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Assessment of parameter uncertainty in hydrological model using a Markov-Chain-Monte-Carlo-based multilevel-factorial-analysis method

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SUMMARY

Without a realistic assessment of parameter uncertainty, decision makers may encounter difficulties in accurately describing hydrologic processes and assessing relationships between model parameters and watershed characteristics. In this study, a Markov-Chain-Monte-Carlo-based multilevel-factorial-analysis (MCMC-MFA) method is developed, which can not only generate samples of parameters from a well constructed Markov chain and assess parameter uncertainties with straightforward Bayesian inference, but also investigate the individual and interactive effects of multiple parameters on model output through measuring the specific variations of hydrological responses. A case study is conducted for addressing parameter uncertainties in the Kaidu watershed of northwest China. Effects of multiple parameters and their interactions are quantitatively investigated using the MCMC-MFA with a three-level factorial experiment (totally 81 runs). A variance-based sensitivity analysis method is used to validate the results of parameters' effects. Results disclose that (i) soil conservation service runoff curve number for moisture condition II (CN2) and fraction of snow volume corresponding to 50% snow cover (SNO50COV) are the most significant factors to hydrological responses, implying that infiltration-excess overland flow and snow water equivalent represent important water input to the hydrological system of the Kaidu watershed; (ii) saturate hydraulic conductivity (SOL_K) and soil evaporation compensation factor (ESCO) have obvious effects on hydrological responses; this implies that the processes of percolation and evaporation would impact hydrological process in this watershed; (iii) the interactions of ESCO and SNO50COV as well as CN2 and SNO50COV have an obvious effect, implying that snow cover can impact the generation of runoff on land surface and the extraction of soil evaporative demand in lower soil layers. These findings can help enhance the hydrological model's capability for simulating/predicting water resources.

1. Introduction

A sound understanding of the hydrological process needs to be emphasized prior to assessment of water resources. This motivates many watershed-scale process-based modeling efforts conceptualizing and aggregating the complex, spatially distributed surface and/or subsurface processes (Galvan et al., 2014; Jordan et al., 2014; Miao et al., 2014; Zhang et al., 2014; Boluwade and Madramootoo, 2015). These hydrological models generally consist of a number of parameters whose values cannot be determined through direct observation in the field, but can be derived by calibration against the input/output records of the watershed response that inevitably contains errors (Joseph and Guillaume, 2013). A number of factors such as correlations amongst parameters and spatiotemporal heterogeneity are sources of uncertainties in estimated parameters (Ma et al., 2014). Without a realistic assessment of parameter uncertainty, decision makers may encounter difficulties in accurately describing hydrologic processes and assessing regional relationships between model parameters and watershed characteristics (Rajabi et al., 2015). Thus, more efforts in quantifying the uncertainties involved in hydrologic simulations are desired.

Interest in the assessment of uncertain parameters and their effects on hydrologic modeling performance, as well as advances in computing technology have led to the development of Monte

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Carlo simulation methods (Arabi et al., 2007; Massoudieh et al., 2014; Mara et al., 2015). Among them, Generalised Likelihood Uncertainty Estimation (GLUE) is widely used for uncertainty analysis due to its conceptual simplicity, ease of implementation and less modification to existing source codes of hydrologic models. However, the procedures of GLUE for summarizing parameter and predictive distributions may be unreliable due to the dependence of likelihood function on subjective decisions and an arbitrary behavioral threshold (Shafii et al., 2014). Bayesian technique can help produce a posterior distribution on which statistical inferences about the system's dependent parameters are based (Panday et al., 2014). Nevertheless, integrating marginal distribution and conditional distribution, the posterior density might have a complicated functional form, which is difficult to calculate (Kim et al., 2014). An attractive method that is aiming at dealing with the above obstacles is Markov Chain Monte Carlo (MCMC) technique, the basic idea of which is to carefully construct a Markov chain based on formal likelihood measures.

In general, MCMC provides an efficient way to draw samples of parameter values from complex, high-dimensional statistical distributions as well as partition the joint densities into a set of marginal posterior densities of parameters of interest in a Bayesian framework (Ahmed, 2014). However, the main limitation of MCMC efforts lies in their incapability of quantitatively analyzing the effects of design parameters on the system performance (Zhou and Huang, 2011). In fact, model parameters that describe different hydrological processes would have varied individual effects on model outputs. Moreover, due to interrelationship amongst different parameters and nonlinear characteristics of modeling system, parameters would have interactions on hydrological responses. Valuable information may be veiled beneath these interrelationships and the consequent effects. Factorial analysis is able to help investigate individual and interactive effects of design parameters (Şahan and Öztürk, 2014). The most common two-level factorial analysis can hardly address the nonlinear relationships between the parameters and the response, which are involved in practical hydrologic processes (Martens et al., 2010; Lekivetz and Tang, 2014). As an extension of the traditional factorial analysis, multilevel factorial analysis (MFA) is launched to detect the curvilinear relationship between the parameters and the response (Wu and Fan, 2008; Badache et al., 2012; Wang and Huang, 2015). Nevertheless, no previous study was conducted to reflect multiple uncertain parameters as well as their multilevel effects on hydrological responses through coupling MCMC with MFA technique.

Therefore, this study aims to advance a Markov-Chain-Monte-Carlo-based multilevel-factorial-analysis (MCMC-MFA) method through integrating Markov Chain Monte Carlo (MCMC) technique and multilevel factorial analysis (MFA) within a general framework. The MCMC-MFA has advantages in (i) generating samples of parameters from a well constructed Markov chain and assessing parameter uncertainties with straightforward Bayesian inference; and (ii) investigating the individual and interactive effects of multiple parameters on model output through measuring the specific variations of hydrological responses. The MCMC-MFA implements

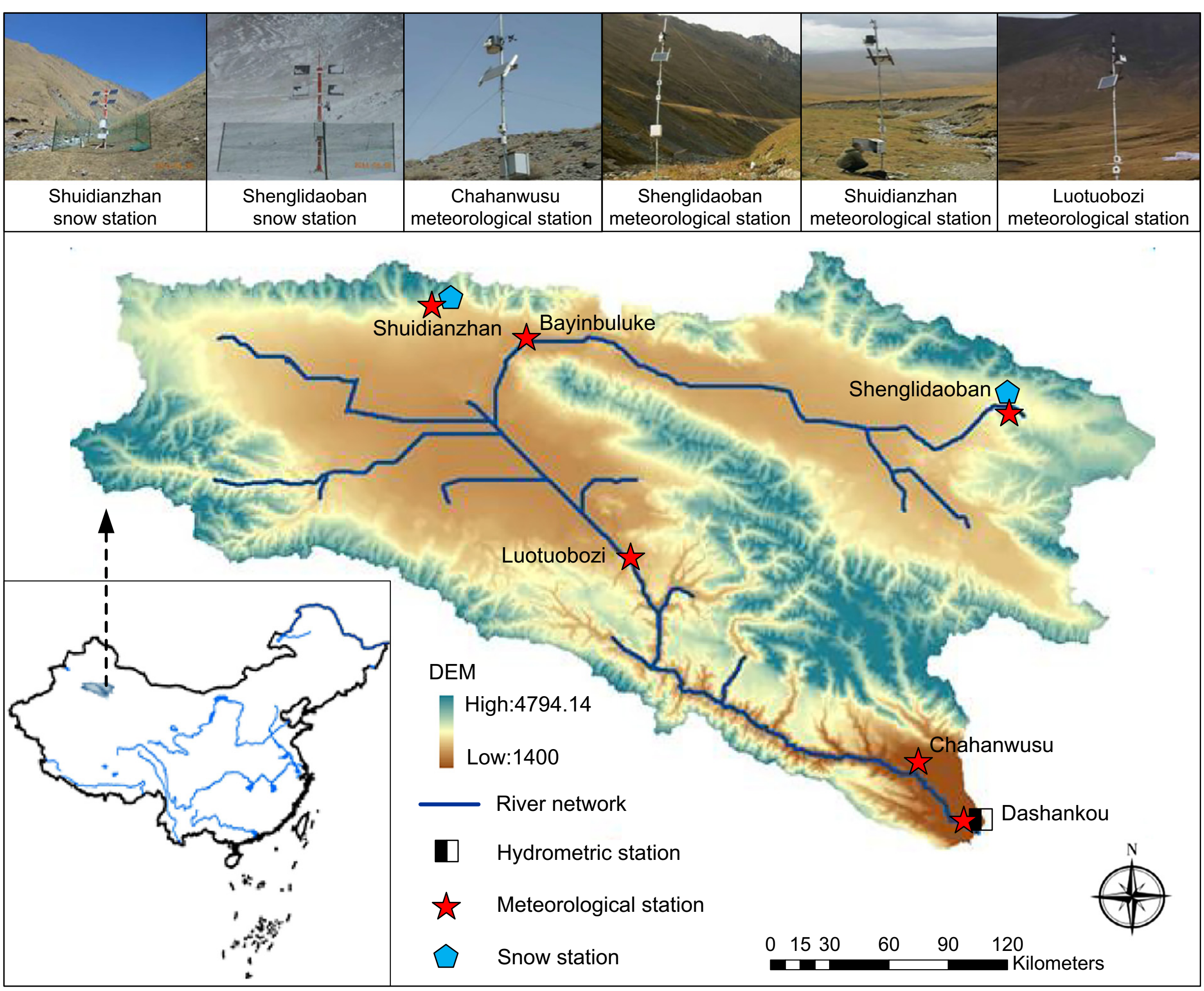

Fig. 1. Topographic characteristic of the Kaidu watershed and distribution of gauge stations.