Quantifying Uncertainty in Flood Modeling Using Bayesian Approaches

Tao Huang

ABSTRACT

Floods all over the world are one of the most common and devastating natural disasters for human society, and the flood risk is increasing recently due to more and more extreme climatic events. In the United States, one of the key resources that provide the flood risk information to the public is the Flood Insurance Rate Map (FIRM) administrated by the Federal Emergency Management Agency (FEMA) and the digitalized FIRMs have covered over 90% of the United States population so far. However, the uncertainty in the modeling process of FIRMs is rarely investigated. In this study, we use two of the widely used multi-model methods, the Bayesian Model Averaging (BMA) and the generalized likelihood uncertainty estimation (GLUE), to evaluate and reduce the impacts of various uncertainties with respect to modeling settings, evaluation metrics, and algorithm parameters on the flood modeling of FIRMs. Accordingly, three objectives of this study are to: (1) quantify the uncertainty in FEMA FIRMs by using BMA and Hierarchical BMA approaches; (2) investigate the inherent limitations and uncertainty in existing evaluation metrics of flood models; and (3) estimate the BMA parameters (weights and variances) using the Metropolis-Hastings (M-H) algorithm with multiple Markov Chains Monte Carlo (MCMC).

In the first objective, both the BMA and hierarchical BMA (HBMA) approaches are employed to quantify the uncertainty within the detailed FEMA models of the Deep River and the Saint Marys River in the State of Indiana based on water stage predictions from 150 HEC-RAS 1D unsteady flow model configurations that incorporate four uncertainty sources including bridges, channel roughness, floodplain roughness, and upstream flow input. Given the ensemble predictions and the observed water stage data in the training period, the BMA weight and the variance for each model member are obtained, and then the BMA prediction ability is validated for the observed data from the later period. The results indicate that the BMA prediction is more robust than both the original FEMA model and the ensemble mean. Furthermore, the HBMA framework explicitly shows the propagation of various uncertainty sources, and both the channel roughness and the upstream flow input have a larger impact on prediction variance than bridges. Hence, it provides insights for modelers into the relative impact of individual uncertainty sources in the flood modeling process. The results show that the probabilistic flood maps developed based on the BMA analysis could provide more reliable predictions than the deterministic FIRMs.

In the second objective, the inherent limitations and sampling uncertainty in several commonly used model evaluation metrics, namely, the Nash Sutcliffe efficiency (*NSE*), the Kling Gupta efficiency (*KGE*), and the coefficient of determination (R^2), are investigated systematically, and hence the overall performance of flood models can be evaluated in a comprehensive way. These

evaluation metrics are then applied to the 1D HEC-RAS models of six reaches located in the states of Indiana and Texas of the United States to quantify the uncertainty associated with the channel roughness and upstream flow input. The results show that the model performances based on the uniform and normal priors are comparable. The distributions of these evaluation metrics are significantly different for the flood model under different high-flow scenarios, and it further indicates that the metrics should be treated as random statistical variables given both aleatory and epistemic uncertainties in the modeling process. Additionally, the white-noise error in observations has the least impact on the evaluation metrics.

In the third objective, the Metropolis-Hastings (M-H) algorithm, which is one of the most widely used algorithms in the MCMC method, is proposed to estimate the BMA parameters (weights and variances), since the reliability of BMA parameters determines the accuracy of BMA predictions. However, the uncertainty in the BMA parameters with fixed values, which are usually obtained from the Expectation-Maximization (EM) algorithm, has not been adequately investigated in BMA-related applications over the past few decades. Both numerical experiments and two practical 1D HEC-RAS models in the states of Indiana and Texas of the United States are employed to examine the applicability of the M-H algorithm with multiple independent Markov chains. The results show that the BMA weights estimated from both algorithms are comparable, while the BMA variances obtained from the M-H MCMC algorithm are closer to the given variances in the numerical experiment. Overall, the MCMC approach with multiple chains can provide more information associated with the uncertainty of BMA parameters and its performance of water stage predictions is better than the default EM algorithm in terms of multiple evaluation metrics as well as algorithm flexibility.