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Uncertainty based analysis of the impact of watershed phosphorus load on reservoir phosphorus concentration

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SUMMARY

In many regions of the world that depend on surface reservoirs as a source of water supply, eutrophication is a major water quality problem. Developing simulation models to evaluate the impact of watershed nutrient loads on the reservoir's water quality is an essential step in eutrophication management. In this regard, analysis of model uncertainty gives an opportunity to assess the reliability and the margin of safety of the model predictions for Total Maximum Daily Load (TMDL) from the watershed nutrient load. In this study, a computational procedure has been proposed for the analysis of the model uncertainties in simulation of watershed phosphorous load and reservoir phosphorous concentration. Data from the Aharchai watershed which is located upstream of the Satarkhan reservoir in the northwestern part of Iran, is used as the study area to test the effectiveness of the proposed methodology. The Soil and Water Assessment Tools (SWAT) is utilized for assessment of watershed phosphorus load as the main agent resulting in the reservoir eutrophication in the region. The most effective parameters in model performance are identified by a global sensitivity analysis technique named modified Fourier Amplitude Sensitivity Test (FAST) which can incorporate parameter interdependencies. The Generalized Likelihood Uncertainty Estimation (GLUE) technique is also applied to set up behavioral ranges of the parameters that are relevant to the actual observations. Finally, the cumulative weighted-likelihood distribution functions (CWLDF) are derived for outputs of the SWAT. They are used jointly for estimation of results uncertainty limits using the Copula method. To assess the effectiveness of applying Best Management Practices (BMPs) in the watershed, two scenarios of with and without BMPs application are tested. The results showed the effectiveness of the proposed model in uncertainty estimation of watershed phosphorus load and reservoir phosphorus concentration as well as the effectiveness of BMPs in reducing P loads from the watershed.

1. Introduction

High concentration of nutrients (phosphorous, nitrogen, etc.) may result in eutrophication which is a major water quality problem in many lakes and reservoirs. This phenomenon is caused by the excessive agricultural and industrial activities in the watershed upstream of a reservoir. Thus control and reduction of watershed nutrient loads is a key issue in successful management of reservoir eutrophication. The choice of effective watershed management practices with the aim of nutrient load reduction depends on the characteristics of watershed and the nutrients concentrations level in the reservoir.

Best Management Practices (BMPs) in a watershed are effective measures for the reduction of pollutants before they enter the receiving water body. Watershed simulation models have been used as effective tools in assessing the suitability of BMPs in reduction of nutrient load to the receiving waters (Santhi et al., 2003; Arabi et al., 2007). Regarding the capabilities of the Soil and Water Assessment Tools (SWAT) model, it can also be used to design BMPs for reducing runoff nutrient loads at the watershed-scale.

Due to limitations in data and model capabilities, there is a great deal of uncertainty in estimating the values of parameters needed for the design of BMPs. Therefore, if realistic bounds of input parameters variability are determined then BMPs can be designed more effectively in a watershed planning scheme.

Sohrabi et al. (2003) selected probability distributions for sensitive parameters of SWAT. These parameters have been determined in pervious investigations in this study area. They showed the combined effect of such variability on model output in the terms of

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cumulative probability distribution functions. Their investigations show that by considering the input parameters' uncertainty, the mean stream flow and sediment loading estimations will change by −64% and +8.2%, respectively in comparison with the results obtained using mean value of input parameters. In another study, Shirmohammadi et al. (2006) reviewed sources and methods of uncertainty analysis including Monte Carlo simulation (MCS), Latin hypercube sampling (LHS), and GLUE. They concluded that uncertainty in TMDL models should be taken into consideration during both the assessment and implementation phases.

Gallagher and Doherty (2007) investigated the use of three methods for uncertainty analysis of the Hydrological Simulation Program-Fortran (HSPF) model in a large watershed. These methods include first-order analysis, Markov Chain Monte Carlo (MCMC) methods and nonlinear calibration-constrained optimization. They compared the performances of the three methods. They concluded that the first-order uncertainty analysis has the advantage to be implemented with virtually no computational burden but its use in analyzing predictive uncertainty is often limited. MCMC methods are far more robust, and can produce reliable estimates of parameter and predictive uncertainty. Nonlinear calibration-constrained optimization can also provide good estimates of parameter and predictive uncertainty. However, they do not provide the same amount of qualitative information on the probability structure of parameter space as do MCMC methods.

Refsgaard et al. (2007) reviewed different methods of uncertainty analysis. They evaluated the performance of the methods in their application, modeling stage, and source and nature of uncertainties. They proposed a terminology for uncertainty consideration in modeling issues of water resources management. They provided an interpretation of uncertainty with focus on the degree of confidence that a decision maker has about results and corresponding probabilities. In another study, Warmink et al. (2010) developed an algorithm for classification of uncertainties in environmental models. Their proposed algorithm can be used in comparing uncertainty analyses in different studies and selection of the best method based on the considered model.

Arabi et al. (2007) proposed a framework for investigation of the uncertainties in the performance of watershed management practices. They generated cumulative likelihood of SWAT outputs using the GLUE method. Their uncertainty analysis was focused on the range of parameters that need site-specific adjustments based on the available data and the uncertainties associated with the BMPs characteristics. Vogel et al. (2008) also utilized the GLUE methodology in a rainfall–runoff model calibration process and concluded that choice of a likelihood function using a statistically valid function can provide reliable domains for model prediction.

Pohlert et al. (2007) used a regression-based global sensitivity analysis to evaluate the impact of the new parameters and outputs sensitivity in an extended version of SWAT model. GLUE method was also used by Karamouz et al. (2009) to evaluate the uncertainty of the SWAT model in simulation of watershed phosphorus load, using quintile analysis of the generated cumulative likelihood and yielding the uncertainty limits.

Previous studies in uncertainty analysis, mainly have focused on uncertainty of watershed load predictions and did not consider its impact on reservoir water quality. Inflow to the reservoir water quality is usually measured, however it is done often at a distance from the reservoir. But in the absence of water quality sampling for the water in the reservoir that supplies demand, providing an estimation of water quality in the reservoir is of high value. In this study, this need has been realized. Furthermore, there has not been a prior specific procedure for assessing uncertainty limits in determining the effectiveness of BMPs in reservoirs' eutrophication management. There are a number of parameters in river and reservoir water quality modeling which there are interactions among them. Ignoring these interactions in different steps of analysis would provide unreliable results. As an example, in the application of the GLUE method for uncertainty estimation, joint probability of occurrence of the uncertain model parameters are not considered. In this study these shortcoming is realized and a scheme is proposed to include parameters interactions in the uncertainty analysis by developing a new joint probability based weighting approach that utilizes the Copula method.

To summarize, integration of modeling and application tools including GLUE, Copula, SWAT and FAST (Fourier Amplitude Sensitivity Test) is done in this study to improve the body of knowledge in uncertainty and sensitivity analyses, river and reservoir water quality modeling, and BMP studies for a watershed water quality management. In this integrated analysis, the effect of uncertainties on the watershed parameters and BMPs, on Phosphorous (P) load from the watershed and reservoir P concentration, are determined.

2. The study area

The study area of this paper is Aharchai river watershed which is located upstream of the Satarkhan reservoir in northwestern part of Iran. The watershed is located between 38° 24′ and 38° 41′N and 46° 20′ and 46° 55′E. Fig. 1 shows the location of the watershed and reservoir.

The area of the watershed is about 93,000 ha which is composed of 36.5% dry farming, 1.4% irrigated farming, 5.3% combination of irrigated farming and orchard land use, 12% open space, 16.6% combination of dry farming and range, 27.3% range, 0.5% urban area, and 0.4% water bodies. The average flow at the outlet of the basin is 2.9 m^3/s, which varies between 0 and 21 m^3/s through the year.

The Satarkhan dam is used to supply water for various regional purposes such as municipal, irrigation, mining and industry. Therefore, the issue of water quality is of great importance. However, uncontrolled entrance of nutrient loads from agricultural fields to the reservoir has resulted in eutrophication and deterioration of the reservoir water quality during recent years. Therefore, the need to utilize water quality management practices has been emerged.

The monthly river water quality and flow data are gathered by the East Azerbaijan Regional Water Company (EARWC). These data are measured at Orang station located at the upstream of the reservoir (Fig. 1) from August 2002 to December 2005 for a period of 41 months. These data are used for development of watershed simulation model.

In the reservoir, one station near dam axis is considered for monthly sampling of nitrogen and phosphorus concentration at about 0.5 m below the water surface. The data are used in calibration and validation of the reservoir water quality model. More detailed information on the data used in this study is provided in Karamouz et al. (2010).

The samples taken from both the river and reservoir were analyzed in the water quality lab of EARWC. The analysis methods were based on EPA method 365.2 for phosphorus and EPA Method 351.3 and 353.2 for nitrogen.

The average TN:TP ratio in the reservoir water based on the measured data from January 2003 to August 2007 is 62. The average ratios in spring, summer, autumn and winter are 101, 66, 37 and 43, respectively. According to USEPA (1990), ratios greater than 10 are indicatives of phosphorus limitation. Therefore phosphorous is the main agent in eutrophication control of the Satarkhan reservoir.

3. Methods

To analyze the uncertainty of the SWAT model parameters including both watershed and reservoir models, a methodology is