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Joint operation and dynamic control of flood limiting water levels for mixed cascade reservoir systems

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SUMMARY

Reservoirs are one of the most efficient infrastructures for integrated water resources development and management; and play a more and more important role in flood control and conservation. Dynamic control of the reservoir flood limiting water level (FLWL) is a valuable and effective approach to compromise the flood control, hydropower generation and comprehensive utilization of water resources of river basins during the flood season. The dynamic control models of FLWL for a single reservoir and cascade reservoirs have been extended for a mixed reservoir system in this paper. The proposed model consists of a dynamic control operation module for a single reservoir, a dynamic control operation module for cascade reservoirs, and a joint operation module for mixed cascade reservoir systems. The Three Gorges and Qingjiang cascade reservoirs in the Yangtze River basin of China are selected for a case study. Three-hour inflow data series for representative hydrological years are used to test the model. The results indicate that the proposed model can make an effective tradeoff between flood control and hydropower generation. Joint operation and dynamic control of FLWL can generate 26.4×10^8 kW h (3.47%) more hydropower for the mixed cascade reservoir systems and increase the water resource utilization rate by 3.72% for the Three Gorges reservoir and 2.42% for the Qingjiang cascade reservoirs without reducing originally designed flood prevention standards.

1. Introduction

With the rapid economic development, the role of reservoirs has become more and more important to meet society's energy and water requirements. Reservoirs are among the most efficient tools for integrated water resource development and management. By altering the spatial and temporal distribution of runoff, reservoirs serve many purposes, such as flood control, hydropower generation, navigation, recreation and ecology (Yeh, 1985; Labadie, 2004; Guo et al., 2004; Ahmed and Sarma, 2005; Eum et al., 2012; Ostadrahimi et al., 2012; Zhou and Guo, 2013; Lu et al., 2013). On the other hand, operation of large reservoirs has also impact on the downstream ecological and water system (e.g., Yang et al., 2012; Li et al., 2013; Urbaniak et al., 2013). In order to address the conflicts between flood control and conservation in China, a great number of research works and practices of the flood limiting water level (FLWL) has been carried out in recent years. The FLWL is an important parameter to trade-off conflicts between flood control and conservation (Cheng et al., 2008; Liu et al., 2008; Yun and Singh, 2008; Eum and Simonovic, 2010; Chen et al., 2013). The FLWL is determined by propagating the annual design storm or annual design flood through reservoir regulation; and has fixed values during the flood season. According to the Chinese Flood Control Act, the pool level of reservoir should be kept below the FLWL during the flood season to provide enough storage for flood prevention in China. 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 the FLWL (SC-FLWL). The advantage of SC-FLWL is its simplicity, but it neglects annual and seasonal variation of inflows 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 reservoir to maximize comprehensive

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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). Seasonal FLWLs 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 is 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 limited water level, which employs a multiple duration design storm, rather than the traditional annual FLWL. The other is dynamic control of the FLWL (DC-FLWL), whereby the water level can fluctuate within dynamic control bounds.

To avoid two types of situations, which are "the FLWL is too low due to enhance flood prevention capacity" and "the 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 of the FLWL. The model was applied to the Three Gorges reservoir, and results show that the dynamic control of the reservoir FLWL could effectively increase hydropower generation and the floodwater utilization rate without increasing flood control risks. For a single reservoir, the higher the water level is, the more hydropower will be generated. The technique of DC-FLWL for a single reservoir is very different from that of DC-FLWL for cascade reservoirs. Chen et al. (2013) proposed a simulation-based optimization model of DC-FLWL that made an effective tradeoff between the flood control and hydropower generation for the Qingjiang River cascade reservoirs.

Since there are hydraulic connections and storage compensations between the upstream and downstream reservoirs in cascade reservoirs or between inter-basin reservoirs in mixed reservoir systems, the DC-FLWL will become more and more complex as the number of reservoirs is increased. In this study, joint operation and use of a dynamic control model of DC-FLWL for mixed cascade reservoir systems are proposed and developed to maximize hydropower generation without reducing flood prevention standards. The Three Gorges reservoir (TGR) and the Qingjiang cascade reservoirs in the Yangtze River basin of China are selected as a case study.

The paper is organized as follows: Section 2 introduces the study area briefly, after which the current operation rules of the investigated cascade reservoir systems are discussed. Section 3 addresses the method adopted in this study, which comprises three parts: introduction of a general framework for joint operation and use of a dynamic control model for mixed cascade reservoir systems by firstly, setup of dynamic control operation module for TGR (Section 3.1), and secondly, setup of a dynamic control operation module for the Qingjiang River cascade reservoirs (Section 3.2), as well as setup of a joint operation module for mixed cascade reservoir systems (Section 3.3). In Section 4 simulation results for the mixed cascade reservoir systems are presented and discussed. The conclusions are drawn in Section 5.

2. Three Gorges and Qingjiang cascade reservoirs

The Three Gorges cascade reservoirs (Three Gorges, Gezhouba) and Qingjiang cascade reservoirs (Shuibuya, Geheyan, Gaobazhou) as shown in Fig. 1 are selected as case study, which is a typical mixed cascade reservoir systems. Since the Gezhouba and Gaobazhou reservoirs are run-of-the-river hydropower plants with small regulation storages, joint operation and the dynamic control model are only applied to simulate the operation of the TGR, Shuibuya and Geheyan reservoirs.

The TGR is a vitally important and backbone project in the development and harnessing of the Yangtze River in China. The upstream of Yangtze River is intercepted by the TGR, with a length of the main course about 4.5×10^3 km and a drainage area of 1 million km^2. The TGR is the largest water conservancy project ever undertaken in the world, with a normal pool level at 175 m above mean sea level and a total reservoir storage capacity of 39.3 billion m^3, of which 22.15 billion m^3 is flood control storage and 16.5 billion m^3 is a conservation regulating storage, accounting for approximately 3.7% of the dam site mean annual runoff of 451 billion m^3.

The Gezhouba reservoir is located at the lower end of the TGR in the suburbs of Yichang City, 38 km downstream of the TGR. The dam is 2606 m long and 53.8 m high, with a total storage capacity of 1.58 billion m^3 and a maximum flood discharging capability of 110,000 m^3/s.

The Qingjiang is one of the main tributaries of Yangtze River, and its basin area is 17,600 km^2. The mean annual rainfall, runoff depth and annual average discharge are approximately 1460 mm, 876 mm and 423 m^3/s, respectively. The total length of the mainstream is 423 km with a hydraulic drop of 1430 m. Along the Qingjiang, a three-step cascade of reservoirs has been constructed comprising from upstream to downstream Shuibuya, Geheyan and

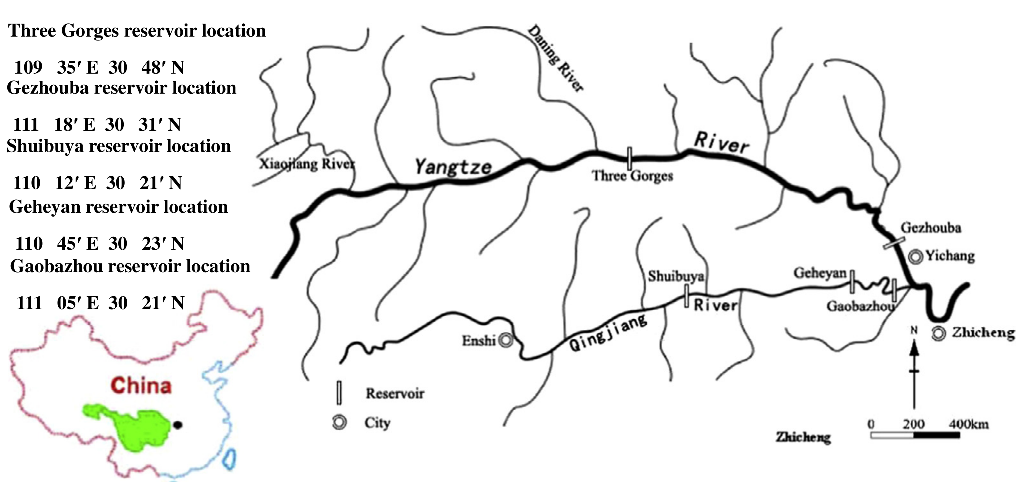

Fig. 1. The location of the Three Gorges and Qingjiang cascade reservoirs.