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Taguchi-factorial type-2 fuzzy random optimization model for planning conjunctive water management with compound uncertainties

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ABSTRACT

In this study, a type-2 fuzzy random optimization (TFRO) method is developed for planning conjunctive water management system associated with compound uncertainties. TFRO can effectively address compound uncertainties expressed as type-2 fuzzy sets, probability distributions, and type-2 fuzzy random variables. Solution algorithm based on the degree of probability and the information of plausibility is proposed to transform nonlinear objective function and constraints into their linear equivalents. A real case of water-resources allocation problem in Zhangweinan River Basin (China) is employed to demonstrate the applicability of the proposed method. A Taguchi-factorial type-2 fuzzy random model is also formulated through introducing Taguchi design and ANOVA technique into the TFRO framework. Results obtained can help reveal the relationship among multiple impact factors of economic, environmental and resource (water conveyance efficiency, water delivery cost, and system violation risk), as well as quantify their contributions to the variability of system benefit and water allocation schemes.
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1. Introduction

Due to rising demand, changing climate, and degrading aquatic ecosystem, water shortage is regarded as one of the most challenging environmental problems, threatening food security, economic development, and ecological sustainability in the twenty-first century (Bodner et al., 2015; Boluwade and Madramootoo, 2015). As the biggest consumer of limited water resources, irrigated agriculture uses about 70% of the global freshwater withdrawals, especially in many arid and semiarid regions (Dai and Li, 2013). In order to meet the objectives of raising food production and alleviating poverty, groundwater as a vital resource is being utilized for irrigation due to insufficiently available surface water. In North China Plain, with the rate of groundwater withdrawal heavily exceeding the rate of recharge, the groundwater level has dropped more than 1 m per year over the last four decades, causing a number of problems such as depletion of groundwater and disturbance of stream aquifer equilibrium, water logging and drainage (Royer et al., 2014; Nguyen et al., 2017). Therefore, system analysis methods are required to assist in identifying cost-effective plans for conjunctive use of surface water and groundwater. Moreover, temporal and spatial variations in temperature, precipitation, evapotranspiration, and soil moisture would impact both irrigation demand and groundwater recharge (Kreins et al., 2015). These complexities and uncertainties existing in conjunctive water management systems pose challenges for decision makers in generating environmentally responsible water allocation schemes.

As a result, a number of optimization techniques were proposed for conjunctive water management under uncertainty (Sethi et al., 2006; Kerachian et al., 2010; Morankar et al., 2013; Tabari and Yazdi, 2014; Maskrey et al., 2016; Pastori et al., 2017). Chance-constrained programming (CCP) was used to determine the optimal decision scheme while allowing for constraint violation with random variables at prescribed possibility levels. Although CCP can effectively deal with probabilistic uncertainties in the right-hand sides, it may encounter difficulties when parameters in the left-hand sides are uncertain or presented as possibilistic distributions (Li et al., 2009; Zeng et al., 2015). Fuzzy possibilistic programming (FPP) was employed widely for solving problems

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involving imprecise, vague and uncertain data (Tayal et al., 2013; Lin and Chen, 2016; Chen et al., 2017). However, it may become ineffective when the membership grade for each element of the fuzzy set is not a deterministic value but a fuzzy set in [0, 1], i.e., uncertainties expressed as type-2 fuzzy sets (T2FS). The enhanced Karnik-Mendel (EKM) algorithm was thus proposed to transform a type-2 fuzzy set into a conventional fuzzy set (Liu, 2008; Starczewski, 2014). To release the difficulty in finding the left and right switch points, Yeh et al. (2011) reconstructed the starting values with the possible switching points to recursively find the minimum upper and maximum lower bounds of the generalized centroid.

In conjunctive water management problems, the systems are characterized by uncertainty due to the randomness of hydrologic processes (e.g., rainfall, evapotranspiration and groundwater availability) (Sahoo et al., 2006; Herrera et al., 2017). Variations in irrigation water quantity, coupled with the indiscriminate nature of irrigation water supply and demand, may create hybrid uncertainties (e.g., fuzzy random variables whose values are not real but fuzzy sets). Moreover, the membership grade of fuzzy random variable may be uncertain due to a number of human activities (e.g., pumping techniques to be used). For example, the available surface water for irrigation may be estimated based on both subjective judgments and objective evaluations, resulting type-2 fuzzy random variables. Randomness and two-level fuzziness need to be taken into account simultaneously. Although the EKM algorithms can effectively tackle fuzzy sets characterized by fuzzy membership functions (Tao et al., 2012; Ruiz-Padillo et al., 2016), it may become useless when the parameters are expressed as probability distributions. It is thus necessary to integrate CCP and EKM into a general framework to address such complexity with characteristic of randomness and two-layer fuzziness.

Therefore, this study aims to develop a type-2 fuzzy random optimization (TFRO) method to support conjunctive water management under uncertainty. TFRO can effectively address uncertainties expressed as type-2 sets and type-2 fuzzy random variables. The developed TFRO method is then applied to a real case for conjunctive water management in Zhangweinan River Basin, which is one of the main food and cotton producing regions in North China. A Taguchi-factorial type-2 fuzzy random optimization model can be formulated through introducing Taguchi design and ANOVA into TFRO. Results can help to (i) disclose the effect of parameters related to economic and environmental factors on system benefit, total crop area, surface water and groundwater allocations, and (ii) identify the optimal parameter values to obtain desired system benefit and conjunctive water allocation scheme.

2. Methodology

In conjunctive water management problems, due to a number of natural processes (e.g., precipitation, evaporation, and infiltration), randomness existing in parameters (e.g., available surface water) need to be reflected in optimization processes. In order to reflect the randomness characteristic of parameters in the right-hand sides, a chance-constrained programming (CCP) model can be formulated as follows (Huang, 1998):

$$\text{Max}\, f = \sum_{j=1}^{n} c_j x_j \tag{1a}$$

subject to

$$\Pr\left\{\sum_{j=1}^{n} a_{ij} x_j \le b_i(w_i)\right\} \ge 1 - p_i, i = 1, 2, \ldots, m \tag{1b}$$

$$x_j \ge 0, j = 1, 2, \ldots, n \tag{1c}$$

where $b_i(w_i)$ (i = 1, 2, …, m) are random variables and p_i is the probability of violating constraint i. Assume $b_i(w_i)$ are Gaussian random variables with expected value w_i and standard deviation δ_i. Since $(b_i(w_i) - w_i)/\delta_i$ is a standard normal random variable with mean 0 and variance 1, the cumulative distribution function (i.e., $\Phi(\cdot)$) of a standard normal random variable is a monotonically increasing function. Thus, constraint (1b) can be reformulated:

$$\sum_{j=1}^{n} a_{ij} x_j \le w_i + \delta_i \bullet \Phi^{-1}(p_i), \quad i = 1, 2 \ldots, m \tag{2}$$

where Φ^{-1} $(\cdot)$ is the inverse function of $\Phi(\cdot)$ and $\theta = \Phi^{-1}\Phi(\theta)$. Although CCP permits constraint violation to some extent and provides a means of analyzing decision risks from different constraints, it may become ineffective when fuzziness existing in objective function and constraints. In fact, the costs for delivering water are usually subjectively estimated by decision makers and stakeholders, and thus may be obtained as fuzzy sets. Moreover, the estimated values of these parameters may acquire from decision makers under varied scenarios. Consequently, the membership grades of fuzzy sets may be uncertain, leading to two-layer fuzziness (i.e., type-2 fuzzy sets, T2FS). Besides T2FS, the estimation of these variables may be associated with randomness due to different subjective judgments from a number of decisions makers. Such deviations in subjective estimations may lead to both randomness and two-layer fuzziness (i.e., type-2 fuzzy random variables in Fig. 1). Correspondingly, to tackle T2FS and type-2 fuzzy random variables simultaneously, a type-2 fuzzy random optimization (TFRO) model can be formulated:

$$\text{Max}\, f = \sum_{j=1}^{n} \bar{c}_j x_j \tag{3a}$$

subject to

$$\Pr\left\{\sum_{j=1}^{n} \bar{a}_{ij} x_j \le b_i(\overline{w}_i)\right\} \ge 1 - p_i, \quad i = 1, 2, \ldots, s \tag{3b}$$

$$\sum_{j=1}^{n} \bar{a}_{ij} x_j \le \bar{b}_i, \quad i = s+1, \ s+2, \ldots, m \tag{3c}$$

$$x_j \ge 0, j = 1, 2, \ldots, n \tag{3d}$$

where $\bar{c}_j$ (j = 1, 2, …, n), $\bar{a}_{ij}$ (i = 1, 2, …, m; j = 1, 2, …, n) and $\bar{b}_i$ ($i = s + 1, s + 2$, …, m) are type-2 fuzzy parameters, $b_i(\overline{w}_i)(i = 1, 2$, …, s) are type-2 fuzzy random variables with type-2 fuzzy expected values. To contend with both randomness and two-layer fuzziness in the constraints, the techniques of EKM algorithm and CCP would be integrated into a general framework. It is assumed that the lower and upper centroids of T2FS are mutually independent (Li et al., 2010). Since centroid of T2FS can be determined by its lower and upper centroid based on the EKM algorithm, interval solutions can be generated. Thus, model (3) can be converted into an equivalent version as follows:

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