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AGWAT-4543; No. of Pages 14
ARTICLE IN PRESS
Agricultural Water Management xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Agricultural Water Management
journal homepage: www.elsevier.com/locate/agwat

Applying uncertain programming model to improve regional farming economic benefits and water productivity

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ARTICLE INFO

Article history:
Received 8 February 2016
Received in revised form 28 June 2016
Accepted 30 June 2016
Available online xxx

Keywords:
Uncertain optimization
Interval numbers
Inexact multi-objective fuzzy programming
Crop area planning

ABSTRACT

The development of optimum crop area planning is valuable for agricultural water management in the arid and semiarid regions. However, the uncertain information existing in the crop area planning system is inevitable, and it cannot be tackled through the traditional multi-objective linear programming model (MOLP). In this study, an inexact multi-objective fuzzy programming model (IMOFP) was developed, considering the multi-objective characteristics, the vagueness associated with the objective functions and constraints, and the interval uncertainty in the parameters. Three objectives were considered including maximizing benefits, minimizing evapotranspiration (ET) and maximizing water productivity (WP). The IMOFP model was applied to solve the problem of crop area planning in Wuwei city of Gansu province in China, and the optimal results under different scenarios of water-saving levels and satisfactory degrees of the decision maker (DM) for available resources were obtained. Different scenarios were also considered to make in-depth analysis of interaction among weight coefficients, economic benefit and water conservation requirement. Moreover, violation variables were introduced to analyze the relationship among system satisfaction, risk level and benefit. Results indicate that using the IMOFP model made the economic benefit, water productivity and water production efficiency of planting in the region increased by 7.05–16.65%, 25.68–33.15% and 39.22–47.59% respectively, and the ET reduced by 20.96–23.10%. Compared to MOLP model, the proposed IMOFP model has advantages in effectively reflecting uncertainties expressed as discrete intervals and fuzzy sets, and can provide reasonable solutions and more stable decision alternatives.

1. Introduction

There is no denying fact that the efficient and sustainable water resources management has become more and more important across the world, especially in arid and semiarid regions where water scarcity keeps growing. Accounting for around 70% of total water withdrawals in the world and 63% in China, the agriculture has been regarded as the largest sector of water-consuming (Kang et al., 2016; Mancosu et al., 2015; Programme, 2012). Irrigated agriculture is essential for guaranteeing food security (Du et al., 2015). Therefore, efficient management of agricultural irrigation water under the limited available water resources and the existing constraints is of paramount significance (Garg and Dadhich, 2014). Crop area planning plays a vital role in agricultural irrigation water management, as it can determine type of crops that should be taken and the area to be utilized for those crops, and decide how much irrigation water should be allocated to those cropped areas, in order to obtain certain goals such as economic benefit, conserve water and food security under the limitation of land and water resources (Niu et al., 2016; Zeng et al., 2010).

Crop area planning problem usually involves with a number of possible and valuable objectives which may conflict with one another. Considering only one objective cannot satisfy the various purposes of local farmers. Traditional multi-objective linear programming model is widely used in dealing with crop area planning problem. And it is considered more superior over the LP model, as it allows for tackling multi-objective. Siskos et al. (1994) used multi-objective linear programming model to determine the optimal area allocation of different crops in a Tunisian region through considering some objectives including maximizing gross margin of profit, employment and forage production, as well as minimizing seasonal labour and tractor utilization. Raju and Kumar (1999) applied multi-objective linear programming model to a case study of Sri Ram Sagar Project, Andhra Pradesh, India, and took into account three conflicting objectives including net benefits, agricultural production and labour employment for optimal cropping

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http://dx.doi.org/10.1016/j.agwat.2016.06.030
0378-3774/

Please cite this article in press as: Li, X., et al., Applying uncertain programming model to improve regional farming economic benefits and water productivity. Agric. Water Manage. (2016), http://dx.doi.org/10.1016/j.agwat.2016.06.030

pattern. In addition, cluster analysis and multicriterion decision-making methods were adopted for selecting the best compromise irrigation plan. Sarker and Quaddus (2002) formulated a goal program model, another multi-objective technique, to tackle with a crop-planning problem, and further discussed the importance of three different goals for a case problem. Sethi et al. (2002) developed a linear programming model to determine optimum cropping pattern and area allocation in regard to the availability of water resources for different seasons. Benli and Kodal (2003) developed a non-linear optimization model for the determination of optimum cropping pattern, water amount and farm income under adequate and limited water supply conditions. Xevi and Khan (2005) applied a multi-objective linear programming model to determine the optimum crop area. The objective functions to be optimized in the problem included maximizing net returns, minimizing variable cost and minimizing total supplementary groundwater pumping requirements.

However, in actual planning practice, several factors and parameters are fraught with uncertainties that cannot be expressed as deterministic values (Montazar et al., 2010; Singh, 2012, 2015; Wang et al., 2015; Zeng et al., 2010). Models taking into account uncertainty are vitally necessary because the traditional mathematical programming models cannot tackle with such problem. Up to now, optimization models under uncertainty can be divided into three categories: stochastic, fuzzy and interval programming. Stochastic programming and fuzzy programming are the two kinds of traditional uncertainty optimization method. For stochastic programming, the uncertain parameters are regarded as random variables through discrete or continuous probability distribution functions to describe. And it requires that the probability distribution functions are known or can be obtained (Darby-Dowman et al., 2000; Kazemi Zanjani et al., 2010; Reddy and Adarsh, 2010; Wang et al., 2015). For fuzzy programming, uncertain parameters are considered as fuzzy numbers which are described by fuzzy membership functions. And it also assumes that fuzzy membership functions are known (Nasseri, 2008; Stanciulescu et al., 2003; Wang et al., 2015; Zeng et al., 2010). These two programming methods can reflect and handle uncertain information which expressed as probability distribution and possibility distribution respectively. A lot of data should be required to establish probability or possibility distribution function. However, acquiring enough uncertainty information for solving the problems is usually very hard or high costs, which would make the two methods contain several limitations on the applicability (Liu, 2002; Wang et al., 2015).

Interval programming is a relatively novel uncertain optimization method, in which uncertain parameters are given in the form of interval numbers. Besides, it is easier than stochastic programming and fuzzy programming in data acquiring. For this method, lower and upper bounds of the uncertain parameters were required to approximate uncertainties. Note that their probability distributions or membership functions were not necessarily known, which makes it more convenience in uncertainty modeling. As Interval programming models have received increasing attention in recent years, a number of models such as interval linear programming, interval multi-objective programming, interval nonlinear programming, and interval mixed integer programming have been developed (Bass et al., 1997; Huang et al., 1992; Rosenberg and Lund, 2009; Wu et al., 2006). Moreover, wide ranges of hybrid models were proposed to address the problems in which multiply types of uncertainties exist (Guo et al., 2014; Li and Guo, 2015; Niu et al., 2016; Wang et al., 2015).

In crop area planning, many parameters such as crop yield, evapotranspiration, irrigation quota and price are uncertain due to natural and market factors. And it is difficult to obtain enough historical data for some parameters, so their probability distributions or membership functions cannot be known. Instead, they are varying within a specific range, and only intervals can be identified. In this case, these data could be given as interval numbers that are useful and easy to be obtained. Moreover, some goals or constraints may not be expressed precisely due to not precisely defined of utility function or only be described in a fuzzy way of the decision problem (Gupta et al., 2000). For instance, the linguistic expression called "approximately equal to" rather than "equal to" (or "approximately satisfactory" rather than "satisfactory") is more acceptable to the decision maker. In such a situation, it would be more appropriate that using fuzzy goals and fuzzy constraints to denote goals and constraints (Zeng et al., 2010).

Taking into account the uncertainty, considerable work has been done for addressing the parameter uncertainties in crop area planning. For example, Itoh et al. (2003) proposed a model of crop planning with profit coefficients for agricultural products as stochastic values. Toyonaga et al. (2005) presented a crop planning model for agricultural management under uncertainty through considering the profit coefficients as discrete randomized fuzzy numbers. Sahoo et al. (2006) developed the linear programming and fuzzy optimization models considering three conflicting objectives for planning and managing of the land-water-crop system of Mahanadi-Kathajodi delta in eastern India. Kakhki et al. (2009) developed the fuzzy multi-objective linear fractional programming (FMOLFP) to determine optimal crop pattern for reducing the hazards of environment. Regulwar and Gurav (2010) developed the multi-objective fuzzy linear programming (MOFLP) irrigation planning model that deals with fuzziness in four objective functions and worked out the compromised solution under fuzzy environment. Regulwar and Gurav (2011) presented a study on irrigation planning under uncertainty considering different cases using MOFLP model. Regulwar and Gurav (2012) considered the fuzziness of all the coefficients in the proposed MOFLP model and taken into account the experience, information and expectations of the decision maker (DM) to solve the problem of optimal cropping pattern in an irrigation system based on fuzzy parametric programming. Regulwar and Gurav (2013) developed two phase multi-objective fuzzy linear programming (TPMOFLP) approach for crop planning in the same irrigation system, and found that there was a significant increase in the value of level of satisfaction compare to that of MOFLP model. Regulwar and Gurav (2014) formulated single objective fuzzy linear programming (SOFLP) irrigation planning model for deriving the optimal cropping pattern plan with the objective of minimizing the cultivation cost and maximizing the net benefits. Zeng et al. (2010) proposed the fuzzy multi-objective linear programming (FMOLP) model with triangular fuzzy numbers, and solved it by transforming the FMOLP model and its corresponding fuzzy goal programming (FGP) problem to crisp ones. The model was applied to the crop area planning in Liang zhou region, Gansu province of northwest China, and then the optimal cropping patterns under different water-saving levels and satisfaction grades for water resources availability of the decision maker (DM) were obtained. El Sayed (2012) used a fuzzy goal programming (FGP) approach to determine the optimum cropping mix in Egypt. In this model formulation, five goals including crop production, net profit, investment, fertilizers and water requirements were modeled. Li (2013) respectively developed three different kinds of programming models: an inexact fuzzy chance-constrained fuzzy linear programming (IFCCFLP) model, a fuzzy optimization theory based fuzzy linear multi-objective programming (FOB-FLMP), and a multi-objective fractional programming (MFP) model. Those models were applied to the planning of planting configuration in Minqin County of China respectively. Zhang et al. (2014) developed an interval-parameter fuzzy linear optimization model (IPFLP) for crop area allocation management, and applied it to Shiyang river basin, China.