Environmental Modelling & Software 25 (2010) 1573–1581

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

A two-stage programming approach for water resources management under randomness and fuzziness

P. Guo [a,1], G.H. Huang [b,d,*], H. Zhu [b,2], X.L. Wang [c]

[a] College of Water Conservancy and Civil Engineering, China Agricultural University, Beijing, 100083, China
[b] Environmental Systems Engineering Program, University of Regina, Regina, SK, S4S 0A2, Canada
[c] School of Civil Engineering, TianJin University, TianJin, 300072, China
[d] North China Electric Power University, Beijing, 102206, China

ARTICLE INFO

Article history:
Received 1 July 2009
Received in revised form
17 April 2010
Accepted 22 April 2010
Available online 9 June 2010

Keywords:
Chance-constrained programming
Decision making
Fuzzy random variable
Fuzzy robust programming
Two-stage programming
Uncertainty
Water resources

ABSTRACT

In this study, a fuzzy stochastic two-stage programming (FSTP) approach is developed for water resources management under uncertainty. The concept of fuzzy random variable expressed as parameters' uncertainties with both stochastic and fuzzy characteristics was used in the method. FSTP has advantages in uncertainty reflection and policy analysis. FSTP integrates the fuzzy robust programming, chance-constrained programming and two-stage stochastic programming (TSP) within a general optimization framework. FSTP can incorporate pre-regulated water resources management policies directly into its optimization process. Thus, various policy scenarios with different economic penalties (when the promised amounts are not delivered) can be analyzed. FSTP is applied to a water resources management system with three users. The results indicate that reasonable solutions were generated, thus a number of decision alternatives can be generated under different levels of stream flows, α-cut levels and different levels of constraint-violation probability. The developed FSTP was also compared with TSP to exhibit its advantages in dealing with multiple forms of uncertainties.

1. Introduction

Water resources management is related to many technical, social, environmental, institutional, political and financial factors (Zarghaami, 2006). However, in the 21st century, the available water resources are becoming over utilized and there is an urgent need to develop sound management plans (Wheida and Verhoeven, 2007). The competitions for water among municipal, industrial and agricultural users have been intensifying. The disparate groups of water users need to know how much water they can expect in order to make appropriate decisions regarding their various activities and investments. If the promised water cannot be delivered due to insufficient supply, users will have to either obtain water from higher-priced alternatives or curb their development plans (Maqsood et al., 2005).

In water resources management, uncertainties that exist in many system parameters could intensify the conflict-laden issue of water allocation among competing municipal, industrial and agricultural interests (Huang and Chang, 2003). The above complexities could become further compounded through not only interactions among the uncertain parameters but also combinations of the uncertainties as presented in multiple formats. In analyzing water resources systems, inexact optimization methods were considered useful for planning water resources systems under uncertainty (Huang and Loucks, 2000; Maqsood et al., 2005; Jung et al., 2006; Li et al., 2006; Dessai and Hulme, 2007; Wu et al., 2007; Guo and Huang, 2009). Two-stage stochastic programming (TSP) is effective for problems where an analysis of policy scenarios is desired and when the right-hand side coefficients are random with known probability distributions. The advantage of TSP is its capability of guiding corrective actions after a random event has taken place. In TSP, a decision is firstly undertaken before values of random variables are known; then, after the random events have happened and their values are known, a second decision is made in order to minimize "penalties" that may appear due to any infeasibility. The TSP methods were widely explored over the past decades (Kall, 1979, 1982; Wang and Adams, 1986; Beraldi et al., 2000; Dai et al., 2000; Huang and Loucks, 2000; Luo et al., 2003; Ahmed

* Corresponding author. Environmental Systems Engineering Program, University of Regina, Regina, SK, S4S 0A2, Canada. Tel.: +1 306 585 4095; fax: +1 306 585 4855.
E-mail addresses: guoping@iseis.org (P. Guo), gordon.huang@uregina.ca (G.H. Huang), wangxl@tju.edu.cn (X.L. Wang).
[1] Tel.: +86 10 68513754.
[2] Tel.: +1 306 501 0126.

1364-8152/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envsoft.2010.04.018

et al., 2004; Maqsood et al., 2005; Guo et al., 2008a). Fuzzy optimization is a flexible approach that permits an adequate solution of real-world problems in the presence of vague information. The fuzzy programming (FP) method considers uncertainties as fuzzy sets and is effective in reflecting ambiguity and vagueness in resource availabilities (Li et al., 2007). The chance-constrained programming (CCP) method was used to deal with random uncertainty information. CCP required that all of the constraints be satisfied in a proportion of cases under given probability levels (Loucks et al., 1981). Previously, a number of research works for FP and CCP methods were undertaken (Huang, 1998; Huang et al., 2001; Liu and Iwamura, 1998; Debjani, 2002; Cooper et al., 2004; Yang and Wen, 2005; Guo et al., 2008b, c, 2009).

However, a remarkable limitation of the aforementioned methods is their incapability in reflecting parameter's multiple uncertainties presented as combinations of fuzzy and probability distributions. In many real-world problems, a number of parameters can hardly be expressed in conventional fuzzy or stochastic formats; instead, they may have characteristics of both probability distributions and fuzzy sets (Luhandjula, 2004). The concept of fuzzy random variable (FRV) was first defined by Kwakernaak (1978, 1979). When the parameters have characteristics of both randomness and fuzziness, the fuzzy random variables would be included in the model. Through the fuzzy random variables, the parameters' multiple uncertainties could be expressed. Therefore, to address fuzzy and probabilistic uncertainties, both fuzzy programming and stochastic programming can be integrated within a general optimization framework (Luhandjula and Gupta, 1996; Luhandjula, 2004, 2006; Liu, 1997, 2001; Katagiri et al., 2005; Liu and Liu, 2005; Huang, 2006).

One potential approach for accounting for various uncertainties in the constraints' left- and right-hand sides is to integrate the fuzzy robust programming (FRP), chance-constrained programming (CCP), and two-stage stochastic programming (TSP) within a general optimization framework. This research aims to develop a fuzzy stochastic two-stage programming (FSTP) method for water resources management under uncertainty. FSTP can handle uncertainties in left-hand sides presented as fuzzy sets and those in right-hand sides as probability distributions and fuzzy random variables. The developed FSTP will then be applied to a case of water resources management to demonstrate its applicability. FSTP can incorporate pre-regulated water resources management policies directly into its optimization process. Thus, various policy scenarios with different economic penalties (when the promised amounts are not delivered) can be analyzed. The developed FSTP will also be compared with TSP to exhibit its advantages in dealing with multiple forms of uncertainties.

2. Modeling formulation

2.1. Problem formulation

The water manager is responsible for allocating the scarce water supply to the competing users within multiple periods. The future availability of this water supply is uncertain. The manager needs to create a plan to effectively allocate the uncertain supply of water to the three users in order to maximize the overall system benefit while simultaneously considering the system disruption risk attributable to the uncertainties. Based on the regional water management policies, an allowable flow level to each user must be regulated. If this level is satisfied, it will result in a net benefit to the system. However, if it is not satisfied, the shortage will lead to a decreased net system benefit. Under such a situation, the shortage amount will be the targeted allocation minus the actual allocation amount. Uncertainties of seasonal water flows presented as probability distributions should also be reflected. The distribution of each seasonal water flow can be converted into an equivalent set of discrete values (Huang and Loucks, 2000). This leads to a two-stage stochastic programming (TSP) problem as follows:

$$\max f = \sum_{i=1}^{m} B_i W_i - \sum_{i=1}^{m} \sum_{j=1}^{n} p_j C_i (W_i - A_{ij}) \tag{1a}$$

subject to

$$\sum_{i=1}^{m} A_{ij}(1+\xi) \le q_j, \quad \forall j \tag{1b}$$

[water availability constraints],

$$A_{ij} \le W_i \le W_{i\,\max}, \quad \forall i \tag{1c}$$

[allowable water-allocation constraints],

$$A_{ij} \ge 0, \quad \forall i, j \tag{1d}$$

[non-negativity and technical constraints]

In model (1), the water-allocation targets (W_i) must be set at the first stage before the stream flows (q_j) are known. The water-allocation plan (A_{ij}) will thus be determined during the second stage when the stochastic stream flows are known. ξ is the loss rate of water process during transportation. The $\sum_{i=1}^{m} B_i W_i$ is the first-stage decision. The $\sum_{i=1}^{m}\sum_{j=1}^{n} p_j C_i (W_i - A_{ij})$ is the second-stage recourse when the random event has happened (Kall, 1979). Model (1) can reflect uncertainties in stream flows presented as probability density functions. However, in many real-world problems, the quality of the uncertain information may be more complex, especially, in large-scale models.

2.2. Methodology

The fuzzy robust linear programming (FRLP) involves the optimization of a precise objective function in a fuzzy decision space delimited by constraints with fuzzy coefficients and capacities (Inuiguchi and Sakawa, 1998). Consider a FRLP problem as follows (Leung, 1988):

$$\min f \cong CX \tag{2a}$$

subject to

$$AX \lesssim B \tag{2b}$$

$$X \ge 0 \tag{2c}$$

where $C \in \{R\}^{1\times n}$ and $X \in \{R\}^{n\times 1}$; $\{R\}$ denote a set of numbers; $A \in \{R\}^{m\times n}$ and $B \in \{R\}^{m\times 1}$ are fuzzy sets; symbols $\simeq$ and $\lesssim$ present fuzzy equality and inequality; Let c_j be the jth element of C, $\tilde{a}_{ij}$ be the ith row and jth line element of A, $\tilde{b}_i$ be the ith element of B, x_j be the jth element of X, and f be the objective's aspiration level.

$$A_1 x_1 \oplus A_2 x_2 \oplus \cdots \oplus A_n x_n \lesssim B \tag{3}$$

where A_j ($j = 1, 2, \ldots, n$) and B are fuzzy subsets, and symbol $\oplus$ denotes the addition of fuzzy subsets. Fuzziness of the decision space is due to uncertainties in the coefficients A_j and B. Letting $\underset{\sim}{U}j$ and $\underset{\sim}{V}$ be base variables imposed by fuzzy subsets A_j and B, we have:

$$\mu_{A_j}: \ \underset{\sim}{U}j \to [0, 1] \tag{4a}$$

$$\mu_B: \ \underset{\sim}{V} \to [0, 1] \tag{4b}$$

where μ_{A_j} indicates the possibility of consuming a specific amount of resource by activity j, and μ_B indicates the possible availability of