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Optimal design of seasonal flood limited water levels and its application for the Three Gorges Reservoir

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SUMMARY

Reservoirs perform both flood control and integrated water resources development, in which the flood limited water level (FLWL) is the most significant parameter of tradeoff between flood control and conservation. This study was aimed at developing the varied seasonal FLWL to obtain more economic benefits without decreasing the original flood prevention standards. The Copula function was used to build the joint distribution of seasonal floods, which clarified the relationship between the frequencies of the seasonal flood quantiles and those of the annual maximum. A constraint was then established to meet the requirement that the total flood risk of the seasonal FLWL should be less than that of the original FLWL. The seasonal FLWL can optimally be determined because numerous schemes of seasonal design floods are able to satisfy a given flood prevention standard. As a result, a simulation-based optimization model was proposed to maximize multiple benefits, such as flood control, hydropower generation and navigation. Using the case study of the China's Three Gorges Reservoir (TGR), the proposed method was demonstrated to provide an effective design for the seasonal FLWL, which decreases a slight FLWL for the main flood season to largely increase the FLWL of the pre-flood and post-flood seasons. The optimal designed seasonal FLWL scheme involves tradeoffs among flood control, hydropower generation and navigation, and enhancement of the economic benefits without increasing the flood risk.

1. Introduction

Reservoirs are one of the most efficient key infrastructure components in integrated water resources development and management (Guo et al., 2004; Loucks and van Beek, 2005). According to the World Commission on Dams (WCD, 2000), most large reservoir projects worldwide are failing to produce the level of benefits that provided the economic justification for their development. Currently, with the rapid development of social economy and water requirements, the water resources shortage problem has deteriorated, and the function of reservoirs, in terms of flood water utilization, has become increasingly important in China (Li et al., 2010; Zhou and Guo, 2014; Ouyang et al., 2015).

The reservoir flood limited water level (FLWL), which should not be kept high during the flood season to offer adequate storage for flood prevention according to the Chinese Flood Control Act, is the most significant parameter of tradeoff between the activities of flood control and conservation (Liu et al., 2008; Yun and Singh, 2008; Li et al., 2010). The conventional FLWL is determined by the reservoir routing of the annual design flood hydrographs. However, the designed flood, based on the annual maximum sample, neglects flood seasonality, and hence, the conventional FLWL is often a fixed value during the entire flood season. Due to the flood seasonality, varied seasonal FLWL are able to obtain more economic benefits without decreasing the original flood prevention standard. For example, in China (MWR, 2006; Zhou and Guo, 2014), the United States (USACE, 1998) and Vietnam (Ngo et al., 2007), such measurements have been implemented for the improvement of floodwater utilization.

The existing method to determine the seasonal FLWL is flood routing the seasonal design flood hydrographs using the predetermined reservoir operating rules (MWR, 2006). After the entire flood season is divided into two or three sub-seasons (Liu et al., 2010), the seasonal FLWL is determined as follows: (1) estimate the seasonal design flood and hydrograph based on the seasonal

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maximum flood samples, and (2) determine the seasonal FLWL based on the seasonal design flood hydrograph, i.e., routing the flood by setting it as the initial water level under the condition that the flood prevention risks are not increased. This approach can be conducted through a trial and error method. However, the conventional method often sets all seasonal flood frequencies to $1/T$ when the original flood prevention standard is a return period of T because of the unclear relationship between the seasonal and annual floods. Indeed, it is a challenge to evaluate the flood risk of the designed seasonal FLWL (Singh et al., 2005).

The conventional seasonal flood frequency analysis methods, which address the seasonal floods as univariate distributions and neglect their corrections, fail to provide a complete description of hydrologic events (Baratti et al., 2012). Thus, the seasonal design of floods should consider both the marginal distribution and their corrections, which can be depicted via a multivariate joint distribution. The Copula function, a promising mathematical tool for investigating multivariate problems, has been applied in hydrologic analysis (e.g., Xiong et al., 2014). The advantages of the Copula function for the model joint distributions are numerous: (1) flexibility in choosing an arbitrary marginal distribution and the structure of dependence, (2) extension to more than two variables, and (3) separate analysis of the marginal distribution and the structure of dependence (Durrans et al., 2003; Chen et al., 2010; Li et al., 2013). Based on this logic, the relationship between the frequencies of seasonal flood quantiles and the annual flood prevention standard can be clarified; as a result, the seasonal FLWL can be derived without increasing the flood risk.

Simulation and optimization are the most commonly used methods to derive the reservoir operating rules (Yeh, 1985; Labadie, 2004; Rani and Moreira, 2010; Liu et al., 2014; Zhu et al., 2014). Simulation-based optimization can be resolved by using the genetic algorithm (GA) because of its ability to perform global searching and its independence of the particular problem (Oliveira and Loucks, 1997; Cai et al., 2001; Koutsoyiannis and Economou, 2003; Chang et al., 2005; Liu et al., 2006, 2011; Herman et al., 2014; Li et al., 2014).

Compared with the previous researches (Yun and Singh, 2008; Liu et al., 2008; Li et al., 2010; Zhou and Guo, 2014), this study provide a novel method to optimal design the seasonal FLWL by considering the correlation among seasonal floods, with a simulation-based optimization model. The objectives of this study are: (1) to clarify the relationship between seasonal and annual floods, and (2) to design the seasonal FLWL via an optimization method. The remainder of this paper is organized as follows. In Section 2, we present the seasonal floods design model via a Copula method, which forms one of constraints for the simulation-based optimization model that is used to design the seasonal FLWL. Section 3 addresses a case study of China's Three Gorges Reservoir (TGR). Finally, conclusions are given in Section 4.

2. Methodology

The following steps are used to optimize the reservoir seasonal FLWL (Fig. 1).

(1) Based on the Copula function, a design flood module is established to produce the seasonal design floods and hydrographs, which are used to evaluate the flood risks by using reservoir routing (Section 2.1).
(2) Without increasing the above risks, a multi-objective criterion is used to evaluate the seasonal FLWL, and then, the Pareto solutions are found by using a simulation-based optimization (Section 2.2).

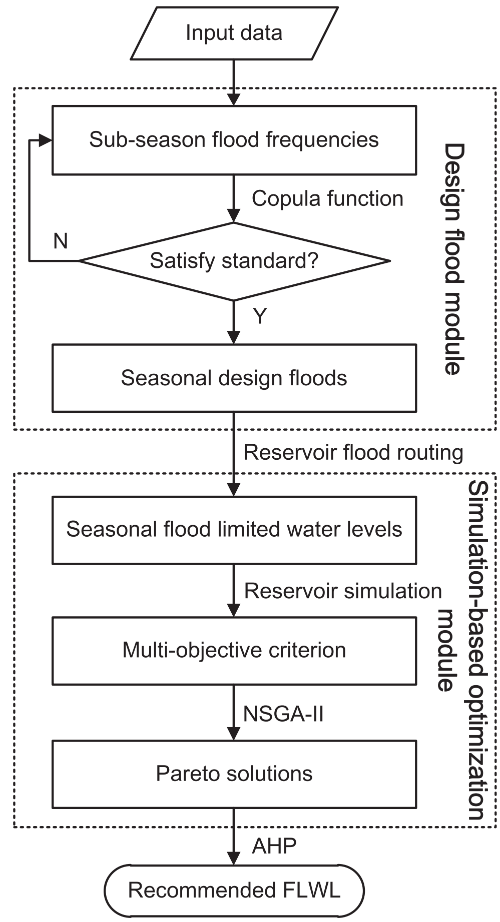

Fig. 1. Flowchart of the method for the optimal design of seasonal flood limited water levels for reservoirs.

2.1. Copula-based seasonal design floods

It is often assumed that various seasonal maximum floods are independent. However, different seasonal maximum floods have a slight correlation, rather than being significantly independent. The Copula function is an efficient way to construct a joint distribution of multiple variables, regardless of the marginal distribution functions (Durrans et al., 2003; Chen et al., 2010; Li et al., 2013). Consequently, the Copula function provides an effective method to express not only the independent variables but also their correlation for seasonal floods.

The Frank Copula function is used to describe the relationship among sub-season floods. Let the entire flood season be divided into three sub-seasons, namely, the pre-flood, main flood and post-flood seasons (Liu et al., 2010), the Copula function is built as follows:

$$C(u_1,u_2,u_3) = -\theta_1^{-1}\log\left\{1-(1-e^{-\theta_1})^{-1}\times(1-[1-(1-e^{-\theta_2})^{-1} \times(1-e^{-\theta_2 u_1})\times(1-e^{-\theta_2 u_2})]^{\theta_1/\theta_2})(1-e^{-\theta_1 u_3})\right\} \quad (1)$$

where θ_1 and θ_2 are the dependence parameters of the Frank Copula function and $\theta_2 \geqslant \theta_1, \theta_1, \theta_2 \in [0, +\infty)$ and u_1, u_2, u_3 represent the marginal distribution function. Note that the joint distribution could be established similarly when the entire flood season is divided into two sub-seasons.

The Copula joint seasonal distribution can be validated by using the annual maximum quantiles, x_0, as a special case, i.e.,