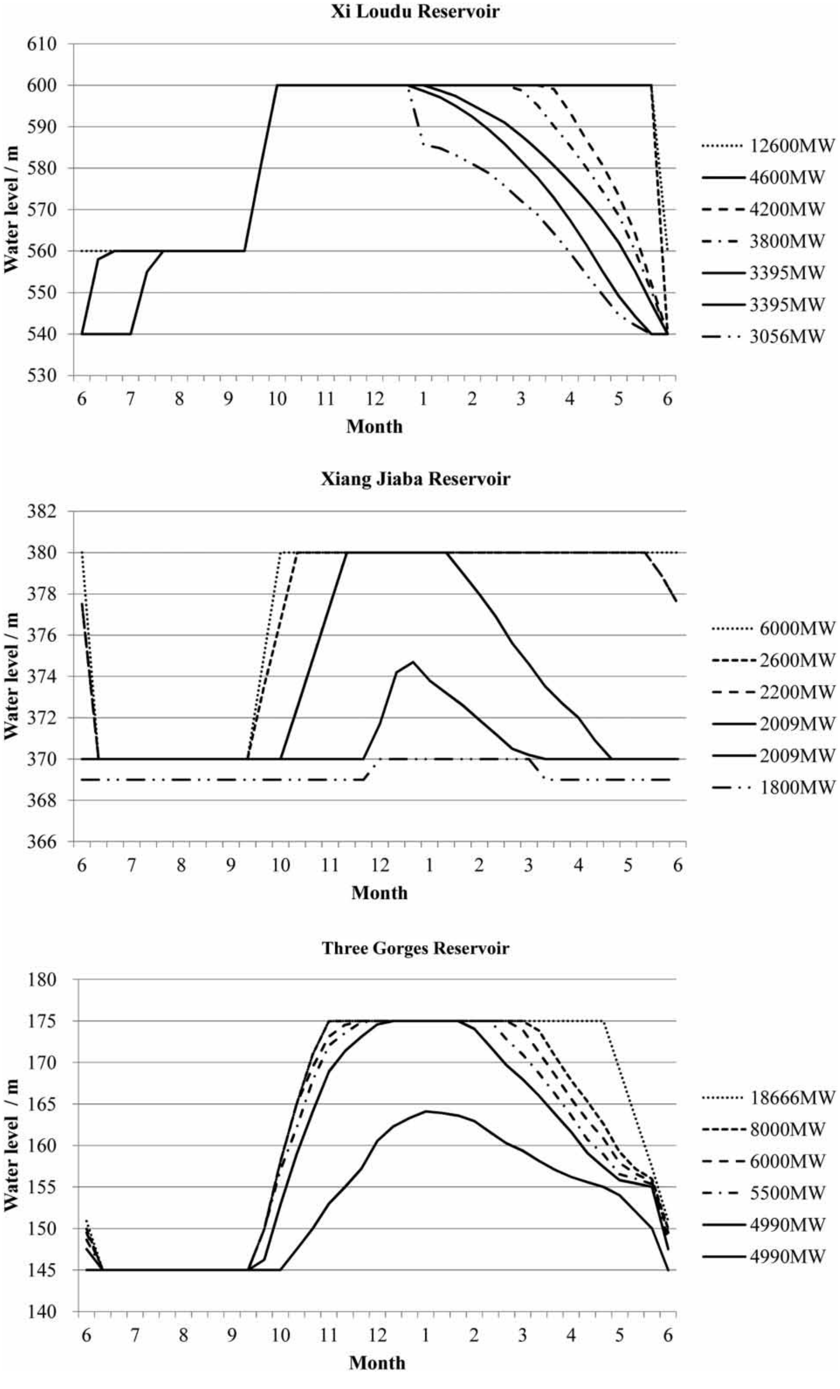

Figure 6 | Conventional reservoir operation chart of each reservoir.

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output. There is a reciprocal relationship between the guaranteed output and assurance rate in reservoir operation. According to Figure 4, we can find that the maximum power generation of the cascade system is 1725.76×10^8 kWh, the corresponding guaranteed output and assurance rate is 10,750 MW and 99.07%, respectively. The corresponding optimal ESOC is shown in Figure 5.

Table 4 | Results of ESOC method and conventional reservoir operation method

Method	Power generation (10^8 kWh)	Guaranteed output (MW)	Assurance rate (%)
ESOC	1725.76	10,750	99.07
Conventional method	1710.02	10,394	90.41
Increment	15.74	356	8.66

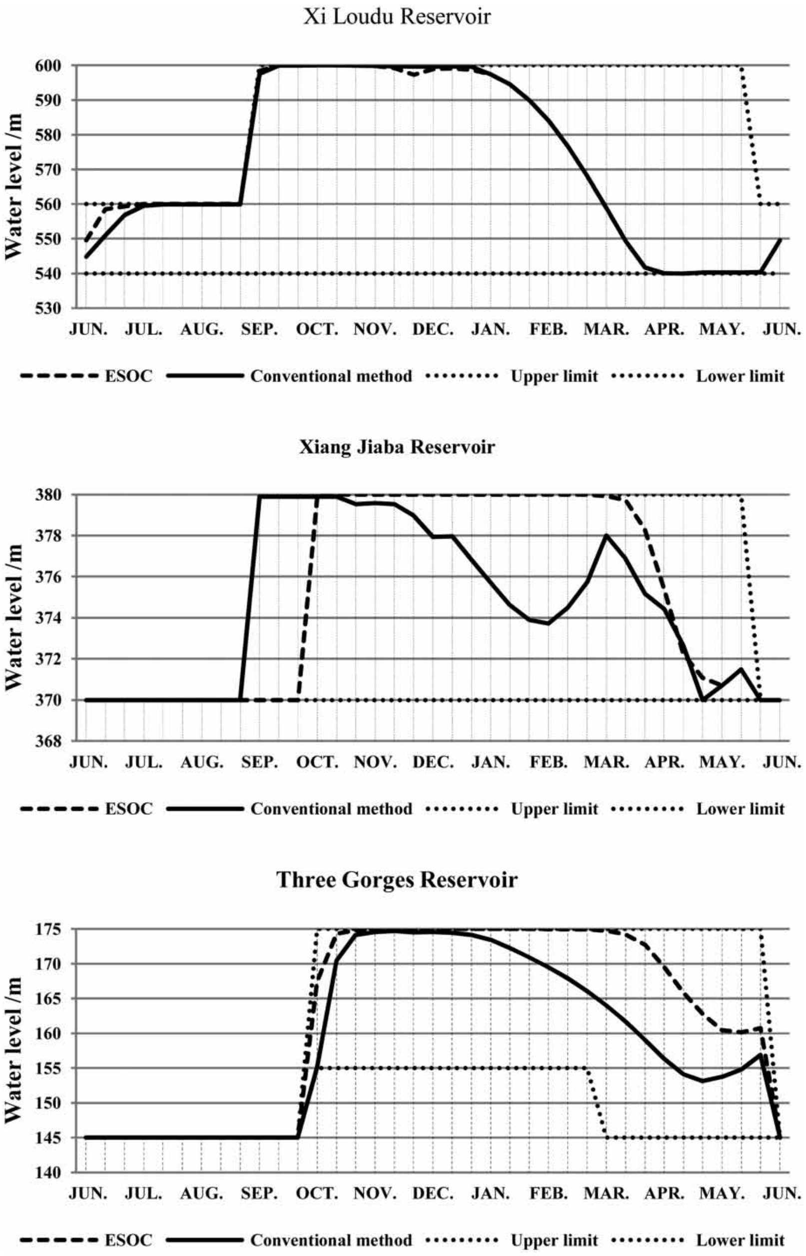

Figure 7 | Average water level variations of the cascade reservoirs.

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In order to contrastingly analyze the ESOC method with the conventional method, simulation through the conventional single reservoir operation chart (as shown in Figure 6) has been done in this paper, and the annual average power generation, guaranteed output and assurance rate of the two methods are shown in Table 4.

In Table 4, the guaranteed output of ESOC is the optimal guaranteed output that corresponds to Figure 5. While, for the conventional method, the total guaranteed output of cascade system is still the sum of the design guaranteed output of each hydropower station, which is unchanged because of without considering the joint operation. The assurance rates in Table 4 are the statistics of simulation operation with a long series of historical runoff data.

From Table 4, it can be seen that the ESOC method in this paper is superior to conventional method in terms of power generation, guaranteed output and assurance rate, especially in terms of assurance rate. The increment of these three indicators is 15.74×10^8 kWh (0.9% growth), 356 MW (3.4% growth) and 8.66 (9.6% growth), respectively. Therefore, compared with the conventional reservoir operation method which is currently used in the actual operation, it can be seen that the proposed ESOC method in this paper can effectively improve the energy efficiency and at the same time ensure a good stability and reliability of power supply for cascade system.

To further analyze the reasons of the difference of the two methods on the results, the average water level variations of each reservoir of the two methods are shown in Figure 7. It is important to note that the water level variations in Figure 7 are drawn by the beginning water level of each stage.

From Figure 7, it can be seen that, firstly, the water levels of the three reservoirs in the simulation operation are all within the feasible range, which means the water level constraints are both not destroyed in the two methods. Secondly, except the first reservoir of the cascade system, the reservoir water level falling is relatively slow in ESOC method compared with the conventional method. Especially for the Xiang Jiaba reservoir, its operating water level is lower and the fluctuation is bigger in conventional method than ESOC method; on the contrary, the operating water level basically maintains a high level in ESOC method, and only drops to a low water level in the last few stages because of the flood control requirements in flood season.

Therefore, the most operation stages of downstream reservoirs maintain a high water level in ESOC method, which can effectively raise the water head of downstream reservoirs, and increase the whole hydroelectricity benefit of the cascade system. This is the main reason why the three statistical indicators of ESOC method are superior to conventional method. In addition, comparing the water level variations of the three reservoirs in ESOC method, it can be found that the upstream reservoir releases the water earlier than the two downstream reservoirs in the dry period, to make full use of the high water head of downstream reservoirs to generate more electricity before it drops down. This phenomenon, which does not appear in the conventional method, is of great significance to guide the actual cascade reservoirs operation, and it is consistent with the basic principle of reservoir storage and supply. So, results reflect that the ESOC method can be applied to the practical operation so as to increase the hydropower generation.

CONCLUSION

A reservoir operation chart is the guideline for long- and mid-term reservoir operation. An efficient extracting technique is required to find the reasonable reservoir operation chart that can improve the water resources utilization efficiency and get the maximum energy using the limited hydropower resources. In this paper, based on DCM, we provided an efficient and practical joint operation method for cascade reservoirs, which is ESOC method. Through taking the cascade reservoirs in Yangtze River of China as an instance, it was found that, compared with the conventional operation method, 0.9% growth on power generation, 3.4% growth on guaranteed output and 9.6% growth on assurance rate can be obtained by ESOC, respectively. On the whole, it can be concluded that the provided ESOC method in this paper gets a good application effect in the cascade reservoirs of Yangtze River, which has a certain popularization value.

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