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Development of an inexact-variance hydrological modeling system for analyzing interactive effects of multiple uncertain parameters

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SUMMARY

Uncertainty assessment of hydrological model parameters has become one of the main topics due to their significant effects on prediction in arid and semi-arid river basins. Incorporation of uncertainty assessment within hydrological models can facilitate the calibration process and improve the degree of credibility to the subsequent prediction. In this study, an inexact-variance hydrological modeling system (IVHMS) is developed for assessing parameter uncertainty on modeling outputs in the Kaidu River Basin, China. Through incorporating the techniques of type-2 fuzzy analysis (T2FA) and analysis of variance (ANOVA) within the semi-distributed land use based runoff processes (SLURP) model, IVHMS can quantitatively evaluate the individual and interactive effects of multiple uncertain parameters expressed as type-2 fuzzy sets in the hydrological modeling system. The modeling outputs indicate a good performance of SLURP model in describing the daily streamflow at the Dashankou hydrological station. Uncertainty analysis is conducted through sampling from fuzzy membership functions under different α-cut levels. The results show that, under a lower degree of plausibility (i.e. a lower α-cut level), intervals for peak and average flows are both wider; while intervals of peak and average flows become narrower under a higher degree of plausibility. Results based on ANOVA reveal that (i) precipitation factor (PF), one of main factors dominating the runoff processes, should be paid more attention in order to enhance the model performance; (ii) retention constant for fast store (RS) controls the amount and timing of the outflow from saturated zone and has a highly nonlinear effect on the average flow; (iii) the interaction between retention constant for fast store (RF) and maximum capacity for fast store (MF) has statistically significant ($p < 0.05$) effect on modeling outputs through affecting the maximum water holding capacity and the soil infiltration rate. The findings can help generate the optimal system inputs and enhance the model's applicability.

1. Introduction

Hydrological models are effective tools for simulating the entire land phase of the hydrological cycle from precipitation to sreamflow through analyzing various flow processes such as overland flow, infiltration into soils, evapotranspiration from vegetation, and groundwater flow (Jin et al., 2010). Hydrological models have widely been used for analyzing water balance, forecasting long-range streamflow, predicting real-time flood, and investigating climate-change impact in watershed management because of the increasing availability of digital elevation models (DEMs), geographical information system (GIS), remote sensing (RS), and terrain analysis tools over a broad range of scales (Vincendon et al., 2010; Assumaning and Chang, 2014; Zhang et al., 2014). However, hydrological models often encounter substantial uncertainties with respect to the input data, initial and boundary conditions, model structure, and parameters due to insufficient of observation data, difference in spatiotemporal scale between the model and measurements and simplification of physical processes within the model (Salamon and Feyen, 2009; Jordan et al., 2014). Particularly, a large number of parameters (from tens to hundreds) can lead to the curse of dimensionality where parameter estimation becomes a high dimensional and mostly nonlinear problem (Song et al., 2015). Therefore, it is imperative to evaluate the effect of parameter uncertainties on modeling outputs to facilitate the calibration process and ensure a high degree of credibility to the subsequent model prediction (Blasone et al., 2008).

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Over the past decades, many research works were conducted for assessment of the effect of parameter uncertainty on modeling performance (Kottegoda et al., 2014; Ma et al., 2014; Ahmadi et al., 2015). Among them, generalized likelihood uncertainty estimation (GLUE) was proved to be an effective approach due to its conceptual simplicity, ease of implementation and flexibility of less modification to existing source codes of hydrological models (Li et al., 2011). McMichael et al. (2006) used the GLUE method for investigating the predictive uncertainty in the application of distributed hydrological model for estimating monthly streamflow in a semi-arid shrubland catchment located in central California, where the acceptable parameter sets were identified and the uncertain intervals for monthly streamflow were calculated. Mannina and Viviani (2010) assessed the parameter uncertainty associated with a developed sewer sediment model, considering the cohesive properties of sewer sediments; the effectiveness of the developed model has been verified by taking into account the uncertainty assessed according to the GLUE method. However, GLUE is inconsistent with the Bayesian inference process, which inevitably leads to large overestimation of uncertainty, both for the parameter estimates and the resulting simulation forecasts (Jackson-Blake and Starrfelt, 2015). Moreover, this approach fails to reflect the sampling distribution of the model errors due to the subjective decisions on the likelihood function (Stedinger et al., 2008).

The Bayesian statistical inferences provided an ideal means of assessing parameter uncertainty through dividing the observations (e.g., river discharges) into two parts: a deterministic component and a random component describing residuals (Bastola et al., 2008). Arabi et al. (2007) integrated Monte Carlo-based simulation method into the soil and water assessment tool (SWAT) to analyze the uncertainty of water quality benefits in the Black Creek watershed, which could adjust the suggested range of model parameters to more realistic site-specific ranges based on the observed data. Wu et al. (2010) implemented a hierarchical Bayesian model to estimate the uncertainties associated with parameters for a conceptual hydrological model through using Markov chain Monte Carlo (MCMC) technique, where the value of soil moisture data for streamflow prediction was evaluated. Cheng et al. (2014) developed a Box-Cox transformation method within MCMC scheme to assess the effect of likelihood functions on the Bayesian inference and to effectively eliminate the heteroscedasticity of model residuals. Although the MCMC technique can handle uncertainties with known probability distributions, it still has difficulty in constructing the likelihood function and requires a large number of simulations to get a good approximation to the posterior distribution (Shafii et al., 2015).

Fuzzy analysis technique is capable of dealing with vagueness and ambiguity based on fuzzy sets theory, where uncertainties are handled in a directly way without generating a large number of realizations (Li et al., 2010). Previously, fuzzy analysis technique was successfully employed for assessment of parameter uncertainty in hydrological modeling (Raj Shrestha and Rode, 2008). The conventional fuzzy analysis technique can effectively reflect parameter uncertainties expressed as crisp fuzzy sets, whose membership grade is a real number in range of $[0,1]$. In fact, in many real-world practical problems, the membership grade may be uncertain due to change of natural condition and limitation of weather monitoring, which is beyond the conventional fuzzy analysis technique (Li and Huang, 2009). The conventional fuzzy analysis approach has difficulties in reflecting such complexities.

Besides, model parameters obtained from calibration based on available data are surrounded with a variety of uncertainties because many uncertain factors (e.g., correlations among parameters, sensitivity or insensitivity in parameters and statistical features of model residuals) are involved (Guerrero et al., 2013). Parameter interactions (i.e. correlations) result in the nonidentifiability of parameter values. When different parameter combinations give rise to equally good predictions, the unique optimal parameter set cannot be determined, leading to increased parameter uncertainty and larger prediction uncertainty (Mortier et al., 2013; Ling et al., 2014). Therefore, the interactions among multiple parameters should not be neglected or underestimated in hydrological modeling system. Analysis of variance (ANOVA) technique is effective for investigating the single or interactive effects (i.e., the negative or positive effects), specifying the magnitude of the effects, as well as identifying the optimal system inputs. In recent years, ANOVA technique has been employed in experiments to reveal the potential interactive effects of multiple parameters on system performance (Cheng et al., 2012; Ozguney and Kardhiqi, 2014). However, previous studies can only address the interactions and complexities among deterministic parameters; they barely take into account the uncertainty associated with parameters or incorporate the uncertainty assessment into the hydrological simulation processes.

Therefore, this study aims at developing an inexact-variance hydrological modeling system (IVHMS) for assessing parameter uncertainties as well as their interactions on hydrological modeling outputs. The IVHMS integrates techniques of type-2 fuzzy analysis (T2FA) and ANOVA into the semi-distributed land use based runoff processes (SLURP) model. Then, the IVHMS will be applied to assess parameter uncertainty on modeling outputs of the Kaidu River Basin in the Xinjiang Uyghur Autonomous Region, an arid region in northwest China. Results will be used for (i) disclosing the effect of multiple uncertain parameters and their interactions on hydrological modeling, (ii) analyzing the non-linear relationship between parameter values and modeling outputs, and (iii) reducing the impacts of parameter uncertainties on hydrological simulation.

2. Methodology

2.1. Framework of IVHMS

A typical hydrological modeling system involves simulation of dynamic flow processes (e.g., evaporation, infiltration, transpiration, percolation, groundwater recharge), identification of the uncertainties existing in hydrological processes (e.g., spatiotemporal heterogeneity associated with system components and imprecision resulting from expert opinion), quantification of parameters' uncertainties and their interactions on modeling outputs, as well as exploration of optimal parameter values under specified temporal and spatial variations. The IVHMS covers these tasks based on an integration of hydrological model, T2FA and ANOVA techniques into a general framework. Each technique has a unique contribution in enhancing the capability of the IVHMS in handling complexities and uncertainties in hydrological modeling. SLURP is used for dealing with the temporal and spatial variations of hydrological elements and tackling the process of runoff generation via the excess infiltration mechanism, runoff concentration, and channel flow routing. T2FA technique specializes in tackling uncertainties expressed as type-2 fuzzy sets through sampling from fuzzy possibility distributions based on α-cut level sets theory (i.e., the set of elements that belong to fuzzy set at least to the degree of α). ANOVA technique cannot only qualitatively estimate the individual and interactive effects of design parameters on modeling performance, but also quantitatively specify the magnitude of the effects on the modeling outputs.

Fig. 1 illustrates the general framework of IVHMS. The first step of IVHMS is to simulate water balance components through