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An interval multistage classified model for regional inter- and intra-seasonal water management under uncertain and nonstationary condition

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ABSTRACT

In regional water management, various uncertainties such as randomness, non-stationarities, dynamics and complexities, lead to difficulties for water managers. To deal with the above problems, a new methodology is proposed by introducing two methods nonstationary analysis, where the generalized additive model is selected to analyze and fit the distribution of water inflow; and model optimization, where an interval multistage water classified-allocation model (IMWCA) is formulated to optimally allocate the available water. By incorporating multistage stochastic programming, interval parameter programming and classification thought, the IMWCA model can tackle both stochastic and imprecise uncertainties, realize inter-seasonal dynamic allocation, and address the complexity of various water users. The methodology is applied to the Zhanghe Irrigation District to optimize water allocation for municipality, industry, hydropower and agriculture among winter, spring, summer and autumn. The Zhanghe Reservoir seasonal inflow is found to be nonstationary for all the seasons and can be well fitted by the corresponding distributions, showing the sense of nonstationary analysis. Additionally, the comparison with the other model demonstrates the need for classification. From the results, municipality and industry are more competitive than hydropower. The Dongbao, Dangyang and Zhanghe districts have a higher priority than the Jingzhou and Shayang districts for irrigation water. Water requirements are more likely to be satisfied in autumn. These solutions of optimal targets and optimal water allocation are valuable for optimizing inter- and intra-seasonal water resource allocation under uncertainty.

1. Introduction

Water is very important for harmonious development, particularly in water scarcity areas (Ward et al., 1996). However, water resources shortage is becoming more serious due to global population growth, social and economic development, available water reduction, and water quality deterioration over the past decades. Therefore, there is an urgent need to develop sound management strategies for the optimal use of available water resources that has challenged water resource managers for years (Wheater and Gober, 2015). However, achieving an effective water management plan is difficult due to uncertainty, dynamics, non-stationarity and complexity of real-world problems.

Various uncertainties, such as the randomness of hydrologic features and imprecision of social-economic parameters, may have an effect on the process of data investigation, modeling computation, result presentation and decision making (Li et al., 2011). To address the above uncertainties, the fuzzy mathematical programming (FMP) method (Srivastava and Singh, 2015; Zeng et al., 2010), the interval parameter programming (IPP) method (Fu et al., 2014), the robust programming (RP) method (Dessai and Hulme, 2007), the stochastic mathematical programming (SMP) method (Pereira and Pinto, 1985; Wang and Adams, 1986) and the hybrid programming method (Guo et al., 2010; Huang, 1998; Li and Zhang, 2015; Lu et al., 2008; Maqsood et al., 2005) were proposed for water resources management. In general, the above optimization models could result in optimal policies by allocating available water to different water users without considering allocation between different seasons. However, water requirements do not correlate with water inflows. The amount of water inflow may be very low in some seasons when a great deal of water is demanded, while there may

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be excessive water inflow in other seasons that require less water. Therefore, the inter-seasonal competition with dynamic features should be considered.

To address this dynamism that is fraught with uncertainties, the stochastic dynamic programming (SDP) method (Alaya et al., 2003; Stedinger et al., 1984; Vedula and Kumar, 1996), and multistage stochastic programming (MSP) method (Dai and Li, 2013) were proposed for inter-seasonal reservoir release, water allocation and irrigation area planning. Compared with SDP, MSP is more capable of reflecting the dynamic variations of system conditions under randomness (Abdelaziz and Masri, 2009; Tarhan and Grossmann, 2008). Interval multistage stochastic programming (IMSP) integrated by IPP and MSP is an effective model for dealing with dynamism, randomness and imprecision. Therefore, it is widely applied to solve uncertain problems in environmental protection (Li et al., 2014), land use (Galán-Martín et al., 2015), oil exploitation (Gupta and Grossmann, 2014), and transportation (Simic, 2016). In recent years, many studies have also used IMSP for water resources management. For example, Li et al. (2006) employed an IMSP model for solving multi-period regional water allocation problems. Based on the previous efforts, Chen et al. (2015) proposed an inexact multistage fuzzy-stochastic model for water resources management. Chen et al. (2017) applied an IMSP model for optimally allocating water to crop different growth stages under inputs uncertainty.

When the IMSP model is applied to water resources management, the probability distributions of the stochastic uncertain inputs, such as the inflow, streamflow and rainfall, should be known beforehand. In most of the above studies, there was an assumption that historical records of those inputs were stationary. The distribution parameters of those inputs were considered to not change over time. However, the assumption of stationarity no longer holds for most parts of the world due to climate change and human activities (Cunderlik and Burn, 2003). For example, hydrologic features have been found to be increasing, decreasing or fluctuation over time in Australia, Brazil, Canada, China, Chinese Taipei, Ethiopia, Europe, Turkey, and the United States (Elsanabary et al., 2014; Kahya and Kalayci, 2004; Li et al., 2005; Madsen et al., 2014; Matsoukas et al., 2000; Sugahara et al., 2009; Tan and Shao, 2017; Yilmaz et al., 2014; Yu and Lin, 2015; Zhang et al., 2001). Therefore, the nonstationary probability distributions of hydrologic features should be analyzed. The generalized additive model for location, scale and shape (GAMLSS) presented by Rigby and Stasinopoulos (2005), which has a wide range of probability distributions and can estimate stationary or nonstationary model parameters, is an effective method for best fitting a hydrologic series to a certain probability distribution. Villarini et al. (2009) used this model to analyze nonstationary annual flood peaks in Charlotte. Machado et al. (2015) applied the model when conducting their nonstationary modeling of flood occurrence on the Tagus River in Spain. Tan and Gan (2015) chose GAMLSS to model the probability distributions of annual maximum streamflow records over Canada.

A decision is first made to promise targets for different water users before the amount of available water is known when the IMSP model is used to optimize water allocation. Water requirement targets for both agricultural users and non-agricultural users were treated as first-stage decision variables in most previous models (Bekri et al., 2015; Fan et al., 2015). However, the irrigation requirement changes over the rainfall level and could not be simplistically represented as definite values or interval values similar to the non-agricultural users beforehand (Dai and Li, 2013). Therefore, there is a need to classify water users into two categories—agricultural users and non-agricultural users—and to treat them in different ways. Li et al. (2010) treated irrigated area targets, which can be transformed into amounts of water by multiplying irrigation quotas, as first-stage decision variables for different crops. However, the irrigation quotas remained unchanged over system water inflow, which is inappropriate. In this paper, irrigated area targets and water requirement targets are treated as first-stage decision variables for agricultural users and non-agricultural users, respectively, and irrigation quotas are considered to vary with inflow.

The object of this study is to propose a new integrated method to optimally plan intra-season and inter-season water resource allocation in a reservoir water supply system. The goal is achieved via the use of two methods: nonstationary probability distribution analysis and interval multistage water classified-allocation model (IMWCA) optimization. The GAMLSS was chosen to analyze the probability distribution of the reservoir inflow in each season. By incorporating multistage stochastic programming, interval parameter programming and classification thought, the IMWCA model can tackle the uncertainties expressed as interval parameters and probability distributions, realize a dynamic allocation among different seasons, and deal with the complexity of first-stage decision variables. The method is applied to the Zhanghe Irrigation District to dynamically allocate available water resources to municipality, industry, hydropower and agriculture to demonstrate its applicability. The optimal solutions obtained can help authorities to develop an appropriate allocation plan for different water users under uncertainty.

2. Research methodology

2.1. Nonstationary probability distribution analysis

For nonstationary hydrologic series, the parameters of the probability distribution are usually expected to change with time and can be expressed as a function of some explanatory variables such as time, climate indices and socio-economic indices. To fit a suitable probability distribution, the generalized additive model location, scale and shape (GAMLSS) is introduced and only time is chosen as an explanatory variable in this study. The GAMLSS model provides a very flexible framework for estimating parameters for many probability distributions applicable to both stationary and nonstationary series. It is flexible and capable of modeling parameters of a probability distribution as linear and/or nonlinear, parametric and/or additive non-parametric, highly skewed and/or kurtotic. A more comprehensive description of GAMLSS can be found at the website (http://www.gamlss.org/).

For GAMLSS, it is assumed that independent observation y_i at time i, with $i = 1, 2, \ldots, I$, has a probability density function $f(y_i|q_i)$, with $\theta_i = (\theta_{i1}, \theta_{i2,} \ldots, \theta_{ip})$, a vector of p parameters accounting for the location, scale and shape of the probability distribution. Generally, p is less than or equal to four, since one- to four-parameter families provide enough flexibility for most applications. Let $g_m(\cdot)$, with $m = 1, \ldots, p$, be monotonic link functions relating the distribution parameters to explanatory variables through an additive model given by

$$g_m(\theta_m) = \eta_m = X_m\beta_m + \sum_{j=1}^{J_m} V_{jm}\lambda_{jm} \tag{1}$$

Where θ_m and η_m are vectors of length I, such as, $\theta_m = (\theta_{1m}, \theta_{2m,} \ldots, \theta_{Im})$; $\beta_m = (\beta_{1m}, \beta_{2m,} \ldots, \beta_{Im})$ is a regression parameter vector; X_m is an explanatory variable matrix; V_{jm} is a fixed known design matrix; λ_{jm} is a random variable vector.

There are many probability distributions applicable in the GAMLSS model. Tan and Gan (2015) found that annual maximum streamflow records over Canada were best fitted by either Gamma or Lognormal distributions. Jiang and Xiong (2012) chose five 3-parameter probability distributions to fit the discharge series of the Yangtze River, and found that Box-Cox Normal and Generalized Gamma were better. Therefore, the two 2-parameter probability