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A type-2 fuzzy interval programming approach for conjunctive use of surface water and groundwater under uncertainty

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ABSTRACT

In this study, a type-2 fuzzy interval programming (T2FIP) method is developed for conjunctive use of surface water and groundwater under uncertainty. T2FIP can effectively tackle uncertainties expressed as a hybrid of type-2 fuzzy sets and interval numbers. In T2FIP, tradeoff between system benefit and system reliability can be analyzed to obtain the practical modeling outputs. Solution method based on interactive algorithm and type reduction technique is proposed to transform fuzzy-interval constraint into its deterministic equivalents. The T2FIP method is then applied to conjunctive use of surface water and groundwater in the Zhangweinan River Basin, China. Scenarios associated with different groundwater utilization ratios are examined to help generate the optimal conjunctive water use pattern. Results show that increased groundwater utilization ratio could lead to increased crop area and system benefit; however, when the utilization ratio of groundwater for irrigation increases to 50%, the system benefit would not increase. Results reveal that, for arid and semi-arid regions, effective conjunctive use of surface water and groundwater is critical for guaranteeing the agricultural sustainability. These findings can help identify desired decision alternatives among crop planning, agricultural irrigation, and groundwater utilization with a maximized system benefit and a minimized system-failure risk.

1. Introduction

Over the past decades, controversial and conflict-laden water resources allocation issue, associated with a variety of factors such as economic development, food security, and environmental concern, has challenged decision makers due to rising demand for freshwater [26]. However, due to lack of effective and efficient management of limited surface water resources, groundwater is often overexploited to increase grain yield and supply reliability [42]. Moreover, persistent groundwater exploitation in excess of natural recharge has induced serious environmental problems. For example, most irrigation areas in the North China Plain are facing problems such as groundwater table variation, groundwater related land subsidence and saltwater intrusion. Conjunctive use of surface water and groundwater, harmoniously combining the use of both sources of

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water to minimize the undesirable physical, environmental and economic effects of using a single water source, is imperative to optimize the water demand/supply balance, particularly for those in arid and semi-arid regions. As a result, systems analysis methods have been developed for assisting generation of effective polices for conjunctive water management [3,16,39,43].

The inherent uncertainties that exist in real-world water resources systems would intensify the conflict-laden issue of conjunctive water management. The errors in estimated modeling parameters and the vagueness of system objectives and constraints are all possible sources of uncertainties, creating complexities which beyond the capabilities of deterministic programming approach [23,25,41]. Fuzzy mathematical programming (FMP) is useful for dealing with vagueness and ambiguity based on fuzzy sets theory, where uncertainties are handled in a direct way without a large number of realizations [21]. Previously, several researchers focused on the application of FMP for conjunctive water management systems. Kerachian et al. [17] proposed a fuzzy game theoretic approach for conjunctive water management considering groundwater table fluctuations and groundwater quality in the Tehran metropolitan area, Iran. Safavi and Alijanian [37] employed a fuzzy inference system for accounting for the experience and expert judgments of decision makers and famers to obtain optimal crop planning for conjunctive water management in Najafabad plain, Iran. Raju and Kumar [35] developed a fuzzy data envelopment analysis approach to elevate the performance of sixteen irrigation subsystems associated with conjunctive use of water resources, environmental conservation, and crop production. Generally, the conventional FMP could solve the decision problems containing conventional fuzzy sets [e.g., (a_1, a_0, a_2) with triangular membership function or (a_1, a_2, a_3, a_4) with trapezoidal membership function], whose membership grade [e.g., $u(x)$] is a real number in [0, 1]. In fact, the membership grades of fuzzy sets may be uncertain (cannot be expressed as precision information), resulting in type-2 fuzzy sets (T2FS).

Type-2 fuzzy approach (T2FA) was developed to address the above deficiencies of the conventional FMP by introducing the concept of T2FS and employed to fuzzy logic systems to investigate linguistic uncertainties [2,18,27,32–34]. Hidalgo et al. [15] presented a genetic algorithm to optimize the type-2 fuzzy inference systems based on the size of the footprint of uncertainty, considering different cases for changing the level of uncertainty of the membership functions to reach the optimal solution. González et al. [13] developed an edge detection method based on generalization of type-2 fuzzy logic; the advantages of this approach were illustrated by employing in the benchmark images and synthetic images. Melin et al. [30] proposed a novel optimization method to find the gain constants involved in tracking controllers based on type-2 fuzzy logic theory; the results demonstrated that the type-2 fuzzy controller performed better under the presence of disturbance. Gaxiola et al. [10] presented an innovative back propagation neural method using type-2 fuzzy inference system; the results indicated that the type-2 fuzzy back propagation approach obtains better behavior and tolerance to noise than the other methods. Maldonado et al. [28] proposed an average approximation of type-2 fuzzy system for hardware implementation; the optimized approximation of type-2 fuzzy logic controller could be obtained using the genetic algorithm. Golsefid et al. [12] proposed a multi-central general type-2 fuzzy clustering approach for pattern recognitions, where the centers of clusters were considered as a set of points and the degree of belonging to the clusters was described as a general type-2 fuzzy set. However, few applications of T2FA to water resources management were reported for reflecting fuzzy sets with uncertain membership functions.

Although T2FA is effective in reflecting uncertainties associated with inexact membership functions of fuzzy sets, it is incapable of addressing uncertain parameters that can hardly be obtained as their possibilistic distributions; when uncertainties exist in the left-hand sides and the objective function, the resulting nonlinear model would encounter difficulties in obtaining optimal solution. For example, the costs for delivering grounder water may be obtained as intervals with known lower and upper bounds due to the quality of available information. Interval-parameter programming (IPP) has been proved to be an effective approach for dealing with uncertainties expressed as intervals, without complicated intermediate models [24]. On the other hand, the available water for irrigation involves a number of processes and factors, including precipitation pattern, temperature variation, seepage pattern, soil type, vegetation cover, and geologic feature. These processes and factors can be compounded by human activities (e.g., the allocation policy to be implemented, the pumping technique to be used and the diversion channels to be constructed). These uncertainties may be further multiplied by the interaction of surface water and groundwater (e.g., recharge and discharge of the aquifer), leading to dual uncertainties in the relevant decision-making processes. For instance, available surface water may be estimated as interval values; at the same time, the lower and upper bounds of these intervals may be expressed as T2FS, leading to type-2 fuzzy intervals $[(a_1^-, a_2^-, a_3^-, a_4^-, a_5^-), (a_1^+, a_2^+, a_3^+, a_4^+, a_5^+)]$ (abbreviated as T2FI). However, both IPP and T2FA have difficulties in addressing such a compounded uncertainty.

Therefore, the objective of this study is to develop a type-2 fuzzy interval programming (T2FIP) method for supporting conjunctive use of surface water and groundwater. Through integrating T2FA and IPP into a general framework, T2FIP cannot only tackle uncertainties expressed as a hybrid of type-2 fuzzy sets and interval numbers, but also reflect the relationship between system benefit and system reliability. A solution method based on interactive algorithm and type reduction technique will be proposed to transform fuzzy-interval constraint into its deterministic equivalents. Then, the T2FIP method will be applied to a real case for conjunctive use of surface water and groundwater in the Zhangweinan River Basin, one of the main food and cotton producing regions in North China. A number of scenarios associated with different groundwater utilization ratios will be analyzed to obtain optimal conjunctive water allocation pattern. The relationship among crop planning, agricultural irrigation and groundwater utilization will be disclosed to obtain a maximized system benefit and a minimized system-failure risk.