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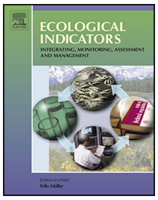

Original Articles

An inexact CVaR two-stage mixed-integer linear programming approach for agricultural water management under uncertainty considering ecological water requirement

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ABSTRACT

In this study, an inexact CVaR (conditional value-at-risk) two-stage mixed-integer linear programming (ICTMLP) approach is developed for agricultural water management under uncertainty considering ecological water requirement. Techniques of interval parameter programming (IPP), two-stage stochastic programming (TSP), CVaR and integer programming (IP) are jointly incorporated into the general optimization framework. The developed model can deal with uncertainties presented as discrete intervals and probability distributions. It has advantages in: (1) considering economic benefits and risk in the objective function simultaneously, (2) reflecting the tradeoffs between conflicting economic benefits and penalties due to violated policies, (3) facilitating dynamic analysis of decision making and (4) generating more flexible solutions under different risk-aversion levels. The model is applied to a realistic case study of agricultural water resources allocation in the middle reaches of Heihe River Basin, northwest China, where three scenarios with different types of ecological water requirements are taken into account. Therefore, optimal water allocation solutions from the ICTMLP model can support in-depth analysis of interactions among economic benefits, violated policies and risk-aversion levels. Moreover, these results are useful for helping decision makers find better decision alternatives to support regional ecological protection and agricultural production.

1. Introduction

Under the condition of limited water resources, it is urgent to implement an effective agricultural water resources management to maximize the system economic benefits and increase the water production efficiency (Shangguan et al., 2002; Qadir et al., 2003; Valipour et al., 2015). Furthermore, a series of environmental problems have been encountering in arid area of northwest China, which is a comprehensive outcome of the intensified contradictions between the agricultural water use and the ecological water use. Additionally, many researchers mainly focus on agricultural water resources management to optimize the economic aspects but less consider the ecological aspects (Dick et al., 2014; Martín-López et al., 2014; Li and Guo, 2015). Ecological water requirement generally means the amount of water at which the environmental quality can be improved or may not be further deteriorated. It is not only an evaluating indicator to diagnose the health regime of ecosystem but also a basis to optimize water resources (Zhao and Cheng, 2002). Therefore, in this region, it is necessary to sustainably utilize regional water resources, to develop water-saving agriculture, and to optimize irrigation management practices considering regional ecological water requirements (Ewing et al., 2012; Gleeson et al., 2012; Cheng et al., 2014).

Previously, many researchers had proposed a series of optimization methods/applications for agricultural water resources management (Richter et al., 2003; Cai and Rosegrant, 2004; Schlüter et al., 2005; Gordon et al., 2010). However, these methods were incapable of addressing various uncertainties existing in the agricultural water management problems. Many system components such as market prices, irrigation targets, irrigation quota and water availability may be uncertain and cannot be expressed as deterministic values accurately. Moreover, such parameters can become more complicated because of their interactions and associated economic penalties if the promised targets are violated (Li and Huang, 2008; Dai et al., 2014; Li and Guo, 2015). Therefore, these uncertainties and pre-regulated policies are indeed needed

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to be incorporated within the planning system to make a desired alternatives to achieve optimal water allocation.

In response to the above complexities and uncertainties, inexact optimization techniques were developed for supporting water resources management and planning within an integer programming framework (Li et al., 2007; Guo et al., 2010; Wang and Huang, 2013). Among these methods, inexact integer programming (IIP) can address uncertainties in the model and accommodate integer decision variables. However, IIP has difficulties in reflecting tradeoffs between conflicting economic benefits and associated penalties because of violated policies. Therefore, a two-stage mixed-integer linear programming (TMLP) model was formulated by incorporating IIP into two-stage stochastic programming (TSP) framework to deal with random uncertainties and integer variables in planning problems. For example, Guo et al. (2010) proposed an inexact fuzzy-chance-constrained two-stage mixed-integer linear programming approach for flood diversion planning under multiple uncertainties; Wang and Huang (2013) developed a two-stage mixed-integer fuzzy programming with interval-valued membership functions approach for flood-diversion planning. Li and Guo (2014) proposed a multi-objective optimal allocation model for irrigation water resources under multiple uncertainties considering integer programming. Nevertheless, there is a limitation in the traditional two-stage stochastic programming model because it is risk neutral and it considers optimization as an expected criterion (Ahmed, 2004; Dai et al., 2014). The TMLP model only takes the maximum/minimum expected values as the objective function without considering the effects of the variability of random variables. Besides, in the second-stage decision variables, TMLP model only considers the expected loss/penalty due to the violated policies and ignores the risk caused by the random variables.

Conditional value-at–risk (CVaR) model can effectively quantify risks based on known probability distributions of random variables, which is enhanced from a value-at-risk model and has been widely used for risk measure (Rockafellar and Uryasev, 1999; Hsu et al., 2012). For example, Yamout et al. (2007) studied the effect of incorporating the conditional value-at-risk (CVaR) for water resources allocation problem using two-stage stochastic programming; Shao et al. (2011) developed a conditional value-at-risk (CVaR) based inexact two-stage stochastic programming (CITSP) model for supporting water resources problems under uncertainty; Xie and Huang (2014) developed a risk-averse inexact two-stage stochastic programming model for supporting regional water resources management. These studies have made significant contributions to water resources management and risk aversion. However, few studies/applications for agricultural water resources management under uncertainty considering ecological water requirements within a CVaR model framework have been undertaken. Furthermore, in many realistic cases, the quality of available information may be not satisfactory enough to be expressed as probabilistic distributions. These uncertainties can only be obtained as interval parameters rather than probabilistic distributions, the abovementioned model may also become inapplicable.

Therefore, one potential approach for better accounting for these complexities and uncertainties associated with ecological aspects will be to jointly integrate techniques including interval parameter programming (IPP), two-stage stochastic programming (TSP), conditional value-at-risk (CVaR) and integer programming (IP) into the general optimization framework. This leads to an inexact CVaR two-stage mixed-integer linear programming (ICTMLP) model. The developed model can deal with uncertainties presented as discrete intervals and probability distributions. It has advantages in: (1) considering economic benefits and risk in the objective function simultaneously, (2) reflecting the tradeoffs between conflicting economic benefits and penalties due to violated policies, (3) facilitating dynamic analysis of decision making and (4) generating more flexible solutions under different risk-aversion levels. The model will be applied to a realistic case study for agricultural water management under uncertainty considering ecological water requirements in arid area of northwest China. Three scenarios corresponding to different types of ecological water requirement will be examined. Therefore, a desired water allocation plan for agricultural irrigation under uncertainty considering different ecological water requirements can be identified. Optimal solutions are useful for supporting regional agricultural and ecological sustainability.

2. Model formulation

Fig. 1 presents the framework of the inexact CVaR two-stage mixed-integer linear programming (ICTMLP) model. This model incorporates techniques interval parameter programming (IPP), integer programming (IP), conditional value-at-risk (CVaR) and two-stage stochastic programming (TSP) into a general optimization framework. Each method plays a specific role in dealing with variables, uncertain information and risk-aversion. For example, TSP is an effective method for problems where policy scenarios analysis are needed and the related uncertainty is random. IPP reflects the uncertainty presented as discrete interval values, IP can address binary decision variables for facilitating dynamic analysis of decision making, CVaR model can not only handle the expected loss considering the effects of the variability of random variables, but also quantify the associated risks. The detailed formulation of the developed ICTMLP model can be written as follows:

2.1. Two-stage stochastic programming

Two-stage stochastic programming (TSP) model can reflect the tradeoffs between pre-regulated policy and the associated economic penalty due to any infeasible event, and the fundamental concept includes recourse and adaptive adjustments. A general TSP model can be formulated as follows:

$$\max f = cx - E\left[Q\left(x, \omega\right)\right] \tag{1a}$$

subject to

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

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

In Eq. (1a), f is the objection function, where c is the vector of coefficients that belongs to $\Re$, and x is the first-stage decision variable, ω is the random variable ($\omega \in \Omega$), and $Q\left(x, \omega\right)$is the expected value of the following nonlinear programming. The inequalities (1b) and (1c) are constraints of the model, where A and b are the coefficient. $Q\left(x, \omega\right)$ can be written as follows:

$$\min q\left(y, \omega\right) \tag{1d}$$

subject to

$$W\left(\omega\right) y = h\left(\omega\right) - T\left(\omega\right) x \tag{1e}$$

$$y \ge 0 \tag{1f}$$

where y is the second- stage decision variable. $q\left(y, \omega\right)$ denotes the second-stage cost function and $\left\{T\left(\omega\right), W\left(\omega\right), h\left(\omega\right) | \omega \in \Omega\right\}$are random model parameters corresponding to their dimensions, they are the functions of the random variable ω.

Model (1) is a two-stage stochastic programming model without considering the effects of variability of random variables. The variability of random variables will directly lead to the risk of decision, a better method for risk measure is CVaR model.

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