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A dual-interval fixed-mix stochastic programming method for water resources management under uncertainty

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ABSTRACT

In this study, a dual-interval fixed-mix stochastic programming (DFSP) method is developed for planning water resources management systems under uncertainty. DFSP incorporates interval-parameter programming (IPP) and fuzzy vertex analysis (FVA) within a fixed-mix stochastic programming (FSP) framework to address uncertain parameters described as probability distributions and dual intervals. It can also be used for analyzing various policy scenarios that are associated with different levels of economic consequences since penalties are exercised with recourse actions against any infeasibility. A real case for water resources management planning of Zhangweinan River Basin in China is then conducted for demonstrating the applicability of the developed DFSP method. Solutions in association with α-cut levels are generated by solving a set of deterministic submodels, which are useful for generating a range of decision alternatives under compound uncertainties. The results can help to identify desired water-allocation schemes for local sustainable development that the prerequisite water demand can be guaranteed when the available water resource is scarce.

1. Introduction

Nowadays, the world population is increasing rapidly and expected to touch 9.30 billion mark by 2050 from 7 billion in 2011, which would result in the desperate need of more agricultural productions to support human life and improve socio-economy (United Nations, 2010; Singh, 2012). However, problems with water resources security resulting from water scarcity are getting more and more serious, particularly in many arid and semiarid regions where development of crops is limited by available water due to low rainfall, runoff, and the uneven temporal distribution (Kirnbauer and Baetz, 2012; Shao et al., 2013). Crop yield cannot achieve the targets when the demand for water exceeds the available amount. The imbalance between increasing consumption and decreasing acquisition of water resources has become a major challenge for the authority. Thus, it is of great importance to make out a sound strategy for water allocation management, which aims at obtaining certain goals such as the maximization of return from cultivated land under the limitation of land and water resources (Barbalios et al., 2013). In fact, in water management problems, uncertainties exist in a number of system components as well as their interrelationship (Li et al., 2009). For example, spatial and temporal variations exist in many system components, such as water requirements, available amount of water, water allocation targets and market situation, which are not easily quantified and not fully controllable. These uncertainties could become further compounded by not only interactions among the uncertain parameters but also their economic implications (i.e. losses and penalties caused by improper water-allocation policies).

Previously, a number of researchers advanced stochastic mathematical programming (SMP) approaches for water resources management problems whose coefficients (input data) were uncertain but could be represented as chances or probabilities (Naadimuthu, 1982; Paudyal and Manguerra, 1990; Vedula and Mujumdar, 1992; Feiring and Sastri, 1998; Paul et al., 2000; Sethi et al., 2006; Li et al., 2008, 2009; Bravo and Gonzalez, 2009; Huang et al., 2012; Zarghami and Akbariyeh, 2012; Su et al., 2013; Anane et al., 2012; Housh et al., 2013). For example, Paudyal and Manguerra (1990) proposed a nonlinear chance-constrained model to resolve a complex problem of agricultural water management with stochastic stream flow. Vedula and Mujumdar (1992) developed a model to obtain an optimal steady state reservoir operating policy for irrigation of multiple crops with stochastic

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inflows and crops water demands (implicitly stochastic) using a stochastic dynamic programming. Feiring and Sastri (1998) offered a stochastic programming model for the evaluation of electricity generation and water supply for agricultural irrigation. Paul et al. (2000) presented a stochastic approach for solving a multi-crop and multi-level irrigation scheduling problem using a dynamic programming decomposition scheme. Sethi et al. (2006) formulated a chance-constrained linear programming model to allocate available land and water resources optimally on seasonal basis so as to maximize the net annual return, considering net irrigation water requirement of crops as stochastic variable. Huang et al. (2012) developed a two-stage interval quadratic programming for supporting agriculture water management and planning in Tarim River Basin, China; water allocation targets and water allocation patterns under different scenarios were optimized and maximized economic net benefit and minimized system-failure risk were evaluated. Among these methods, stochastic dynamic programming (SDP) methods that can account for uncertainties expressed as probability distributions. However, the conventional SDP methods are effective for low-dimensional state problems with dynamic and sequential structures; moreover, in the SDP models, no recourse actions are taken to minimize the economic penalty (due to uncertainty). Two-stage stochastic programming (TSP) is effective for problems where an analysis of policy scenarios is desired and the related data are mostly uncertain; however, it cannot adequately reflect the dynamic variations of system conditions, especially for sequential structure of large-scale problems. In fact, in water management systems, vague information may exist in the objective function and the constraints; results produced by optimization techniques can thus be rendered highly questionable if the modeling inputs cannot be expressed with precision. Although SMP could deal with various probabilistic uncertainties, the increased data requirements for specifying the parameters' probability distributions can affect their practical applicability (Li et al., 2009).

Fuzzy mathematic programming (FMP), based on fuzzy sets theory is effective in dealing with decision problems under fuzzy goal and constraints and in handling ambiguous coefficients of objective function and constraints caused by imprecision and vagueness (Zadeh, 1975; Inuiguchi and Tanino, 2000). Biswas and Pal (2005) presented a fuzzy goal programming method for modeling and solving land-use planning problems in agricultural systems, which optimized production of several seasonal crops in a planning year. Sahoo et al. (2006) proposed a multiobjective fuzzy linear programming model for planning a land–water–crop system, which was used to optimize the economic return, production and labor utilization, and to search the related cropping patterns and intensities with specified land, water, fertilizer and labor availability, and water-use pattern constraints. Zhou et al. (2007) formulated a multiobjective fuzzy crop planning model for determining the optimal crop pattern and water allocation in an irrigated agriculture system, where a number of conflicting objectives (i.e. net economic returns, expected grain yield, and environmental returns) were compromised. Li et al. (2009) proposed a hybrid fuzzy-stochastic programming model to help decision makers identify desired water-allocation schemes for supporting agricultural sustainability when limited water resources were available for multiple competing users. Pal et al. (2012) presented a fuzzy goal programming method for modeling and solving agricultural planning problems, which aimed at allocating the arable land properly and utilizing the available water resources efficiently to achieve the aspiration levels of production of various seasonal crops cultivated in a plan period. In fact, in real-world water management problems, various uncertainties may exist with varied presentation formats in the system components. For example, uncertainties may be estimated as interval values; at the same time, the lower and upper bounds of these intervals may also be fuzzy in nature, leading to dual intervals. However, the conventional FMP methods have difficulties in addressing such a complexity.

Therefore, a dual-interval fixed-mix stochastic programming (DFSP) method will be developed in response to the above challenges. DFSP will incorporate techniques of interval-parameter programming (IPP) and fuzzy vertex analysis (FVA) within a fixed-mix stochastic programming (FSP) framework to deal with uncertainties presented as probability distributions and dual intervals. Then, a real case for water resources management planning of Zhangweinan River Basin in China is then conducted for demonstrating the applicability of the developed DFSP method. It will facilitate dynamic analyses for decisions of water-allocation plans within a multistage context. The results will generate a set of decision alternatives to help decision makers identify water resources management strategies with maximized economic returns and minimized system-failure risk.

The paper will be organized as follows: Section 2 describes the development process of the DFSP method; Section 3 provides a real case study of water resources management planning; Section 4 presents result analysis and discussion; Section 5 draws some conclusions and extensions.

2. Methodology

Firstly, consider a deterministic linear programming (LP) problem as follows:

$$\text{Max} \quad f = CX \tag{1a}$$

subject to:

$$AX \le B \tag{1b}$$

$$X \ge 0 \tag{1c}$$

where $A \in \{R\}^{m\times n}$, $C \in \{R\}^{1\times n}$, $B \in \{R\}^{m\times 1}$, and $X \in \{R\}^{n\times 1}$ form sets of deterministic parameters; $X = (a_{ij})^{m\times n}$, $C = (c_1, c_2, \ldots, c_n)$, $B = (b_1, b_2, \ldots, b_m)^T$ and $X = (x_1, x_2, \ldots, x_n)^T$. However, in real-world decision problems, uncertainties exist in many system components and their interactions. For example, the crop productivity and cost benefit coefficients are often to be presented as intervals. This kind of uncertainty makes it more difficult to quantify the efficiency of any potential water-allocation efforts for agricultural production increment. When uncertainties exist as intervals with known lower and upper bounds, the above problem can be converted into an interval-parameter programming (IPP) model as follows:

$$\text{Max} \quad f = C^{\pm}X^{\pm} \tag{2a}$$

subject to:

$$A^{\pm}X^{\pm} \le B^{\pm} \tag{2b}$$

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

where $A \in \{R^{\pm}\}^{m\times n}$, $C^{\pm} \in \{R^{\pm}\}^{1\times n}$, $B^{\pm} \in \{R^{\pm}\}^{m\times 1}$, $X^{\pm} \in \{R^{\pm}\}^{n\times 1}$; $R^{\pm}$ denotes a set of interval numbers with deterministic lower and upper bounds; the "−" and "+" superscripts represent the lower and upper bounds of parameters (or variables), respectively (Fan and Huang, 2012). In water resources planning problems, the lower and upper bounds of some interval parameters can rarely be acquired as deterministic values (Luciano and Peccati, 2001; Li et al., 2010a). Instead, they may often be given as subjective information by decision makers that can only be expressed as fuzzy sets; this leads to dual uncertainties. For example, decision makers may estimate that there is no possibility for the net benefit value of water to be lower than RMB¥ [450,480] or more than RMB¥ [600,630] per m^3 of water allocated; such a dual interval cannot be addressed through the conventional IPP method. Since FVA is effective for dealing with