Agricultural Water Management 155 (2015) 53–66

Contents lists available at ScienceDirect

Agricultural Water Management

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

A coupled random fuzzy two-stage programming model for crop area optimization—A case study of the middle Heihe River basin, China

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ARTICLE INFO

Article history:
Received 3 October 2014
Accepted 15 March 2015
Available online 7 April 2015

Keywords:
Random fuzzy variable
Chance-constrained programming
Inexact two-stage stochastic programming
Crop area optimization
Uncertainty

ABSTRACT

Crop area optimization is essential for agricultural water management. However, decision makers are challenged by the complexity of fluctuating stream condition and irrigation quota, varying economic profits and crop yield, as well as grayness and errors in the estimated modeling parameters. A random-fuzzy-variable-based inexact two-stage stochastic chance-constrained programming (RFV-ITSCCP) model is developed for crop area optimization in response to such complexities in more efficient and sustainable ways. The model is capable of tackling parameters' dual uncertainties of both randomness and fuzziness and meanwhile reflecting uncertainties expressed as intervals and probability distributions. Moreover, the developed model is helpful for managers in gaining insight into the tradeoffs between the system benefit and the constraint-violation risk. The RFV-ITSCCP model is applied in crop area optimization in the middle reaches of Heihe River basin, northwest of China. The results provide crop area allocation under various flow levels with the maximum system benefit under uncertainty, minimizing the penalty due to water deficit especially in arid and semi-arid area. The results show that the system efficiency (benefit per unit area) increases by 13.2% than conventional linear programming (LP) model with the most credible fuzzy number values under the same condition of water supply, irrigation regimes and socio-economic conditions, which can demonstrate the feasibility and applicability of the developed RFV-ITSCCP model. Sensitivity analysis is also conducted to analyze the impacts of key model parameters on the results. The obtained results are valuable for supporting the adjustment of the existing crop area patterns and identifying desired crop area schemes under complex uncertainties.

1. Introduction

For many decades, water resources scarcity is getting serious due to the speedy population growth and shift economic development and has become a pressing issue in formulating sustainable development policies (Dai and Li, 2013; Mianabadi et al., 2014). In many countries, agriculture is the largest water consumer, e.g. in China, agricultural water use accounts for 63.6% of the national total water use (The Ministry of Water Resources of the People's Republic of China (MWRPRC), 2013), making agricultural water management become more crucial. Crop area is considered as an important reference data for agricultural water management and plays increasingly significant role in agricultural sustainable development (Cai and Cui, 2009; Singh, 2015). Thus, efficient optimization methods for crop area planning, which can decide how much water should be allocated to different cropped areas in obtaining certain goals such as maximizing/minimizing system's benefit/water-use (Zeng et al., 2010), are desired and beneficial to agricultural water management.

Previously, many real-life case studies about crop area optimization have been addressed during the last three decades (Mainuddin et al., 1997; Ruju and Kumar, 1999; Saker and Quaddus, 2002; Benli and Kodal, 2003; Gorantiwar and Smout, 2005; Sethi et al., 2006; Singh, 2014; Garg and Dadhich, 2014). However, various parameters that are involved in crop area optimization are not easily quantified and not fully controllable which further exacerbates the complexity of crop area planning system (Regulwar and Gurav, 2011). For example, the temporal and spatial variation of stream condition and irrigation quota, the errors in estimating the crop prices and cropping pattern, etc. (Li and Huang, 2011; Cid-Garcia et al., 2014). Accordingly, introducing uncertainty theory into traditional optimization method which can tackle various uncertain factors of parameters and their interrelationship is a sound way to reflect the complexity and reality of crop area optimization system.

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http://dx.doi.org/10.1016/j.agwat.2015.03.013
0378-3774/

In recent years, some scholars have studied the uncertainties for crop area planning. For example, Zeng et al. (2010) proposed a fuzzy multi-objective linear programming (FMOLP) model for crop area planning which can express the fuzzy information effectively. Li et al. (2010) proposed an inexact two-stage water management (ITWM) model for planning agricultural irrigation that could reflect system's gray and random uncertainties and meanwhile reflect tradeoffs between economic benefits and penalties attributed to the violation of irrigation target. Afterwards, Li and Huang (2011), and Dai and Li (2013) respectively improved the uncertain model of Li et al. (2010) by introducing fuzziness and dynamics for agricultural land-use. Such works made good matting for later scholars in crop area optimization. Among which, inexact two-stage stochastic programming (ITSP) model has been proven an effective technique where an analysis of policy scenarios is desired. It can also deal with uncertain coefficients with known probability distributions in the right-hand sides and independent uncertain coefficients in the left-hand sides and the objective function (Maqsood and Huang, 2003; Lu et al., 2009; Li et al., 2010; Li et al., 2011).

However, in real-word decision making, the existence of dual and even multiple uncertainties makes it difficult in obtaining optimal strategies with high randomness and vagueness. For example, a random parameter with certain probability distribution may also be associated with fuzziness (Liu et al., 2013). In crop area optimization, stream condition which can be considered as the major restriction of the final determined crop schemes shows a random feature due to natural conditions, underlying surface and human activities; meanwhile, the statistical information of such a random parameter is affected by data error (e.g. lack of information) and human judgment (e.g. data selection) that could be described as fuzzy set. This complexity has placed crop area optimization beyond the conventional uncertainty analysis methods. In response to this difficulty, random fuzzy variable (RFV) method is capable of describing such variables which presents both probabilistically uncertain and fuzzily imprecise. Recently, RFV method draws attention as a new tool for decision making problems under random fuzzy environments and a serious of solving methods were proposed (Liu, 2002; Liu and Liu, 2002; Ferrero and Salicone, 2004; Zhao et al., 2006; Huang, 2007; Xu et al., 2009; Sinova et al., 2012; Katagiri et al., 2012, 2013). Among which, stochastic fuzzy linear programming (SFLP) method is effectively used to deal with RFV (Katagiri et al., 2013). While SFLP method can be used to tackle variables that are affected by dual uncertainties (i.e. both randomness and fuzziness), it lacks capacity to reflect the risk of constraint violations. Based on this consideration, the coupling of SFLP with chance-constrained programming (CCP), which can effectively reflect the reliability of satisfying (or risk of violating) system constraint under uncertainty, is an extension of SFLP method. Thus the random-fuzzy-variable-based chance-constrained programming (RFV-CCP) method is developed. But few RFV-CCP approaches are applied in crop area optimization. Furthermore, considering the advantages of both ITSP method and RFV-CCP method for crop area optimization, a potential approach is to integrate the RFV-CCP method with the ITSP method to face to the above challenges by identifying the uncertainties of the system more precisely.

Therefore, the aim of this study is to develop a random-fuzzy-variable-based inexact two-stage chance-constrained programming (RFV-ITSCCP) model for crop area optimization through incorporating ITSP with RFV-CCP. The developed model is advantageous in (1) effectively tackling the random fuzzy variables in both sides of the constraints; (2) handling the uncertain parameters described as intervals and probability distributions; (3) permitting in-depth analysis of various inflow scenarios and realizing crop area decisions to minimize penalties when the promised area target are violated after random events have happened. The RFV-ITSCCP model will be applied to a real case study of crop area optimization in the middle reaches of Heihe River basin, China. The generated crop area patterns will demonstrate the feasibility and applicability of the developed model and will be helpful for managers to identify a desired crop area allocation plan under uncertainty.

This paper will be organized as follows: Section 2 describe the development process of the RFV-ITSCCP model; Section 3 provides a real case study to examine the model potential for crop area optimization; Section 4 presents results analysis and discussion; Section 5 draws some conclusions and extensions.

2. Methodology

This section is to develop a RFV-ITSCCP model. It emphasizes on (1): how to integrate RFV-CCP with ITSP within a general optimization framework, leading to RFV-ITSCCP model; (2) how this developed model accounts for economic penalties with recourse against any infeasibilities and handles the multiple uncertainties, including uncertainty expressed as interval numbers, fuzziness, randomness and their combinations; (3) how to solve this RFV-ITSCCP model.

2.1. A double-sided RFV-CCP model

In optimization model, when parameters of constraint present randomness or have large intervals which will lead to highly uncertain solutions, probability distribution can be considered to mitigate this impact. CCP is an effective method to deal with uncertainties at both sides of the constraints when their probability distributions are available as well as to help decision makers to obtain the system's benefit considering the risk of violating uncertain constraints (De et al., 1982; Cooper et al., 2004; Guo et al., 2008). Besides randomness, the parameters at both sides of constraints are usually fuzzy due to objective and subjective factors. This lead to the necessity of coupling RFV with CCP. A double-sided FRV-CCP model can be formulated as follows:

$$\min f(X) \tag{1a}$$

Subject to:

$$Pr\left\{\left[t\left|A_{RFV}(t)X \le B_{RFV}(t)\right.\right]\right\} \ge 1-q \tag{1b}$$

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

where $f(X)$ is objective function and it is a matrix of parameters; X is a vector of decision variables; $Pr\{\bullet\}$ denotes the probability of random event $\{\bullet\}$; $A_{RFV}(t)$ and $B_{RFV}(t)$ are vectors of random fuzzy variables. In this study, $A_{RFV}(t)$ and $B_{RFV}(t)$ respectively obey normal distribution $N(\tilde{m}_A, \tilde{\delta}_A^2)$ and $N(\tilde{m}_B, \tilde{\delta}_B^2)$ on probability space T $(t \in T)$. Other types of probability density functions are out of scope of this paper and will be considered in future research work. $\tilde{m}$ ($\tilde{m}_A$ and $\tilde{m}_B$) and $\tilde{\delta}$ ($\tilde{\delta}_A$ and $\tilde{\delta}_B$) respectively denote the mean value and the standard deviation. $\widetilde{m}$ and $\widetilde{\delta}$ are fuzzy numbers with membership functions $\mu(\tilde{m})$ ($\mu(\tilde{m}_A)$ and $\mu(\tilde{m}_B)$) and $\mu(\tilde{\delta})$ ($\mu(\tilde{\delta}_A)$ and $\mu(\tilde{\delta}_B)$); q ($q \in [0, 1]$) is a given level of probability.

To solve model (1), the (1b) should be transferred from uncertain model into deterministic model by letting $Y_{RFV}(t) = A_{RFV}(t)X - B_{RFV}(t)$, so $Y_{RFV}(t)$ obeys $N\left(\tilde{m}_A X - \tilde{m}_B, \sqrt{(\tilde{\delta}_A)^2 X^2 + (\tilde{\delta}_B)^2}\right)$ and $\frac{Y_{RFV}(t) - (\tilde{m}_A X - \tilde{m}_B)}{\sqrt{(\tilde{\delta}_A)^2 X^2 + (\tilde{\delta}_B)^2}} \sim N(0, 1)$. Thus, $Pr\{[t\left|A_{RFV}(t)X \le B_{RFV}(t)\right.]\} \ge 1-q \Leftrightarrow \tilde{m}_A X + \Phi^{-1}(1-q)\sqrt{(\tilde{\delta}_A)^2 X^2 + (\tilde{\delta}_B)^2} \le \tilde{m}_B$. Where $\Phi^{-1}(1-q)$ is the inverse function of cumulative distribution function of standard normally distributed random variable. The detailed transformation process