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A multi-stage fuzzy stochastic programming method for water resources management with the consideration of ecological water demand

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ABSTRACT

In this paper, a multi-stage fuzzy stochastic programming (MFSP) method is introduced to deal with uncertainties presented as fuzzy sets and probability distributions. Moreover, it is able to reflect dynamics of uncertainties and the related decision processes through constructing a series of representative scenarios within a multi-stage context under a set of fuzzy α-cut levels. A management problem about long-term planning of water resources system has been studied to illustrate applicability of the proposed approach. With ecological water demand being considered, the framework solves the complex problems that can hardly be solved in previous individual model research and promotes sustainable development. The results indicate that the dynamic and complexity of water resources allocation can be reflected through the multilayer discrete context tree. Moreover, real-time correction for reducing the risk of water shortage and low economic penalty can be presented. They can also help identify satisfaction degree of the goal and feasibility degree of constraints in an interactive way, enabling decision makers to generate a series of alternatives under various system conditions. Overall, it can not only contribute to decision makers for in-depth analysis, but also for sustainable development of ecosystem.

1. Introduction

The management of water resources is a worldwide issue due to increasing demands and limited water availability (Loucks et al., 2005; Gu et al., 2013). Sustainable management of water resource systems is essential to meet demands not only by human society, but also by various ecosystems (Cai et al., 2011; Wang and Huang, 2012). This requires efficiently allocating water resources to maintain integrity of ecology, environment and hydrology (Chang, 2005). However, water resources managers are challenged to meet multiple and often conflicting demands because of various uncertainties existing in water resources systems. They often result from numerous factors such as the randomness of available water (e.g., stream flow, precipitation and climate change), the imprecision in modeling parameters (e.g. uncertainty of data acquisition and data utilization), and the fuzziness of system objectives and constraints (Tan et al., 2010, 2011, 2017; Du et al., 2013), which intensifying the dynamic complexities. These complexities have placed many water-resources management problems beyond the conventional optimization methods. Consequently, there is an urgent need to develop effective systems analysis techniques for supporting sustainable water management under uncertainty with the consideration of ecological water demand in efficient and environmental ways.

Over the past decades, many scholars have applied stochastic and fuzzy mathematical programming to deal with the uncertainty of water resources management system (Guo et al., 2010; Huang et al., 2010; Wang and Huang, 2012). Multi-stage stochastic programming (MSP) with the concept of recourse was developed and applied to a number of regions, which is effective in dealing with uncertainties expressed as probability distributions. In MSP, a first-stage decisions are set before the random variables are known, and then a recourse measure is taken to minimize the penalties when the random event is known. In this way,

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decision makers are able to make water supply schemes timely under discrete probability levels in each stage, to obtain the best economic benefits of the whole planning system (Huang and Loucks, 2000; Wang et al., 2012). For instance, Pereira et al. (1991) proposed a multi-stage stochastic programming model and applied to energy planning for a 39-reservoir system. Watkins et al. (2000) proposed a scenario-based stochastic programming model and applied it to highland lakes. In order to tackle uncertainties in the right-hand sides of constraints, Charnes and Cooper (1959) proposed chance-constrained programming (CCP). Cai et al. (2011) applied it to the renewable energy systems planning under uncertainty. Qin et al. (2009) develop an inexact chance-constrained quadratic programming model for stream water quality management and planning. Du et al. (2013) proposed an inexact chance-constrained waste-load allocation model and applied it to water quality management of Xiangxihe River. As subjective information can mostly be expressed as fuzzy sets, fuzzy mathematical programming (FMP) was proposed by Zadeh (1975) to handle uncertainties in system model, of which membership function was used to describe the degree of truth as an extension of valuation. Jimenez (2007) proposed method for solving linear programming problems with fuzzy parameters. Lee and Chang et al. (2005) proposed an interactive fuzzy approach for planning a stream water-resources management system that involved vague and imprecise information. With the increasing importance of water quality management, lots of methods with fuzzy sets such as fuzzy logic to water quality classification and fuzzy water quality index to river quality analysis have also been made (Icaga, 2007; Lermontov et al., 2009).

Previously, more explorations and prominent achievements have already been made to evaluate whether the water quality were suitable for benthonic animal or aquatic plant (Gobeyn et al., 2016; Lazaridou et al., 2018). For example, Bouchet et al. (2018) assessed the ecological quality status using the diversity index to protect and restore fragile ecosystems. Duarte et al. (2017) reviewed and discussed the methods and metrics used for the assessment of the ecological status of marine angiosperms comparing the European with the South African situation. Chi Thanh et al. (2017) assessed the contamination and potential ecological risk posed by heavy metals to the Houjing River in source apportionment of the contamination in sediments and water. Several studies were conducted on water management with the consideration of ecological water demand. Dong et al. (2009) constructed a rational allocation model which has a priority to satisfy ecological water demand in Ebinur Lake. Cai et al. (2011) presented the application of an inexact quadratic programming (IQP) approach for sustainable water supply under multiple uncertainties. Ye et al. (2012) demonstrated the application of inexact fuzzy multi-objective model on water resources allocation in an ecological city. Li et al. (2016) discussed the ecological groundwater level and establishes a three-layer optimal allocation model of water resources based on the theory of large scale systems in Jinghui Irrigation District. Arfanuzzaman (2017) suggested an integrated sustainable water demand management (SWDM) for social-ecological resilience building. De Paula et al. (2018) assessed the forest cover in an agricultural landscape to promote conservation of stream habitat and water quality. Jiang et al. (2018) explored a geogrid-based framework of agricultural zoning for management of water and land resources.

Although the previous studies were effective in dealing with water resources supply and demand, several disadvantages remain. Firstly, most of the previous studies relied on fuzzy or stochastic methods for water management, it may be extremely difficult to solve such complexities, robustness of management problems if merely use individual fuzzy or stochastic methods (Huang et al., 2000). Furthermore, the previous allocation model mainly emphasizes domestic, industrial and agricultural water demand, there are few studies with the consideration of ecosystem water demand, which violates the requirement of coordination and sustainable development between society, economy and environment, causing environmental deterioration and resource shortage. The multi-stage fuzzy stochastic programming (MFSP) method has great advantages in dealing with multiple uncertainties and dynamic complexities in water resources management. However, the model has not been applied to water resource systems that considers ecological water demand.

Therefore, the objective of this study is to develop a multi-stage fuzzy stochastic programming (MFSP) method to the hybrid uncertainties with the consideration of ecological water demand. The MFSP method has great advantages in dealing with multiple uncertainties and dynamic complexities in water resources management. It can not only deal with uncertainties expressed as fuzzy sets and random variables, but also reflect dynamics of uncertainties and related decision processes through constructing a multilayered scenario tree with a set of scenarios. Solutions under a set of α-cut levels can be generated by solving a series of deterministic submodels. The optimization model is able to tackle uncertainties and dynamic complexities under a variety of economic, environmental, ecological targets. Furthermore, it can help decision-makers to balance the economic benefits and ecological water demand of the system, thus achieving ecologically sustainable water supply.

2. Methodology

2.1. Water demand by ecosystems

Ecological water demand is the water amount required to solve the ecological issues, such as the protection of wetlands, aquatic organisms, vegetation, and so on (Luttge et al., 1987; Wang et al., 2002; Yan et al., 2003). Since 1990, the importance of eco-environmental water demand has been gradually recognized, and many methods for determining and calculating the amount have been put forward (Richter,1996). Wang (2006) and Liu (2004) considered that inland river is cutoff and groundwater level greatly reduced in the arid areas, which is not necessary to consider the water requirement of sediment transport and self-purification, water demand for vegetation makes up an important component of the ecological water requirement (Chen, 2014). The growth of natural vegetation in arid area depends on shallow groundwater and precipitation. Therefore, we can calculate the ecological water demand of vegetation through the representative empirical and semi empirical estimation method of Aver'yanov's phreatic evaporation equations (Li and Kang, 2003; Hu et al., 2006). The calculation formula is as follows (Chen, 2014):

$$W_V = \sum_{t=1}^{T} \sum_{i=1}^{I} S_{it} E_{it} K_i \tag{1a}$$

$$E_{it} = a(1-H/H\max)^b \times E_{\Phi 20} \tag{1b}$$

where, W_v is the natural vegetation ecological water demand; S_{it} and E_{it} are the natural vegetation area and evaporation intensity of each vegetation type i in period t, respectively; K_i is vegetation coefficient; a, and b is empirical coefficient; H is groundwater depth (m); H_{max} is limit depth of groundwater evaporation; and $E_{\Phi 20}$ is evaporation value of conventional meteorological petri dish. The vaporization parameters of natural vegetation such as a, b, H_{max} and $E_{\Phi 20}$ can be obtained from the literature. Vegetation coefficient (K_i) refers to the ratio of phreatic evaporation under the vegetation growth condition to the evaporation under the bare land during the same period. Each type of plant has its suitable growth range of groundwater depth, the empirical formula of the vegetation coefficient K and the groundwater depth H is:

$$K = 1 + 2.0317e^{-0.5072H} \tag{1c}$$

2.2. Development of a multi-stage fuzzy stochastic programming method

Due to the randomness of available water, the water supply in the planning period has dynamic characteristics. Based on the analysis of