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Interactive decision procedure for watershed nutrient load reduction: An integrated chance-constrained programming model with risk–cost tradeoff

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A B S T R A C T

Nutrient load reduction is a well-recognized requirement for aquatic ecosystem restoration. However, decision making is difficult due to challenges related to uncertainty and the interaction between decision makers and modelers, including (a) the quantitative relationship between risks arising from different aspects and the fact that cost is not usually revealed and (b) the fact that decision makers are not significantly involved in the modeling process. In this study, an interactive optimal-decision procedure with risk–cost tradeoff is proposed to overcome these limitations. It consists of chance-constrained programming (CCP) models, risk scenario analysis using the Taguchi method, risk–cost tradeoff and feedback for model adaption. A hybrid intelligent algorithm (HIA) integrating Monte Carlo simulation, artificial neural networks, and an augmented Lagrangian genetic algorithm was developed and applied to solve the CCP model. The proposed decision procedure and HIA are illustrated through a case study of uncertainty-based optimal nutrient load reduction in the Lake Qionghai Watershed, China. The CCP model has four constraints associated with risk levels indicating the possibility of constraint violation. Sixteen risk scenarios were designed with the Taguchi method to recognize the interactions between multiple constraint risks and total cost. The results were analyzed using the signal-to-noise ratio, analysis of variance, and multivariate regression. The model results demonstrate how cost is affected by risk for the four constraints and show that the proposed approach can provide effective support for decision making on risk–cost tradeoffs.

1. Introduction

Nutrient enrichment has resulted in the widespread eutrophication of lakes and estuaries worldwide (Hautier et al., 2009; Huisman et al., 2005; Seehausen et al., 1997). The reduction of nutrient inputs is thus urgently needed to restore the health of aquatic ecosystems and to protect drinking water supplies (Conley et al., 2009; Diaz and Rosenberg, 2008). However, the costs of implementing load reduction strategies are substantial. The development of effective decision making about appropriate nutrient-load reduction strategies and the identification of optimal combinations of management strategies are of vital importance.

The optimal decision-making process involves deterministic and non-deterministic decision making. Deterministic decision making is based on the assumption that the system is fully recognized and its states are completely assured; that is, uncertain factors are not considered in this process. The most commonly used deterministic decision-making method in water quality management is linear programming (Revelle et al., 1968; Ogg et al., 1983; Eshleman, 2000). However, in practical situations, uncertainty is inevitable, and a single "optimal" scheme is not appropriate to support decision making (Beck, 1987; Reckhow, 1994; Gallagher and Doherty, 2007). Various sources of uncertainty affect the decision-making process, including (a) the complexity of the targeted system, (b) parameter uncertainty, (c) uncertainties in numerical solutions resulting from incomplete information, and (d) deviations in the judgment and comprehension of stakeholders. The neglect or erroneous estimation of uncertainty will result in

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decision outcomes that deviate from expectations. In the nutrient load reduction decision-making process, minimum cost is estimated under constraints of certain environmental goals. However, the failure to properly consider uncertainty will result in serious problems. Uncertainty can be quantitatively measured as randomness, fuzziness, and intervals (Sengupta et al., 2001). Randomness of parameters can be expressed as stochastic distributions, which can provide more detailed information about parameters than the other two measures. Stochastic analysis is thus used widely to handle parameter uncertainty (Wagner and Gorelick, 1987; He et al., 2006).

Stochastic mathematical programming (SMP) is an effective method for obtaining optimal decisions about stochastic systems. In recent decades, SMP models have been used to tackle probabilistic uncertainties in a broad range of areas (Wets, 1974; Stedinger et al., 1984; Shea and Possingham, 2000; Santoso et al., 2005; Pena-Haro et al., 2011). Chance-constrained programming (CCP), developed by Charnes and Cooper (1959), is a commonly used SMP method to handle randomness of optimization problems. It was designed to determine the optimal decision scheme while allowing for constraint violation with random variables at prescribed possibility levels (Charnes and Cooper, 1959). These constraint-violation possibilities are defined as risk levels in this study. In contrast to deterministic linear programming, CCP permits violation of constraints to some extent; thus, a means of analyzing decision risks from different constraints must be identified. CCP models have been applied widely in water quality management. For example, Huang (1998) proposed a stochastic water-management model based on an inexact CCP method, Wang et al. (2004) applied a CCP model to analyze point–nonpoint source effluent trading in the Lake Taihu watershed, He et al. (2008) involved fuzzy simulation in a CCP model of groundwater remediation, and Gren (2008) studied adaptation and mitigation strategies to control water pollution in the Baltic Sea with a CCP model. These studies have proven the advantages of CCP in assisting optimal decision making under conditions of randomness. Despite the wide application of CCP in decision making, this method has the following limitations.

(a) In the current CCP model, decision makers' aspirations of risk levels were determined in advance. Decision makers have difficulty judging risk ahead of time, without awareness of correlations between risk and cost. They may have high expectations of confidence levels that make the total cost difficult to accept. Thus, modelers have the responsibility of presenting risk–cost tradeoff alternatives to support decision making. More importantly, modelers must revise models in a timely manner upon receiving actual decision requests when decision makers are involved in the modeling process. Otherwise, the gap between modelers and decision makers will lead to unrealistic and infeasible decisions.
(b) In previous studies, constraints of CCP models were usually related to the same predefined risk level (Xu et al., 2009; Zhang et al., 2009; Qin et al., 2010). However, decision makers may have risk bias toward constraints of the optimization model. Moreover, risks from different constraints may have different effects on the objective value. The analysis of multiple constraint risks and risk–cost tradeoffs are thus essential for the development of an optimal CCP model.
(c) The traditional method of solving CCP problems is to convert objective and constraint functions to deterministic equivalent forms (DEFs). However, this process is possible only in certain situations (Liu and Iwamura, 1998; Qin et al., 2010). For complex CCP models, DEFs are usually difficult to identify.

The limitations of the current CCP model in the absence of risk–cost tradeoff and the gap between modelers and decision makers reveal the need for an interactive optimal-decision procedure to present risk–cost tradeoffs in watershed nutrient-load reduction decision making. An innovative optimal-decision procedure with risk scenario analysis under conditions of uncertainty, based on CCP and the Taguchi method, is proposed in this study.

To overcome the limitation of the traditional deterministic equivalent method and to address complex CCP constraints, a more general method, the hybrid intelligent algorithm (HIA), was developed and applied to solve CCP problems under different risk scenarios. This algorithm combined Monte Carlo (MC) simulation (Binder and Heermann, 2010), artificial neural networks (ANNs) (Hsu et al., 1995), and the augmented Lagrangian genetic algorithm (ALGA) (Conn et al., 1991; Srivastava and Deb, 2010).

However, application of HIA to solve CCP models is time-consuming. The traditional method of generating a large number of risk scenarios and selecting an appropriate one results in low-efficiency decision making. In this study, the Taguchi method was used to provide a brief understanding of the association between cost and risk levels for decision makers with a limited number of risk scenarios. Risk aspiration levels were identified by assistance of the risk scenario analysis, and then the final scheme was confirmed by solving the CCP with the specific risk aspiration levels. With this, the calculation period was shortened and decision making became more efficient.

The Taguchi method is a statistical process of experiment design that determines the best combination of control factors. It is usually applied in areas such as engineering design (Ghani et al., 2004) and biochemistry (Venkata Dasu et al., 2003). This study explored a new application of the Taguchi method in analyzing risk scenarios (combination of risk levels for CCP constraints), which was used to design and analyze risk scenarios. Risk–cost tradeoffs were evaluated by comparative analysis of designed scenarios. Scenario design by the Taguchi method was realized by application of orthogonal arrays, whose rows demonstrated different combinations of risk levels.

Some of our previous studies focused on decision making for watershed nutrient load reduction under conditions of uncertainty (Liu et al., 2007, 2008, 2011), but they did not analyze risks from different constraints or implement appropriate tradeoffs between multiple risks and cost. The main objectives of this study were to identify a method that overcomes the above-mentioned shortcomings of the traditional CCP model and to fit this method into an interactive decision procedure with risk–cost tradeoffs. The decision procedure and the corresponding methodology are described and illustrated in detail with an application in decision making for nutrient load reduction in the Lake Qionghai Watershed, China.

2. Material and methods

2.1. Study area and background

Lake Qionghai is the second largest freshwater lake in Sichuan Province, China. The watershed is located at 27°N and 102°E, with an area of 27.88 km^2, capacity of 2.89×10^8 m^3, and normal water level of 1510.3 m above sea level (Liu et al., 2006a,b). Lake Qionghai is on the high-priority decision agenda of the local government for water quality protection because it is now facing the threat of eutrophication. Water and soil loss, which bring large quantities of nutrients to the lake, are also very serious problems because of the special natural conditions. The implementation of nutrient load reduction measures is thus urgently needed to reduce nutrient impacts on the aquatic ecosystem, including water and soil conservation and ecological remediation measures.

To help the local government (Administration of Lake Qionghai, ALQ) make appropriate plans for alternative pollution control measures, the development of a mathematical programming model was necessary to provide scientific decision support. In this paper, a watershed nutrient load reduction programming model was studied in 20 sub-watersheds with the goal of improving water quality and restoring the aquatic ecosystem in the next 15 years. The model developed in this study was