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Credibility theory based dynamic control bound optimization for reservoir flood limited water level

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SUMMARY

The dynamic control operation of reservoir flood limited water level (FLWL) can solve the contradictions between reservoir flood control and beneficial operation well, and it is an important measure to make sure the security of flood control and realize the flood utilization. The dynamic control bound of FLWL is a fundamental key element for implementing reservoir dynamic control operation. In order to optimize the dynamic control bound of FLWL by considering flood forecasting error, this paper took the forecasting error as a fuzzy variable, and described it with the emerging credibility theory in recent years. By combining the flood forecasting error quantitative model, a credibility-based fuzzy chance constrained model used to optimize the dynamic control bound was proposed in this paper, and fuzzy simulation technology was used to solve the model. The FENGTAN reservoir in China was selected as a case study, and the results show that, compared with the original operation water level, the initial operation water level (IOWL) of FENGTAN reservoir can be raised 4 m, 2 m and 5.5 m respectively in the three division stages of flood season, and without increasing flood control risk. In addition, the rationality and feasibility of the proposed forecasting error quantitative model and credibility-based dynamic control bound optimization model are verified by the calculation results of extreme risk theory.

1. Introduction

Reservoirs are one of the most efficient infrastructures for integrated water resources development and management (Jiang et al., 2014; Zhang et al., 2015). 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; Ahmed and Sarma, 2005; Eum et al., 2012; Ostadrahimi et al., 2012; Yang et al., 2012; Urbaniak et al., 2013). For flood control and conservation, FLWL is a very sensitive parameter, which is determined by the annual design floods and reservoir regulation in the planning and designing stage, and it usually has only one value for the whole flood season. Neglecting annual and seasonal variation of inflow, the application of only one FLWL for the whole flood season may give rise to two kinds of conflicted situations for the reservoir operation in flood season. One is "the FLWL is too low due to enhance flood prevention capacity", the other is "the FLWL is too high due to increase conservation benefits". In order to compromise this conflict between flood control and conservation during the flood season, dynamic control of reservoir FLWL is a valuable and effective approach. The dynamic control bound is a fundamental key element to implement reservoir dynamic control operation for FLWL (West, 1974; Li et al., 2012; Tang et al., 2014; Zhou et al., 2014; Zhou and Guo, 2014; Liu et al., 2015).

The lower limit of dynamic control bound is generally the fixed original FLWL, while the upper limit needs to be determined through a certain method, including the flood control forecast operation method, statistical method that considering the time-series variation law of flood, the improved drainage capacity constraint method, the capacity compensation method, and risk analysis method, etc. A great number of researches and practices about FLWL have been carried out in recent years (Cheng et al., 2008; Eum and Simonovic, 2010). Zhou et al. (2006) studied the combined flood control forecast operation manner and limited water level, and the research results show that the benefits can be enhanced and the risks aren't increased. Wu et al. (2006) suggested the reasonable schemes of limited water level for reservoirs by taking the quantitative influences of design flood uncertainty, flood forecast error and the lag of operation into account. Liu et al. (2008) developed a simulation-based optimal seasonal FCWL model to simultaneously maximize the benefits and minimize the

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flood risk for the Three Gorges Reservoir. Yun and Singh (2008) suggested two approaches which are multiple duration limited water level and dynamic limited water level to increase water storage of a reservoir, while maintaining its security for flood control. Cao et al. (2008) analyzed the utilization and benefit of excessive store flood water and determined the control range by using the marginal cost method. Zhou et al. (2009) established an evaluation index system on the optimization of dynamic flood control limited water level (DFCLWL) based on the analysis of factors influencing DFCLWL. Dong et al. (2010) carried out the reliability and risk analysis of a methodology of dynamically applying FLWL within a constraint boundary for the Three Gorges Reservoir based on the mid-term inflow forecasts. Chen et al. (2013) proposed a composition and decomposition-based model for the joint operation and dynamic control of FLWL to Qingjiang River cascade.

A variety of uncertainties need to be considered in implementing reservoir dynamic control operation for FLWL, in which the forecasting uncertainty is the primary risk source. Related researches about the random forecasting uncertainty have been carried out by some scholars. Such as Li et al. (2010) proposed a dynamic control operation model by considering the inflow forecasting error and uncertainty of the flood hydrograph shape, and Zhang et al. (2011a) studied the risk of dynamic control of reservoir FLWL within different flood forecasting error boundaries.

It is well known that there are two types of uncertainties: randomness and fuzziness. Randomness is usually related to statistical information and can be modeled using a probability distribution whereas fuzziness represents vagueness, which is derived from human incomplete knowledge with an imprecise description (Feng and Wu, 2008). However, to the best of the author's knowledge, nowadays, there is little research in modeling and solving the dynamic control bound of FLWL by considering fuzziness which is actually existed.

As we know, possibility is an important measure for a fuzzy event. However, possibility measure is not self-dual, yet the self-dual property is very important both in theory and in practice. A fuzzy event with maximum possibility value 1 can still fail to happen. In addition, sometimes a fuzzy event with maximum possibility value 1 carries no information to the decision maker (Huang, 2008a). As an alternative measure of a fuzzy event, credibility was proposed recently as a measure of confidence level in fuzzy environment to tackle uncertainties expressed as fuzzy sets (Liu and Liu, 2002). It was recognized as a competent measure of the confidence level regarding fuzzy constraints in optimization models (Rong and Lahdelma, 2008; Zhang et al., 2011, 2012). Credibility is self-dual, and when the credibility value of a fuzzy event achieves 1, the fuzzy event will surely happen (Huang, 2008b).

As far as we know, the credibility theory has not been applied in the research of reservoir dynamic control operation for FLWL. However, it has been successfully applied in many other engineering areas and optimization problems due to its simplicity and efficiency in reflecting the fuzziness inherited with parameters associated with subjective considerations, such as environmental standards and strategies (Luo et al., 2004; Zhang and Huang, 2010; Lu et al., 2011), integrated power system scheduling (Yan and Luh, 1997), dynamic economic dispatch (Attaviriyanupap et al., 2004), web mining of traversal patterns (Wu et al., 2005), and system reliability design (Zhao and Liu, 2005). Furthermore, Zhao and Liu (2004) presented three types of system performance by using random fuzzy lifetimes as basic parameters, and constructed a spectrum of random fuzzy models for redundancy optimization problems. Ji and Shao (2006) applied the credibility theory with multilevel programming to solve a newsboy problem with fuzzy demands and quantity discounts in hierarchical decision system. In particular, a lot of researches on credibility theory have been carried out by Huang, for example, in 2006, Huang (2006a, 2006b) presented two types of credibility-based portfolio selection model according to two types of chance criteria, and discussed a problem involving capital budgeting in a fuzzy environment by employing the spirit of credibility. In 2007, Huang (2007a, 2007b) studied the capital budgeting problem with fuzzy investment outlays and fuzzy annual net cash flows based on credibility measure, and proposed a practical tool of incorporating random fuzzy uncertainty into project selection. In addition to above, Huang (2007c) discussed portfolio selection problem in fuzzy environment based on credibility measure, and proposed two new fuzzy mean–variance models for portfolio selection with fuzzy returns. Further studies about credibility theory can be found in recent papers (Liu, 2002; Liu and Liu, 2003; Zhu and Liu, 2004) and in Liu's recent book (Liu, 2004, 2009).

Credibility measure is self-dual while possibility measure is not. When using credibility measure, fuzzy events with different occurring chances will have different credibility values. The fuzzy event with higher credibility value will have more chance to happen. Therefore, in this paper, we will adopt credibility theory instead of possibility to solve the dynamic control bound of FLWL in a fuzzy environment. In fact, there are a lot of the adoptions of credibility as the measure of a fuzzy event instead of possibility in academic papers (Chen et al., 2005; Fung et al., 2005; Zhao and Liu, 2003) nowadays.

The rest of the paper is organized as follows. Section 2 will briefly review some necessary knowledge about fuzzy variable and the concept of credibility. Section 3 will describe the models and its solving. After showing the quantification method of flood forecasting error by considering it as a fuzzy variable, a credibility-based fuzzy chance constrained model for the upper limit optimization of dynamic control bound will be provided, and its solving process by using fuzzy simulation technology will be presented. Section 4 will show the application of the established credibility-based model to the FENGTAN reservoir in central China, and the results will be presented. In Section 4.2, the results will be analyzed and discussed. Finally, Section 5 will present the conclusions.

2. Preliminaries (credibility and some fundamentals)

Fuzzy set theory was introduced by Zadeh (1965), and it has been well employed to solve a variety of practical problems since then. As a new mathematics branch in fundamental mathematics field, credibility theory provides theory foundation for the comprehensive evaluation of randomness and fuzziness. Fuzzy variable is a type of mathematical tool to describe fuzzy uncertainty. To better understand the new credibility theory for the following research, let us briefly review some necessary knowledge about credibility theory and fuzzy variable.

Let Θ be a nonempty set, and $P(\Theta)$ the power set of Θ. For any $A \in P(\Theta)$, a credibility measure $\mathrm{Cr}\{A\}$ was presented to express the chance that fuzzy event A occurs. The literature (Liu, 2006) proved that a set function $\mathrm{Cr}\{\}$ is a credibility measure if and only if

(1) $\mathrm{Cr}\{\Theta\} = 1$.
(2) Cr is increasing, i.e., $\mathrm{Cr}\{A\} \leqslant \mathrm{Cr}\{B\}$ whenever $A \subset B$.
(3) Cr is self-dual, i.e., $\mathrm{Cr}\{A\} + \mathrm{Cr}\{A^c\} = 1$ for any $A \in P(\Theta)$.
(4) $\mathrm{Cr}\{\cup_i A_i\} \wedge 0.5 = \sup_i \mathrm{Cr}\{A_i\}$ for any A_i with $\mathrm{Cr}\{A_i\} \leqslant 0.5$.

The triplet $(\Theta, P(\Theta), \mathrm{Cr})$ is called a credibility space and a fuzzy variable is defined as a function from this space to the set of real numbers.

In fuzzy sets, there are three important types of measures: possibility, necessity, and credibility. Let ξ be a fuzzy variable with membership function μ, and let r be real numbers. The possibility of a fuzzy event, characterized by $\xi \leqslant r$, is defined by