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An Interval-based Fuzzy Chance-constrained Irrigation Water Allocation model with double-sided fuzziness

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ABSTRACT

This study presents an Interval-based Fuzzy Chance-constrained Irrigation Water Allocation (IFCIWA) model with double-sided fuzziness for supporting irrigation water management. It is derived from incorporating double-sided chance-constrained programming (DFCCP) into an interval parameter programming (IPP) framework. The model integrates interval linear crop water production functions into its general framework for irrigation water allocation. Moreover, it can deal with uncertainties presented as discrete intervals and fuzziness. It can also allow violation of system constraints with double-sided fuzziness, where each confidence level consists of two reliability scenarios (i.e. minimum and maximum reliability scenarios). To demonstrate its applicability, the model is then applied to a case study in the middle reaches of the Heihe River Basin, northwest China. Therefore, optimal solutions have been generated for irrigation water allocation under uncertainty. The results indicate that planning under a lower confidence level and a minimum reliability scenario can provide maximized system benefits. System benefits under the high water level are [2.659, 7.913] × 10^9 Yuan when $\alpha = 0$, [2.650, 7.822] × 10^9 Yuan when $\alpha = 0.5$ and [2.642, 7.734] × 10^9 Yuan when $\alpha = 1.0$ under the minimum reliability scenario. Furthermore, the results can support in-depth analysis of interrelationships among system benefits, confidence levels, reliability levels and risk levels. These results can effectively provide decision-support for managers identifying desired irrigation water allocation plans in study area.

1. Introduction

Nowadays, there is a growing awareness of the necessity to effectively alleviate the contradiction between the increasing demands for agricultural production and the shortages of agricultural water supply from a global perspective, which has a profound effect on arid areas already dominated by irrigated agriculture (Elliott et al., 2014; Kang et al., 2017). In fact, irrigation water consumption accounts for nearly 90% of the total water availability in arid areas of northwestern China (Li et al., 2016a). Moreover, unscientific and unreasonable irrigation water management can also directly cause environmental and ecological degradations and natural resources shortages problems. Therefore, it is indeed necessary to improve irrigation water management and optimize irrigation water allocation, which will ensure the sustainable development of agricultural production (Lu et al., 2016).

Optimizing irrigation water allocation, in the technical sense, implies how much water should be allocated to different subareas under certain goals (Zeng et al., 2010). Therefore, various mathematical methods have been developed for irrigation planning and management to identify optimal solutions (Singh and Panda, 2012), including traditional methods including linear programming (Bartolini et al., 2007), nonlinear programming (Cai et al., 2001), dynamic programming (Shang and Mao, 2006), and artificial intelligence search methods like genetic algorithms (Arabi et al., 2006; Safavi and Esmikhani, 2013) and simulated annealing (Brown et al., 2010; Pérez-Sánchez et al., 2018). These techniques have made significant contributions to the development of irrigation water management. However, the above methods may have limitations in response to uncertainties (e.g. stochastic, fuzzy and interval variables/parameters) existing in irrigation water management problems. Practically, an irrigation system typically covers a multitude of aspects associated with resources capacity, economic development and environmental impact (Xu and Qin, 2010), leading to uncertain factors such as water availability, irrigation water demand, market price, and crop yields. Such inherent uncertainties may cause intensified difficulties in the decision making of practical applications.

Therefore, a series of inexact mathematical programming methods

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including interval mathematical programming (IMP), stochastic mathematical programming (SMP) and fuzzy mathematical programming (FMP) have been developed for generating effective decision solutions under uncertainty. Generally, SMP can provide more explicit decision solutions while it may be impeded by its rigorous data requirements, complicated probability analysis and time-consuming computational burden (Xu and Qin, 2010; Tan et al., 2011). Conversely, IMP, based on interval analysis using interval parameters or variables, is more convenient for dealing with uncertain information with known ranges but unknown distributions. More practically, as a basic tool for irrigation planning and management, crop water production functions (CWPFs) can be empirically obtained by the fitting results based on field experimental data. These data, including actual evapotranspiration (ET) and crop yields, are easily influenced by the measurement methods, observation error and calculation methods, leading to imprecise and uncertain specifications of CWPFs. Therefore, interval CWPFs can be considered as a better choice to quantitatively describe the relationship between ET and crop yield in practical problems (Tong and Guo, 2013; Li et al., 2016b). Accordingly, IMP is capable of handling such a problem of integration interval CWPFs and other interval information into its optimization framework. For example, Li et al. (2016b) developed an interval linear fractional irrigation water allocation model by integrating interval CWPFs into the model's framework. However, it does not allow violation of system constraints and may be infeasible when the right-hand side coefficients of constraints are highly uncertain (Huang et al., 1992). Furthermore, some parameters are subject to human judgments, and the linguistic terms of "approximately equal" and "approximately satisfactory" are more acceptable in decision making (Zeng et al., 2010). It is desired that optimization methods be developed to further address above-mentioned problems.

Therefore, fuzzy chance-constrained programming (FCCP), as an improved FMP method, can be introduced to effectively tackle fuzzy uncertainties and violation of system constraints. The fuzzy constraints can be transformed into deterministic ones at predetermined confidence levels, which has a lower computational burden and provides more flexible solutions. There are two types of FCCP model from the literature review, including chance-constrained programming with fuzzy parameters (Liu and Iwamura, 1998) and chance-constrained programming with DFP (distribution with fuzzy probability) parameters (Iskander, 2005; Guo and Huang, 2009; Guo et al., 2014). For example, Guo and Huang (2009) developed a two-stage fuzzy chance-constrained programming approach for water resources management under dual uncertainties and applied it to a hypothetical case. Zhang and Guo (2018) developed a fuzzy linear fractional programming model with double-sided fuzziness for irrigation water management. Although the FCCP model with DFP parameters can reflect the dual-uncertainty feature (i.e. probabilistic and possibilistic information), it is difficult to acquire the dual-uncertain information and further popularize the model in practical application. Moreover, it can only address the fuzzy uncertainties in the right-hand side constraints, while those in the left-hand side constraints are presented as interval numbers. This will lead to the potential to miss some valuable uncertain information. In practice, fuzzy uncertainties may exist in both sides of constraints of the model. Thus, double-sided FCCP (DFCCP) is introduced to address the above complexities. Additionally, few studies of the DFCCP model for irrigation water management have been conducted.

Therefore, this study aims at integrating the advantages of the above outlined methods. An Interval-based Fuzzy Chance-constrained Irrigation Water Allocation (IFCIWA) model with double-sided fuzziness is developed for supporting irrigation water management. It is derived from incorporating double-sided chance-constrained programming (DFCCP) into an interval parameter programming (IPP) framework. Moreover, it integrates the interval CWPFs into its optimization framework. The objective of the developed model is to optimize irrigation water allocation to different crops in different subareas, achieving maximum system benefits. It is able to handle uncertainties that are presented as intervals and fuzzy sets arising from the subjective and objective variability of the irrigation systems. To demonstrate its applicability, it will be applied to a case study in the middle reaches of the Heihe River Basin in northwest China to optimize irrigation water allocation under uncertainty. Thus, more flexible and tractable solutions can be generated under different scenarios. These optimal solutions can provide decision support for managers to make final decisions for irrigation water allocation. Fig. 1 graphically illustrates the framework of the study.

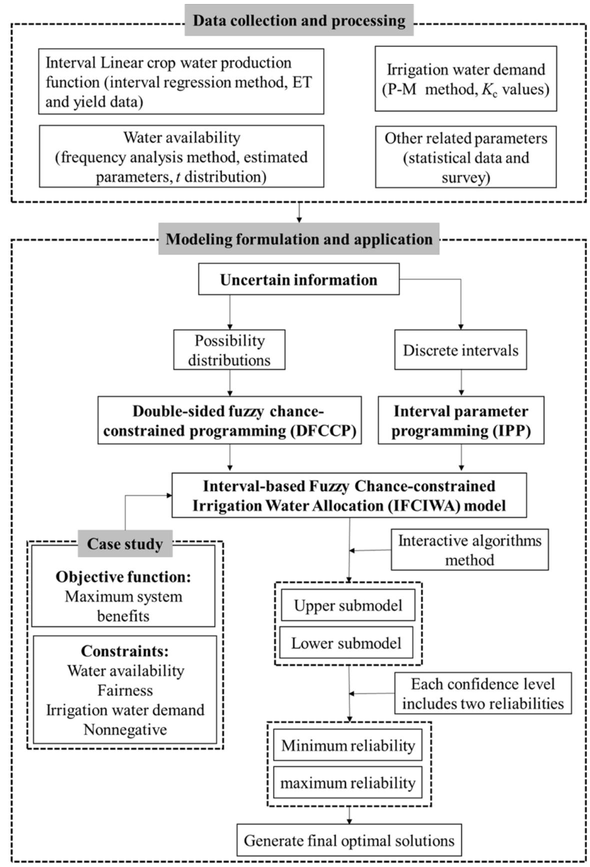

Fig. 1. The general framework of the study.

2. Methodology

In this section, three aspects of methodology including interval linear crop water production functions, Interval-based Fuzzy Chance-constrained Irrigation Water Allocation (IFCIWA) model with double-sided fuzziness and the corresponding solution method will be presented. Therefore, the further details can be outlined as follows.

2.1. Interval linear crop water production functions (ILCWPFs)

In this study, the linear CWPFs (i.e. $Y = aET + b$, where Y is the harvested crop yield, kg/ha; ET is the actual evapotranspiration, m^3/ha; and a, b are empirical coefficients mathematically determined by fitting the field experimental data) are chosen to quantitatively express the relationship between crop yield and ET (Li et al., 2016b). Due to the actual conditions, the collected field experimental data is easily influenced by measurement methods and observation errors, causing uncertainties in determining CWPFs. Using deterministic CWPFs may thereby have difficulties in dealing with these uncertainties. Thus, interval linear crop water production functions (ILCWPFs) are introduced to better reflect the above concerns. Then, an interval regression method is used to calculate ILCWPFs for different crops (Tanaka and