A real-time dynamic flood prevention storage control model for Qingjiang cascade reservoirs

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Abstract By considering real-time flood forecasting and storage compensate capacity, a Real-time Dynamic Flood Prevention Storage Control Model (RDFPSCM) was proposed and developed for cascade reservoirs. The RDFPSCM consists of two components. The first component is a compensate operating module for obtaining the optimal operation processes of all the reservoirs with the suggested flood prevention storage constraints of the same iterative calculation; the second one is a flood storage module for calculating the allowable minimum flood storage of each reservoir according to the results of the other reservoirs calculated by the first module. The successive approximation approach is used to coordinate the differences between flood prevention storage constraints in the first module and allowable minimum flood prevention storage in the second module. The merits of the proposed methodology were demonstrated with an application to the Qingjiang cascade reservoirs in Hubei Province, China. The application results show that the RDFPSCM can obtain the optimal flood prevention storage operation rules and enhance the efficiency of reservoir system management and flood water resource utilization. Compared with the design rule, the proposed model can increase the water resources utilization from 92.09% to 94.80%, and generate an extra 1.99×10^8 kW·h hydropower (increase 2.74%) and save 9.29×10^8 m^3 flood water resources (increase 34.79%) annually, without decreasing the design flood prevention standards.

Key words cascade reservoir; compensate operation; decomposition and coordination; flood control; successive approximation

INTRODUCTION

The Qingjiang is the second largest tributary of the Yangtze River in Hubei Province, China, winding through southwest Hubei, from west to east, with a basin area of 16 700 km^2. The total length of the mainstream is 423 km, with a hydraulic drop of 1430 m. A three-step cascade reservoirs development scheme of the Qingjiang is Shuibuya–Geheyan–Gaobazhou from upstream to downstream. The development task is mainly for power generation, flood control and navigation, etc. According to the designed operating rules, the Shuibuya and Geheyan reservoirs not only provide 2.70×10^8 m^3 and 2.13×10^8 m^3 flood prevention storages, respectively, for Qingjiang basin, but also reserve 5×10^8 m^3 flood prevention storage each for flood protection in the downstream district of the Yangtze River basin. The Geheyan and Gaobazhou reservoirs have been built and operated for many years, while the Shuibuya reservoir is

Table 1 Characteristic parameters of the Qingjiang cascade reservoirs.

Reservoir	Normal water level (m)	Total storage ($10^8 m^3$)	Dead water level (m)	Permanent storage ($10^8 m^3$)	Flood prevention storage ($10^8 m^3$)	Install capability (MW)	Firm output (MW)	Regulate ability
Shuibuya	400	43.45	350	19.41	7.70	1600	310	multi-year
Geheyan	200	31.2	160	16.42	7.13	1200	241.5	annual
Gaobazhou	80	3.56	78	3.05	0	270	77.3	daily

still in construction and will be completed in 2007. The characteristic parameters of the Qingjiang cascade reservoirs are listed in Table 1.

In the application, a lot of flood water resources are wasted during the flood season because the Geheyan reservoir must reserve enough flood prevention storage. Once the Shuibuya reservoir starts to store water at the end of 2007, the water resources system in the Qingjiang basin will be changed and it will enhance the existing flood prevention capability downstream of the Qingjiang and Yangtze River basins. With the rapid development of the Chinese economy, the issue of water shortage is of great importance, and how to enhance the efficiency of reservoir system management is becoming more urgent than ever. According to the new idea of the Chinese government about flood water management and application, it is now transferring from flood water control to flood water management.

Various reservoir operation models based on optimization and simulation methods have been proposed and reviewed by many authors (Yeh, 1985; Simonovic, 1992; Guo *et al.*, 2004). From these works, optimization techniques have been discussed in detail to determine the best sequence of release. The simulation techniques have also been suggested to verify and analyse the performance of the reservoir under changing conditions. Recently, Labadie (2004) reviewed the optimal operation of the multi-reservoir systems, along with the application of new techniques, such as genetic algorithm, artificial neural network, and fuzzy theory. In this paper we attempt to develop a new methodology and operation policy for the changing situation of the Qingjiang cascade reservoirs. The objective of this study is to seek the optimum flood prevention storage operation rule for the cascade reservoirs, with maximum social and economic benefits.

THE PROPOSED MODEL

The aim of dynamic flood prevention storage control in cascade reservoirs is to obtain as many benefits as possible from flood water, without decreasing design flood prevention standards. By considering real-time flood forecasting and storage compensate capacity, a Real-time Dynamic Flood Prevention Storage Control Model (RDFPSCM) was proposed and developed for cascade reservoirs.

Model structure

A double coordination layer structure is used in this model to deal with the complex restrictions among the reservoirs, which are the flood storage limitations, hydraulic relations, etc. The RDFPSCM consists of two components. The first one is a compensating operating module for obtaining the optimal operation processes of all the reservoirs with the flood prevention storage constraints. In this module, the decomposition–coordination approach is adopted and the objective function is to maximize hydropower output based on real-time flood forecasting information and flood storage compensate capacity of the cascade reservoirs. The second one is a flood storage module for calculating the allowable minimum flood prevention storage for each reservoir according to the results of the first module. If the constraints of the reservoir's flood prevention storage between these two modules do not coincide, the suggested flood prevention storage constraints in the first module will be coordinated, and a new iteration will be continued until they coincide.

Compensate operating module

The aim of a compensate operating module for reservoirs in series is to obtain the optimal operation processes that satisfies all objectives and constraints based on the forecasting information. Many authors have examined the importance of forecasting information in real-time control of reservoir systems (Labadie *et al.,* 1981; Mishalani & Palmer, 1988; Georgakakos, 1989; Guo *et al.*, 2004). The compensate operating module can be described as:

$$\text{Maximize} \quad F = \gamma \sum_{t=1}^{T}\sum_{i=1}^{N} \eta_i H_{i,t} Q_{i,t} \Delta t \quad t = 1,2,\cdots,T \quad i = 1,2,\cdots,N \tag{1}$$

$$\text{s.t.} \quad V_{i,t+1} = V_{i,t} + (I_{i,t} - q_{i,t})\Delta t \tag{2}$$

$$I_{i+1,t} = q_{i,t} + IB_{i,t} \tag{3}$$

$$VF_{i,t}^{\min} \le VF_{i,t} \tag{4}$$

$$q_{i,\min} \le q_{i,t} \le q_{i,\max} \tag{5}$$

$$E_f \le \sum_{i=1}^{N} E_{i,t} \le \sum_{i=1}^{N} ET_{i,t} \tag{6}$$

where i is the index for reservoir number, N is the number of reservoirs in the cascade reservoir system; t is the index for the current period; T is the length of time series; F is the sum of energy produced by all reservoirs; H is the water head; Q is the release through the turbines of reservoir; η is the hydropower generation efficiency of reservoir; Δt is the time interval; γ is the unit weight of water; I is the total inflow; IB is the intermediate flow into reservoir; q is the spillway release; V is the reservoir storage volume; $VF^{\min}$ is the minimum flood prevention storage volume; VF is the actual flood prevention storage volume; $q_{\min}$ is the minimum release for other purposes, such as environment protection or safety of navigation; $q_{\max}$ is the maximum release subjected to the constraints of spillway structure; E_f is the firm output for reliability of power systems; E is the hydropower output; ET is the install capability.

Li *et al.* (1990) presented a new decomposition–coordination approach for solving the long-term optimal scheduling of interconnected multi-reservoir power systems with stochastic river inflows. Fawal *et al.* (1998) developed this algorithm for the optimal control of complex irrigation systems. Nishi *et al.* (2005) proposed a distributed route-planning method for multiple mobile robots using an augmented Lagrangian decomposition and coordination technique. Comparing with dynamic programme methods, the decomposition–coordination approach can avoid the cause of over dimensionality and has been widely used in multi-reservoir operation researches (Li *et al.*, 1990). Therefore, the decomposition coordination approach using the Lagrangian relaxation techniques is used to solve the above equations. In order to consider the electrical relationship among the hydropower plants, equation (7) is used as a correlative constraint:

$$X_{i,t} = \sum_{j=1}^{N} E_{j,t} \qquad j \neq i \tag{7}$$

where $X_{i,t}$ is the total hydropower energy produced in time t by all other reservoirs except reservoir i. Based on equations (6) and (7), the Lagrange equation can be obtained by importing the penalty factor of power generation:

$$L = \sum_{i=1}^{N}\sum_{t=1}^{T}[E_{i,t} - \omega(E_f - X_{i,t} - E_{i,t})] + \sum_{i=1}^{N}\sum_{t=1}^{T}\lambda_{i,t}(X_{i,t} - \sum_{\substack{j=1 \\ j\neq i}}^{n} E_{j,t}) \tag{8}$$

where ω is the penalty factor, $\lambda_{i,t}$ is the Lagrange-multiplier. If $E_f < X_{i,t} + E_{i,\,t}$, then $\omega >$ 0, otherwise, $\omega = 0$.

Flood storage module

The purpose of the flood storage module is to obtain the allowable minimum flood prevention storage for each reservoir by using the simulation method during the forecast period. The object function of flood storage module can be expressed as:

$$max \qquad VF_{i,t}^{'} = VF_{i,t} \qquad i = 1,2,\cdots,N \quad t = 1,2,\cdots,T \tag{9}$$

where VF' is the allowable minimum flood prevention storage. Besides equations (2) and (3), equation (9) is also subjected to constraint of:

$$\Delta t_f = t_{ff} - t_{fd} \tag{10}$$

where t_{ff} is the real-time flood forecast period, t_{fd} is the total time used for hydrological data acquisition and processing, calculation and decision making etc., Δt_f is the actual forecast period that can be used in the model calculation. The cascade reservoirs are divided into three parts, which are object reservoir, upstream and downstream reservoirs. In order to obtain the allowable minimum flood prevention storage of the object reservoir, the minimum average inflow is calculated by a simulation method from upstream to downstream reservoirs, while the maximum average outflow is obtained in reverse order. If reservoir i is suggested as the object reservoir, the minimum average release of upstream reservoir and the maximum average inflow of downstream reservoir can be calculated by the following equations:

Upstream reservoir, $$\overline{q_{j,t}^{\min}} = \overline{I_{j,t}} + (V_{j,t} - V_j^0)/\Delta t_f \qquad j \in (1, i-1) \tag{12}$$

Downstream reservoir, $$\overline{I_{j,t}^{\max}} = q_{j,t}^A - (V_{j,t} - V_j^0)/\Delta t_f \qquad j \in (i+1, N) \tag{13}$$

where $\overline{I_{j,t}^{\max}}$ and $\overline{q_{j,t}^{\min}}$ are the maximum average inflow and the minimum average release of reservoir j during time t, respectively; $q_{j,t}^A$ is the allowable maximum release of reservoir j, V_j^0 is the design flood prevention storage for reservoir j.

For the object reservoir i, the inflow includes $\overline{q_{j,t}^{\min}}$ of the upstream reservoirs and the release is a portion of $\overline{I_{j,t}^{\max}}$ in the downstream reservoirs. When $\overline{I_{j,t}^{\max}}$ and $\overline{q_{j,t}^{\min}}$ are calculated, the minimum average inflow and maximum average release of object reservoir i at time t can be obtained by equations (3), (11) and (12). The allowable minimum flood prevention storage of object reservoir ($VF_{i,t}^{'}$) is calculated by:

$$VF_{i,t}^{'} = V_i^N - [V_i^0 + \Delta t_f (\overline{q_{i,t}^{\max}} - \overline{I_{i,t}^{\min}})] \tag{14}$$

where V_i^N is the water storage corresponding to normal level of reservoir I, $\overline{I_{j,t}^{\min}}$ and $\overline{q_{j,t}^{\max}}$ are the minimum average inflow and the maximum average release of reservoir i during time t, respectively.

Coordinating method

It is important to coordinate the results of these two modules in the proposed RDFPSCM. The successive approximation approach is adopted and used to coordinate the differences between flood prevention storage constraints used in the first module and allowable minimum flood prevention storage obtained from the second module. Equation (15) is used to judge whether the iteration should be stopped or not.

$$\begin{cases} VF_{i,t}^{\min(k)} = [VF_{i,t}^{'\,(k-1)} + VF_{i,t}^{\min(k-1)}]/2 & \left|VF_{i,t}^{'\,(k-1)} - VF_{i,t}^{\min(k-1)}\right| > \varepsilon \\ VF_{i,t}^{\min(k)} = VF_{i,t}^{\min(k-1)} & \left|VF_{i,t}^{'\,(k-1)} - VF_{i,t}^{\min(k-1)}\right| \le \varepsilon \end{cases} \tag{15}$$

where k is the index of iterative, ε is the tolerance deviation.

RESULTS AND DISCUSSION

Ten-day runoff data during 1951–2005 of the Qingjiang cascade reservoirs are also used to compare the different operation rules. For the long-time series simulation, the beginning and ending time are 1 May 1951 and 30 April 2005, and the corresponding water levels of the Shuibuya and Geheyan reservoirs are 370.0 m and 190.0 m, respectively. The water level of Gaobazhou reservoir remains at 79.5 m all the time since it is a daily runoff hydropower plant. Table 2 shows the application results of the

Table 2 The results of the Qingjiang cascade based on different operation rules.

Reservoir	Items	E (10^8kW·h)	q (10^8 m^3)	η_f (%)
Shuibuya	Design rule	35.34	3.44	96.16%
	RDFPSCM	35.50	1.57	98.25%
	Increment	0.16	–1.87	0.02
	Increase rate	0.45%	–54.45%	2.17%
Geheyan	Design rule	28.99	7.96	93.29%
	RDFPSCM	30.55	4.78	95.96%
	Increment	1.56	–3.18	0.03
	Increase rate	5.39%	–39.93%	2.86%
Gaobazhou	Design rule	8.29	15.30	88.16%
	RDFPSCM	8.56	11.06	91.29%
	Increment	0.27	–4.24	0.03
	Increase rate	3.23%	–27.69%	3.54%
Qingjiang cascade	Design rule	72.62	26.70	92.09%
	RDFPSCM	74.61	17.41	94.80%
	Increment	1.99	–9.29	0.03
	Increase rate	2.74%	–34.79%	2.94%

design and RDFPSCM rules. It is obvious that the RDFPSCM can obtain the optimal dynamic flood prevention storage operating rules for cascade reservoirs and enhance the efficiency of reservoir management and flood water resource utilization. Compared with design rule, the proposed RDFPSCM can increase the water resources utilization from 92.09% to 94.80%, and generate an extra 1.99×10^8 kW·h hydropower (an increase of 2.74%) and save 9.29×10^8 m^3 flood water resources (an increase of 34.79%) annually without decreasing the design flood prevention standards.

CONCLUSIONS

Since the water resources system in the Qingjiang basin will be changed once the Shuibuya reservoir is completed in 2007, it is necessary to develop a new operation rule for these cascade reservoirs. A real-time dynamic flood prevention storage control model, named RDFPSCM, was proposed and developed by considering flood forecasting information and reservoir storage compensate capacity. The RDFPSCM can help to achieve the maximum utilization of flood water resources with the objective of reducing spill release as much as possible during reservoir operation. Application results show that the RDFPSCM can increase hydropower output and flood water resources utilization efficiency without decreasing the design flood prevention standards.

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