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An inexact robust two-stage mixed-integer linear programming approach for crop area planning under uncertainty

Chenglong Zhang [a], Bernard A. Engel [b], Ping Guo [a, *], Fan Zhang [a], Shanshan Guo [a], Xiao Liu [a], Youzhi Wang [a]

[a] *Center for Agricultural Water Research in China, China Agricultural University, Beijing, 100083, China*
[b] *Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN, 47907, USA*

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ABSTRACT

This study presents an inexact robust two-stage mixed-integer linear programming (IRTMLP) approach for crop area planning under uncertainty. The approach is developed by incorporating the techniques of interval parameter programming, robust optimization method, and mixed-integer linear programming within a two-stage stochastic programming optimization framework. In the IRTMLP, uncertainties presented in terms of probability distributions and discrete intervals can be reflected. Moreover, the approach improves upon the previous stochastic programming method and thus has the following four major advantages. First, the IRTMLP approach can incorporate pre-defined irrigation water policies directly into its optimization framework, and second, it can readily facilitate dynamic analysis of water-saving irrigation pattern planning for irrigation water management. Third, it can explicitly account for the variability of the second-stage variables within a conventional two-stage stochastic programming context. Fourth, it can generate more flexible solutions under different robustness levels. The IRTMLP approach is applied to a case study of crop area planning in the middle reaches of the Heihe River Basin, northwest China. Therefore, a variety of decision alternatives for binary and continuous variables can be generated by giving different robustness levels, which will demonstrate how the developed approach can provide desired and stable solutions. In addition, the results can support in-depth analysis of the interrelationships among system benefits, robustness levels and the system-failure risk levels. These results can provide more reliable scientific basis for supporting irrigation water management under arid and semiarid environments.

1. Introduction

In recent years, booming population growth, environmental pollution and naturally dry conditions have undoubtedly exacerbated water shortage problems in arid areas (Elliott et al., 2014). Moreover, the rapid development of industrial and agricultural industries also lead to water shortages. Meanwhile, when agricultural irrigation water is being reduced by water shortages, illegal groundwater overexploitation activities have occurred, which will directly affect regional ecological security and sustainable development (Zhang and Guo, 2017). Therefore, in the arid inland river oasis area dominated by irrigated agriculture in northwest China, it is necessary to optimize irrigation water allocation and crop area planning (Georgiou and Papamichail, 2008). Furthermore, crop area planning is essential for irrigation water management, which can determine how much water should be allocated for different crops to different subareas with limited land and water resources (Zeng et al., 2010).

Although remarkable contributions have been made in optimization techniques, generating optimal solutions to irrigation water management problems under uncertainty remains a challenging issue. For the crop area planning problem, optimization becomes more complicated with the inherent system uncertainties. For example, the determination of irrigation targets, irrigation patterns, and the randomness of runoff inflow, market price and national policies may be uncertain. Moreover, the interrelationships of these different forms of uncertainty and the impact of economic factors also render research more complex (Li et al., 2010).

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* Corresponding author. Center for Agricultural Water Research in China, China Agricultural University, Tsinghuadong Street No.17, Beijing, 100083, China.
E-mail addresses: engelb@purdue.edu (B.A. Engel), guop@cau.edu.cn (P. Guo).

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Therefore, how to effectively reflect and address these uncertainties in the optimization model is indeed needed. Recently, many researchers have studied optimal irrigation water resources management under uncertainty (Marques et al., 2005; Schoups et al., 2006; Li et al., 2010; Lu et al., 2011; Huang et al., 2012; Dai and Li, 2013; Guo et al., 2014; Yang et al., 2015; Li et al., 2016a; b). In these optimization methods, the interval two-stage stochastic programming (ITSP) method is commonly adopted, which is derived by incorporating interval parameter programming into a two-stage stochastic programming general framework. The ITSP can reflect uncertainties expressed in terms of probability distributions and discrete intervals. More importantly, its main advantage lies in illustrating the tradeoff associated with conflicting system benefits and the associated penalties because of the violation of the pre-defined policies. The decision variables of a problem under uncertainty are partitioned into the following two sets. The first-stage decision variables should be decided before the realization of the uncertain events. Subsequently, when the random events have occurred, the corrective actions known as recourse can be undertaken for further policy improvements, and it is also referred to as second-stage variables (Ahmed and Sahinidis, 1998). Therefore, the objective function is to maximize the sum of first-stage benefits and the expected value of the random second-stage resources penalties. However, it should be noted that the standard two-stage stochastic programming method is based on the assumption that the decision-maker is risk neutral (Takriti and Ahmed, 2004). It cannot address the variability of the uncertain recourse variables (i.e. second-stage variables), especially in a high-variability environment.

In response to the above tradeoff between the expected value of the second-stage variables and the associated variability, Mulvey et al. (1995) initially proposed the concept of robustness. However, this method makes it highly difficult be solved due to nonlinearities in the two-stage stochastic programming optimization formulation. Ahmed and Sahinidis (1998) thus proposed a robust optimization framework through a linear programming technique by introducing a goal programming weight (i.e. ρ). It can balance the relative importance of the expected values and variability of the second-stage variables in the objective function via a weighted variability contribution. Generally, the proposed framework has been widely used to apply to power-system capacity planning, chemical-process planning (Ahmed and Sahinidis, 1998), telecommunications-network design (Laguna, 1998), financial planning (Mulvey et al., 1995), and water resources management (Chen et al., 2013). However, few applications of the robust optimization method to crop area planning have been undertaken. Furthermore, it does not address dynamic analysis where integer variables are needed to indicate whether a particular facility development or expansion choice should be done.

In particular, especially in the arid inland river oasis area dominated by irrigated agriculture, the adoption of water-saving technology can help reduce irrigation water demand, improve water use efficiency and alleviate the situation of water shortage (Blanke et al., 2007). For example, technologies are currently being used to improve water retention in soil, production of biochar (Maroušek et al., 2015) and their use as soil improver (Smetanová et al., 2013; Maroušek et al., 2016, 2017). Therefore, a related optimization analysis will require the use of integer variables to indicate whether or not a particular water-saving irrigation pattern is to be adopted. For this reason, the integer variables will be introduced into the optimization model. If integer and continuous variables exist together in the programming and thus mixed-integer linear programming is used for addressing this purpose (Huang et al., 1995; Zhang and Guo, 2018). Therefore, one potential approach to better account for these complexities and uncertainties of water-saving irrigation pattern planning, system benefits, robustness levels and risk levels is to incorporate techniques of robust optimization and mixed-integer linear programming into the ITSP optimization framework.

Therefore, the primary objective of this study is to develop an inexact robust two-stage mixed-integer linear programming (IRTMLP) approach for crop area planning under uncertainty. The IRTMLP approach can effectively integrate uncertainties expressed as both discrete intervals and probability distributions into its solution process. In detail, it has advantages in: (1) incorporating pre-defined irrigation water policies directly into its optimization framework; (2) facilitating dynamic analysis of water-saving irrigation pattern planning for irrigation water management; (3) accounting for the variability of the second-stage variables within a conventional two-stage stochastic programming context and (4) generating more flexible solutions by giving different robustness levels. The IRTMLP approach is applied to a case study of crop area planning in the middle reaches of the Heihe River Basin, northwest China. Two scientific hypotheses will be tested: firstly to verify the impact of robustness levels on model results and secondly to examine whether or not water-saving irrigation pattern is adopted for each crop in each subarea. Therefore, a variety of decision alternatives for binary and continuous variables can be obtained to provide decision support for desired irrigated crop area plans with maximized system benefits. These results will support in-depth analysis of the interrelationships among system benefits, robustness levels and the risk levels.

2. IRTMLP modeling formulation

The general framework of the inexact robust two-stage mixed-integer linear programming (IRTMLP) approach is shown in Fig. 1. The detailed modeling formulation of the IRTMLP approach is presented in sections that follow.

2.1. Interval two-stage stochastic programming (ITSP)

A general two-stage stochastic programming model is presented as follows:

$$\text{Max}\, f = Cx + E[Q(x,\omega)] \tag{1a}$$

subject to

$$Ax \le b \tag{1b}$$

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

where f is the objective function, and C is the vector of coefficients that belongs to $\Re$. x is the first-stage decision variables, ω is the random variable that belongs to random event Ω, and $Q(x,\omega)$ is the expected value of the following nonlinear programming. A and b are coefficients. Thus, $Q(x,\omega)$ can be written as follows:

$$\min q(y,\xi) \tag{2a}$$

subject to

$$W(\xi)y = h(\xi) - T(\xi)x \tag{2b}$$

$$y \ge 0 \tag{2c}$$

where y is the second-stage decision variable, and $q(y,\xi)$ presents the expected value of the second-stage decision variables.