Journal of Environmental Management 128 (2013) 615–624

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Interval multistage joint-probabilistic integer programming approach for water resources allocation and management

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ARTICLE INFO

Article history:
Received 26 September 2011
Received in revised form
6 June 2013
Accepted 16 June 2013
Available online 8 July 2013

Keywords:
Dynamic
Joint probability
Multistage
Scenarios
Uncertainty
Water resources

ABSTRACT

In this study, an interval multistage joint-probabilistic integer programming method was developed to address certain problems in water resource regulation. This method effectively deals with data in the form of intervals and probability distribution. It can also process uncertain data in the form of joint probabilities. The proposed method can also reflect the linkage and dynamic variability between particular stages in multi-stage planning. Sensitivity analysis on moderate violations and security constraints showed that the degree of constraint violation was closely linked to the final benefits of the system. The developed method was applied in the case study of the joint-operation of the Tianzhuang and Bashan Reservoirs in Huaihe River, China. In this case study, the proposed method can deal with the water shortage problems downstream and the distribution problems caused by excess water in the reservoir. It can also guarantee the optimization of long-term water usage of both Reservoirs and the river downstream.

1. Introduction

Unreliable water supplies and flooding are threats that hamper effective sustainable water resource management. These have led to a variety of adverse impacts on the socio–economic development of local areas. The Huaihe River Basin is a disaster-prone area in China. Due to the heavy rainfall, serious floods have often occurred in this basin, especially during the flood season. Serious drought may also occur because of the lack of rain. Sometimes, droughts may come after the floods within one year; at other times, droughts and floods alternate or occur in consecutive years one after the other. The weather here is complex, changeable, and may be terrible at times. Historically, floods and droughts have taken place frequently in the Huaihe River basin. Due to uncertain floods and droughts in the Basin and because of their uncertain spatial and temporal distributions, it is extremely important to find ways to effectively regulate and control water resources in the Basin.

Reservoir operation is an effective method in the rational utilization of water resources. In order to achieve the best interests of the reservoir, i.e., maximizing the benefits of irrigation, water supply, flood control, power generation and shipping, researchers have developed a number of approaches to deal with such problems (Loucks, 1976; Stancu-Minasian and Wets, 1976; Huang and Loucks, 2000; Olsen et al., 2000; Barbaro and Bagajewicz, 2004; Maqsood et al., 2005; Ganji et al., 2007). These methods represent various kinds of operations, such as random optimal, determinate optimal, optimal control, multi-objective optimization, etc. Most of these methods are designed to tackle problems with uncertainties.

In water resource management planning, hydrology is the basis for forecasting and planning future regulation measures. Given that varied control measures are needed at different periods during the planning process, multistage planning approaches should be considered. Since the results of previous stages can carry over to the next stage of reservoir regulation in multi-stage planning, the related variables throughout the different stages must be considered in succession. The method of multistage stochastic programming can solve this problem effectively. In multistage stochastic

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http://dx.doi.org/10.1016/j.jenvman.2013.06.013

programming, the uncertainty elements can be revealed one by one in a continuous process; its basic function is to take the appropriate measures in coping with changes resulting from random incidents. A number of multistage fuzzy-stochastic programming models have been proposed in order to support sustainable water-resources allocation and management (Guo et al., 2009, 2010a,b; Li et al., 2009b).

Another effective way for solving the uncertainties in water resources system is applying interval chance constrained programming method. Interval chance constrained programming method is the integration of interval-parameter programming and chance constrained programming, which can solve the uncertain problem by converting the uncertainty factors into interval input, and meanwhile converting the uncertainty distribution into known probability distribution.

Chance constrained programming consisted of two categories: the individual probabilities constraints and joint probabilistic constraints (Loucks et al., 1981). Joint probabilistic distribution may exist when there is a mainstream and tributaries in study area and the flow of mainstream and tributaries are mutually independently. Joint probabilistic constraints are suitable for dealing with such problem. The interval joint probabilistic constraint is got by integrating joint probabilistic constraint and interval-parameter programming. The interval joint probabilistic programming can both reflect the risk of system constraints violations and handle uncertainties with joint probabilistic distributions and interval parameters.

Uncertainties, in the form of interval-parameter and joint probabilistic, in water resources multistage programming can be tackled by using the model integrated multistage stochastic programming with interval joint probabilistic constraints. Li et al. (2009a) developed an interval multistage joint-probabilistic programming method by integrating multistage stochastic programming and interval joint probabilistic constraint into one formula for tackling uncertainties presented as interval values and joint probabilities.

In water resource regulation, the reservoir must be expanded to address the dangers related to the problems of security and the growing demands for irrigation, industrial, and living water needs. Implementing these actions in the planning period depends on the results of the data obtained during the planning session. The integer programming method is useful in analyzing these results. This method is mainly based on the branch and bound method, which uses branch and delimiting non-integer solutions. The integer programming method is useful to make such judgment. It is an optimization method for finding the optimal solution to extend capacity and has been used in many recent studies (Haight et al., 2005). However, using the integrated method of incorporating integer programming, multistage stochastic programming, and interval joint probabilistic programming in a general optimization framework for solving complex water resources planning problems has not been considered in previous studies.

The objective of the current study is to improve the existing approach by developing an interval multistage joint-probabilistic integer programming (IMJIP) method and apply it to the Huaihe River case study. The advantages of IMJIP are as follows: 1) it can work out the reservoir operation plan during floods and design the reservoir operation measures under drought conditions, 2) it can be used in water resource regulation in cascade reservoirs as well as the management of multiple tributaries, 3) it can create a dynamic programming for the future development of the reservoir, and 4) when setting decision variables of objective functions in previous similar uncertainty function models, it can set the upper bound of the variables first and then compute the lower bound variables based on these.

2. Modeling formulation

The problem under consideration can be formulated as a multistage stochastic programming model (Li et al., 2009c). The model can be expressed as:

$$\text{Max } f = \sum_{t=1}^{T} C_t X_t - \sum_{t=1}^{T} \sum_{k=1}^{K_t} p_{tk} D_{tk} Y_{tk}, \tag{1a}$$

subject to:

$$A_{rt} X_t \le B_{rt},\ r = 1,2,...,m_1;\ t = 1,2,...,T, \tag{1b}$$

$$A_{it} X_t + A'_{itk} Y_{tk} \le \widetilde{\omega_{itk}}, i = 1,2,...m_2;\ t = 1,2,...,T;\ k = 1,2,...K_t, \tag{1c}$$

$$x_{jt} \ge 0, x_{jt} \in X_t, j = 1,2,...n_1;\ t = 1,2,...,T, \tag{1d}$$

$$y_{jtk} \ge 0, y_{jtk} \in Y_{tk}, j = 1,2,...n_2;\ t = 1,2,...,T;\ k = 1,2,...,K_t, \tag{1e}$$

where f is the expected system cost; X are decision variables; Y are recourse decision variables which is got based on decision variables; p_{tk} is the probability of occurrence for scenario k in period t; D_{tk} are coefficients of recourse decision variables Y_{tk}; A_{rt} are coefficients ofX_t in constraint r;A'_{itk} are coefficients of Y_{tk} in constraint i; $\widetilde{\omega_{itk}}$ is random variable; A, B, C are sets with random elements; K_t is the number of scenarios; m_1 is number of constraints r; m_2 is number of constraints i; t is period; n_1 is number of decision variables x_{jt} in period t; n_2 is number of recourse decision variables y_{jtk} for scenario k in period t; T is the specific stage of the event occurring.

The decision variables are composed of two types of variables: one is determined before the realizations of random variables are disclosed, such as x_{jt} (j variables of X_t, n_1 is number of j variables); the other is determined after the random variables are computed, such as y_{jtk} (j variables of Y_{tk}, n_1 is number of j variables).

In model (1), uncertainties, presented as random variable in right hand sides, can be tackled when coefficients in objective function and in the left hand sides are deterministic (Li et al., 2008). However, it cannot effectively reflect uncertainties presented as probability distribution in right hand side, especially when there is a link among variables in the right hand side. The method of joint probabilistic constraint programming can be used to deal with such problem.

Joint probabilistic constraint programming model can be represented as follows (Miller and Wagner, 1965):

$$\text{Max} f = \text{CX}, \tag{2a}$$

subject to:

$$\text{AX} \le B, \tag{2b}$$

$$X \ge 0. \tag{2c}$$

$$\Pi_{i \in S} \Pr\left(a_i X \le \tilde{b}\right)_i \ge \beta_i > 0 \tag{2d}$$

where α_i is n-dimensional row vector, $\tilde{b}_i$ is random variable, β_i is a specified probability value, $0 < \beta_i \le 1$, S is the set of chance constraints.

In general, although joint probabilistic constraint programming can process the right-hand side uncertainty problems through the form of probability distribution, there are still limiting factors in