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Quantifying parameter uncertainty in reservoir operation associated with environmental flow management

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ABSTRACT

Parameter uncertainty inherent in reservoir operation affects operation model robustness and has been considered in conventional operation focusing on improving hydropower generation. With more attention paid to ecological environment protection recently, riverine ecosystem protection requires environmental flow (e-flow) management to sustain a near-natural flow regime. Whether there is e-flow management in reservoir operation has an impact on the uncertainty of reservoir operation, but parameter uncertainty was rarely considered in reservoir operation with e-flow management. In this study, a framework is proposed for performing parameter uncertainty analysis in reservoir operation associated with e-flow management. Both e-flow requirements and hydropower generation are considered in reservoir operation to sustain the harmonious development between ecological environment and human society. To compare the effect of different e-flow managements on the uncertainty of reservoir operation, three e-flow management scenarios are set. The Metropolis-Hastings algorithm of Markov Chain Monte Carlo (MCMC) sampling approach was applied for parameter estimation and uncertainty quantification. We used this framework in a case study of Nuozhadu hydropower station on the Lancang River in southern China to test its effectiveness. The results demonstrated that parameter uncertainty greatly affects the robustness of reservoir operation model. The comparison of reservoir operation under different e-flow management scenarios shows that more detailed e-flow management can effectively reduce uncertainty in reservoir operation and sustain the near-natural flow regime in a river.

1. Introduction

The reservoir operation model is an important tool to study reservoir operation, but it adopts relatively simple mathematical formulas or physical equations to conceptually and abstractly describe reservoir operation, which often causes distortion phenomena (the alteration from the reality to estimated decision) (Celeste and Billib, 2009; Liu et al., 2014b). Because of the mutual influence of different external factors in the simulation process, a reservoir operation simulation model always has errors between the true optimal and simulation values. The resulting uncertainty from inevitable distortion phenomena and errors needs to be analyzed and evaluated for developing a robust reservoir operation model. Uncertainty always exists in physical parameters of a reservoir operation model such as reservoir characteristics (e.g., stage-storage curve, hydropower generation process and parameters representing operation performance). Therefore, uncertainty in reservoir operation is a problem that cannot be ignored in modeling research.

Uncertainty analysis is a hot topic in current scientific research on reservoir operation (Engeland et al., 2005; Wang et al., 2009; Yang et al., 2007). The sources of model uncertainty can be summarized as parameters, inputs, structure, and observations (Refsgaard and Storm, 1990). Most research on uncertainty in reservoir operation has been about model inputs, structure, or observations (Ahmadi et al., 2010; Liu et al., 2014a; Mujumdar and Nirmala, 2007; Ticlavilca and Mckee, 2011; Xu et al., 2014). A little research considers parameter uncertainty in reservoir operation. Simulation results for reservoir operation depend largely on model parameter estimation, which is the key factor influencing model

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performance. In a reservoir operation model, we often have many choices for one parameter. In some situations, different parameter combinations have the same or similar effects and it is impossible to judge the pros and cons, which is equifinality (a set of parameters having the same average annual hydropower production) for different parameters (Beven and Binley, 1992; Li et al., 2010). To judge the pros and cons and choose suitable parameter combinations is an important step for model development. The majority of research focuses on uncertainty associated with the inflow parameters to study the effect of inflow (model input) uncertainty on reservoir operation (Karamouz and Vasiliadis, 1992). Other research treats reservoir decision (e.g., release R_i or storage V_i) as parameters and analyzes the uncertainty in reservoir operation (Liu et al., 2011). Liu et al. (2014b) analyzes the operating rule parameter uncertainty in conventional reservoir operation. Considering that little research has been done on the operating rule parameter uncertainty in reservoir operation, we focus on parameter uncertainty associated with operating rules in this paper and study its effect on reservoir operation.

The study of Liu et al. (2014b) is about quantifying parameter uncertainty in conventional reservoir operation without considering e-flow requirements. It's necessary to consider parameter uncertainty in reservoir operation associated with environmental flow (e-flow) management. In conventional reservoir operation, in order to produce more electric energy, decision makers always choose to impound more water over the cost of ecological damage (Guisández et al., 2013; Pérez-Díaz and Wilhelmi, 2010). However, riverine ecosystem protection needs e-flows to sustain a regime that resembles the natural flow variability. E-flows have a vital impact on maintaining biodiversity and ecological integrity of downstream riverine ecosystems (Cardwell et al., 1996; Petts, 2009; Yang et al., 2008b; Yin et al., 2011, 2012). More and more attention has been paid to ecological environment protection through developing e-flow management in reservoir operation (Jager and Smith, 2008; Mathews and Richter, 2007; Sun et al., 2008; Tharme, 2003; Yin et al., 2012). They all are reservoir operation to sustain e-flows without considering parameter uncertainty. Reservoir operation associated with e-flow management also has parameter uncertainty, which cannot be ignored but have not been considered. Compared with the conventional reservoir operation, incorporating e-flows into reservoir operation will change the mutual influences among physical parameters. Different e-flow managements have different effects on the uncertainty of reservoir operation. Moreover, analysis of parameter uncertainty is necessary for a robust reservoir operation aiming to sustain e-flows. Rather than determining an optimal parameter for e-flow management, parameter uncertainty analysis considers a set of decisions and obtains their confidence intervals of flow regime alteration. With these confidence intervals, more information and the probability coverage for the best solution about the flow regime alteration can be obtained to have a better protection of the riverine ecosystems. Therefore, the study of quantifying parameter uncertainty in reservoir operation associated with e-flow management is very important.

In this paper, we incorporate e-flows into reservoir operation during a reservoir simulation process for the harmonious development between hydropower generation and ecological environment protection. We assign reservoir releases with different e-flows for different periods and simultaneously conduct parameter uncertainty analysis. This paper provides a framework to quantify parameter uncertainty in reservoir operation associated with e-flow management based on the Bayesian theorem. We applied the popular Markov Chain Monte Carlo (MCMC; McMillan and Clark, 2009) method to quantify parameter uncertainties and conduct probabilistic Bayesian inferences. This paper is organized as followed. In the Methodology section, we give a detail description of reservoir operation associated e-flow management and present the method (MCMC) to estimate parameter uncertainty. In Sections 3 and 4, a case study of Nuozhadu hydropower station is applied to this framework to test its effectiveness and compare the results from three e-flow management scenarios. Section 5 discusses the trade-off between ecological environment protection and hydropower generation under three hydropower production targets. Finally, conclusions are given in Section 6.

2. Methodology

The methodology comprises several steps, as described in the following subsections. First, we provide a brief depiction of e-flow analysis in Section 2.1 to develop a better e-flow management and the range of variability approach (RVA) method is introduced in Section 2.2 to measure flow regime alteration. Next, reservoir operation with different e-flow management scenarios is established in Section 2.3. Assessing reservoir operation under different e-flow management scenarios depends on information of the optimal releases, so the theoretical optimal release scheme is described in Section 2.4. Model parameter uncertainty analysis methods are then described in Section 2.5.

2.1. Environmental flow analysis

Riverine ecosystems have different e-flow requirements in different periods to maintain different ecological functions. To sustain the majority of ecological functions, we need to provide specific e-flows for different periods. According to Mathews and Richter (2007), four flow periods (Table 1) are required to protect riverine ecosystems in reservoir operation. E-flow requirements vary in accordance with these four flow periods as follows (Yin et al., 2011, 2012):

The Tennant method, which is a common method, is used to determine seasonal e-flows (Tennant, 1976). From Tennant's opinion, 10% of average daily flow (ADF) is recommended as the minimum instantaneous flow to sustain short-term survival habitat and 30% ADF is recommended as a base flow to sustain good habitat for most aquatic species. In low flow periods, the base flow in wet

Table 1
The definition and the set of e-flows of four flow periods (on the basis of their magnitudes).

Periods	Definition	E-flow is set equal to
Flood periods	flows equal to or greater than bds	the bd of 1.5-year floods
High-flow pulse periods	flows less than bds but greater than the 25th percentile exceedance flow	the reservoir inflow
Low flow periods	the base flow in each month	30% of ADF in the wet season and 10% of ADF in the dry season (seasonal base flows)
Extreme low flow periods	flows equal to or less than the 95th percentile exceedance flow	the reservoir inflow

Notes. bd is the bankfull discharge; ADF is the average daily flow.