Ecological Modelling 222 (2011) 370–379

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

An inexact-stochastic with recourse model for developing regional economic-ecological sustainability under uncertainty

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ARTICLE INFO

Article history:
Available online 13 January 2010

Keywords:
Decision making
Ecological
Modeling
Optimization
Stochastic with recourse
Sustainability
Uncertainty
Resources management

ABSTRACT

Effective planning of resources management is important for facilitating socio-economic development and eco-environmental sustainability. Such a planning effort is complicated with a variety of uncertain, dynamic and nonlinear factors as well as their interactions. In this study, an inexact-stochastic quadratic programming with recourse (ISQP-R) method is developed for reflecting dynamics of system uncertainties based on a complete set of scenarios as well as tackling nonlinearities in the objective function to reflect the effects of marginal utility on system benefits and costs. Moreover, since penalties are exercised with recourse against any infeasibility, the ISQP-R can support the analysis of various policy scenarios that are associated with different levels of economic consequences when the promised targets are violated. The developed method is applied to a case study of planning resources management and developing regional ecological sustainability. The results have been generated and are helpful for decision makers in not only identifying desired resources-allocation strategies but also gaining insight into the tradeoff between economic objective and eco-environment violation risk.

1. Introduction

Effective planning of resources management is important for facilitating socio-economic development and eco-environmental sustainability. However, achieving a reasonable and efficient management strategy is difficult since many conflicting factors have to be balanced due to complexities of the real-world problems. Ecological destruction, environmental deterioration, and resources shortage often become serious issues when development of economy is over stressed. This is particularly true for many developing countries since rapid economic growth, decentralization, privatization, and related socio-cultural changes are leading to the emergence of a complex decision making environment. In addition, local managers have difficulties in seeking cost-effective and resource-sustainable management alternatives due to the lack of scientific systems analysis tools. Although many optimization models are developed for such a purpose, it is still difficult for decision makers to gain an in-depth insight into the tradeoffs when uncertainties exist in many ecosystem components and their interrelationships. There are many sources of uncertainty in modeling ecosystems due to parameter estimations, input data, and model structure (Lindenschmidt et al., 2007). In detail, the uncertainties may be derived from random feature of resources conditions and natural processes as well as the errors in estimated modeling parameters; uncertainties can also arise due to human-induced imprecision or fuzziness, such as lack of available data and biased judgment (or preferences) in assigning priority factors (weighting levels) to multiple management objectives. Moreover, uncertainties may exist in multiple levels: vagueness and/or impreciseness in the outcomes of a random sample, and randomness and/or fuzziness in the lower and upper bounds of an interval (Krätschmer, 2001; Karmakar and Mujumdar, 2006; Li et al., 2009; Qin and Huang, 2009). Therefore, it is desired that effective modeling tools be advanced to address such complexities and uncertainties.

Previously, there were a number of research efforts focusing on various uncertainties and complexities in resources management and eco-environmental system planning (Trezos and Yeh, 1987; Dupačová et al., 1991; Martin, 1995; Russell and Campbell, 1996; Huang and Loucks, 2000; Seifi and Hipel, 2001; Maqsood et al., 2005; Li et al., 2006; Glenz et al., 2008; Hessea et al., 2008; Zhao et al., 2009). Stochastic mathematical programming (SMP) is a useful tool for modeling decision problems whose coefficients

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doi:10.1016/j.ecolmodel.2009.12.010

(input data) were uncertain but could be represented as chances or probabilities. For example, Pereira and Pinto (1991) proposed a multistage stochastic optimization approach and applied to hydroelectric energy planning, which was based on the L-shaped method by allowing the large-scale problem to be decomposed by scenarios. Watkins Jr. et al. (2000) proposed a scenario-based multistage stochastic programming model for planning water supplies from highland lakes. By explicitly considering a number of inflow scenarios, the stochastic model could help determine a contract for water delivery in the coming year. Maksimovic and Makropoulos (2002) proposed an integrated modeling framework based on distributed hydrological and pollution transport simulation models, ecological health indicators, fuzzy inference, and GIS to analyze the effects of diffused pollution in the Black Sea. Karimi and Hüllermeier (2007) proposed a fuzzy probability approach to assess the risk of natural disasters under highly uncertain environments, where the damage or loss from the disasters was expressed in terms of possibility-probability distributions. Li et al. (2008) proposed an interval-fuzzy multistage stochastic programming method for water resources allocation, where uncertainties were expressed as random variables, intervals and fuzzy sets through constructing a set of scenarios that are representative for the universe of possible outcomes. Williams (2009) discussed uncertainties in natural resources management using Markov decision processes. However, SMP methods required probabilistic specifications for uncertain parameters; the increased data requirements for specifying the parameters' probability distributions could affect their practical applicability. In addition, for real-world management problems, nonlinear relationships could exist among many system components where revenue and cost parameters were expressed as functions of resources demand and supply.

Quadratic programming (QP) can reflect nonlinearity in cost/benefit objectives, and has global optimum under a number of system conditions (Hillier and Lieberman, 1986). Previously, a number of studies for QP were reported (Rockafellar and Wets, 1986; Cui and Blockley, 1990; Tanaka and Ishibuchi, 1991; Shil'man, 1992; Huang et al., 1994). For example, Sugimoto et al. (1995) proposed a parallel relaxation method for handling quadratic programming problems with interval constraints. Lau and Womersley (2001) proposed a stochastic quadratic programming method in which each subproblem was a convex quadratic program with probabilistic information. Chen and Huang (2001) developed an inexact quadratic programming (IQP) model through introducing interval parameters into a QP framework for dealing with uncertainties expressed as intervals. Fliege and Heseler (2002) proposed an efficient method for approximating the solution set of convex quadratic multiobjective programming problems. Ammar (2009) studied a multiobjective quadratic programming problem having fuzzy random coefficient matrix in the objective and constraints, and the decision vector were fuzzy pseudorandom variables. Li and Huang (2009a) advanced an inexact two-stage stochastic quadratic programming method for stream water quality management under uncertainty. However, two-stage stochastic programming method could not adequately reflect the dynamic variations of system conditions, particularly for sequential structure of large-scale problems (Li et al., 2006). In comparison, multistage stochastic programming (MSP) can address the above deficiencies by permitting revised decisions in each time stage based on the information of sequentially realized uncertain events.

Therefore, the objective of this study is to develop an inexact-stochastic quadratic programming with recourse (ISQP-R) method through incorporating techniques of multistage stochastic programming (MSP) and inexact quadratic programming (IQP) within a general framework. The developed ISQP-R can tackle uncertainties expressed in terms of interval values and probability distributions within a multistage context. Moreover, it can not only handle dynamics of system uncertainties based on a complete set of scenarios but also deal with nonlinearities in the objective function such that the effects of marginal utility in the stochastic program can be quantified. Besides, since penalties are exercised with recourse against any infeasibility, the ISQP-R can be used for analyzing various policy scenarios that are associated with different levels of economic consequences when the pre-regulated targets are violated. A case study for resources management and regional ecosystem sustainability will then be provided for demonstrating the applicability of the developed method.

2. Methodology

In many eco-environmental and resources management problems, when uncertainties of the model's right-hand sides are expressed as random variables and decisions need to be made periodically over time, the study system can be formulated as a multistage stochastic with recourse model. In recourse models, decision variables are divided into two subsets: those (first-stage variables) that must be determined before the realizations of random variables are known, and those (recourse variables) that are determined after the random variables are disclosed. Moreover, using the technique in a nested manner allows multistage problems to be decomposed by both scenario and decision period (Birge, 1985). In general, a multistage stochastic linear recourse model can be formulated as follows:

$$\text{Max } f = \sum_{t=1}^{T} C_t X_t - \sum_{t=1}^{T}\sum_{k=1}^{K_t} p_{tk} D_{tk} Y_{tk} \tag{1a}$$

subject to:

$$A_{rt} X_t \le B_{rt}, \qquad r = 1, 2, \ldots, m_1; \quad t = 1, 2, \ldots, T \tag{1b}$$

$$A_{it} X_t + A'_{itk} Y_{tk} \le \widetilde{w_{itk}}, \qquad i = 1, 2, \ldots, m_2; \quad t = 1, 2, \ldots, T; \quad k = 1, 2, \ldots, K_t \tag{1c}$$

$$x_{jt} \ge 0, \qquad x_{jt} \in X_t, \quad j = 1, 2, \ldots, n_1; \quad t = 1, 2, \ldots, T \tag{1d}$$

$$y_{jtk} \ge 0, \qquad y_{jtk} \in Y_{tk}, \quad j = 1, 2, \ldots, n_2; \quad t = 1, 2, \ldots, T; \quad k = 1, 2, \ldots, K_t \tag{1e}$$

where p_{tk} is probability of occurrence for scenario k in period t, with $p_{tk} > 0$ and $\sum_{k=1}^{K_t} p_{tk} = 1$; C_t are coefficients of the first-stage variables (X_t) in the objective function; D_{tk} are coefficients of recourse variables (Y_{tk}) in the objective function; A'_{itk} are coefficients of Y_{tk} in constraint i; $\widetilde{w_{itk}}$ is random variable of constraint i, which is associated with probability p_{tk}; K_t is number of scenarios in period t, with the total being $K = \sum_{t=1}^{T} K_t$.

Obviously, model (1) can deal with uncertainties in the right-hand sides presented as random variables when coefficients in the left-hand sides and in the objective function are deterministic. However, in many real-world resource management problems, results produced by conventional optimization techniques can be rendered highly questionable if the modeling inputs cannot be expressed with precision (Li and Huang, 2009b). Uncertainties are often caused by both the lack of knowledge (i.e. data imperfection) and the variability of models and parameters, while data may contain errors that result from either sampling, measurement or estimation mistakes (Regan et al., 2002). Moreover, uncertainties may relate to the impacts of various management actions, which may alter the model structure and parameters as well as the degree of inherent stochasticity. On the other hand, nonlinear relationships may exist among multiple system components. For example,