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Crop planning and water resource allocation for sustainable development of an irrigation region in China under multiple uncertainties

G. Niu[a], Y.P. Li[a,b,*], G.H. Huang[b], J. Liu[a], Y.R. Fan[b]

[a] Sino-Canada Resource and Environmental Research Academy, North China Electric Power University, Beijing 102206, China
[b] Institute for Energy, Environment and Sustainable Communities, University of Regina, Saskatchewan S4S 0A2, Canada

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ABSTRACT

In this study, an interactive two-stage fuzzy stochastic programming (ITFSP) method is developed for supporting crop planning and water resource allocation under uncertainty. ITFSP can effectively address uncertainties expressed as probability distributions and fuzzy-boundary intervals. It can also be utilized for in-depth analyzing different policy scenarios that are integrated with various economic implications since penalties are executed with recourse actions. ITFSP enables decision makers to identify a tradeoff between higher objective values and feasibility of constraints. The ITFSP method is applied to a real case of Hetao irrigation district, one of the largest irrigation districts for food production in China. Different scenarios for crop planning targets which reflect the attitudes of local authority to the available water resources are examined. Results discover that different scenarios lead to changed irrigation patterns, water shortages, penalties, as well as system benefits. Results also reveal that decision makers would be more positive to water allocation to crops of wheat and oil than maize; oil crop always possesses the priority of water allocation and would be partly satisfied even under the low flow. Solutions are useful for determining optimized cropland use and water allocation patterns in such an agricultural system in the arid region, which could hedge appropriately against future available water levels in more profitable and sustainable ways.

1. Introduction

Nowadays, rapid population and economy growth have led to increasing reliance on agricultural production. Development of water resource for agricultural irrigation plays a vital role in guaranteeing food security to provision human life and improves socio-economic development (Sharma and Minhas, 2005; Singh, 2014). However, more and more irrigation districts where demands outstrip agricultural water resource availabilities have suffered from serious shortages, especially for many arid and semi-arid regions where are main features of low rainfall, high evaporation and uneven temporal distribution (Tran et al., 2011; Garg and Dadhich, 2014). The balance between increasing consumption and decreasing acquisition of water resource to realize optimal water allocation has become a major challenge for many authorities. Therefore, sound system planning for agricultural water resource allocation is desired to reduce such conflicts, as well as to obtain certain goals such as economic merits, conserve water, reduce pollution, and food security under the limitation of cropland and water resource (Zhou et al., 2010; Kang and Park, 2014). In fact, agricultural water resource system is related to various uncertainty variables such as soil moisture, rainfall, temperature, resource availability, irrigation quota, economic benefit, and market demand, which are not easily quantified and not fully controllable (Regulwar and Gurav, 2011; Zhang et al., 2011a). In addition, interactions among these uncertain parameters and additional economy implications can further complicate the agricultural water resource system.

In response to the above complexities and uncertainties, a number of stochastic mathematical programming (SMP) methods were proposed for planning water resource systems (Sethi et al., 2006; Li et al., 2011; Housh et al., 2013; Zhang et al., 2014; Akbari et al., 2014; Mun et al., 2015). For example, Marques et al. (2010) developed a two-stage stochastic quadratic programming to optimize farmer's expected revenue and cropping decisions through conjunctive use

* Corresponding author. Fax: +86 10 6177 3887.
E-mail addresses: brandon_j@163.com (G. Niu), yongping.li@iseis.org (Y.P. Li), gordon.huang@uregina.ca (G.H. Huang), zyljing@126.com (J. Liu), yurui.fan@gmail.com (Y.R. Fan).

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of groundwater and artificial recharge, in which hydrology, annual crops, and irrigation technology decisions were treated as a random event. Huang et al. (2012) presented a two-stage interval quadratic programming for supporting agriculture water management in the Tarim River Basin, China, where the available irrigation water was presented as a random variable and the other parameters were expressed as interval values. Two-stage stochastic programming (TSP) is useful for tackling problems where an analysis of policy scenarios is desired and related data are random; however, TSP is incapable of addressing uncertainties exist as vagueness interval due to the quality of information can not satisfactory enough to specify distributions than to define fluctuation ranges (Li et al., 2006).

Fuzzy mathematical programming (FMP) is effective for reflecting ambiguity and vagueness in resource availabilities as well as dealing with decision problems under fuzzy goal and constraints (Zimmermann, 1995; Li et al., 2009; Zhang et al., 2009b). Biswas and Pal (2005) presented a fuzzy goal programming method for planning agricultural land use problems, where total cultivable land, productive resource, production aspiration levels and total expected benefit were fuzzily described and cropping plan of several seasonal crops were optimized. Sahoo et al. (2006) developed a fuzzy multiobjective optimization model for planning an agricultural land-water-crop system to explore the related cropping patterns in an uncertain environment where existed imprecision in fuzzy objectives and fuzzy constraints. Zhang et al., 2009a proposed a hybrid fuzzy possibilistic robust programming approach to help generate decision schemes for agricultural activities by allowing fuzzy information to be directly communicated into the optimization processes and resulting solutions. In fact, in real-world irrigation water management problems, parameters or variables appear in modeling formulation (e.g., water availability, irrigation target and crop/yield production) may be estimated as intervals; at the same time, the lower and upper bounds of these intervals are also fuzzy in nature, which derives dual uncertainties expressed as fuzzy-boundary intervals (Liu et al., 2014). Moreover, decision makers often face conflicting desires of greater objective values and higher constraint feasibility. These complexities have placed many agricultural water management problems beyond the conventional FMP methods. An interactive fuzzy resolution (IFR) approach, based on fuzzy sets theory, is proposed for solving such problems (Jiménez et al., 2007; Wang and Huang, 2013). The advantages of IFR methods include: (1) handling fuzzy-boundary interval parameters; (2) allowing the decision makers to consider in an interactive style and express their preferences in linguistic terms; (3) tackle relationship between the fuzzy left- and right-hand sides of constraints and search the optimal values of the fuzzy objective function. Nevertheless, how to efficiently tackle both multi-uncertainty of data and interactions between objective and constraints has become a major challenge for decision makers.

Therefore, this study aims to develop an interactive two-stage fuzzy stochastic programming (ITFSP) approach through integrating interval-parameter programming (IPP), interactive fuzzy resolution (IFR), and two-stage stochastic programming (TSP) into a general framework. ITFSP method can handle multiple uncertainties expressed as probability distributions and fuzzy-boundary intervals. Then, the ITFSP method is applied to crop planning and water resource allocation of Hetao irrigation region in China. This area is one of the largest irrigation regions for food production in China and is a typical water-deficient region with the features of arid climate, low and uneven distribution rainfall. Results obtained will be used for generating decision alternatives, and thus help decision makers to identify cropland use and water allocation patterns with a maximized economic return and a sustainable development manner.

2. Methodology

2.1. Interval two-stage stochastic programming

Interval-parameter programming (IPP) is an effectively alternative for deal with uncertainties expressed as discrete intervals which not require probability distributions that are hardly describable in practical application. However, IPP encounter difficult for handing two layers uncertainties that interval coefficients with fuzzy sets information. Moreover, it is incapable of incorporate with the subjective information of the authorities into decision-making process (Li et al., 2006). In many realistic agricultural water management problems, since the available water expressed as random variable is uncertain, decision variable is divided into two types, which include decision target must be determined before the realization of random variable, and recourse variable that is determined after the disclosure of random variable. A two-stage stochastic programming (TSP) model for planning water resource systems can be formulated as follows:

$$\text{Maximize} f = \sum_{i=1}^{m} NB_i T_i - E\left[\sum_{i=1}^{m} C_i S_{iQ}\right] \tag{1a}$$

subject to:

(Water availability constraint)

$$\sum_{i=1}^{m} (T_i - S_{iQ})(1+) \le Q \tag{1b}$$

(Water allocation goal constraint)

$$S_{iQ} \le T_i \le T_{i\max}, \forall i \tag{1c}$$

(Non-negativity and technical constraint)

$$S_{iQ} \ge 0, \forall i \tag{1d}$$

where f = objective benefits (RMB¥); NB_i = net benefit to crop i per m3 of water allocated (RMB¥/m3); T_i = promised target of water allocation quantity for crop i (m3); $E[\cdot]$ = expected value of a random variable; C_i = deficit to crop i per m3 of water not delivered, $C_i > NB_i$ (RMB¥/m3); SiQ = water deficit to crop i when the stream flow is Q (m3); Q = the total amount of stream flow (m3); = water loss rate in transport process; $T_{i\max}$ = the maximum allowable allocation for crop i (m3); m = the total number of crops; i = type of crop, i = 1, 2, . . ., m.

The distribution of Q must be approximated by a set of discrete values which for deal with above issues through the linear programming method. Letting Q take values q_j with probabilities p_j (j = 1, 2... n), then have: $E\left[\sum_{i=1}^{m} C_i S_{iQ}\right] = \sum_{i=1}^{m} C_i \sum_{j=1}^{n} p_j S_{ij}$. Meanwhile, parameters such as benefits (NB_i) and penalties (C_i) are seldom expressed as deterministic values. Correspondingly, interval-parameters are introduced into the TSP framework which can allow uncertainties expressed as intervals to be directly communicated into the optimization process. Thus, an interval two-stage stochastic programming (ITSP) model can be formulated as follows:

$$\text{Maximize} f^{\pm} = \sum_{i=1}^{m} NB_i^{\pm} T_i^{\pm} - \sum_{i=1}^{m}\sum_{j=1}^{n} p_j C_i^{\pm} S_{ij}^{\pm} \tag{2a}$$

subject to:

$$\sum_{i=1}^{m} \left(T_i^{\pm} - S_{ij}^{\pm}\right)\left(1+\delta^{\pm}\right) \le q_j^{\pm}, \forall j \tag{2b}$$

$$S_{ij}^{\pm} \le T_i^{\pm} \le T_{i\max}^{\pm}, \forall i, \tag{2c}$$