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Planning water resources management systems using a fuzzy-boundary interval-stochastic programming method

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ABSTRACT

In this study, a fuzzy-boundary interval-stochastic programming (FBISP) method is developed for planning water resources management systems under uncertainty. The developed FBISP method can deal with uncertainties expressed as probability distributions and fuzzy-boundary intervals. With the aid of an interactive algorithm woven with a vertex analysis, solutions for FBISP model under associated α-cut levels can be generated by solving a set of deterministic submodels. The related probability and possibility information can also be reflected in the solutions for the objective function value and decision variables. The developed FBISP is also applied to water resources management and planning within a multi-reservoir system. Various policy scenarios that are associated with different levels of economic consequences when the pre-regulated water-allocation targets are violated are analyzed. The results obtained are useful for generating a range of decision alternatives under various system conditions, and thus helping decision makers to identify desired water resources management policies under uncertainty.

1. Introduction

The constantly increasing demand for water in terms of both sufficient quantity and satisfied quality has forced planners to contemplate comprehensive, complex and ambitious plans for water resources management systems. In recent decades, water shortage, flood event, unreliable water supply, and poor water quality have led to a variety of adverse impacts on social-economic development and human life. One of the major reasons for these disasters is the lack of efficient, equitable and sustainable water-resources management as well as effective policy instructions from decision makers. Consequently, effective planning of water resources management is important for developing regional and/or national socio-economic sustainability.

Previously, a large number of methods were developed for allocating and managing water resources in more efficient and sustainable ways [2,5,6,17,23,24,26,32,37,42]. For example, Slowinski [43] proposed an interactive fuzzy multiobjective linear programming method and applied it to water supply planning; Huang [19] proposed an interval-parameter programming (IPP) method for dealing with uncertainties expressed as interval numbers in a water resources management system. Bender and Simonovic [3] proposed a fuzzy compromise approach to water resources planning under imprecision uncertainty. Jairaj and Vedula [22] optimized a multi-reservoir system through using fuzzy mathematical programming (FMP) technique, where uncertainties existing in reservoir inflows were treated as fuzzy sets. Faye et al. [15] proposed a fuzzy approach for the short-term of water resource systems under uncertainty. Lee and Chang [28] proposed an interactive fuzzy approach for planning a stream water resources management system that involved vague and imprecise information. Summarily, FMP is effective in dealing with decision problems under fuzzy goal and constraints and handling ambiguous coefficients in the objective function and constraints; however, it has difficulties in tackling uncertainties expressed as probabilistic distributions in a non-fuzzy decision space [21,35]. IPP can handle uncertain parameters that are expressed as intervals with known lower and upper bounds, but unknown membership or distribution functions; nevertheless, when some right-hand-side parameters have wide intervals, the IPP model may not have a feasible solution [18].

As a result, a number of researchers tackled uncertainties in water resources management problems through stochastic programming approaches [16,20,30,31,36,39,41,44–46,49]. For example, Stedinger and Loucks [44] proposed a stochastic dynamic programming model to calculate single reservoir operation, where optimal reservoir operating policies which are subject to reliability constraints could be derived. Pereira and Pinto [39] proposed a stochastic optimization approach for the planning of a multi-reservoir hydroelectric system under uncertainty, through associating a given probability to each of a range of inputs that occurred at different stages of an optimization horizon. Feiring and Sastri [16] advanced a stochastic programming model for planning of a water resources management system with a dual-purpose of generating electricity and supplying water for

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agricultural irrigation. Huang and Loucks [20] developed an inexact two-stage stochastic programming method for water resources management, which could tackle uncertainties expressed as both probability distributions and intervals and account for economic penalties due to infeasibility. Watkins Jr et al. [46] 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. Li et al. [30] proposed an inexact multistage stochastic programming method for water resources management under uncertainty; this method could deal with uncertainties expressed as random variables and interval values through constructing a set of scenarios that were representative for the universe of possible outcomes. In general, multistage stochastic programming (MSP) approach permitted modified decisions in each time stage based on the real-time realizations of uncertain system conditions [1,4,30]. The uncertain information in a MSP was often modeled through a multilayer scenario tree [13]. However, MSP had a difficulty in dealing with uncertain parameters when their probabilistic distributions were not available; moreover, even if these distributions were known, reflection of them in large-scale stochastic models could be extremely challenging [4,14].

In fact, in practical water resources management systems, uncertainties exist in many impact factors and system components such as available resources, water demands/supplies, related cost/benefit coefficients, sustainability requirements, and policy regulations. Some uncertainties can be quantified as probabilities while the others may exist as fuzzy membership functions and/or discrete intervals. For example, stream inflows may be expressed as several random variables with known probabilities; also, the economic data of benefit and cost may not be available as deterministic values, and they may be acquired as interval values. It may often be difficult for a planner to promise a deterministic water-allocation target to user when the available water resources are uncertain. Moreover, the system may possess multiple tributaries and multiple reservoirs where uncertainties can lead to interactive and dynamic complexities in terms of water allocation and flood diversion over a multistage context. The system may face both problems of insufficient capacity to retain the surplus water during the high-flow season as well as to satisfy the demand during the low-flow season (e.g. a serious water shortage could occur when flows are continuously low; while flooding disaster could happen when flows are continuously high exceeding the retention capacities of tributaries and/or reservoirs). An effective approach that cannot only address the above uncertainties and complexities but also hedge against both drought and flooding is desired.

Therefore, the objective of this study aims to develop a fuzzy-boundary interval-stochastic programming (FBISP) method in response to the above challenges. The FBISP will incorporate techniques of interval-parameter programming (IPP), fuzzy programming (FP), and multistage stochastic programming (MSP) to deal with uncertainties expressed as probability distributions and fuzzy-boundary intervals (i.e. the lower and upper bounds of some intervals may rarely be acquired as deterministic values, and they may be fuzzy in nature). A case study will then be provided for demonstrating how the developed method will support the planning for water resources management within a multi-tributary, multi-reservoir and multi-period context. The results obtained can help water resources managers identify desired alternatives against water shortage and flood control with a maximized economic objective.

The paper will be organized as follows: Section 2 describes the development process of the FBISP; Section 3 provides a case study of water resources management planning; Section 4 presents result analysis and discussion; Section 5 draws some conclusions and extensions; the detailed solution method for solving FBISP is introduced in Appendix A.

2. Methodology

The problem, whose coefficients in the objective and constraints are ambiguous and can be expressed as possibility distributions, can be formulated as a fuzzy programming (FP) model as follows:

$$\text{Max}\,\widetilde{f} = \sum_{j=1}^{n} \widetilde{c_j} x_j \tag{1a}$$

subject to:

$$\sum_{j=1}^{n} \widetilde{a_{ij}} x_j \le \widetilde{b_i}, \quad i = 1, 2, \cdots, m \tag{1b}$$

$$x_j \ge 0, \quad j = 1, 2, \cdots, n \tag{1c}$$

where x_j ($j = 1, 2, \ldots, n$) are decision variables; $\widetilde{c_j}$, $\widetilde{a_{ij}}$ and $\widetilde{b_i}$ are fuzzy coefficients of the objective and constraints. The possibility distributions of fuzzy parameters can be characterized as fuzzy sets. For example, fuzzy parameter $\widetilde{a_{ij}} = \left(\underline{a}_{ij}, a_{ij1}, a_{ij2}, \overline{a}_{ij}\right)$ can be presented as a triangular fuzzy set when $a_{ij1} = a_{ij2}$, or a trapezoidal fuzzy set when $a_{ij1} < a_{ij2}$. A fuzzy set ($\tilde{A}$) in $\mathbf{X}$ can be defined as a set of ordered pairs of $\tilde{A} = \{x, \mu_{\tilde{A}}(x) | x \in X\}$, where $\mu_{\tilde{A}}(x)$is named the membership function or grade of membership [50]. The $\mu_{\tilde{A}}(x)$ value ranges from 0 to 1, where 1 represents full membership and 0 denotes non-membership. The closer $\mu_{\tilde{A}}(x)$ is to 1, the more likely it is that an element x belongs to $\tilde{A}$; conversely, the closer $\mu_{\tilde{A}}(x)$ is to 0, the less likely it is that x belongs to $\tilde{A}$ [27,48,50]. Application of the extension principle to fuzzy sets can be viewed as its extension to α-cuts when the membership functions are continuous [10,29]. An α-cut can be defined as the set of elements that belong to fuzzy set $\tilde{A}$ at least to the degree of α, and this degree is also called the degree of confidence (or the degree of plausibility) [11,12]. The vertex method based on α-cut analysis is useful for dealing with fuzzy sets [8–10]. Through using the α-cut concept, each fuzzy variable characterized by a convex membership function can be converted into a group of intervals with various α-cut levels. Then, intervals with the same α-cut level from all fuzzy variables can be processed through interval analysis, resulting in an interval function associated with an α-cut level. The detailed definitions related to fuzzy vertex analysis can be found in a number of literatures [7,9,25,29,34].

In an interval-parameter programming (IPP) model, uncertain parameters are expressed as intervals without any distributional information that is always required in fuzzy and stochastic programming. The IPP allows the interval information to be directly communicated into the optimization process and resulting solution [18]. An IPP model can be written as follows:

$$\text{Max}\, f^{\pm} = \sum_{j=1}^{n} c_j^{\pm} x_j^{\pm} \tag{2a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{\pm}, \quad i = 1, 2, \cdots, m \tag{2b}$$

$$x_j^{\pm} \ge 0, \quad \forall j \tag{2c}$$

where $c_j^{\pm}$, $a_{ij}^{\pm}$ and $b_i^{\pm}$ form sets of interval values with deterministic lower and upper bounds; the '−' and '+' superscripts represent the lower and upper bounds of parameters/variables, respectively. An interactive solution algorithm was proposed by Huang et al. [18] to solve the above problem through analyses of the interrelationships between the parameters and the variables and between the objective function and the constraints. Therefore, when the objective is to be