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An integrated approach for water resources decision making under interactive and compound uncertainties

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ABSTRACT

In recent years, the issue of water allocation among competing users has been of great concern for many countries due to increasing water demand from population growth and economic development. In water management systems, the inherent uncertainties and their potential interactions pose a significant challenge for water managers to identify optimal water-allocation schemes in a complex and uncertain environment. This paper thus proposes a methodology that incorporates optimization techniques and statistical experimental designs within a general framework to address the issues of uncertainty and risk as well as their correlations in a systematic manner. A water resources management problem is used to demonstrate the applicability of the proposed methodology. The results indicate that interval solutions can be generated for the objective function and decision variables, and a number of decision alternatives can be obtained under different policy scenarios. The solutions with different risk levels of constraint violation can help quantify the relationship between the economic objective and the system risk, which is meaningful for supporting risk management. The experimental data obtained from the Taguchi's orthogonal array design are useful for identifying the significant factors affecting the means of total net benefits. Then the findings from the mixed-level factorial experiment can help reveal the latent interactions between those significant factors at different levels and their effects on the modeling response.

1. Introduction

Due to population growth and economic development, water demand for municipal, industrial, and agricultural uses is increasing, while the surface and groundwater pollution is deteriorating, and fresh water supplies are going to run out. Water scarcity is thus becoming a critical issue in many countries. According to the United Nations, approximately 700 million people in 43 countries are now suffering from water scarcity, and it is projected that 1.8 billion people will be living in countries or regions with absolute water scarcity by 2025 [1].

Conflict can arise from different water users competing for a limited water supply [2]. To achieve sustainable development, wise decisions are desired to make best use of limited water resources. Optimization techniques have played an important role in helping decision makers allocate and manage water resources in an effective and efficient way. For example, Wang et al. [2] introduced a cooperative water allocation model (CWAM) for pursuing fair and efficient water resources allocation among competing users while taking into account hydrologic, economic and environmental interrelationships; CWAM was applied to a large-scale water allocation problem in the South Saskatchewan River Basin located in southern Alberta, Canada. Almiñana et al. [3] presented optimization algorithms implemented in a decision support system that provided dynamic scheduling of the daily water irrigation for a given land area by taking into account the irrigation network topology, the water volume technical conditions and the logistical operation. Yang et al. [4] combined a decentralized optimization method with a multiple agent system for solving a water allocation problem considering both human and natural water demands in the Yellow River Basin, China. De Corte and Sörensen [5] conducted a thorough review of existing methods for the optimization of water distribution networks. In water management systems, however, the inherent uncertainty exists due to unavailability of system information, modeling inaccuracy, randomness of natural processes, and diversity in subjective judgments. Thus, decisions have to be made in the face of an uncertain and risky future. These complexities can become further intensified by latent interactions among various uncertainties and their consequent effects on system performance. As a result, conventional optimization methods would become ineffective when a variety of uncertainties exist in system components.

Over the past years, a number of optimization methods have been proposed for dealing with uncertainties in water resources management [6–11]. For example, Chung et al. [12] applied a robust optimization approach in a water supply system to minimize the

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total system cost; this approach could address parameter uncertainty without excessively affecting the system. Guo et al. [13] developed a fuzzy stochastic two-stage programming approach for supporting water resources management under multiple uncertainties with both fuzzy and random characteristics. Gaivoronski et al. [14] developed a quantitative approach for cost/risk balanced planning of water resources systems under uncertainty; this approach incorporated risk management approaches into a multi-stage stochastic optimization model that tackled uncertainty being described by scenario trees. Among these methods, two-stage stochastic programming (TSP) has the ability to take corrective actions after a random event occurs [15–20]. It can be used to deal with random variables and make decisions in a two-stage fashion. For example, a water manager needs to promise water allocation to water users before the rain season, and may need to take some recourse action after the rain season. Chance-constrained programming (CCP) is another alternative for tackling random variables and supporting risk-based decision making [21,22]. It can be used to provide a trade-off analysis between the economic objective and the system risk. However, both TSP and CCP can tackle uncertain information only presented as probability distributions; they are incapable of addressing uncertainties in other formats, resulting in difficulties when the available data is insufficient to generate distribution functions in real-world water management problems. In comparison, interval-parameter linear programming (ILP) is effective in dealing with uncertain information expressed as interval numbers with known lower and upper bounds but unknown distribution functions [23]. It can reflect interval information in model parameters and resulting solutions, which is helpful for decision makers to interpret and adjust decision schemes according to practical situations. Consequently, an integration of TSP, CCP, and ILP is desired to support water resources management under multiple uncertainties and risks.

On the other hand, uncertainty and risk are not independent in water resources management systems; they may interact in significant ways. It is thus necessary to analyze the potential interactions between uncertainty and risk as well as their effects on system performance. Factorial designs have been recognized as a powerful tool to study the combined effects of two or more factors on a response variable [24–28]. In this study, a mixed-level factorial design is proposed to explore the correlations between factors at different levels and detect the curvature in the response function [29,30]. As the number of factors of interest increases, the mixed-level factorial design would become infeasible from a time and resource viewpoint due to the large number of the experimental runs required for conducting a factorial experiment. To reduce the number of experiments to a practical level when there are many factors to be studied, factor screening is necessary to identify a few factors that have significant effects on the response, and remove those insignificant ones at the early stage of the factorial experiment. The concept of Taguchi's orthogonal arrays is an effective means for identifying the importance of factors through performing only a small subset of the experimental runs [31]. Nevertheless, it can hardly provide information on how these factors interact. Combining the Taguchi's orthogonal arrays with the mixed-level factorial design is thus a sound strategy to study the potential interactions for a large number of factors with different number of levels in a computationally efficient way.

The objective of this study is to develop an integrated approach through incorporating approaches of ILP, TSP, CCP, Taguchi's orthogonal arrays, and mixed-level factorial design within a general framework. A water resources management problem will be used to demonstrate the applicability of the proposed methodology.

2. Methodology

2.1. Interval-parameter stochastic programming

Consider a problem wherein a water manager is in charge of allocating water to multiple users, with the objective of maximizing the total net benefit through identifying optimized water-allocation schemes. As these users need to know how much water they can expect so as to make appropriate decisions on their activities and investments, a prescribed amount of water is promised to each user according to local water management policies. If the promised water is delivered, it will bring net benefits to the local economy; otherwise, the users will have to obtain water from other sources or curtail their expansion plans, resulting in economic penalties [32].

In this problem, two groups of decision variables can be distinguished. A first-stage decision of water-allocation targets must be made before the uncertain seasonal flow is realized; when the uncertainty of the seasonal flow is uncovered, a second-stage recourse action can be taken to compensate for any adverse effects that may have been experienced as a result of the first-stage decision. Thus, this problem under consideration can be formulated as a TSP model [33]:

$$Max\, f = \sum_{i=1}^{m} NB_i T_i - E[\sum_{i=1}^{m} C_i S_{iQ}]$$

$$\text{subject to}: \tag{1a}$$

$$\sum_{i=1}^{m} (T_i - S_{iQ}) \le Q,$$

$$\text{(Water availability constraints)} \tag{1b}$$

$$S_{iQ} \le T_i \le T_{i\,\max}, \quad \forall i,$$

$$\text{(Water} - \text{allocation target constraints)} \tag{1c}$$

$$S_{iQ} \ge 0, \quad \forall i.$$

$$\text{(Non} - \text{negativity constraints)} \tag{1d}$$

where f is total net benefit ($); NB_i is net benefit to user i per m^3 of water allocated ($/$m^3$) (first-stage revenue parameters); T_i is allocation target for water that is promised to user i (m^3) (first-stage decision variables); $E[\cdot]$ is expected value of a random variable; C_i is loss to user i per m^3 of water not delivered, $C_i > NB_i$ ($/$m^3$) (second-stage cost parameters); S_{iQ} is shortage of water to user i when the seasonal flow is Q (m^3) (second-stage decision variables); Q is total amount of seasonal flow (m^3) (random variables); $T_{i\,\max}$ is maximum allowable allocation amount for user i (m^3); m is number of water users; i is index of water user, $i=1$–3, with $i=1$ for the municipality, $i=2$ for the industrial user, and $i=3$ for the agricultural sector.

To solve the above problem through linear programming, the distribution of Q must be approximated by a set of discrete values (i.e. random seasonal flow can be discretized into three values representing low, medium and high flows with each having a probability of occurrence). Letting Q take values q_j with probabilities p_j ($j=1, 2,\ldots, n$), we have:

$$E[\sum_{i=1}^{m} C_i S_{iQ}] = \sum_{i=1}^{m} C_i (\sum_{j=1}^{n} p_j S_{ij}) \tag{2}$$

Thus, model (1a–d) can be reformulated as follows:

$$Max\, f = \sum_{i=1}^{m} NB_i T_i - \sum_{i=1}^{m}\sum_{j=1}^{n} p_j C_i S_{ij}$$

$$\text{subject to}: \tag{3a}$$

$$\sum_{i=1}^{m} (T_i - S_{ij}) \le q_j, \quad \forall j, \tag{3b}$$