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A Bayesian method for multi-pollution source water quality model and seasonal water quality management in river segments

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ABSTRACT

Excessive pollutant discharge from multi-pollution resources can lead to a rise in downriver contaminant concentration in river segments. A multi-pollution source water quality model (MPSWQM) was integrated with Bayesian statistics to develop a robust method for supporting load (I) reduction and effective water quality management in the Harbin City Reach of the Songhua River system in northeastern China. The monthly water quality data observed during the period 2005–2010 was analyzed and compared, using ammonia as the study variable. The decay rate (k) was considered a key factor in the MPSWQM, and the distribution curve of k was estimated for the whole year. The distribution curves indicated small differences between the marginal distribution of k of each period and that water quality management strategies can be designed seasonally. From the curves, decision makers could pick up key posterior values of k in each month to attain the water quality goal at any specified time. Such flexibility is an effective way to improve the robustness of water quality management. For understanding the potential collinearity of k and I, a sensitivity test of k for I_{2i} (loadings in segment 2 of the study river) was done under certain water quality goals. It indicated that the posterior distributions of I_{2i} show seasonal variation and are sensitive to the marginal posteriors of k. Thus, the seasonal posteriors of k were selected according to the marginal distributions and used to estimate I_{2i} in next water quality management. All kinds of pollutant sources, including polluted branches, point and non-point source, can be identified for multiple scenarios. The analysis enables decision makers to assess the influence of each loading and how best to manage water quality targets in each period. Decision makers can also visualize potential load reductions under different water quality goals. The results show that the proposed method is robust for management of multi-pollutant loadings under different water quality goals to help ensure that the water quality of river segments meets targeted goals.

1. Introduction

Effective water quality management requires robust methods for assessing the influence of various point and non-point pollution sources on water quality as well as methods for estimating the expected compliance with water quality goals (Rode et al., 2010; Nigel et al., 2010). Water quality modeling (WQM) is considered an effective approach to support water quality management decisions (Saadatpour and Afshar, 2007; Zou et al., 2007; Qin et al., 2009). Water quality models are necessary auxiliary tools to scientifically assess environmental problems in support of water quality management and decisions, such as total maximum daily load (TMDL) determinations (National Research Council, 2001). A series of equations based on such models can provide decision makers the ability to speculate about environmental changes to evaluate potential outcomes of alternative management actions (Stow et al., 2007).

Three key issues need to be addressed before WQM can be used for practical water quality management: (1) estimation of pollutant load; (2) estimation of model parameters; and (3) assessment of the uncertainties in model development and application (National Research Council, 2001). In recent years, inverse methods have

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been widely applied to settle environmental issues, in applications such as model parameter estimation (Shen and Kuo, 1998; Zou et al., 2007; Liu et al., 2008), non-point source estimation and computational inefficiency of traditional methods for load estimation (Shen et al., 2006; Shen and Zhao, 2010; Chen et al., 2011), groundwater (Michalak andKitanidis, 2004; Vermeulen et al., 2005; Snehalatha et al., 2006), and wastewater systems (Bumgarner and McCray, 2007).

In water quality management problems, uncertainty in potential outcomes of water quality models is difficult to assess, thus, the outcomes may greatly influence the effectiveness of water quality management. Multiple uncertainties exist in environmental system components as well as in their interrelationships (Babaeyan-Koopaei et al., 2003; Robertson et al., 2009). Such uncertainties include the characteristics of natural processes (e.g., precipitation and climate change), river conditions (e.g., stream flow and point/non-point source pollution), the vagueness of targeted water quality objectives, and the errors in estimated modeling parameters (Lia and Huang, 2009). A practical water quality management strategy must then consider: (1) the uncertainties in model structure and parameters; (2) the uncertainties in model output; and (3) the risk of water quality violating targeted standards and adaptive management under uncertainty (Liu et al., 2007); (4) the completeness and availability of historical data ad expert knowledge.

In recent years, Bayesian statistics have been increasingly applied to study uncertainty in water quality modeling. The prominent advantage of Bayesian statistics is their capability in transforming the uncertainty problem into estimated model parameters or loads in terms of a joint posterior distribution. The Bayesian approach can be used to quantify the information the data contain about model inputs, to offer insights into parameter interdependence, to obtain predictions along with credible intervals for model outputs, and to effectively address complex environmental problems (Rode et al., 2010). The Bayesian approach can identify the uncertainty in model parameters, structure, model inputs, and calibration data (Marshall et al., 2005; Spiegelhalter et al., 2002; Liu et al., 2008; Faulkner, 2008; Shen and Zhao, 2010; Patil and Deng, 2011; Alameddine et al., 2011), and is thus an attractive approach to identify and resolve environmental problems. Decision makers can easily assess uncertainty and, accordingly, formulate water quality management strategies using a Bayesian formulation. In addition, Bayesian methods incorporate existing expert knowledge and experiences via the prior distribution (Freni and Mannina, 2010; Neumanet al., 2012), and so can result in more precise estimation than traditional methods do, especially when the observed data are insufficient.

The integration of inverse methods and Bayesian modeling should hold well with the WQM questions mentioned above. The utility of Bayesian methods has been confirmed in many environmental case studies, including ground water quality modeling (Woodbury and Ulrych, 2000), contaminant source identification (Michalak and Kitanidis, 2003), shellfish aquaculture ecosystem modeling (Dowd and Meyer, 2003), non-point source load estimation (Liu et al., 2008), and loading estimation and uncertainty assessment (Chen et al., 2011, 2012). However, this combination has seldom been used in multi-pollution source water quality model and corresponding water quality management.

Many factors can influence downriver water quality, including point sources, non-point sources, and the integrated effect of polluted branches on the river network. For most water resource systems, these multi-pollution sources are correlative, they mutually influence the water quality of the river system. Analyzing the relationship of these factors and assessing their influence on downriver water quality are important for setting up an effective WQM and water quality management plan. The completeness and availability of historical data and expert knowledge are also important for water quality management strategies. Available data can improve the applicability of the model and make it more effective. Expert knowledge can also provide information to improve model estimates.

In this study, a Bayesian approach combined with inverse methods for a river multi-pollution source waster quality model (MPSWQM) was developed to determine practical adaptive water quality management strategies under uncertainty. The methods described in this study provide decision makers with information regarding the uncertainty of the WQM at different time periods for improved water quality management (Mujumdar and Sasikumar, 2002; Nigel et al., 2010). Heavily- polluted segments of the Songhua river system in the Heilongjiang Province in northeastern China were studied. The model results should help local decision makers confirm load reduced amounts of each influencing factor and formulate seasonal water quality management strategies under different water quality goals.

2. Materials and methods

2.1. Study area and data source

The Songhua River system (see Fig. 1, right) originates from Tianchi of the Changbai Mountain in Jilin in northeastern China. The main stream of the Songhua River system runs through the center of Harbin City (the provincial capital of Heilongjiang Province; see Fig. 1, left) from west to east and is the biggest basin for irrigation in this city. Most rivers in and around Harbin City belong to the Songhua River system. The Songhua River system has obvious seasonal dynamics, as there is abundant rain in summer (from June to September) accounting for about 70% of total rainfall in a year, whereas in winter River system remains frozen for almost four months (from December to March).

For better controlling the pollution of the rivers and for convenient water management, the rivers in China are usually divided into different Water Environment Function Areas (WEFA) according to the water quality goals (National People's Congress, 2008). There are three WEFA (here namely segments) in the Harbin Reach of the Songhua River system:(1) Zhushun Village (M_0) to Dongjiang Bridge (M_2); (2) Dongjiang Bridge (M_2) to Dadingzi Mountain (M_5); and (3) Dadingzi Mountain to Yilan. The first two segments cover Harbin City, and the water quality of these two segments is important for the socio-economic development of the city. The Harbin City Reach of Songhua River system (Fig. 1, right), including the two segments (Zhushun Village to Dongjiang Bridge and Dongjiang Bridge to Dadingzi Mountain), is taken here as the main study area. The length of this reach is 39 km.

In recent years, the Harbin City Reach of the Songhua River system has been heavily polluted by both point and non-point pollution sources due to rising population, which has resulted in ecological destruction impacts. Most river segments in the study area cannot meet targeted water quality goals set by the Environmental Protection Bureau (EPB) of Heilongjiang Province. Indeed, the Songhua river system was one of the key river basins identified as needing control of heavy pollution by the Chinese major special project for water pollution control technology formulated in 2012. In this river system, accurate load reduction is highly important for protecting the regional water resource system. Within the study area, gutter and polluted branches are important direct pollution sources for downriver water quality besides conventional point and non-point sources. Hejia gutter (M_1) and Songbei sewage treatment plant (P_1) are the main pollution sources from Zhushun Village to Dongjiang Bridge (segment 1). Hejia gutter is the biggest sewage gutter in Harbin City and receives most non-point pollution sources of this district. There are three main pollution sources from Dongjiang Bridge to Dadingzi Mountain (segment 2), including the Taiping sewage treatment plant (P_2), the Ashi river (M_3), and the Hulan river (M_4). The Ashi river and the Hulan river are two polluted branches of the Songhua River system that receive all point pollution sources and most non-point pollution sources of this district. So in the above two segments, the defined loadings (I) include point sources and most non-point sources of the study area, but some non-point sources were ignored in the present study due to difficulty in calculating the loadings.

The segment 2 (SG_2) is polluted more seriously than segment 1 (SG_1). In this study, all gutter and polluted branches were assumed to be point sources because they were assessed and controlled easily. For each segment, there are several pollution sources, so a robust WQM is desirable to precisely estimate load allocated weights and according reduced ratios for each pollution source. The WQM will be useful for decision makers to control multi-pollution sources and for ensuring that downriver water quality of the segment meets targeted goals.