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Calibration and uncertainty analysis of the SWAT model using Genetic Algorithms and Bayesian Model Averaging

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SUMMARY

In this paper, the Genetic Algorithms (GA) and Bayesian Model Averaging (BMA) were used to simultaneously conduct calibration and uncertainty analysis for the Soil and Water Assessment Tool (SWAT). In this combined method, several SWAT models with different structures are first selected; next GA is used to calibrate each model using observed streamflow data; finally, BMA is applied to combine the ensemble predictions and provide uncertainty interval estimation. This method was tested in two contrasting basins, the Little River Experimental Basin in Georgia, USA, and the Yellow River Headwater Basin in China. The results obtained in the two case studies show that this combined method can provide deterministic predictions better than or comparable to the best calibrated model using GA. The 66.7% and 90% uncertainty intervals estimated by this method were analyzed. The differences between the percentage of coverage of observations and the corresponding expected coverage percentage are within 10% for both calibration and validation periods in these two test basins. This combined methodology provides a practical and flexible tool to attain reliable deterministic simulation and uncertainty analysis of SWAT.

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Introduction

In recent years, hydrologic models are more and more widely applied by hydrologists and resource managers as a tool to understand and manage ecological and human activities that affect basin systems. Traditionally, the hydrologic models are calibrated to find one optimal hydrologic model with the optimum objective functions (e.g. sum square error). The optimized model is then used to assess water resources practices. The inferences based on a single model implicitly assumes that the probability that the single model generates the data accurately is 1, and neglects the uncertainty inherent in the model selection process (Montgomery and Nyhan, 2008; Raftery and Zheng, 2003). Uncertainty within model output is a major concern, particularly when modeling results are used to set policy. Because of uncertainties associated with input, model structure, parameter, and output, the model predictions are not a certain value, and should be represented with a confidence range (Beven and Binley, 1992; Gupta et al., 1998; Beven, 2000, 2006; Beven and Freer, 2001; Van Griensven et al., 2008). Reasonable estimates of prediction uncertainty of hydrologic processes are valuable to water resources and other relevant decision making processes (Liu and Gupta, 2007). Uncertainty estimates are routinely incorporated into Total Maximum Daily Load (TMDL) estimates and are an important part of the TMDL implementation plan (Shirmohammadi et al., 2006). Usually, water management projects are planned and designed using scenarios that fall at the conservative end of the range of plausible outcomes. Over estimation of uncertainty can result in over design of mitigation measures, while under estimation of uncertainty can lead to inadequate preparation for potential situations. In order to successfully apply hydrological models in practical water resources investigations, careful calibration and prediction uncertainty analysis are required (Duan et al., 1992; Beven and Binley, 1992; Vrugt et al., 2003; Yang et al., 2008; Van Griensven et al., 2008).

As a physically based hydrologic model that can simulate most of the key hydrologic processes at basin scale, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) has been applied world wide for assessing water resources management (Gassman et al., 2007). In order to efficiently and effectively apply the SWAT model, different calibration and uncertainty analysis methods have been developed and applied to improve the prediction reliability and quantify prediction uncertainty of SWAT simulations (Eckhardt and Arnold, 2001; Bekele and Nicklow, 2007; Yang et al., 2007; Harmel and Smith, 2007; Arabi et al., 2007; Kannan et al., 2008). For example, Van Griensven and Meixner (2006) incorporated the

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shuffled complex evolution (SCE) algorithm for parameter calibration of SWAT, which was later extended to an uncertainty analysis method known as Sources of Uncertainty Global Assessment using Split SamplES (SUNGLASSES) (Van Griensven et al., 2008). Muleta and Nicklow (2005) combined Genetic Algorithms (GA) and Generalized Likelihood Uncertainty Estimation (GLUE) methods to conduct parameter calibration and uncertainty analysis of SWAT. Yang et al. (2008) compared four uncertainty analysis algorithms, that is GLUE (Beven and Binley, 1992), Sequential Uncertainty Fitting SUFI-2 (Abbaspour et al., 2004), Parameter solutions (ParaSol) (Van Griensven and Meixner, 2006), and Markov Chain Monte Carlo (MCMC) based Bayesian analysis techniques for assessing the uncertainty of SWAT predictions. These uncertainty analysis algorithms are differing in philosophy, assumptions, and sampling strategies. Yang et al. (2008) suggested that, if computationally feasible, Bayesian Markov Chain Monte Carlo (MCMC) approaches are most recommendable because of their solid conceptual basis. It is worth noting that the MCMC method requires a large number of SWAT runs. For example, 45,000 runs of SWAT were performed in Yang et al. (2008). Zhang (2008b) tested an evolutionary Monte Carlo based MCMC method for SWAT, which took about 200,000 model runs for convergence. Applying the MCMC based methods to assess water resources under future scenarios (e.g. best management practices, and land use/climate change) is very computationally intensive. In the previous uncertainty studies using SWAT, model prediction uncertainty is mainly attributed to parameter values. It is worth noting that the bias and uncertainty resulting from model structures selection can exert important impact on model prediction (Neuman, 2003; Butts et al., 2004a, 2004b). Butts et al. (2004a) presented an evaluation of model structure on hydrologic modeling uncertainty by selecting different plausible model structures within a general hydrological modeling tool, and emphasize the importance of exploring different model structures as part of the overall modeling approach. The SWAT model provides a hydrologic modeling tool that allows different model structures to be selected for representing different hydrological processes (e.g. potential evapotranspiration, snow routing, and flood routing). The major purpose of this study is to explore ensemble hydrologic simulation and uncertainty analysis using several model structures within the SWAT model framework.

Recently, Bayesian Model Averaging (BMA), a method for averaging over different competing models, has been applied to allow incorporating model uncertainty into model prediction. BMA possesses a range of theoretical optimality properties and has shown good performance in reliable prediction and uncertainty analysis in a variety of simulated and real data situations (e.g. weather forecast and hydrologic predictions) (Raftery et al., 2005; Ajami et al., 2006; Duan et al., 2007; Vrugt and Robinson, 2007; Montgomery and Nyhan, 2008). The BMA can be used to examine several competitive models for hydrologic modeling and assessment. In practical applications of SWAT, modelers usually select one or several model structures and choose the best among them. To the best of the authors' knowledge, seldom studies have been conducted to jointly use multiple structures within the SWAT model. In this study, a combined method, which implements the Genetic Algorithms (GA) and BMA, was proposed to conduct calibration and uncertainty analysis of the SWAT model through jointly using multiple model structures. The general procedures for applying GA and BMA to conduct ensemble hydrologic predictions applied here are: (1) select the specific model components of SWAT to be examined, here we examined different snow, potential evapotranspiration and flow routing methods; (2) calibrate the parameters for each combination of model components using GA to provide competing models and model results; and (3) use BMA to combine the ensemble predictions and provide uncertainty interval estimation. The examination was limited to the snow, potential evapotranspiration and flow routing to present a manageable number of modeling options for illustration purposes. Compared with running thousands of models for assessing management practices or climate/land use change scenarios using MCMC based method, the BMA has the potential to save a large number of runs of SWAT. Two basins were used to test the validity of this framework for providing accurate hydrologic prediction and uncertainty intervals estimation using SWAT. The combination of GA and BMA is expected to provide a practical tool for implementing calibration and uncertainty analysis of computationally intensive hydrologic models.

Materials and methods

Study area description

Two basins, the Little River Experimental Basin (LREB) in the Southeastern USA and Yellow River Headwater Basin (YRHB) in central China were used in this study (Fig. 1). The basins were selected to offer a contrast in hydrology for testing purposes. The basic characteristics of the two basins are introduced as follows.

The LREB (Fig. 1) is the upper 334 km^2 of the Little River in Georgia, USA, and is the subject of long-term hydrologic and water quality research by USDA-ARS and cooperators (Sheridan, 1997; Bosch et al., 2007). The LREB is located in the Tifton Upland physiographic region, which is characterized by intensive agriculture in relatively small fields in upland areas and riparian forests along stream channels. The region has low topographic relief and is characterized by broad, flat alluvial floodplains, river terraces, and gently sloping uplands (Sheridan, 1997). Climate in this region is characterized as humid subtropical with an average annual precipitation of about 1167 mm based on data collected by USDA-ARS from 1971 to 2000. Soils on the basin are predominantly sands and sandy loams with high infiltration rates. Since surface soils are underlain by shallow, relatively impermeable subsurface horizons, deep seepage and recharge to regional ground water systems are impeded (Sheridan, 1997). Land use types include forest (50%), cropland (31%), pasture (10%), water (2%), and urban (7%) (Bosch et al., 2006).

The YRHB (Fig. 1) is an 114,345 km^2 mountainous river basin, which is located in the northeastern part of Tibetan plateau in China. This area is the primary source of water availability for the Yellow River Basin (Zhang et al., 2008a). The average elevation is about 4217 m, and ranges between 2600 and 6266 m. The area slopes downward from west to east, ranging from a combined landform of low-mountains and wide valleys with lakes to smooth plateaus. The headwater area has a typical continental alpine cold and dry climate. The annual precipitation amount is around 600 mm and the average annual temperature for the YRHB is near 0 °C. In winter the average temperature is below 0 °C for most of the weather stations, while in summer the average temperature is above 0 °C. This seasonal temperature variation makes snowmelt an important process in this area (Zhang et al., 2008a). This basin is characterized by gently sloping upland, river bed, and swamp and wetland. The major types of soils in this area are clay and loam with relatively low infiltration rates. The major land cover in the study area is grassland, which accounts for approximately 90% of the total area. Other land use/land cover (forest land, rangeland, agriculture land, and bare area) accounts for the remaining 10% of the area.

SWAT model description

SWAT is a continuous time, physically based hydrological model. SWAT subdivides a basin into sub-basins connected by a stream network, and further delineates Hydrologic Response Units (HRUs)