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Assessment of uncertainty effects on crop planning and irrigation water supply using a Monte Carlo simulation based dual-interval stochastic programming method

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ABSTRACT

In this study, a Monte Carlo simulation based dual-interval stochastic programming (MC-DSP) method is developed for assessment of uncertainty effects on crop planning and irrigation water supply associated with multiple uncertainties expressed as dual intervals and probability distributions. MC-DSP can permit in-depth analyses of various policies that are associated with different levels of economic consequences (due to uncertain water inflow) when the pre-regulated irrigation targets are violated. The developed method is applied to crop planning and water allocation for the Zhangweinan River Basin in China. Solutions of crop planning and irrigation-water allocation under different probability distributions and plausibility degrees are generated. Results reveal that surface water availabilities associated with different probability distributions can lead to changed system benefits and irrigation shortages. Moreover, water is insufficient to satisfy the requirement for wheat due to its high requirement for irrigation, which may lead to the risk of food supply. Each subarea of farmland would suffer water deficit under all scenarios (particularly for subareas of Daming county and Neihuang county) when inflow level range from very-low to high. The conflicts between economic development and agricultural sustainability would be a challenged issue that would enforce the local authority to adjust the current food security policy.

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1. Introduction

Crop areas increase rapidly to produce enough agricultural production (e.g., food and fiber) for the burgeoning global population which is predicted to reach around 9 billion by 2050, leading to increased irrigation-water demand (Singh, 2012; Ali et al., 2015). However, one major bottleneck is the lack of clean water resources, due to urbanization, contamination as well as climate change impacts (Pfister and Bayer, 2015). Besides, water is transferred from low-value irrigation to high-value industrial, domestic, and hydroelectric uses, putting additional stresses on the performance of the agriculture (Das et al., 2015; Morillo et al., 2015). Food security can hardly be guaranteed when water resources are insufficient to satisfy essential irrigation demand. This problem becomes more and more serious in many countries (e.g., China) with speedy growth of population and high dependence on the agriculture (FAO, 2015). To solve the problem of irrigation water scarcity, the simultaneous use of surface water and groundwater for irrigation (i.e., conjunctive use) was adopted. Nevertheless, the intensive agricultural activities resulted in raised demand for groundwater due to surface water shortage, leading to many environmental problems such as groundwater table declined, waterlogging and salinization (Mishra et al., 2016). Therefore, seeking participatory and innovative policy, governance and management options for the sustainable utilization of water resources are vital for the food security, maintaining environmental quality, and sustaining a desirable pace of economic development.

Previously, deterministic optimization models were developed to identify effective water resources allocation strategies (Montazar

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et al., 2010; Singh and Pand, 2012; Lin and Chen, 2016). However, in the real-world problems, optimal water resources allocation schemes for effective irrigation of crops should vary in response to the temporal changes of the available water resources (Unami et al., 2015). Then, a variety of optimization techniques were proposed for coping with random uncertainties in water resources allocation problems (Zhang and Li, 2014; Joodavi et al., 2015; Fan et al., 2015; Rahman et al., 2015). Azaiez (2002) advanced a multistage decision model for the conjunctive use of groundwater and surface water with an artificial recharge, attempting to access the impact of partially not meeting the irrigation demand for a particular period and the impacts of excessive groundwater pumping (future irrigation demands cannot be satisfied). Bravo and Gonzalez (2009) proposed a stochastic goal programming model for supporting public water agencies decisions on surface water allocation and authorize the use of groundwater for irrigation under uncertainty, oriented to improve their supply policies for sustainable development. Marques et al. (2010) employed a two-stage stochastic quadratic program to optimize conjunctive use operations of groundwater pumping and artificial recharge with farmer's expected revenue and cropping decisions. Galán-Martína et al. (2015) presented a multistage linear programming model for optimizing cropping plan decisions with maximized farmer's return in each region as well as calculating the minimum subsidy value that would make the implementation of greening rules economically appealing, thereby promoting the widespread adoption of more sustainable agricultural practices.

Among these methods, multistage stochastic programming (MSP) with recourse can adequately reflect the dynamic variations of system conditions under uncertainty, especially for sequential structure of large-scale problems. The uncertain information in a MSP is often modeled through a multi-layer tree permitting revised decisions based on revealed uncertainties (Dai and Li, 2013). It is suitable for keeping the modeling of uncertainties simple which is preferable when probabilities are determined based on assumptions. The model should always be solved for a variation of probability distributions around the one that the decision maker believes in to check for robustness in the probability range of interest. The sensitivity of the solution with respect to the tree structure may be questioned (Svensson et al., 2011). A large tree should correspond to representative scenarios based on previous research concerning the variations of available water resources; however, it has difficulties in determining probabilities and in keeping computation times reasonable. Monte Carlo simulation (MCS) is an effective tool for dealing with such a concern, which can catch the randomness of available water resources (Canizes et al., 2012; Martín-Fernández et al., 2016). MCS is regarded as a more reliable method of uncertainty assessment because it makes no assumptions about linear model behavior (James and Oldenburg, 1997). MCS has been widely used in probability and statistics analysis due to the simple process and high precision; it also describes the uncertainty propagation of the input/output variables. Moreover, in water resources allocation problems, the related economic data, such as income of selling crop, cost of allocating water, and economic loss of water deficit often act as the coefficients of the objective function in a benefit maximization model. They are commonly presented as interval values or membership distributions due to lack of available data and biased judgment of human, which may also be crucial in determining the actual water allocation activities.

Therefore, this study aims to develop a Monte Carlo simulation based dual-interval stochastic programming (MC-DSP) method in response to the above challenges. MC-DSP will incorporate techniques of Monte Carlo simulation (MCS), interval fuzzy programming (IFP), multistage stochastic programming (MSP) within a general framework to cope with uncertainties presented as probability distributions and dual intervals (i.e., interval with fuzzy lower and upper bounds). Then, the MC-DSP method will be applied to crop planning and water resources allocation in the Zhangweinan River Basin in China. Results of optimal cropping and water allocation patterns will be generated, which will be used for providing insight into the tradeoff among system benefit, irrigation strategy, and agriculture sustainability.

2. The study system

2.1. Study area

The Zhangweinan River Basin (which ranges in longitude from 112 to 118°E, and in latitude from 35 to 39°N) is located in North China, which consists of five primary rivers (including Zhang River, Wei River, Wei Canal, Zhangweixin River and Nan River). The total area of this basin is approximately 37,700 km^2, in which mountainous area (i.e. Taihang Mountains and Taiyue Mountain) is about 25,466 km^2 and plain area is 12,234 km^2. The basin features semi-arid, semi-humid climatic conditions with an average annual precipitation of 608.4 mm and an mean annual temperature of 14 °C. The distribution of temporal precipitation is uneven, which varies largely among different seasons. For example, more than 50% precipitation occurs in July and August, and the rainfall in the spring, autumn, and winter seasons occupy 8–16%, 13–23%, and 2% of the total precipitation per year, respectively.

The basin is one of the most productive and intensively cultivated agricultural regions in North China with a population of about 30 million and the cultivated area reaches to 293×10^3 ha. The main land cover is cropland with cultivated crops, including wheat, maize, cotton, rice, bean, oilseed, and vegetables. About 75% of the cropland is irrigated and consumes 70–80% of the total water resources allocation due to the fact that the insufficient annual precipitation cannot fulfill the crop water demand. It is a reservoir based flow irrigation system providing irrigation partly to the crops planted in the basin. Yuecheng Reservoir is the main reservoir for flow regulation for water supply in this basin. The reservoir has a capacity of 1.3 billion m^3 and a controlled area of 18,100 km^2. It provides storage for water supply for the two cities of Anyang and Handan and irrigation for the two large agricultural areas of Minyou and Zhangnan. Actually, irrigation with groundwater is a significant contributor to the basin's food supply because of the reduction of surface water supply and the increase of water consumption in upstream. The estimated amount of renewable groundwater resources in the study area is 3.635 billion m^3/year (Statistical yearbook of Zhangweinan River Basin, 2013).

2.2. Problem statement

Sustained production from irrigated agriculture is vital to food security; however, serious irrigation water scarcity is a challenge to guarantee sustained production in this basin. Decreasing precipitation and increasing reservoirs and diversion channels in the upper reaches of the river lead to much less inflow of Yuecheng Reservoir now than that in decades ago. As a result, water supply to the two main irrigation areas is reduced, particularly for the Zhangnan irrigation area. For example, the average amounts of inflows to Zhangnan are 51.7×10^6 m^3 from 1981 to 1986, 30.5×10^6 m^3 from 1991 to 1996, and 7.0×10^6 m^3 from 2001 to 2006 (Du et al., 2012). Moreover, the local authority initiates strategic changes to reform water resources allocation, especially to transfer agricultural water to other sectors (i.e., municipal and industrial sectors). Farmers are enforced to extract groundwater due

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