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A probabilistic approach for analysis of uncertainty in the evaluation of watershed management practices

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Summary A computational framework is presented for analyzing the uncertainty in model estimates of water quality benefits of best management practices (BMPs) in two small (<10 km^2) watersheds in Indiana. The analysis specifically recognizes the significance of the difference between the magnitude of uncertainty associated with absolute hydrologic and water quality predictions, and uncertainty in estimated benefits of BMPs. The Soil and Water Assessment Tool (SWAT) is integrated with Monte Carlo-based simulations, aiming at (1) adjusting the suggested range of model parameters to more realistic site-specific ranges based on observed data, and (2) computing a scaled distribution function to assess the effectiveness of BMPs. A three-step procedure based on the One-factor-At-a-Time (OAT) sensitivity analysis and the Generalized Likelihood Uncertainty Estimation (GLUE) was implemented for the two study watersheds. Results indicate that the suggested range of some SWAT parameters, especially the ones that are used to determine the transport capacity of channel network and initial concentration of nutrients in soils, required site-specific adjustment. It was evident that uncertainties associated with sediment and nutrient outputs of the model were too large, perhaps limiting its application for point estimates of design quantities. However, the estimated effectiveness of BMPs sampled at different points in the parameter space varied by less than 10% for all variables of interest. This suggested that BMP effectiveness could be ascertained with good confidence using models, thus making it suitable for use in watershed management plans such as the EPA's Total Maximum Daily Load (TMDL) program. The potential impact of our analysis on utility of models and model uncertainties in decision-making process is discussed.

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Introduction

The analysis of uncertainty associated with the utility of simulation models is an important consideration in the development of watershed management plans. Modeling uncertainty should be rigorously addressed in development and application of models, especially when stakeholders are affected by the decisions contingent upon model-supported analyses (NRC, 2001). Watershed models are commonly utilized to investigate rainfall-runoff generation, and fate and transport of contaminants resulting from nonpoint source activities. Nonpoint source activities are perceived to be the most important source of pollution in the United States (Ice, 2004). The evaluation of the success of best management practices (BMPs) in meeting their original goals has also been facilitated by watershed models (Griffin, 1995; Edwards et al., 1996; Mostaghimi et al., 1997; Saleh et al., 2000; Santhi et al., 2001; Kirsch et al., 2002; Santhi et al., 2003; Arabi et al., 2006). Uncertainty associated with absolute estimates of design quantities tends to be very high because of data sparsity and model limitations (Osidele et al., 2003; Benaman and Shoemaker, 2004). Thus, models are found to be more useful when making relative comparisons rather than making absolute predictions. It may be more meaningful to implement the uncertainty associated with effectiveness of BMPs in the planning process.

The common modeling approach entails the {calibrate → validate → predict} process. The thrust of the calibration procedure is to identify a set of model parameters by optimizing a goodness-of-fit statistic between observed and predicted values such as the Nash–Sutcliff coefficient of efficiency. The calibrated model is then used to examine the impact of various management scenarios on the future behavior of the system. Such an analysis is subject to *identifiability*, and *non-uniqueness* of the optimal (calibrated) parameter set (Beck, 1987), i.e. there may be several sets of model parameters that fit the observed data equally (Beven and Binely, 1992). Calibration of a simulation model for a given watershed will reduce, but not totally remove, modeling uncertainties associated with both structure of the model and parameter estimates. Even with the best model structure, parameter estimation contains *residual uncertainty* (Beck, 1987) that propagates forward into model predictions and evaluation of effectiveness of management practices.

Although the literature is replete with sensitivity analysis and uncertainty analysis methods (Spear and Hornberger, 1980; Beven and Binely, 1992; Spear et al., 1994; Saltelli et al., 2000), implications of uncertainty associated with model predictions have not been widely endorsed in the decision making process mainly as a result of large uncertainty estimates. The magnitude of uncertainty itself is a key factor in its acceptance as the cost of implementation of management actions such as the Total Maximum Daily Load (TMDL) program may significantly increase with larger uncertainty estimates (Dilks and Freedman, 2004). In a case study in the Cannonsville Reservoir system watershed (1178 km^2) located in upstate New York, Benaman and Shoemaker (2004) concluded that even in the presence of observed data it was not possible to reduce the uncertainty of absolute sediment predictions in their study to practical values for the TMDL program. The argument, however, is that if the goal of a modeling study is to examine the impact of management scenarios on water quality of a study area, it may be neither practical nor necessary to incorporate large uncertainty of absolute predictions in the decision making process. It would be perhaps more feasible (and more desirable) to communicate and implement uncertainty of estimated effectiveness of management scenarios rather than uncertainty of absolute predictions (Zhang and Yu, 2004). Moreover, the importance of such a formulation would be particularly appreciated when the reduction of a variable of concern (sediment, nutrients, etc.) due to implementation of an abatement action is less than estimated uncertainty of absolute predictions. In such cases, evaluation of impact of management scenarios would not be inhibited by uncertainty of model outputs.

The impact of modeling uncertainties on evaluation of management practices has not been addressed sufficiently, as studies have generally focused on uncertainty of point predictions. Specifically, a computational procedure that can be used to establish uncertainty bounds for the estimated effectiveness of BMPs has not been developed to the best of our knowledge. In this paper, a Monte Carlo-based probabilistic approach is utilized (i) to develop a computational procedure for analysis of uncertainty; (ii) to examine the effect of modeling uncertainties on evaluation of long-term water quality impacts of BMPs using a distributed watershed model, SWAT; and (iii) to provide a comparison between magnitudes of uncertainties associated with absolute predictions versus effectiveness of BMPs. The analysis is demonstrated for two small watersheds in Indiana where water quality data were collected and several structural BMPs were implemented.

Theoretical considerations

Watershed model

Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2002) is a process-based distributed-parameter simulation model, operating on a daily time step. The model was originally developed to quantify the impact of land management practices in large, complex watersheds with varying soils, land use, and management conditions over a long period of time. SWAT uses readily available inputs and has the capability of routing runoff and chemicals through streams and reservoirs, and allows for addition of flows and inclusion of measured data from point sources. Moreover, SWAT has the capability to evaluate the relative effects of different management scenarios on water quality, sediment, and agricultural chemical yield in large, ungaged basins. Major components of the model include weather, surface runoff, return flow, percolation, evapotranspiration (ET), transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loads, and water transfer. Table 1 provides a listing of important SWAT input parameters corresponding to the above-mentioned components.

For simulation purposes, SWAT partitions the watershed into subunits including subbasins, reach/main channel seg-