Ecological Indicators xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ecological Indicators

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

An inexact stochastic-fuzzy optimization model for agricultural water allocation and land resources utilization management under considering effective rainfall

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ARTICLE INFO

Keywords:
Land resources utilization
Agricultural water management
Inexact stochastic-fuzzy programming
Imprecise crops water consumption
Random effective rainfall

ABSTRACT

Agricultural water management faces challenges from ecological environment stress (e.g. water scarcity issues, land resources pressure, and climate conditions) and uncertainties exist among multifarious activities in agricultural water resources management systems. In this study, an inexact stochastic-fuzzy programming model was proposed for irrigation water resources allocation and land resources utilization management under considering multiple uncertainties. In the model, uncertainties can be directly integrated into the optimization process through reflecting parameters and coefficients as interval values, fuzzy sets, random variables, and their combinations. The developed method is applied to planning irrigation water resources allocation and cropland pattern under considering the limited surface water and groundwater, the random effective rainfall, and the imprecise crops water requirements in Jining City. A number of scenarios corresponding to different fuzzy probability of violating constraint are examined in order to obtain the best management program under various scenarios, and search reasonable tradeoffs between varied system benefit and system-failure risk. The results indicated that agricultural water allocation is explicitly affected by uncertainties expressed as randomness and fuzziness, and the results are valuable for supporting the adjustment or justification of the existing water resources management schemes and a desired land utilization plan for regions socioeconomic development under uncertainty.

1. Introduction

Increased population, rapid urbanization process, and mind-bending economic development have cased tremendous ecological environment stress and increasing water demand, and the water scarcity issues are being intensified that have directly influenced agricultural water resources and food security, and regional stable and prosperous development in many areas (Zhang et al., 2008; Singh and Panda, 2012; Zhang and Yang, 2014; Fan et al., 2015a). Moreover, in agricultural water resources system, various uncertainties that exist in many system parameters and their interrelationships, are multiplied by the mixed features of natural variations and human interference, such as random rainfall process, available water and cultivated land conditions, and the complexities in water transferring, irrigation, and crops water requirements (Li et al., 2010; Bryan et al., 2011; Lu et al., 2012a,b; Xie et al., 2013; Juwana et al., 2016). All of these uncertainties could intensify the conflict-laden issue of water resources among multiple crops, and have concern with the effectiveness of agricultural water resources management (Geng et al., 2014). Therefore, effective planning for agricultural water resources management incorporating of uncertainties within a general regional irrigation and cropland utilization optimization framework is desired.

Previously, a number of inexact optimization techniques were proposed for reflecting uncertainties and complexities in agricultural water resources and land utilization management, including interval parameter programming (IPP), fuzzy mathematical programming (FMP), and stochastic mathematical programming (SMP) (Cai and Rosegrant, 2004; Lacroix et al., 2005; Zhang et al., 2009, 2011; Tan et al., 2011; Lu et al., 2009, 2011; Koichi et al., 2013; Liu et al., 2013; Peña-Haro et al., 2011; Li et al., 2014a,b; Chen et al., 2015; Fan et al., 2015b; Dai et al., 2016). For example, Ghahraman and Sepaskhah (2002) proposed a nonlinear stochastic-dynamic programming to derive an optimal convergent reservoir operation schemes for the irrigation of predetermined multiple cropping patterns. Marques et al. (2005) developed a two-

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http://dx.doi.org/10.1016/j.ecolind.2017.09.026
Received 26 June 2017; Received in revised form 10 August 2017; Accepted 13 September 2017

stage economic production model to examine the effects of hydrologic uncertainty and water prices on agricultural production, cropping patterns, and water and irrigation technology use. Lu et al. (2012a,b) proposed a simulation-based inexact rough-interval programming approach for agricultural irrigation management in a China's rural region, where the conjunctive use of multiple water sources is examined under a set of land-area, water-availability, environmental standard, capital, and technical constraints. Li et al. (2013) advanced an inexact two-stage stochastic programming for irrigation water allocation optimization in Minqin County of China, which was derived from incorporation of interval parameter programming within a two-stage stochastic programming framework. Dong et al. (2014) developed an inexact-stochastic programming approach for agricultural water resources planning and land use management, where the inexact modeling approach was integrated with interval parameter programming and chance-constraint programming methods. Li et al. (2014a,b) proposed an inexact stochastic programming model for agricultural irrigation management in Yongxin County of China, where functional intervals were first introduced to deal with water management problems, along with probability distribution functions and conventional intervals to express a variety of parameter uncertainties. Tan et al. (2016) developed a robust interval fuzzy programming approach with superiority-inferiority and risk-aversion analyses for identifying sustainable agricultural and industrial production strategies at the watershed scale in a highly uncertain environment. Cai et al. (2016) proposed an integrated approach through incorporating operational research and uncertainty analysis methods within a general life cycle assessment framework for water resources allocation management.

In general, the above methods have advantages in their effectiveness for dealing with uncertainties in water resources system. However, in many agricultural water resources management problems, several types of uncertainties may exist as multiple levels in a complex system, and the multiple uncertainties characteristics exist among many of irrigation water resources management components, such as such as the vagueness and/or impreciseness in the outcomes of a random rainfall sample, and the randomness and/or fuzziness in the lower and upper bounds of an interval (Liu et al., 2003; Li and Huang, 2009). In addition, the parameters of linear programs such as the right-hand-sides and coefficients of the objective and constraints could be fuzzy random variables due to the fact that they depend on many factors (Nguyen, 2007; Li and Zhang, 2010). Thus, it is difficult to determine exactly the values of these parameters. When applying the above approaches to real agricultural irrigation management problems, difficulties in formulating and solving the resulting agricultural water resources allocation optimization problems under uncertainty arise due to the system multiple uncertainties, and these complexities have placed water resources management programs beyond the conventional systems analysis methods (Huang and Loucks, 2000).

Therefore, as an extension of the previous study, the aim of this study is to develop an inexact stochastic-fuzzy programming (ISFP) for water resources allocation and cropland structure management under multiple uncertainties. In the ISFP, uncertainties can be directly integrated into the optimization process through reflecting the uncertain parameters and coefficients as interval values, fuzzy sets, random variables, and their combinations. Moreover, the developed model will be applied to planning irrigation water resources allocation and cropland pattern under considering surface water, groundwater, effective rainfall, and crops water requirements in Jining City. The City, as a major base of grain-production in China with a comparatively nice natural condition, faces serious ecological environment stress due to increasing demand and decreasing availability, and water shortage is crucial for restricting agricultural development. The generated management strategies from the ISFP model will be used for facilitating decision makers in regulating sustainable development plans.

2. Methodology

An inexact stochastic-fuzzy programming model for regional agricultural water resources management and planning was based on interval-parameter programming (IPP), and stochastic-fuzzy programming. In the ISFP, each technique has its unique contribution in enhancing the capacities for reflecting multiple uncertainties and system risk. For example, the uncertainties presented as discrete intervals (e.g. technical-economic parameters) were reflected through IPP, and the relationship between fuzzy parameter (e.g. crops water requirements) and stochastic information (e.g. effective rainfall) can be reflected by the stochastic-fuzzy programming. The modeling framework would offer feasible and reliable solutions under different fuzzy tolerance levels, which are helpful for decision makers in the future agricultural system development.

2.1. Interval-parameter programming

In interval-parameter programming (ILP), interval values are allowed to be directly communicated into the optimization process (Huang et al., 1992). An IPP model can be defined as follows (Huang, 1996):

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

subject to

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

$$x_j^{\pm} \ge 0 \tag{1c}$$

where $a_{ij}^{\pm} \in \{R^{\pm}\}^{m\times n}$, $b_i^{\pm} \in \{R^{\pm}\}^{m\times 1}$, $c_j^{\pm} \in \{R^{\pm}\}^{1\times n}$, and $R^{\pm}$ denotes a set of interval numbers. Let $x^{\pm}$ be a set of intervals with crisp lower bound (e.g., x^{-}) and upper bounds (i.e., x^{+}), but unknown distribution information. Let x be a set of closed and bounded interval numbers $x^{\pm}$, $x^{\pm} = [x^{-}, x^{+}] = \{t|x^{-} \le t \le x^{+}\}$. The IPP can directly handle uncertainties presented as interval numbers. However, it has difficulties in reflecting uncertainties expressed as probabilistic distributions; moreover, there is a lack of linkage to the economic consequences of violated polices predefined by the authorities (Huang, 1998).

2.2. Inexact stochastic- fuzzy programming

IPP can tackle uncertainties expressed as intervals, but has difficulties in handling stochastic variables with known probability density distributions. In real-world practical problems, the incompleteness or impreciseness of observed information would lead to dual uncertainties of randomness and fuzziness due to the fact that decision makers express different subjective judgments upon a same problem. When uncertainties of some elements in $a_{ij}^{\pm}$ can be expressed as fuzzy sets and those in $b_i^{\pm}$ can be expressed as probability distributions, the inexact stochastic- fuzzy programming (ISFP) problem can be formulated as follows:

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

subject to

$$\sum_{j=1}^{n} \tilde{a}_{ij} x_j^{\pm} \le b_i,\ \forall\ i = 1,2,...,\ i_s \tag{2b}$$

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{\pm},\ \forall\ i = i_s + 1,\ i_s + 2,\ ...,m \tag{2c}$$

$$x_j \ge 0,\ \forall\ j = 1,2,...,\ n \tag{2d}$$