Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Hydrology 320 (2006) 37–61
Journal of Hydrology
www.elsevier.com/locate/jhydrol

On the assessment of the impact of reducing parameters and identification of parameter uncertainties for a hydrologic model with applications to ungauged basins

Maoyi Huang, Xu Liang*

Department of Civil and Environmental Engineering, University of California, 631 Davis Hall # 1710, Berkeley, CA 94720-1710, USA

Abstract

In this paper, we investigate model parameter uncertainties associated with hydrological process parameterizations and their impacts on model simulations in the Three-Layer Variable Infiltration Capacity (VIC-3L) land surface model. We introduce an alternative subsurface flow parameterization into VIC-3L to reduce the impacts of model parameter uncertainties on model simulations by reducing the number of model parameters that need to be estimated through a calibration process. The new subsurface flow parameterization is based on the concepts of kinematic wave and hydrologic similarity, and has one parameter for calibration. Results from the 12 MOPEX (Model Parameter Estimation Experiment) basins obtained by applying the VIC-3L model with the new subsurface flow formulation show that the performance of the new parameterization is comparable to the original subsurface flow formulation, which has three parameters for calibration. In addition, a probabilistic approach based on Monte Carlo simulations is used to evaluate model performance and uncertainties associated with model parameters over different ranges of streamflow. Studies based on the 12 MOPEX watersheds show that compared to the parameter associated with the new subsurface flow parameterization, the VIC shape parameter (i.e. the *b* parameter that represents the shape of the heterogeneity distribution of effective soil moisture capacity over a study area) has a larger impact on model simulations and could introduce more uncertainty if not estimated appropriately. Furthermore, investigations on the *b* parameter suggest that the ensembles (i.e. the mean response and its bounds) from the Monte Carlo simulations could provide reasonable predictions and uncertainty estimates of streamflows, which have important implications for applications to ungauged basins. The study also shows that appropriate reduction of the number of model parameters is an effective approach to reduce the impacts of parameter uncertainties on model simulations. This is more so for applications to ungauged basins or basins with limited data available for calibration. The new subsurface flow parameterization and the probabilistic uncertainty analysis approach are general and can be applied to other modeling studies.

Keywords: MOPEX; Monte Carlo; Simulation; Uncertainty; Subsurface flow; Model parameters; Land surface model; Ungauged watersheds

1. Introduction

Uncertainties associated with hydrological modeling generally come from two main sources. They are: (1) the uncertainties associated with available data

* Corresponding author. Tel.: +1 510 642 2648; fax: +1 510 642 7483.
E-mail address: liang@ce.berkeley.edu (X. Liang).

0022-1694/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jhydrol.2005.07.010

(e.g. forcing data, model input data, initial and boundary conditions, etc.); and (2) uncertainties arising from model structure and model parameters. The first type of uncertainty is and will be continually reduced with advancements in information and measuring technology. The second type is related mainly to our understanding of hydrological processes and the way these processes are parameterized. Therefore, reductions of the second type of uncertainty rely on improved understanding of the physics and effective representation of the associated hydrological processes. This can be achieved through improvements in model structure and model parameter estimations.

Tremendous efforts have been carried out to reduce uncertainties associated with the second type by finding optimal model parameter sets using model calibration techniques and historical data for a given watershed. Efforts include developments of measures used to evaluate goodness-of-fit between model simulations and observations (e.g. Sorooshian and Dracup, 1980; Sorooshian, 1981), and of global optimization schemes, such as the shuffled complex evolution (SCE-UA) method developed by the University of Arizona (e.g. Duan et al., 1992, 1993; Sorooshian et al., 1993), used to obtain 'optimal' parameter sets. These optimization schemes generally assume that an optimal parameter set exists and implicitly ignore the estimation of predictive uncertainties. Also, recent studies by researchers (e.g. Klepper et al., 1991; van Straten and Keesman, 1991; Beven and Binley, 1992; Yapo et al., 1996) suggest that a single optimal parameter set for a hydrologic model may not exist and the uncertainties associated with the optimal parameter sets could be large. A model with the optimal parameter set may have the best fit over the period of the calibration data, but there may exist multiple parameter sets that are as good as the 'optimal' set. In addition, using different performance evaluation criteria could result in different optimal parameter sets. These resulted parameter sets are referred to as, for example, 'equifinality' (Beven and Binley, 1992), 'equally probable parameter sets' (van Straten and Keesman, 1991), and 'acceptable sets' (Klepper et al., 1991).

One approach to address these limitations is to provide predictions within a range to reflect the fact that an optimal parameter set alone is not enough to represent the possible uncertainty associated with the model predictions. Thus, the parameter space needs to be sampled to generate realizations of the model simulations so that the prediction range can be estimated based on the model simulations. Several studies use this approach, for example, the generalized likelihood uncertainty estimation (GLUE) method (Beven and Binley, 1992; Freer et al., 1996), and the prediction uncertainty method (PU) (e.g. Klepper et al., 1991). However, these methods have not been widely applied to hydrological modeling due to two reasons: (1) an effective and efficient method to sample the parameter space is needed, and (2) a subjective choice of the model performance evaluation criteria needs to be specified (e.g. in the GLUE method). Kuczera and Parent (1998) pointed out that the above algorithms were sensitive to the space to be sampled. Therefore, extensive sampling in the parameter space is usually required by these algorithms. Comparing the GLUE algorithm to a Markov Chain Monte Carlo (MCMC) (Metropolis et al., 1953; Hastings, 1970) algorithm, Kuczera and Parent (1998) concluded that importance sampling based on the GLUE algorithm is inferior to the MCMC sampling, because the latter is capable of producing reliable inferences of the posterior probability distribution of the parameters with modest sampling. The advantage of the MCMC sampling becomes more significant when the sampling space has a high dimension. Inspired by the promising features of the MCMC sampling method, Vrugt et al. (2003a) recently proposed a Shuffled Complex Evolution Metropolis (SCEM-UA) algorithm that combines the strengths of the classical Markov Chain Monte Carlo (MCMC) methods with those of complex shuffling method (Duan et al., 1992). The SCEM-UA algorithm is an adaptive MCMC sampler that can sample the parameter space effectively and efficiently in the framework of Bayesian inference and is able to estimate uncertainty of parameters based on the inferred posterior distribution. Although the MCMC sampling is better than the basic importance sampling, we investigate the parameter uncertainties in this study by employing a probabilistic approach based on importance sampling, owing to the low-dimensional sampling spaces of only one or two parameters. The MCMC sampler can be employed in