Joint Operation and Dynamic Control of Flood Limiting Water Levels for Cascade Reservoirs

Jionghong Chen · Shenglian Guo · Yu Li · Pan Liu · Yanlai Zhou

Abstract Reservoirs are among the most effective tools for integrated water resources development and management. The dynamic control of reservoir flood limiting water level (FLWL) is a valuable and effective method to compromise the flood control and conservation for reservoir operation during the flood season. This paper focuses on joint operation and dynamic control of FLWL for cascade reservoirs. A composition and decomposition-based model that consists of an aggregation module, a storage decomposition module and a simulation operation module was developed. The model was applied to the Qingjiang basin in south of China using the 3-hour inflow data series for representative hydrological years. Application results indicate that the proposed model can make an effective tradeoff between the flood control and hydropower generation. Joint operation and dynamic control of FLWL can increase power production by 4.51 % (1.79×10^8 kWh) and increase water use rate by 2.73 %. It can enhance benefits of the Qingjiang cascade reservoirs without compromising flood prevention objectives.

Keywords Cascade reservoirs · Joint operation · Flood limiting water level · Dynamic control · Flood prevention · Hydropower generation · Qingjiang basin

1 Introduction

Water is becoming more and more important as a result of the growing demand for various purposes such as water supply, irrigation, navigation, hydropower generation, etc. Human beings are affected by too much or too little water compared to requirements. As the scarcity of water is a grave concern for management, so also is its excess as floods (Kumar and Baliarsingh 2009). Reservoirs are one of the most efficient measures to address both

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situations for integrated water resources management (Guo et al. 2004). A reservoir operation policy should specify releases from reservoir storage at any time as a function of the current reservoir water level, the hydro-meteorological conditions, the magnitude of current, near-term and long-term demands and the time of the year, and these different purposes cause conflicts and disputes related to the water storage and release (Xu et al. 1997; Ngo et al. 2007).

According to the World Commission on Dams (WCD 2000), many large storage projects worldwide are failing to produce the level of benefits that provided the economic justification for their development. This may be due in some instances to an inordinate focus on project design and construction, with inadequate consideration of the more plain operations and maintenance issues once the project is completed. Performances related to original project purposes may also be undermined when new unplanned uses arise that were not originally considered in the project authorization and development (Labadie 2004). Meanwhile, with the fast development of social economy, the operation conditions of reservoirs may change in comparison with those prevailing in the planning and designing stages.

The flood limiting water level (FLWL) is the most significant parameter in assessing the tradeoff between flood control and conservation (Liu et al. 2008; Yun and Singh 2008). The FLWL is determined using the annual design storm or annual design flood (whose design frequency or return period is chosen according to the importance of the reservoir) through reservoir regulation, and has fixed values during the flood season. According to the Chinese Flood Control Act, the pool level of reservoirs in China, should be kept below the FLWL during the flood season to provide enough storage for flood protection. After the inflow hydrograph reaches its peak and begins to recede, the reservoir water level must be drawn down to the FLWL as soon as possible to make storage available for the next flood event. The currently designed approach is called static control of FLWL (SC-FLWL). The advantage of SC-FLWL is simplicity, but it neglects variation during the flood season and wastes water resources, which often results in the reservoir being unable to refill to the normal water level by the end of the year.

With advancements in meteorological and hydrological forecasting capabilities, it is desirable to improve the operational efficiency of existing reservoirs to maximize benefits (Li et al. 2010). For seasonally flooded river basins, the flood season can be divided into several sub-seasons. Seasonally variable flood storage allocation is advocated by the US Army Corp of Engineers (USACE 1998). The seasonal flood control limit water levels can be adapted to obtain more economic benefits without reducing flood prevention standards. Liu et al. (2008) developed a simulation-based optimal seasonal FLWL model to simultaneously maximize benefits under the condition that the seasonal FLWL risk was less than that of an annually designed one. Yun and Singh (2008) suggested two approaches to increase water storage of a reservoir, while maintaining its security for flood control. One is a multiple duration limiting water level, which employs a multiple duration design storm, rather than the traditional annual FLWL. The other is dynamic control of FLWL (DC-FLWL), whereby the water level can fluctuate within dynamic control bounds.

To avoid two types of phenomenon, which are "FLWL is too low due to enhance flood prevention capacity" and "FLWL is too high due to increase conservation benefits", a reasonable bound of DC-FLWL must be estimated, which is a key element for implementing reservoir FLWL dynamic control operation. Li et al. (2010) presented a dynamic control operation model that considers inflow uncertainty

consisting of three modules: a pre-release module to estimate the upper dynamic control bound based on inflow forecasting results, a refill module to retain recession floods, and a risk analysis module to assess flood control risk. The model was applied to the Three Gorges reservoir and results showed that the dynamic control of reservoir FLWL can effectively increase hydropower generation and the floodwater utilization rate without increasing flood control risk.

Previous research on DC-FLWL has been for single reservoirs. However, rivers typically have many reservoirs in series and the ideal of integrating water resources management for a basin has been accepted by many countries. Yeh (1985) and Labadie (2004) provided state-of-the art reviews of multi-reservoir systems operation. Reservoirs have to be best operated to achieve maximum benefits from them. For many years rule curves, which define ideal reservoir storage levels for each season or month, have been an essential operational tool. Reservoir operators are expected to maintain these pre-fixed water levels as closely as possible while generally trying to satisfy various downstream water demands. If the water level of a reservoir is above the target or desired level, then release rates are increased. Conversely, if the water level is below the target, then release rates are decreased. During the flood season, the reservoir water level fluctuates within a dynamic control bound. For a single reservoir, the higher the pre-fixed water level is, the more hydropower will be generated. Since there are a hydraulic connection and storage compensation between the upstream and downstream reservoirs, the DC-FLWL problem is complicated for cascade reservoirs. With the number of reservoirs (dimension) increasing, the DC-FLWL problem will become more and more complex in practice.

In this study, a simulation-based optimization model of DC-FLWL for cascade reservoirs has been established to maximize hydropower generation without affecting flood prevention standards. The Qingjiang cascade reservoirs in the south of China were selected as a case study.

2 Methodology

To solve high-dimensional optimization problems, the cascade reservoirs could be considered as an "aggregated reservoir" using large-scale system decomposition and coordination. The aim of aggregation is to develop auxiliary models, which are reduced in complexity and provide good approximations of the original problem. In most applications, multiple-reservoir systems are aggregated into a single reservoir, with subsequent optimization carried out for this simplified composite representation of the system. It is quite common for aggregation methods to be used in combination with some decomposition principles to alleviate computational difficulties encountered in complex reservoir system operation optimization (Turgeon 1981; Archibald et al. 1997).

Various decomposition approaches seem to be the most frequent means to alleviate dimensionality problems in operational analysis of large-scale systems. Yeh (1985) observed that the majority of methods devised for dimensionality reduction involved some type of decomposition of the system into smaller and simpler subsystems, and subsequent use of iterative procedures to find a solution to the complex problem. The advantage of decomposition is that it allows a large, unsolvable problem to be reduced to a series of small tractable tasks (Nandalal and Bogardi 2007). Decomposition approaches have been applied to cascade hydropower reservoirs, and

many studies (Archibald et al. 1997; Liu et al 2011) have shown that near-optimal solutions derived by decomposition techniques could provide significant improvements in operation of the systems.

The general framework of joint operation of the DC-FLWL model for cascade reservoirs is shown in Fig. 1. The proposed model consists of three modules: an aggregation module, a storage decomposition module and a simulation operation module. The aggregation module is used to estimate the maximum available flood prevention storage of the "aggregated reservoir" in the cascade reservoir system. The storage decomposition module is used to find the flood prevention storage relationship between upstream and downstream reservoirs and allocate the maximum available flood prevention storage into individual reservoir units. The simulation operation module is used to find and update the optimal storage allocation strategy in order to maximize the benefits of cascade reservoirs based on operation rules.

The configuration of the cascade reservoirs is illustrated in Fig. 2, where A and B represent the upstream and downstream reservoirs; Q_A and Q_B are the inflows of reservoir A and B, respectively; F1 and F2 represent the flood control objectives downstream of reservoir A and B; and $Q_{max,A}$ and $Q_{max,B}$ are the maximum allowed outflow of reservoir A and B, respectively.

2.1 Aggregation Module

Flood control operations for one flood hydrograph can be divided into three stages, namely pre-release operation at rising flood stage, normal flood control operation at large flood stages, which is conducted by current operation rules, and pre-fill operation at recession flood stages. The reservoir water level must be lowered to the currently designed FLWL in effective lead-time before the next large inflow occurs; the upper boundary of the dynamic control bound is tightly related to the reservoir's release capacity. The pre-release operation uses effective lead-time inflow forecasting and the safety discharge of downstream flood protection section to

Fig. 1 Flow chart of joint operation of the DC-FLWL model for cascade reservoirs
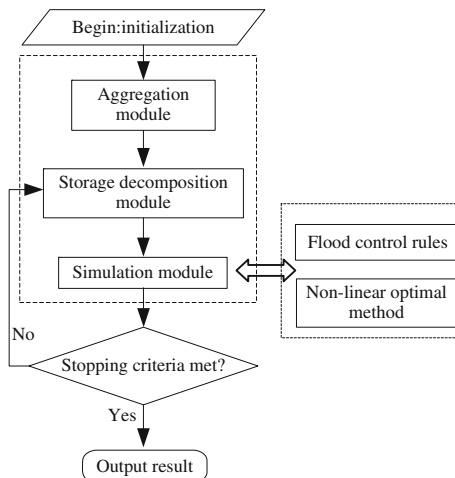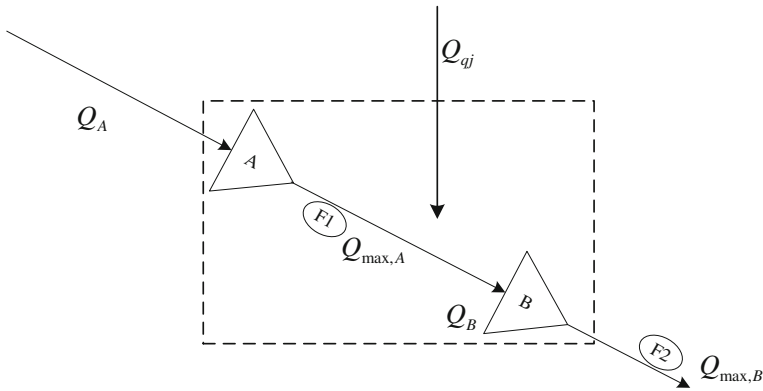
Fig. 2 Sketch of a cascade reservoirs

estimate the upper boundary of the dynamic control bound during the planning and designing stage.

The aggregation module is used to adjust the FLWL from the water level Z at the planning and design stage to water level Z′ by pre-release operation. If the forecasting results show that there will be a large flood event, then the reservoirs can pre-release to provide enough flood storage space. The capacity-constrained pre-release operation uses effective lead-time of inflow forecasting and the safety discharge of the downstream flood protection section to estimate the upper bound of DC-FLWL. The maximum allowed FLWL Z′(t) is

$$f\left(Z'(t)\right) = f(Z(t)) + \int^{T_y} Q_{out}(t)dt - \int^{T_y} Q_{in}(t)dt \qquad (1)$$

where $Q_{in}(t)$ and $Q_{out}(t)$ are the inflow and outflow of "aggregated reservoir" respectively, T_y is the effective lead-time of inflow forecasting, and $f(*)$ is the relationship between reservoir water level and storage.

The maximum available flood prevention storage $V_{yx}(t)$ of "aggregated reservoir" at the current time t is then

$$\max \quad V_{yx}(t) = f\left(Z'(t)\right) - f(Z(t)) \qquad (2)$$

2.2 Storage Decomposition Module

Based on the principle of decomposition techniques and a subsequent iterative determination of individual reservoir operation policies, the storage decomposition module is used to allocate the available flood prevention storage into each individual reservoir.

The maximum available flood prevention storage is determined by the current reservoir storage, flood control objectives and forecast information. The relationship of DC-FLWL for cascade reservoirs is established without affecting flood prevention standards, and the bound of DC-FLWL is satisfied with the reservoir flood control constraints.

As there is a hydraulic connection between the upstream and downstream reservoirs, the maximum available flood space of a reservoir is affected by the current storage capacity of the other reservoirs. Therefore, there is a mutual restrained relationship between the upstream and downstream reservoirs. This module can estimate the maximum allowable FLWL of reservoirs in period t, according to their spatial relationship and flood control constraints, i.e.

$$\max Z'_A(t) \quad \max Z'_B(t) \tag{3}$$

where $Z'_A(t)$ is the allowable FLWL of reservoir A in period t, $Z'_B(t)$ is the allowed FLWL of reservoir B in period t.

The relationship between reservoir A and B is given by

$$\text{Reservoir } A : \int^{T_y} Q_{out,A}(t)dt - \int^{T_y} Q_A(t)dt = f_A\left(Z'_A(t)\right) - f_A(Z_A(t)) \tag{4}$$

$$\text{Reservoir } B : \int^{T_y} Q_{out,B}(t)dt - \int^{T_y} Q_B(t)dt = f_B\left(Z'_B(t)\right) - f_B(Z_B(t)) \tag{5}$$

The hydraulic connection between upstream reservoir A and downstream reservoir B can be described by the Muskingum method (Al-Humoud and Esen 2006), i.e.

$$Q_B(t) = C_0 Q_{out,A}(t) + C_1 Q_{out,A}(t-1) + C_2 Q_B(t-1) + Q_{qj}(t) \tag{6}$$

in which the outflows of reservoir A and reservoir B should satisfy flood control constraints, i.e.

$$Q_{out,A}(t) \leq Q_{max,A} \tag{7}$$

$$Q_{out,B}(t) \leq Q_{max,B} \tag{8}$$

where $Z_A(t)$ and $Z_B(t)$, $Q_A(t)$ and $Q_B(t)$, $Q_{out,A}(t)$ and $Q_{out,B}(t)$ are the FLWLs, the inflows and the outflows of reservoirs A and B in period t, respectively; $Q_{qj}(t)$ is the basin inflow between reservoir A and reservoir B; $Q_{max,A}$ and $Q_{max,B}$ are the maximum flow through flood control point F1 at the downstream reservoir A and the maximum flow through flood control point F2 at the downstream reservoir B; and C_0, C_1, and C_2 are the coefficients of the Muskingum equation.

The relationship of reservoir DC-FLWL pre-storage between the upstream reservoir A and downstream reservoir B can be solved from downstream reservoir B to upstream reservoir A. The reverse successive estimation is used to solve this problem.

The probable inflow of reservoir B can be derived from the outflow constraint in the downstream control point F2 and the state storage of reservoir B. That is, from Eqs. (5) to (8), we have:

$$\int^{T_y} Q_{out,B}(t)dt - \int^{T_y} Q_B(t)dt = f_B\left(Z'_B\right) - f_B(Z_B) \leq \int^{T_y} Q_{max,B}dt - \int^{T_y} Q_B(t)dt$$

$$= Q_{max,B}T_y - \int^{T_y} Q_B(t)dt \tag{9}$$

Since intermediate variables $Q_{out,A}(t-1)$, $Q_B(t-1)$, and $Q_{qj}(t)$ in period t are known, the relationship between $Q_B(t)$ and $Q_{out,A}(t)$ can be expressed by

$$Q_B(t) = C_0 Q_{out,A}(t) + K(t) \tag{10}$$

where $K(t) = C_1 Q_{out,A}(t-1) + C_2 Q_B(t-1) + Q_{qj}(t)$. Equation (9) can be rewritten as

$$f_B\left(Z_B'\right) - f_B(Z_B) \le Q_{\max,B} T_y - \int^{T_y} \left(C_0 Q_{out,A}(t) + K(t)\right) dt \tag{11}$$

The maximum allowed FLWL of reservoir A can be estimated based on inflow forecasting, allowed outflow and current storage, i.e.

$$\int^{T_y} Q_{out,A}(t) dt = \int^{T_y} Q_A(t) dt + f_A\left(Z_A'(t)\right) - f_A(Z_A(t)) \tag{12}$$

From Eqs. (11) and (12), we have

$$f_B\left(Z_B'\right) \le f_B(Z_B) + Q_{\max,B} T_y - C_0 \left(\int^{T_y} Q_A(t) dt + f_A\left(Z_A'\right) - f_A(Z_A)\right) - K(t) T_y \tag{13}$$

Equation (13) is the relationship of reservoir DC-FLWL pre-storage between upstream reservoir A and downstream reservoir B.

If the initial adjusted water level of upstream reservoir A is fixed, the maximum allowed FLWL of downstream reservoir B can also be estimated by the effective lead-time inflow forecasting, current storage and flood control constraints.

The allocation of available reservoir flood space is an inter-dependent and inter-restricted relationship. Figure 3 shows the optimal search interval of operation for DC-FLWL for cascade reservoirs, where the SC-FLWL is the lower bound and the allowed DC-FLWL is the upper bound.

2.3 Simulation Operation Module

The simulation operation module is used to determine the optimal reservoir storage strategies. The aim of joint operation for cascade reservoirs is to generate as much hydropower as possible.

Fig. 3 Diagram of optimal search interval of DC-FLWL for cascade reservoirs
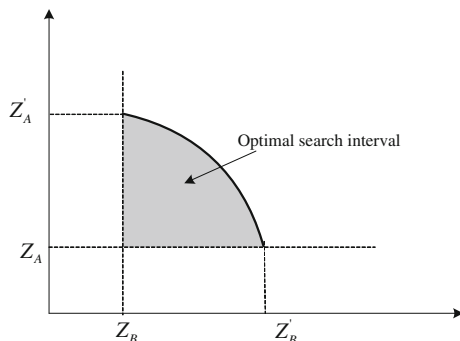
2.3.1 Objective Function

If the cascade reservoirs can meet the water supply and initial power generation requirements, then the objective function that generates maximum hydropower is selected, i.e.

$$Max \quad E = \sum_{t=1}^{T} \sum_{i=1}^{L} N_i(t) \cdot \Delta t, \quad N_i(t) = K_i Q_{o,i}(t) H_i(t) \tag{14}$$

2.3.2 Subject to the Following Constraints

(1) Water balance equation

$$V_i(t) = V_i(t-1) + \big(Q_{in,i}(t) - Q_{out,i}(t) - EP_i(t)\big) \cdot \Delta t \tag{15}$$

(2) Reservoir water level limits

$$ZL_i(t) \leq Z_i(t) \leq ZU_i(t) \tag{16}$$

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

$$QL_i(t) \leq Q_{out,i}(t) \leq QU_i(t) \tag{17}$$

(4) Power generation limits

$$PL_{i,t} \leq N_{i,t} \leq PU_{i,t} \tag{18}$$

where

E	The sum of the hydropower generation of the cascade reservoirs, kWh
T	The number of periods
L	The number of reservoirs in the multi-reservoir system
$N_i(t)$	Power output of the ith reservoir in period t, kW
K_i	The hydropower generation efficiency of the ith reservoir
$Q_{o,i}(t)$	The release discharge for power generation of the ith reservoir in period t; m³/s
$H_i(t)$	The average hydropower head of the ith reservoir in period t, m
$V_i(t)$	The reservoir storage in period t of the ith reservoir, m³
$Q_{in,i}(t)$	The reservoir inflow of period t of the ith reservoir, m³/s
$Q_{out,i}(t)$	The water discharge of period t of the ith reservoir, or the sum of $Q_{o,i}(t)$ and $Q_{w,i}(t)$, m³/s
$EP_i(t)$	The sum of evaporation and leakage of the tth period of the ith reservoir, m³/s
$QL_i(t)$	The minimum water discharge for all downstream uses, m³/s
$QU_i(t)$	The maximum water discharge for all downstream uses, m³/s
$Z_i(t)$	The reservoir water level of the ith reservoir, m
$ZL_i(t)$	The minimum water level of the ith reservoir, m
$ZU_i(t)$	The maximum water level of the ith reservoir, m
$PL_i(t)$	The minimum power limits of reservoir, kW
$PU_i(t)$	The maximum power limits of reservoir, kW

2.3.3 Optimization Algorithm

The simulation operation module uses a decomposition strategy to maximize the economic benefits of the reservoirs. First, a set of optimal strategies is sought by forecasting inflow and operation results of the design rules. With the forecasting information updated, the strategy is subsequently changed. Since the optimal allocation of DC-FLWL for cascade reservoirs is a multidimensional and multi-stage optimization problem, the progressive optimality algorithm (POA) (Turgeon 1981) was chosen to solve this problem.

The POA divides a multi-stage problem into several two-stage problems. It is run iteratively to solve the optimization of a two-stage problem, while the other stage variables remain fixed. After solving the problem at the stage below, the next two-stage problem is considered, with the optimal result of the previous stage problem used as the next initial condition. The algorithm continues its iterations until the difference between the current value of every state variable and the value at the last iteration is less than the specified precision limit. When this condition is reached, the resulting values represent the optimal path as they satisfy the principle of progressive optimality (Guo et al. 2011).

The penalty function was used to deal with the constrained optimization problem, and the gold dividing point combined dynamic reduced search corridor technique was used for multidimensional non-linear optimal search problem (Labadie 2004).

For clarity, we use the following terminology: k is the length of the time series; $I_1, I_2,\ldots,$ I_{k-1} is the inflow series of the reservoir; Z_1 is the initial water level, Z_{n+1} is the final water level; $B(V_{k-1}, V_k)$ is the benefit from the $(k-1)$th period to kth period; and V_k and V_{k-1} are the storages in the kth and $(k-1)$th period, respectively. The algorithm to be used iteratively solves the optimization of a two-stage problem, i.e.,

$$\text{Opt}(G) = \text{Opt}[B(V_{k-2}, V_{k-1}) + B(V_{k-1}, V_k)] + \sum_{j=1}^{k-2} B(V_j, V_{j+1}) + \sum_{j=k}^{n+1} B(V_j, V_{j+1}) \quad (19)$$

$$V_1 = V(Z_1) \quad (20)$$

$$V_{n+1} = V(Z_{n+1}) \quad (21)$$

The reservoir operation optimization procedure is illustrated in Fig. 4.

3 Case Study

The Qingjiang basin is located between the east longitudes $108°35' \sim 111°35'$ and the north latitudes $29°33' \sim 30°50'$ in the subtropical area. The Qingjiang is one of the main tributaries of Yangtze River, with a basin area of 17,600 km^2. The mean annual rainfall, runoff depth and annual runoff are approximately 1,460 mm, 876 mm and 423 m^3/s, respectively. The total length of the mainstream is 423 km, with a hydraulic drop of 1,430 m. The upstream Shuibuya and downstream Geheyan reservoirs are primarily operated for power generation and flood control (see Fig. 5). Reservoir characteristic parameters are listed in Table 1. Since the Qingjiang is a seasonal river, the flood season is divided into three sub-seasons: pre-flood (from 1st to 31th May), main flood (from 1st June to 31th July) and post-flood (from 1st August to 30th September) sub-seasons (Fang et al. 2007).
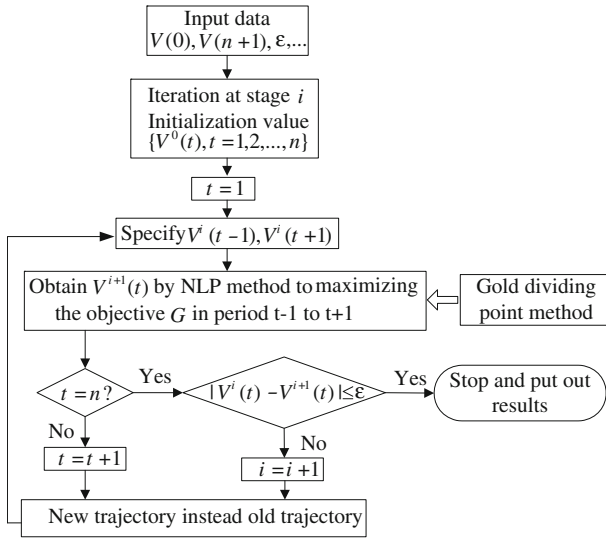
Fig. 4 Sketch of the progressive optimality algorithm (POA) to solve the reservoirs' optimal operation

The following formula is used to estimate the water resources utilization efficiency (η) for the cascade reservoirs, i.e.

$$\eta = 1 - \frac{\sum_{i=1}^{L} \sum_{t=1}^{T} Q_{s,i}(t) \cdot \Delta t}{\sum_{i=1}^{L} \sum_{t=1}^{T} Q_{in,i}(t) \cdot \Delta t} \tag{22}$$

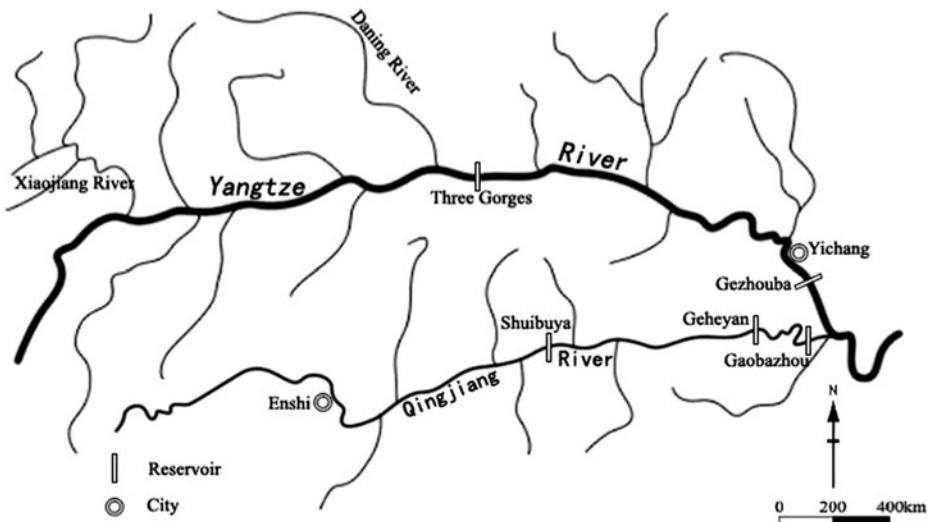where $Q_{s,i}(t) = Q_{out,i}(t) - Q_{o,i}(t)$ is spill at the beginning of period t of the ith reservoir.

Fig. 5 The location of Qingjiang cascade reservoirs

Table 1 Characteristic parameters of the Qingjiang cascade reservoirs

Reservoir	Normal water level (m)	Total storage ($10^8 \, m^3$)	Dead water level (m)	FLWL (m)			Install capability (MW)
				5.1–5.31	6.1–7.31	8.1–9.30	
Shuibuya	400	43.45	350	397.0	391.8	397.0	1600
Geheyan	200	31.20	160	200.0	192.2	200.0	1200

4 Results and Discussions

Three typical hydrologic years, i.e. wet (1983), normal (1987) and dry (1992) year were selected as case study. For simulation operation, 3-h runoff data series was used, from 2:00 on 1st May to 23:00 on 30th September. The initial water levels of the Shuibuya and Geheyan reservoirs are 395.0 m and 195.0 m respectively.

For a comparative study, joint operation based on both SC-FLWL and DC-FLWL for cascade reservoirs was performed. The results of hydropower generation (HG) and spilled water (SW) during the flood season estimated by these two operation modes are summarized in Table 2. Joint operation of DC-FLWL can generate 1.79×10^8 kWh (or an increase of 4.51 %) more hydropower than SC-FLWL during the flood season. Compared with SC-FLWL, DC-FLWL increases hydropower production by 2.27×10^8 kWh (4.85 %), 2.80×10^8 kWh (6.35 %) and 0.31×10^8 kWh (1.09 %) in the wet, normal and dry years considered, respectively. Spill decreases greatly, particular in the normal and dry years.

Results of water resource use rates during the flood season were also calculated and listed in Table 3. Water resource use rates using the DC-FLWL for cascade reservoirs increased by 1.77 %, 3.64 % and 3.72 % in the wet, normal and dry year, respectively, compared to SC-FLWL. On average, water resource use rates increased by 2.73 % during the flood season.

**Table 2** Comparison between SC-FLWL and DC-FLWL for cascade reservoirs

Reservoir		wet year		normal year		dry year	
		HG (10^8 kWh)	SW ($10^8 \, m^3$)	HG (10^8 kWh)	SW ($10^8 \, m^3$)	HG (10^8 kWh)	SW ($10^8 \, m^3$)
Shuibuya	SC-FLWL	27.33	35.89	25.05	8.54	14.70	0.96
	DC-FLWL	28.50	33.87	26.10	7.20	14.78	0.00
	Change	1.17	−2.02	1.05	−1.34	0.08	−0.96
	Rate	4.28 %	−5.63 %	4.19 %	−15.69 %	0.54 %	−100.00 %
Geheyan	SC-FLWL	19.51	63.86	19.06	15.21	13.65	2.31
	DC-FLWL	20.61	61.61	20.81	10.73	13.88	0.00
	Change	1.10	−2.25	1.75	−4.48	0.23	−2.31
	Rate	5.64 %	−3.52 %	9.18 %	−29.45 %	1.68 %	−100.00 %
Cascade	SC-FLWL	46.84	99.75	44.11	23.75	28.35	3.27
	DC-FLWL	49.11	95.48	46.91	17.93	28.66	0.00
	Change	2.27	−4.27	2.80	−5.82	0.31	−3.27
	Rate	4.85 %	−4.28 %	6.35 %	−24.51 %	1.09 %	−100.00 %

**Table 3** Comparison of water resource use rates for cascade reservoirs

FLWL	wet year	normal year	dry year	average
SC-FLWL	58.67 %	85.14 %	96.28 %	74.08 %
DC-FLWL	60.44 %	88.78 %	100.00 %	76.81 %
Change rate	1.77 %	3.64 %	3.72 %	2.73 %

The jointly operated water levels using DC-FLWL for cascade reservoirs in the wet, normal and dry years are shown in Figs. 6, 7 and 8, respectively.

In the wet year, the inflow of Qingjiang river is small before June 25, the DC-FLWL begins to pre-storage water and the allowed pre-storage capacity is allocated to the downstream Geheyan reservoir. The water level of the Geheyan reservoir is higher than that based on SC-FLWL as shown in Fig. 6. The reason is that this storage allocation strategy can generate more hydropower for cascade reservoirs without affecting originally designed flood prevention standards. When the inflow begins to increase after June 25, the reservoirs are operated based on the based on the SC-FLWL flood control rules, and water is discharged from the spillway to lower the water level to the FLWL. The reservoir can pre-release water by using forecasting information, thereby creating more flood space before next large flood.
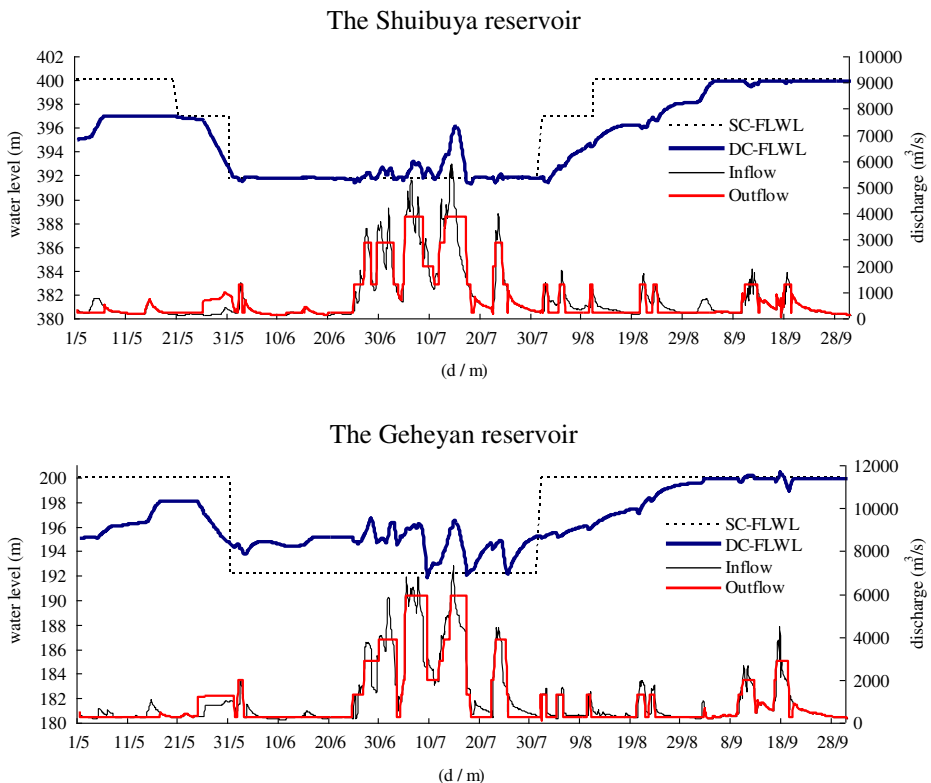
Fig. 6 Joint operation of DC-FLWL for cascade reservoirs (wet year)
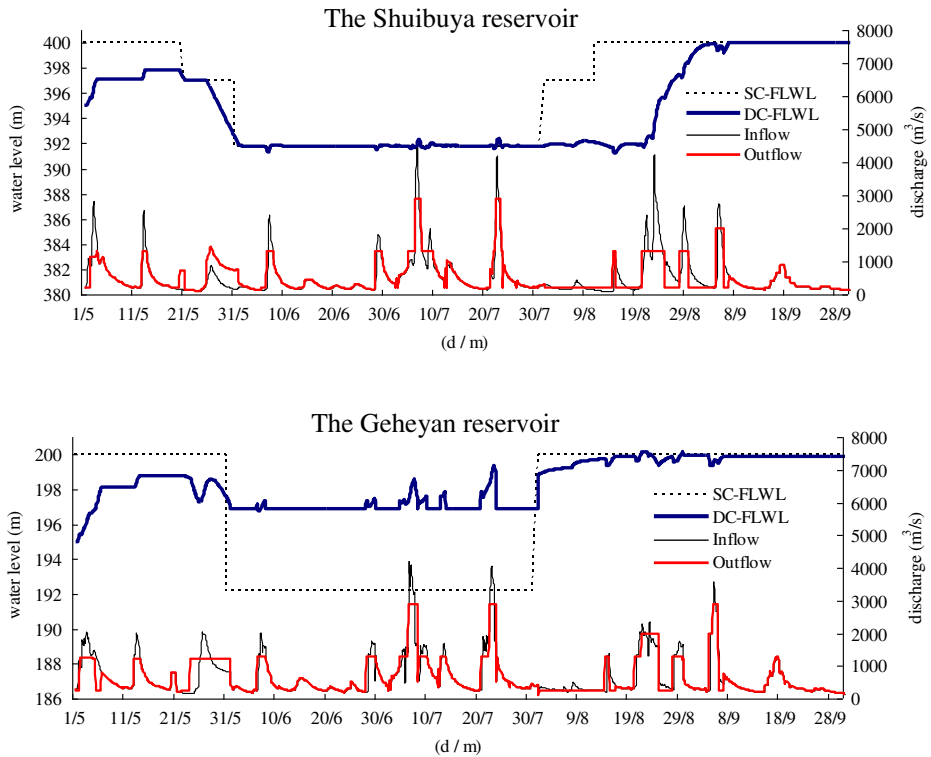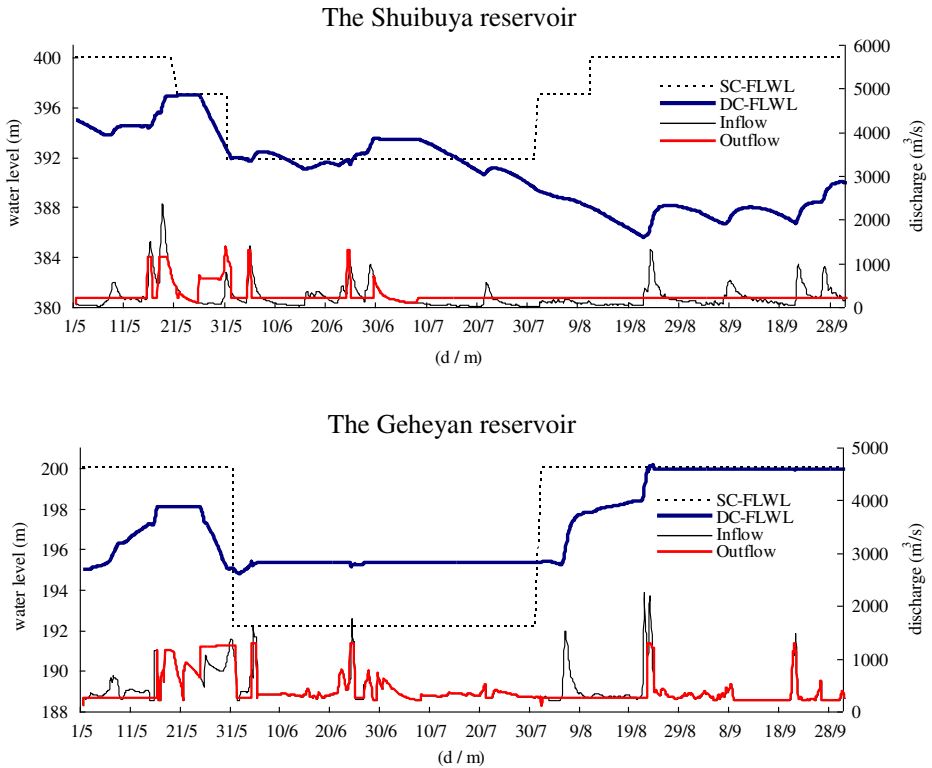
Fig. 7 Joint operation of DC-FLWL for cascade reservoirs (normal year)

When the reservoir receives the flood and the inflow exceeds the hydropower turbine flow capacity, the water level is raised to avoid spill. The reservoir is operated based on the forecasted inflow and the current state reservoir capacity.

In the normal year, only small and medium floods occur. With the upstream Shuibuya reservoir adjusted, the inflow to downstream Geheyan reservoir is relatively stable. As shown in Fig. 7, the water level of the Geheyan reservoir can be operated nearly at the upper bound by DC-FLWL during the main flood season, and the water level of the Shuibuya reservoir remains at the lower bound. Because the total amount of water stored in this system is limited, the aim of allocation of limited amount of storage between these reservoirs is to maximize hydropower production. This hydropower maximizing water storage allocation depends on reservoir capacities, inflow, efficiencies of energy production and the total amount of water to be stored. Since the storage capacity of Geheyan reservoir is less than that of Shuibuya reservoir, the water head of Geheyan reservoir increases more per unit volume of additional storage than that of the Shuibuya reservoir. As the downstream reservoir receives more direct and indirect inflows, the water level of Geheyan reservoir is kept at a high level to take advantage of power generation.

As shown in Table 3, when the runoff of Qingjiang basin is small during a dry year, the effect of joint operation of DC-FLWL for cascade reservoirs is unremarkable. However, the flood water resource use rate increases to 100 % with DC-FLWL, compared to 96 % with SC-FLWL. As shown in Fig. 8, the water level of Geheyan reservoir is kept high during the

The Shuibuya reservoir

The Geheyan reservoir

Fig. 8 Joint operation of DC-FLWL for cascade reservoirs (dry year)

flood season, whereas the water level of Shuibuya reservoir is kept lower, especially in the post-flood sub-season. This is because the reservoirs usually are operated with low water head to guarantee minimum power outputs.

5 Conclusions

A joint operation DC-FLWL model for cascade reservoirs was developed in this study. Hydropower was maximized using the progressive optimality algorithm. The Qingjiang cascade reservoirs were selected as a case study with results summarized as follows:

(1) Compared with current design operations based on SC-FLWL for cascade reservoirs, joint operation based on DC-FLWL can generate 1.79×10^8 kWh (4.51 %) more hydropower and increase water resource use rate by 2.73 % on average.
(2) The allowable pre-storage capacity allocated to the downstream reservoir is an optimal reservoir storage strategy during the flood season, which can generate more hydropower from cascade reservoirs without affecting original flood prevention standards.

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