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A hybrid fuzzy-stochastic programming method for water trading within an agricultural system

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ABSTRACT

In this study, a hybrid fuzzy-stochastic programming method is developed for planning water trading under uncertainties of randomness and fuzziness. The method can deal with recourse water allocation problems generated by randomness in water availability and, at the same time, tackle uncertainties expressed as fuzzy sets in the trading system. The developed method is applied to a water trading program within an agricultural system in the Zhangweinan River Basin, China. Results can reflect the decisions for water allocation and crop irrigation under various flow levels; this allows corrective actions to be taken based on the predefined policies for cropping patterns and can thus help minimize the penalty due to water deficit. The results indicate that trading can release excess water while still keeping the same agricultural revenue obtained in a non-trading scheme. This implies that trading scheme is effective for obtaining high economic benefit, particularly for one water-resources scarcity region. Results also indicate that the effectiveness of the trading program is explicitly affected by uncertainties expressed as randomness and fuzziness, which challenges the users to make decisions of their water demands due to uncertain water availability. Sensitivity analysis is also conducted to analyze the impacts of trading costs, demonstrating that the trading efforts could become ineffective when the trading costs are too high.

1. Introduction

Over the past decades, controversial and conflict-laden water resources allocation issue has challenged decision makers due to rising demand pressure for freshwater associated with a variety of factors such as population growth, economic development, food security, environmental concern, and climate change. Shrinking water availability and deteriorating water quality have exacerbated such competitions, leading to complexities in generating desired decisions for usable freshwater allocation. Practically, around 70% of global freshwater diverted to agriculture and, at the same time, irrigation water demand is still increasing because the farmland being irrigated continues to be expanded (Cai et al., 2003). Water shortage is subject to increasing pressure particularly for many semi-arid and arid regions that are mainly characterized by low rainfall and high evaporation. When the demand for water has reached the limits of what the natural system can provide with, water shortage may become a major obstacle to social and economic development for the region. Awareness of growing water scarcity has led to increasing interest in modeling of water resources systems, both in terms of supply and demand, with the aim of developing and implementing appropriate water resources infrastructure and management strategies (Davies and Simonovic, 2011).

Market-based approach to water allocation problem has been advocated, which has been expected to provide gains in economic efficiency since water can be reallocated from lower- to higher-value when water becomes increasingly scarce (Turral et al., 2005). Water trading, which is market-based strategy and can provide cost-effective and flexible-reallocation compliance in watershed, has been recognized as one of the most promising policy alternatives for addressing water shortage problems. Trading helps equalize the marginal prices faced by various water users, thereby providing information about the value of water in alternative uses and creating compatible incentives (Chong and Sunding, 2006; Wang, 2011). The concept of water trading has received an increasing amount of attention amidst a growing world population, with its increased need for food security and associated impacts on increasingly scarce water resources (Dabrowski et al., 2009). Especially in semi-arid and arid regions, valuable water can be released through trading to improve deteriorated water quality and endangered ecosystems (Rosegrant et al., 1995; Landry, 1998).

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Nomenclature

i	agricultural irrigation subarea, and $i = 1,2,\ldots,15$
j	the main crops in the river basin, $j = 1$ for wheat, $j = 2$ for maize, and $j = 3$ for cotton
h	water level of inflow, $h = 1,2,\ldots,7$ with $h = 1$ representing low level, $h = 7$ representing very-high level
$\widetilde{B}_{ij}$	benefit parameter for crop j in subarea i per unit of water allocated (US$/ha), which is expressed as fuzzy sets with known trapezoidal membership functions
$\widetilde{C}_{ij}$	reduction of net benefit (economic loss) per unit of water not delivered to crop j in subarea i (US$/ha), which is expressed as fuzzy sets with known trapezoidal membership functions, and $\widetilde{C}_{ij} \geqslant \widetilde{B}_{ij}$
Y_{ijh}	probabilistic deficit of cropland that cannot be irrigated by the surface water under level h (ha), which is the recourse decision variable
f	net system benefit over the planning horizon ($)
p_h	related probability of inflow level, with $p_h > 0$ and $\sum p_h = 1$
$\widetilde{\theta}_j$	irrigation coefficient for crop j in subarea i (10^3 m^3/ha), which is used for identifying the relationship between water and cropland
$\widetilde{\gamma}$	fuzzy tolerance measure for water availability
R_h	available flow from the reservoir under level h (m^3)
X_{ij}	irrigation target of crop j in subarea i (ha), which is the first-stage decision variable
$X_{ij}^{\max}$	maximum irrigation area of crop j in subarea i (ha)
$X_{ij}^{\min}$	minimum irrigation area of crop j in subarea i (ha)
W_{ij}	water permit to crop j in subarea i (m^3)

Previously, numerous water trading programs have been established and/or under development throughout the world (Becker et al., 1996; Tisdell, 2001; Brookshire et al., 2004; Dabrowski et al., 2009; Smajgl et al., 2009; Zaman et al., 2009; Kirnbauer and Baetz, 2012). However, such trading programs in practice have not always been implemented successfully on account of the heterogeneity of the river basins to which they are applied, due to the variety of hydrological and climatic regimes within each basin as well as the inherent difficulties in assessing economic impacts and tradable permits.

In water trading programs, uncertainties that exist in many system parameters and their interrelationships could intensify the conflict-laden issue of water allocation among multiple competing interests (e.g., municipal, industrial, agricultural and ecological). Although a number of research efforts have disclosed that water trading effectiveness is explicitly influenced by various uncertainties existing in water resources systems, the problem induced by randomness in water availability has not been well treated (Jenkins and Lund, 2000; Etchells et al., 2004; Gohar and Ward, 2010; Deviney et al., 2012; Xu et al., 2012; Graveline et al., 2012). For example, available water resources are influenced by stochastic events such as temperature and precipitation, which are not measured with certainty but in fact represented as a probability distribution around the actual streamflow. A random water supply can make trading efficient in a dry season, while it may become unnecessary during a wet season (Luo et al., 2007). The targeted water use (associated with various municipal, industrial and agricultural activities) often needs be optimally allocated in order to get a maximized system benefit. However, such efforts can be complicated since the water-use targets are often determined before the amount of available water is known. If the target is regulated high, it will bring high net-system benefit when water demand is satisfied; however, it can result in penalties if the demand cannot be met; conversely, reducing target means a low risk of penalties when water is in shortage but it will also not maximize the utility of water resources. Such a recourse problem could become further complicated by not only interactions among uncertain system components but also economic implications of water trading. Moreover, in water resources allocation problems, uncertainties may exist as multiple levels: vagueness and/or impreciseness in the outcomes of a random sample, and randomness and/or fuzziness in the lower and upper bounds of an interval (Li and Huang, 2009). These complexities have placed water trading programs beyond the conventional systems analysis methods.

The aim of this study is to develop a hybrid fuzzy-stochastic programming method for planning water trading, where uncertainties can be directly communicated into the optimization process through representing the uncertain parameters as fuzzy sets, random variables, and their combinations. The paper will be organized as follows: Section 2 is devoted to advancing the hybrid fuzzy-stochastic programming method, such that how stochastic programming to be coupled with fuzzy programming are described; Section 3 provides a case study for examining the potential for irrigation water trading as a measure to improve the utility of water resources in the Zhangweinan River Basin; Section 4 presents result analysis and discussion, where both trading efficiency on allocated water and cropped area and trading-cost consequence on the system effectiveness are analyzed; some conclusions are drawn in Section 5.

2. Methodology

When uncertainties are expressed as probability distributions while decisions need to be made periodically over time, the study problem can be formulated as a two-stage stochastic programming (TSP) with recourse model. In TSP, decision variables are divided into two subsets: those that must be determined before the realizations of random variables are disclosed and those (recourse variables) that will be determined after the realized values of the random variables are available (Birge and Louveaux, 1988; Huang and Loucks, 2000; Li et al., 2010a). Therefore, the TSP methods require decision makers to assign a cost to recourse activities that are taken to ensure feasibility of the second-stage problem. This means that, in TSP, infeasibilities in the second stage are allowed at a certain penalty (i.e. the second-stage decision is used to minimize penalty that may appear due to any infeasibility). A TSP model can be formulated as follows:

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

$$\text{s.t.} \quad Ax \leqslant b \tag{1b}$$

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

where x is the first-stage anticipated decisions made before the random variables are observed, and $Q(x, \xi)$ is the optimal value, for any given Ω, of the following nonlinear program:

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

$$\text{s.t.} \quad W(\omega)y = h(\omega) - T(\omega)x \tag{2b}$$

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

where y is the second-stage decision variables (i.e. recourse variables) that depend on the realization of the first-stage random