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(RESEARCH ARTICLE)

Cascade reservoirs optimal operation through combined guide curves

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Abstract

This study is concerned with the optimal operation of cascade reservoir system for hydropower generation. The problem involves optimizing hydropower production while reducing excess water spill during the flood season. A new combined reservoir operation model is proposed based on combined guide curves for optimizing hydropower production and for better storage distribution among cascade reservoirs. The storage distribution among cascade reservoirs is achieved by the storage effectiveness index method. The model is optimized with the particle swarm optimization algorithm and applied to the Qingjiang River cascade reservoir system in China. The optimized combined guide curves for Shuibuya-Geheyan reservoirs are obtained and compared with conventional reservoir operation charts and Lund analytical solution method. Simulation results show that the proposed model can modulate water levels of the Shuibuya reservoir and effectively increase hydropower heads of the Geheyan reservoir. Comparing with the original design, the proposed model enhances hydropower production considerably while reducing the spill release. It is capable to produce an extra amount of 201 GWh electrical energy (a 2.77% increment) and save 1067 Mm^3 of flood water resources (a 38.96% reduction) annually in the Qingjiang cascade reservoirs.

Keywords: Reservoir operation； Cascade； Water levels; Optimization; Hydropower plant

1. Introduction

Currently water is considered as a scarce resource as a result of the growing demand for its use in various purposes such as hydropower, irrigation, water supply, etc. Reservoir operation forms an integral part in water resources development [1,2]. During the past few decades, various optimization and simulation models have been developed in order to support the decision-making process of the reservoir operation and reviewed by many authors [3–8].

Young [9], Bhaskar and Whitlatch [10], Karamouz and Houck [11], and Karamouz and Houck [12] used linear regression and dynamic programming based optimization models for deriving general operating rules for reservoir operation. In the field of water resources engineering, particularly reservoir operations, genetic algorithm (GA) has been proved to be computationally superior to traditional methods like linear programming, nonlinear programming and dynamic programming. Wide range applications of GAs in optimizing reservoir operation rules can be seen in the academic literature [13–18]. Application of artificial neural networks (ANN) in water resources system analysis can be identified as a fast growing area of reservoir system optimization. Recently, ANN and several hybrids of ANN models, such as neural-fuzzy system and the combination of ANN with GA, have been successfully applied to derive reservoir operating rules by many researches [19–22].

Despite the potential for the use of optimization in real-time reservoir operation, with some exceptions, optimization models still play a minor role in identifying possible reservoir releases. Most of the reservoir systems in the world are still managed on fixed predefined operating rules. This is mainly due to institutional, rather than technological and

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mathematical limitations [13]. These predefined operating rules are usually presented in the form of graphs and tables [5,23] and called reservoir operation charts. It represents all the regular functions of operating rules and provides guidance to system operators. Although various operation models based on optimization and simulation techniques are available, conventional operation chart is still widely used for deriving operation rules due to its concise and direct-viewing. However, it is only used in single reservoir operations, and cannot be used in combined operation of cascade reservoirs. Therefore, poor storage distribution can be seen among cascade reservoirs, and much of flood water resources are wasted. Several attempts have been made to solve this problem in the recent past. The Storage Effectiveness Index (SEI) introduced by U.S. Army Corps of Engineers is one of the decision making rules in the cascade reservoirs operation for maximizing firm hydropower production [24]. Lund [25] presented an analytical solution method to determine which reservoir would be drawn down first to optimize marginal energy demands from reservoirs in series. The HEC-ResSim model introduced by U.S. Army Corps of Engineers [26] is a useful tool for reservoir system simulations.

A new reservoir operation model for combined operation of cascade reservoirs is proposed in this paper. The total power generation capacity of the whole cascade is achieved by combined guide curves which is a new idea in cascade reservoirs operation. The Storage Effectiveness Index (SEI) method is used to distribute storage among each reservoir and the Particle Swarm Optimization (PSO) algorithm is used to optimize combined guide curves. The proposed model was applied to Qingjiang cascade reservoir system in China and combined guide curves were derived. In order to ascertain the reliability and performance, the proposed model was compared with conventional reservoir operation charts and Lund [25] analytical solution method.

2. Material and methods

2.1. Combined reservoir operation model

The proposed combined reservoir operation model has three components. (1) Combined guide curves (2) storage distribution and (3) optimization. During the release process, it requires to synthesize reflecting hydrological characteristics of the river basin and unique features of reservoirs by the combined reservoir operation model. It should also satisfy with the guide rules of reservoirs in different inflow scenarios and different water level conditions.

2.2. Combined guide curves

Combined guide curves, which is a new idea in cascade reservoirs operation, is proposed to determine the total generation capacity of cascade reservoirs. It is determined according to the current water level of each reservoir in the proposed combined reservoir operation chart with particular judging rules.

2.3. Combined Reservoir Operation Chart

The proposed combined reservoir operation chart for a hypothetical cascade with two reservoirs is shown in Figure 1. It is similar to conventional operation charts, and mainly consists of different guide curves and corresponding operational zones. Accordingly, upper and lower combined guide curves of each individual operation chart divide the whole storage space into three operational zones, named higher capacity zone (Z_1), firm capacity zone (Z_2) and lower capacity zone (Z_3). The combined guide curves have particular features relative to conventional operation charts. Those reflect the total generation capacity of the cascade reservoir system in every time interval and do not mention the individual reservoir generation capacity. However, guide curves in the conventional operation chart correspond to individual reservoir generation capacity. The combined guide curves display the relationship between reservoir water level and the total generation capacity of the reservoir system through each reservoir operation charts. When water levels are in higher capacity zone, firm capacity zone and lower capacity zone, corresponding total generation capacities of the cascade are N_1, N_2 and N_3, respectively ($N_1 > N_2 > N_3$). Another unique feature of the combined guide curve is that it demonstrates the optimized power generation capacity and better storage distribution among cascade reservoirs.

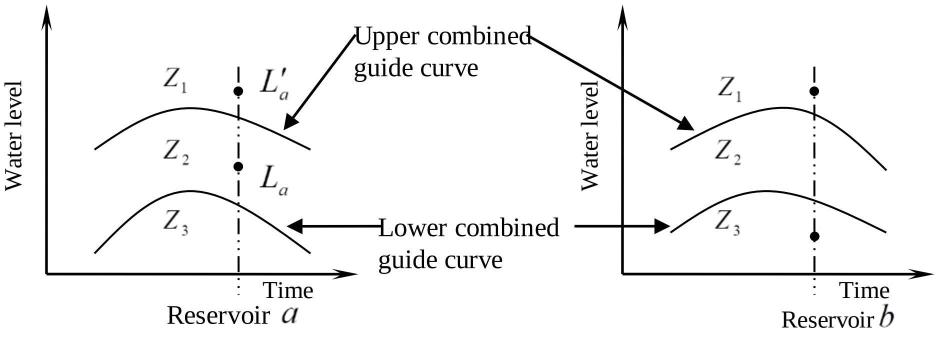


Figure 1 Combined reservoir operation chart for a hypothetical cascade

Three steps are involving in using the combined reservoir operation chart. (1) Obtain the current water levels of each reservoir in the cascade. (2) Compare each reservoir water level and decide the total generation capacity of the cascade (here, some empirical judging rules were introduced for determining the total generation capacity). (3) Determine each reservoir's hydro power demand according to the total generation capacity using the SEI method and establish better storage distribution among cascade reservoirs.

2.4. Judging Rules

Rule 1: "If the water levels of every reservoir are in the same operational zone, the cascade total generation capacity would be the same as individual generation capacities in the corresponding operation zone". As an example, at the current time t, water levels of reservoirs a and b in Figure 1 are L'_a and L'_b respectively. The corresponding generation capacities are N_1 in both cases. Since both water levels are in the same operation zone Z_1, N_1 is considered as the total generation capacity of the cascade.

Rule 2: If water levels of each reservoir are in different operational zones, the judging rule becomes complex than the above. The principle in such a case is, water levels of each reservoir should be in the same operational zone or as close as possible after releases are made at the current time-step. This is achieved by releasing water for power generation from the reservoir which has highest total generation capacity at the current time while other reservoirs reduce or stop their releases. As an example, if water levels of two reservoirs in Figure 1 are L_a and L_b which are in different operational zones, corresponding total generation capacities are N_2 and N_3, respectively ($N_2 > N_3$). In this case, reservoir a undertakes the main role in power generation by increasing its generation rate while reservoir b reduces its generation rate to push water levels into the same operational zone. Main steps of this rule can be summarized as follows.

"First assume N_2 as the cascade total generation capacity and undertake power generation to push each reservoir's water level into the same operation zone or as close as possible at the end of the current time-step. Second, when water level of each reservoir comes into the same operational zone, releases are made according to storage effectiveness index for better storage distribution among cascade reservoirs".

During the first step it should avoid increasing the reservoir b 's generation rate more than the total generation capacity of the cascade, N_2. If the actual generation rate, N_t is smaller than N_3 during the computing time interval, then decide N_3 as the total generation capacity of the cascade. If water levels are still in different operation zones after the estimation and also actual generation rate, N_t is less than N_2 and larger than N_3 ($N_2 > N_t > N_3$) then the total generation capacity of the cascade is considered as N_t. It is neither N_2 nor N_3.

2.5. Storage Distribution

Storage Effectiveness Index (SEI) developed by U.S. Army Corps of Engineers [24] is used to achieve better storage distribution among cascade reservoirs. SEI is one of the decision making rules in the reservoir system operation for maximizing firm hydropower production. For each reservoir in the cascade, a "SEI" is calculated for each time-step, using forecast inflow and power demands for the current time-step and remaining time-steps. In the release process, it is accomplished according to the magnitude sequence of SEI values of each reservoir. The reservoir with lowest SEI value is drawn down first during the release season and, vice versa during the refill season or period. Here, the refill season is defined as the season when system inflows exceed the needs to meet hydropower production demands.

Assuming all flow can be utilized through turbines for power generation, the energy shortage for the current time step, E_q is computed by

$$E_q = E_x - \sum_{i=1}^{N} 9.8\eta_i I_i H_i \Delta t \qquad (1)$$

where E_x is the energy requirement for the current time-step; i is the reservoir index; N is the total number of reservoirs in the cascade; η_i is the turbine efficiency of reservoir i; I_i is the inflow to reservoir i during the current time-step; H_i is the hydropower head as a function of reservoir storage of reservoir i; and Δt is the computing time-step.

The drawdown storage of reservoir i for power generation, ΔS_i is expressed by,

$$\Delta S_i = E_q / (9.8\eta_i H_i) \qquad (2)$$

The drawdown period power loss, E_i due to drawdown of reservoir i by ΔS_i is expressed by;

$$E_i = 9.8\eta_i (W_{oi} + W_{qi}) H_i (S_i - \Delta S_i) \qquad (3)$$

where W_{oi} is the cumulative outflow capacity of upstream reservoir i during the remainder of the drawdown season; W_{qi} is the cumulative inflow capacity of upstream reservoir i during the remainder of the drawdown season; S_i is the current reservoir storage of reservoir i.

The storage effectiveness index of reservoir i, SEI_i is calculated by

$$SEI_i = E_i / E_q \qquad (4)$$

The SEI method is used with the proposed combined operation chart as following,

If the water levels of every reservoir are in the same operational zone, the SEI method is directly used to achieve better storage distribution among cascade reservoirs. The sequence of release is the same with SEI of each reservoir from small to large during the drawdown period, and vice versa during the reservoir refill period.

If the water level of each reservoir is in different operational zones, the reservoir with highest total generation capacity supplies water for power production first. Other reservoirs reduce or stop their releases for bringing the water level of each reservoir into the same operational zone. When the water levels of each reservoir come into the same operational zone, the SEI method is used to determine storage distribution among cascade reservoirs as mentioned above.

2.6. Optimization

Particle Swarm Optimization (PSO) is a population based stochastic optimization technique proposed by Kennedy and Eberhart [27], inspired by social behavior of bird flocking or fish schooling. PSO shares many characteristics with other evolutionary computation techniques such as Genetic Algorithms (GA). The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation [28]. PSO as an optimization tool provides a population-based search procedure in which individuals called particles change their position (state) with time. In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience, and according to the experience of a neighboring particle, making use of the best position encountered by itself and its neighbor. Thus, as in modern GAs and memetic algorithms, a PSO system combines local search methods with global search methods, attempting to balance exploration and exploitation [29]. PSO has a flexible mechanism to enhance the global and local exploration abilities [30]. PSO also has few parameters to adjust. One version, with slight variations, works well in a wide variety of applications [31]. Hu et al. [32] demonstrated that PSO can get better results in a faster, cheaper way compared with other optimization methods such as GA and simulated annealing for some problems. During the past several years, PSO has been applied in many research areas [33]. For example, Yoshida et al. [34] used PSO algorithm for optimization of reactive power and voltage control, Abido [30] used PSO to optimize parameter settings of power system stabilizers and Robinson and Rahmat-Samii [35] used PSO for electromagnetic optimization. However, few applications are found in the field of water resources engineering. Chuanwen and Bompard [36] has used PSO algorithm to solve the short term generation scheduling of a hydro-system in a deregulated environment. Since its better characteristics as an optimization tool, and also ascertain its ability in using reservoir operation, PSO algorithm is used to optimize combined guide curves in this study.

Assume the population (swarm) is made up of m particles and n dimensional searching space. It means, particle i has n dimensional velocity vectors in the searching space. If x_i is the current position of the particle i in the swarm, { $x_i = (x_{i1}, x_{i2}, \cdots, x_{in})$, $i = 1,2,\cdots,m$ } the best position where particle i has encountered during its flight is p_i { $p_i = (p_{i1}, p_{i2}, \cdots, p_{in})$ } and it is called P_{best}. The global optimized position where particle has encountered, when the particle takes all the population as its topological neighbors, is p_g { $p_g = (p_{g1}, p_{g2}, \cdots, p_{gm})$ } and it is called G_{best}. v_i is the current velocity of particle i during the search in n dimensional searching space { $v_i = (v_{i1}, v_{i2}, \cdots, v_{in})$ }. Modified velocity, x_{ij}^{k+1} of particle i can be written as,

$$x_{ij}^{k+1} = x_{ij}^{k} + v_{ij}^{k+1} \tag{5}$$

$$v_{ij}^{k+1} = wv_{ij}^{k} + c_1 r_1 [p_{ij} - x_{ij}^{k}] + c_2 r_2 [p_{gj} - x_{ij}^{k}] \tag{6}$$

where w is a parameter called “inertia”, $v_{ij} \in [-v_{\max}, v_{\max}]$, $v_{\max}$ is a constant; c_1 and c_2 are accelerated velocity constants which push particle to P_{best} and G_{best}; r_1 and r_2 are stochastic constants in the interval of (0,1).

2.7. Guide Curve Establishment

Each particle i in the particle swarm algorithm represents a specific position, x_i in the combined reservoir operation chart. When all these particle positions, $(x_{i1}, x_{i2}, \cdots, x_{in})$ are connected together from beginning to end, it represents guide curves of each reservoir in the combined reservoir operation chart.

The particle dimension of this problem can be written as,

$$n = T \times L \tag{7}$$

where n is particle dimension; T is the total number of time periods in the year; and L is the total number of guide curves in all reservoirs.

During the solution process, particles carry on optimization using single guide curve as the basic unit, because we assume a guide curve is made up of current position of connected particles. The location of guide curve changes as particles move to their best positions.

2.8. Objective Function and Constraints

If all hydropower plants meet the required water supply and initial power supply, the objective is to generate maximum power from the whole system, i.e.,

$$max \quad f=\sum_{t=1}^{T}\sum_{i=1}^{N}9.8C_{i,t}\eta_i H_{i,t}Q_{i,t}\,\Delta t \qquad t=1,2,\cdots,T \quad i=1,2,\cdots,N \tag{8}$$

where t is the computation time interval index; T is the total number of computation time intervals; $Q_{i,t}$ is the flow rate use for power generation of reservoir i during the time interval t; $C_{i,t}$ is the price for the electricity of reservoir i during the time interval t; $H_{i,t}$ is the hydropower head of reservoir i during the time interval t; and other notations have same meaning with above.

subject to, $$V_{i,t+1}=V_{i,t}+(I_{i,t}-q_{i,t})\Delta t \tag{9}$$

$$I_{i+1,t}=q_{i,t}+IB_{i,t} \tag{10}$$

$$q_{i,\min}\le q_{i,t}\le q_{i,\max} \tag{11}$$

$$N_f\le\sum_{i=1}^{N}N_{i,t}\le\sum_{i=1}^{N}NT_i \tag{12}$$

where $V_{i,t}$ is the storage of reservoir i at the beginning of the time interval t; $I_{i,t}$ is the inflow to reservoir i during the time interval t; $q_{i,t}$ is the outflow of reservoir i during the time interval t; $IB_{i,t}$ is the inflow between reservoir i and $i+1$ during the time interval t; $q_{i\min}$ is the minimum discharge capacity of reservoir i for down stream ecological requirements; $q_{i\max}$ is the maximum discharge capacity of reservoir i and it is limited by the down stream flood prevention limitations; N_f is the firm capacity of the cascade reservoir system; NT_i is the maximum generation capacity of reservoir i; and $N_{i,t}$ is the generation capacity of reservoir i during the time interval t.

Considering constraints of the electric power system of Qingjiang cascade hydropower plants, the adjusted objective function for particle swarm algorithm optimization can be written as,

$$max \quad F=\sum_{t=1}^{T}[\sum_{i=1}^{N}C_{i,t}N_{i,t}+\alpha(\sum_{i=1}^{N}N_{i,t}-N_f)^{\beta}]\Delta t \tag{13}$$

where α and β are penalty for electric power system constraints; if $\sum_{i=1}^{N}N_{i,t}\ge N_f$ then $\alpha=0$, otherwise $\alpha>0$. Other notations have same prior introduced meanings.

3. Application of combined reservoir operation model to qingjiang cascade

3.1. Qingjiang Cascade Reservoir System

The Qingjiang basin is situated at southwest Hubei province in China and located between the east longitudes 108°35 ' ~ 111°35 ' and the north latitudes 29°33 ' ~ 30°50 ' in the subtropical area. It is mountainous and has multi karsts land form with basin area of 17600 km^2. Abundant rainfall is found in the basin and mean annual rainfall is approximately 1460mm. Mean annual runoff depth is 876mm and mean annual runoff is 423m^3/s. Qingjiang River is one of the main tributaries of Yangtze River, and winding from west to east. The total length of the mainstream is 423km with a hydraulic drop of 1430m. Qingjiang River has a total exploitable hydropower potential of 3500MW with annual output more than 10000 GWh. Along the Qingjiang River, a three-step cascade reservoir system is found from upstream to downstream namely, Shuibuya, Geheyan and Gaobazhou. Main objectives of this cascade reservoir system are power generation and flood control. Improving navigation and fisheries facilities are the other benefits. A diagram of Qingjiang basin with the cascade reservoir system is shown in Figure 2, and the basic physical parameters of three reservoirs are listed in Table 1. In the original design, these reservoirs use predefined guide rules based on conventional method for instructing reservoir releases. However hydropower plants are considered independently in the operation process. Therefore it is impossible to realize better storage distribution among cascade reservoirs and does not display the overall power generation performance.

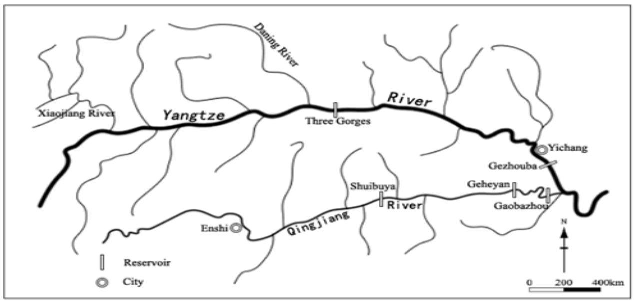


Figure 2 The Qingjiang basin with cascade reservoir system

Table 1 Basic physical parameters of the Qingjiang cascade reservoirs

Reservoir	Normal Pool level（m）	Flood Prevention water level（m）	Dead water level（m）	Total storage（Mm^3）	Dead storage（Mm^3）	Installed capacity（MW）	Firm Capacity（MW）	Regulation ability
Shuibuya	400	391.8	350	4,345	1,941	1,600	310.0	Multiyear
Geheyan	200	193.6	160	3,120	1,642	1,200	241.5	Annual
Gaobazhou	80	78.5	78	356	305	270	77.3	Daily

The individual conventional operation charts of Shuibuya and Geheyan reservoirs are shown in Figures 3 and 4, respectively. According to the Shuibuya reservoir conventional operation chart, the whole storage space is divided into five operational zones. Accordingly, following generation parameters are used in the operation process. When the reservoir water level is between upper and lower basic guide curves, the hydropower plant is working under its firm capacity (310MW). If the water level falls into operation zone ③, which is between upper basic guide curve and 800MW guide curve, the power plant capacity is 800MW. If the reservoir water level lies in the operational zone ②, the power plant capacity is 1600MW which is the installed capacity. When the reservoir's water level rises to flood prevention limit or enters into the flood prevention zone, the reservoir adjusts according to designed flood control rules and power plant works under the installed capacity (1600MW). If the water level falls below the lower basic guide curve, the power plant capacity is 250MW.

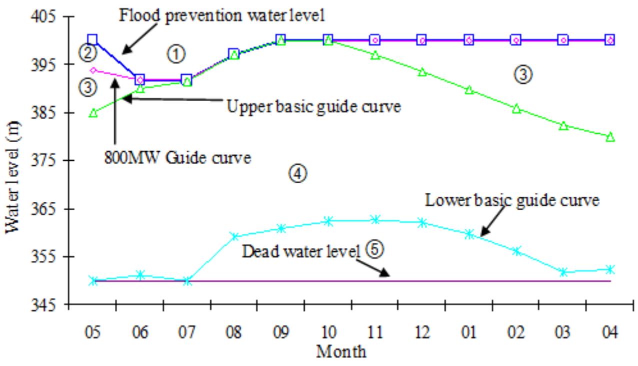


Figure 3 Conventional operation chart of the Shuibuya reservoir

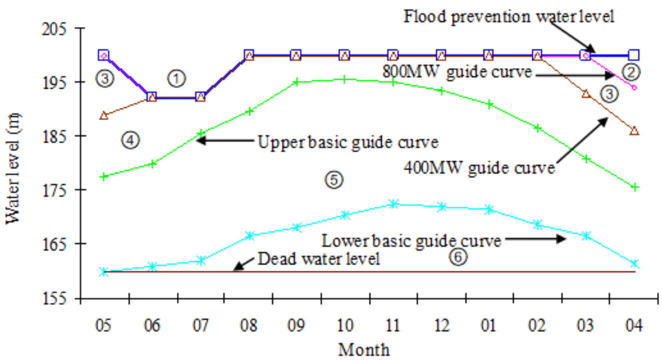


Figure 4 Conventional operation chart of the Geheyan reservoir

Six operational zones are found in the Geheyan reservoir conventional operation chart as shown in Figure 4. When the reservoir water levels are in different operational zones, respective generation parameters of the Geheyan reservoir are shown in Table 2. If the water level rises to flood prevention limit or into the flood prevention zone, the reservoir is adjusted according to designed flood control rules, and the power plant works under the installed capacity (1200MW).

Table 2 Generation parameters of the Geheyan reservoir conventional operation chart

Operational zone	Area	Generation capacity (MW)
①	Above the flood prevention water level	1,200.0
②	Flood prevention water level ~ 800MW guide curve	1,200.0
③	800MW guide curve ~ 400MW guide curve	800.0
④	400MW guide curve ~ Upper basic guide curve	400.0
⑤	Upper basic guide curve ~ Lower basic guide curve	241.5
⑥	Below the lower basic guide curve	73.0

3.2. Parameter Establishment

Since the effective storage capacity and hydraulic head of the Gaobazhou reservoir is very small comparing to other two reservoirs in Qingjiang cascade, it is operated as a run-of-river hydropower plant. Therefore, this study is focused on the combined operation of Shuibuya and Geheyan reservoirs. The flood prevention water level of each reservoir is taken as the normal water level and optimum algorithm is adopted to derive upper and lower combined guide curves. Those upper and lower combined guide curves divide the whole reservoir storage space into three operational zones namely, higher capacity zone, firm capacity zone and lower capacity zone. Another operational zone is found when the water level is above the flood prevention water limit. Table 3 shows the area belonging to each operation zone, and the respective generation parameters.

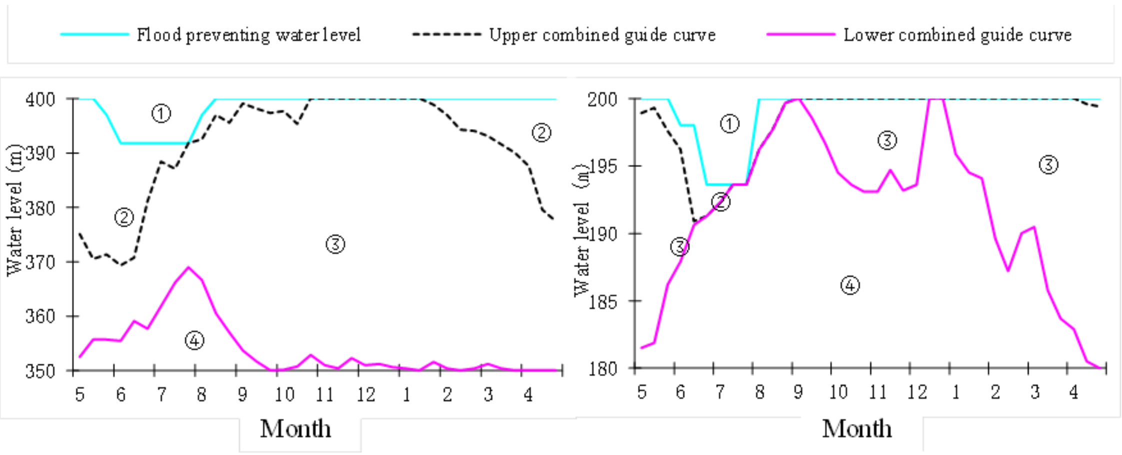
Table 3 Zones and generation parameters of the Qingjiang cascade combined reservoir operation chart

Operational zone	Area	Generation Capacity (MW)
Installed capacity	Above the flood prevention water level	1,800.0
Higher capacity	Flood prevention water level ~upper combined guide curve	1,800.0
Firm capacity	Upper combined guide curve ~ lower combined guide curve	628.8
Lower capacity	Below the lower combined guide curve	420.1

Ten-day interval inflow records from 1951 to 2005 were used in this study. With this inflow records, Qingjiang River combined reservoir operation chart is optimized by using the PSO model. In this optimization, the highest hydropower generating capacity was taken as the research goal with considering uncertainty of electric price. Price of the electricity $C_{i,t}$ is assumed to be 1; $T = 36$, by ten-day time intervals; $L = 4$, number of guide curves to be optimized; the electric constraint penalty $\alpha = 10$ and $\beta = 1$; number of particles in the population $m = 20$; accelerated velocity constants c_1 and c_2 are both 20; inertia parameter $w = 0.5$; $v_{\max} = 0.1$; and beginning water levels of Shuibuya and Geheyan reservoirs are 365m and 195m respectively, according to their mean water levels. During the operation process, cascade total generation always satisfy the designed guarantee output rate of 95%.

3.3. Analysis of Guide Curves

Qingjiang cascade optimized combined reservoir operation chart is obtained by the proposed combined reservoir operation model and shown in Figure 5. In the Figure 5, ① is the installed capacity zone, ② is the higher capacity zone, ③ is the firm capacity zone and ④ is the lower capacity zone. According to the runoff records, the mean runoff rate of Qingjinag basin is high during May to September and low during October to April. With the fluctuating inflow capacity, the corresponding guide curves also fluctuate as shown in Figure 5.



(a) Shuibuya reservoir

(b) Geheyan reservoir

Figure 5 Combined reservoir operation guide curves for the Qingjiang cascade reservoirs.

Before the flood season, higher capacity zones enlarge and increase hydropower generation capacity in order to avoid spilling. After ceasing the flood season, the area of the higher capacity zones decreases and reduce water usage for power generation to avoid water level falling excessively. Higher capacity and firm capacity zones of the Shuibuya reservoir are large and the lower capacity zone is small, while it is opposite in the Geheyan reservoir. Because, when optimizing combined operation model of two reservoirs, higher priority is given to the Shuibuya reservoir for hydropower generation while the Geheyan reservoir is maintained a higher water level. The lower combined guide curve of the Shuibuya reservoir has its highest value during the flood season. During the dry season, it is very close to the dead water level. The lower combined guide curve of the Geheyan reservoir reaches to its maximum during the flood season. In overall, the Geheyan reservoir's combined guide curves are entirely different from the Shuibuya reservoir's guide curves. This is due to recapturing the Shuibuya reservoir's release by the Geheyan reservoir, and raising of its water level. The area of the lower capacity zone of Shuibuya reservoir increases during the flood season. This is resulted from the use of SEI for better storage distribution among cascade reservoirs and increases the flood water resources utilization.

4. Simulation results and discussion

Using ten-day interval inflow records of Qingjiang cascade reservoirs from 1951-2005, a simulation was carried out with the proposed combined reservoir operation model. Parallel simulations were also done with the conventional and Lund (2000) analytical solution methods for the same data set for comparison purposes. The simulation results are summarized in Table 4.

Table 4 Simulation results of conventional operatin chart, Lund J.R. analytical method and combined operation model

Parameter	**Comparing parameter**	**Individual reservoir**			**Total**
		Shuibuya	**Geheyan**	**Gaobazhou**	
Annual electricity generation (GWh)	Conventional operation chart	3,525	2,903	835	7,263
	Lund J.R. analytical method	3,253	3,148	926	7,327
	Combined operation model	3,551	3,049	864	7,464
Annual spillage (Mm³)	Conventional operation chart	355	815	1,568	2,738
	Lund J.R. analytical method	123	206	2,014	2,343
	Combined operation method	195	475	1,001	1,671

Comparing to the original design, the Shuibuya and Geheyan hydropower plants can generate additional 26 and 146 GWh annually when using combined reservoir operation model, respectively. The whole cascade power generation increment is 201 GWh and it is a 2.77% improvement over the original design. Besides, combined reservoir operation model is capable to store 160 Mm^3 and 340 Mm^3 flood water resources annually in the Shuibuya and Geheyan reservoirs, respectively. The total reduction of spill release is 1067 Mm^3 per year and it is a 38.96% reduction to the original design. Comparing with the Lund (2000) analytical solution method, proposed combined reservoir operation model shows better power generation and flood water resources utilization results in cascade reservoirs operation. Figures 6 and 7 show the annual mean, highest and lowest water levels of two reservoirs from original design and combined reservoir operation methods for long period simulation. It is obvious that the Geheyan reservoir water levels maintain at higher elevation by the combined reservoir operation model and also lowest water levels of both reservoirs have been prominently raised during the flood season.

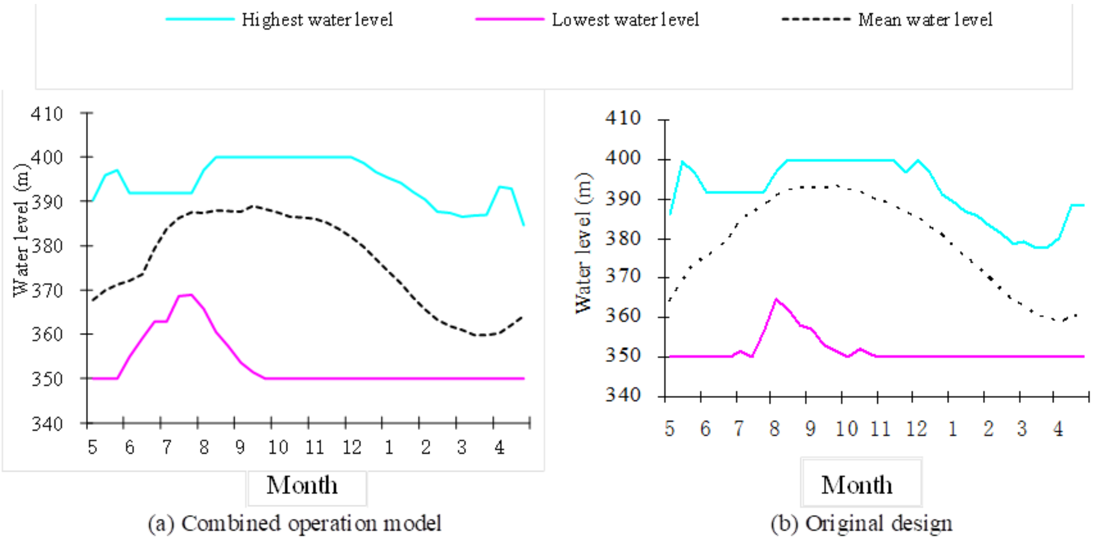
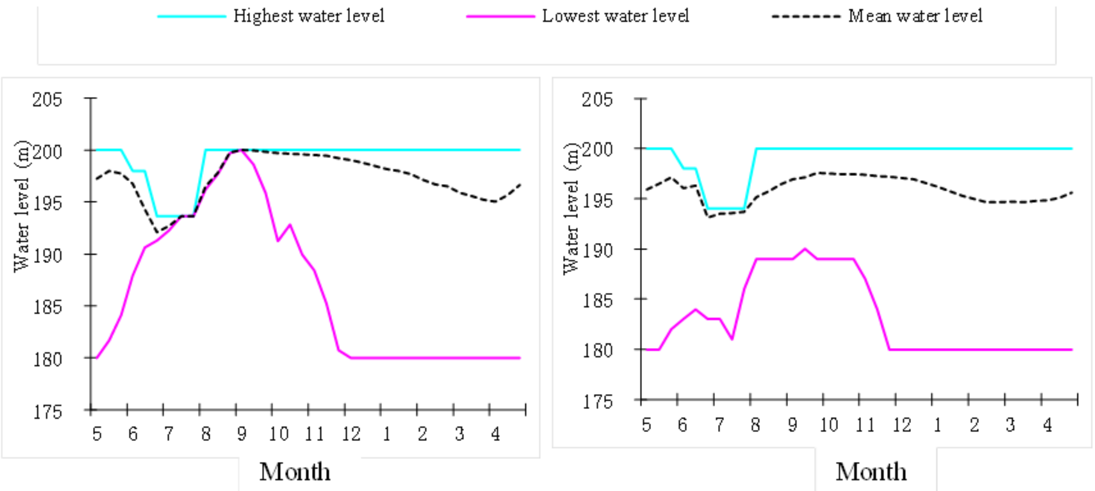


Figure 6 Annual operational water levels of the Shuibuya reservoir.



(a) Combined operation model

(b) Original design

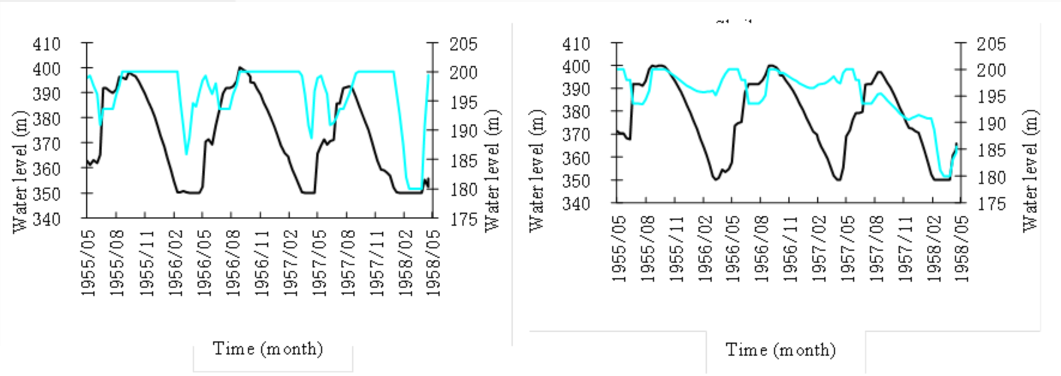
Figure 7 Annual operational water levels of the Geheyan reservoir.

The year 1955 was a wet year and following two hydrological years were dry for Qingjiang basin. Therefore these three years represent different characteristic release patterns and is suitable for short term analysis. Similar to long period simulation, ten-day interval inflow data series from May 1955 to May 1958 were analyzed and summarized in Table 5.

Table 5 Simulation results of conventiaonl opeartion chart, Lund J.R. analytical method and combined reservoir operation model during May, 1955 to May, 1958.

Parameter	**Comparing parameter**	**Individual reservoir**			**Total**
		Shuibuya	**Geheyan**	**Gaobazhou**	
Annual electricity generation (GWh)	Conventional operation chart	3,297	2,816	804	6,917
	Lund J.R. analytical method	3,180	2,925	853	6,958
	Combined operation model	3,341	2,871	814	7,026
Annual spillage (Mm^3)	Conventional operation chart	153	557	1,239	1,950
	Lund J.R. analytical method	65	105	2,174	2,344
	Combined operation model	119	369	880	1,368

Results are equivalent with the long period analysis. The water levels of the Shuibuya and Geheyan reservoirs both for combined reservoir operation model and conventional operation method are plotted in Figure 8. The Shuibuya reservoir water level shows annual cyclic modulation phenomenon clearly when using the combined reservoir operation model.



(a) Combined operation model

(b) Original design

Figure 8 Water levels of the Shuibuya and Geheyan reservoirs during May1955~May1958.

Furthermore, the combined reservoir operation model can raise the Geheyan reservoir water level in a varying degree. During the flood season, both reservoirs increase their generation capacity before the onset of flood season, make more space for oncoming flood water and reduce the spillage. After the flood season, combined reservoir operation model clearly modulates the Shuibuya reservoir water level and maintains higher water level of the Geheyan reservoir to enhance the power generation capacity. The original design conventional operation plans do not realize storage distribution among cascade reservoirs, and cannot use both reservoirs' water storage space efficiently. Therefore, the flood water resources utilization efficiency is less than the combined reservoir operation model.

Although the proposed model yields better results in hydropower generation and flood water resources utilization, it has several limitations and constraints in practical application. The proposed model can only be used for cascade reservoirs operation and unsuitable for parallel reservoirs or reservoir systems. The cascade reservoirs should have close hydrologic and hydraulic relationships and should be operated by the same institute.

5. Conclusion

A novel combined reservoir operation model is proposed based on combined guide curves for optimizing hydropower production and for better storage distribution among cascade reservoirs. The model is applied to the Qingjiang River cascade reservoir system and optimized combined reservoir operation chart is obtained for Shuibuya-Geheyan reservoirs. The combined reservoir operation model can modulate Shuibuya reservoir water level and effectively increase the Geheyan reservoir hydropower head for enhancing power generation capacity. By satisfying the Qingjiang cascade's guaranteed output rate, the model is able to produce 7464 GWh with additional 201 GWh (a 2.77% increment), annually. The annual spill release reduction is 1067 Mm^3 (a 38.96% reduction). Therefore, it can be concluded that the proposed combined reservoir operation model can enhance power production and improve the flood water resources utilization of cascade reservoirs. The method is simple and practical, convenient in operation, has higher reliability, and has application and further researching value.

Compliance with ethical standards

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Disclosure of conflict of interest

The author declares no conflicts of interest regarding the publication of this paper.

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