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A multi-objective optimal allocation model for irrigation water resources under multiple uncertainties

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ABSTRACT

This paper proposed a multi-objective optimal water resources allocation model under multiple uncertainties. The proposed model integrated the chance-constrained programming, semi-infinite programming and integer programming into an interval linear programming. Then, the developed model is applied to irrigation water resources optimal allocation system in Minqin's irrigation areas, Gansu Province, China. In this study, the irrigation areas' economic benefits, social benefits and ecological benefits are regarded as the optimal objective functions. As a result, the optimal irrigation water resources allocation plans of different water types (surface water and groundwater) under different hydrological years (wet year, normal year and dry year) and probabilities are obtained. The proposed multi-objective model is unique by considering water-saving measures, irrigation water quality impact factors and the dynamic changes of groundwater exploitable quantity in the irrigation water resources optimal allocation system under uncertain environment. The obtained results are valuable for supporting the adjustment of the existing irrigation patterns and identify a desired water-allocation plan for irrigation under multiple uncertainties.

1. Introduction

Because of the growing demand for water of both sufficient quantity and satisfied quality, water resources optimization allocation management is at the forefront in formulating sustainable development policies for many countries [1,2]. Among all the water users, agriculture is a major user for many countries, e.g. China, where agricultural water consumption accounts for about 64.8% of the national total water consumption, of which 90–95% is for irrigation. More than 70% of food crops, 80% of cotton and 90% of vegetables are produced in irrigation land in China. However, irrigation water resources shortage phenomenon is very prominent in China. The uneven distribution phenomenon of soil and water resources in irrigation areas is also existed. Therefore, in order to improve the comprehensive benefit and promote sustainable development of irrigation areas, it is important to allocate the limited irrigation water resources reasonably in space and time in China.

Previously, many works about irrigation water resources optimal allocation have been addressed. For example, Raju and Kumar [3] developed a multi-criterion decision model for irrigation planning in India, which dealt with three conflicting objectives such as net benefits, agricultural production, and labor employment. Shangguan et al. [4] proposed a water

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resources optimal allocation model based on the insufficient irrigation amount supplied to irrigation areas. Sethi et al. [5] studied the uncertainty of random that existed in the irrigation water resources allocation system. Lorite et al. [6] made an evaluation for water resources allocation based on the insufficient irrigation water resources in the southern of Spain. Prasad et al. [7] built a linear programming model of water resources allocation. This model could allocate water in different crops planting periods under different flow levels. However, in many previous irrigation optimization models, the maximum economic benefit was regarded as the only objective in order to simplify the actual situation, which did not conform to the requirements of sustainable development. In reality, many objectives (e.g. economic, social. ecological, etc.) and constraints should be considered in irrigation water resources optimal allocation system. Unfortunately, only a few models considered the multiple aims of irrigation water resources optimal allocation, especially, few considered its ecological goal, because it is difficult to be quantified. Moreover, in the constraints of the irrigation water resources optimal allocation models, many studies ignored food security constrains and groundwater exploitation quantities constraints, which are very important to guarantee the security of people's normal life and underground ecological of irrigation areas.

Irrigation water resources optimal allocation system is a complex system, in where, many uncertainty factors are involved [8], such as crop planting area, irrigation water use efficiency, irrigation quota, water supply, groundwater resources, economic parameters, etc. All these parameters and phenomena have characteristics of uncertainty and affect the model's comprehensive benefits. If we simply use determined parameters or models instead of uncertain ones, the unreasonable results will be obtained due to missing important information. The stochastic, fuzzy, and interval-parameter programming techniques have been employed in order to counteract these difficulties [9,10]. For example, interval linear programming (ILP) is an alternative for handing uncertainties in the objective function and constrains. It can tackle uncertainties that cannot be quantified as distribution functions, since interval numbers are acceptable as uncertain inputs [11,12]. Moreover, in the irrigation water resources optimal allocation system, there are many random parameters and phenomena associated with various right-hand-side parameters in the constraints, such as water supply, etc. [13]. When some right-hand-side parameters in the constraints are of stochastic features and can be represented as probability distributions, the chance-constrained programming (CCP) method can be employed. It is effective in dealing with uncertainties at right-hand side of the constraints when their probability distributions are available [14]. Combination of ILP and CCP can offset the disadvantage of each method, such as ILP may become infeasible when right-hand side parameters of constraints are highly uncertain and CCP is not so much effective in reflecting independent uncertainties of the left-hand side coefficients [15–19].

Despite the successes of the previous studies in inexact programming based on interval parameters and probability distributions under a finite number of inequality constraints, many parameters in irrigation water resources systems may be more complex, and can hardly be expressed as intervals or probability distributions, for example groundwater level's burial depth amplitude. The functional interval is described by assigning its lower and upper bound being to be functions of independent variables. The functions are based on the relationship between the parameters and the independent variables. There will be different upper bounds and lower bounds at different times. When parameters in the programming problems are expressed as functional intervals, the dynamic feature, i.e. variations of the parameters with independent variables, can be reflected. Each constraint with functional interval parameters implies infinite deterministic constraint. The study of semi-infinite programming, which can transform discrete points into an function interval form changing over time, is proposed in recent years [20–23,11,24,25] and the development of this new approach is of great significance in the development of irrigation water resources optimal allocation system. However, there was hardly any scholar has researched both the multiple uncertainties and multi-objective optimization of irrigation water resources optimal allocation.

This paper aims to develop an inexact chance-constrained semi-infinite mixed-integer multi-objective programming (ICSIMP) model for irrigation water resources optimal allocation, integrating chance-constrained programming (CCP), semi-infinite programming (SIP), integer programming (IP) into an interval linear programming (ILP). Proceeding from the realities, the developed model improves the form of the previous irrigation water optimal allocation models, and some uncertain methodologies are introduced into the modified multi-objective model, in which, the economic benefit objectives, social benefits and ecological benefits are considered. The developed irrigation water resources optimal allocation model will be applied to a real case study in Minqin County, Gansu Province, China. The ICSIMP model can be used to help decision makers to identify sound water resources allocation plans for irrigation system under multiple uncertainties.

2. The multi-objective model for irrigation water resources optimal allocation under uncertainty

2.1. Deterministic model

According to the characteristic of irrigation water resources optimal allocation system, an improved multi-objective model for irrigation water optimal allocation was established, considering water-saving measures, food security, the dynamic changes of groundwater exploitable quantity and environmental impact, which are often ignored in previous irrigation water resources optimal allocation models. The proposed model has three objectives: (1) Economic objective (RMB), whose final goal is to maximize economic benefit of irrigation areas; (2) Social objective (m^3/hm^2), whose final goal is to minimize crops' water shortage; (3) Ecological objective (g), whose final goal is to minimize the main pollutants in irrigation water, both from surface water and from groundwater. The decision variables are irrigation water amount (surface water and groundwater) allocated to different crops in the irrigation areas. The proposed model can be represented as follows: