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Planning of water resources management and pollution control for Heshui River watershed, China: A full credibility-constrained programming approach

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HIGHLIGHTS

- A full credibility-based chance-constrained programming method is developed.
- The method is applied to Heshui River watershed in south-central China.
- Credibility affects system benefit but slightly impact pollution control cost.
- Increased credibility suggests reduced cost for surface water acquisition.
- Increased credibility suggests enhanced cost for groundwater withdrawal.

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ABSTRACT

A key issue facing integrated water resources management and water pollution control is to address the vague parametric information. A full credibility-based chance-constrained programming (FCCP) method is thus developed by introducing the new concept of credibility into the modeling framework. FCCP can deal with fuzzy parameters appearing concurrently in the objective and both sides of the constraints of the model, but also provide a credibility level indicating how much confidence one can believe the optimal modeling solutions. The method is applied to Heshui River watershed in the south-central China for demonstration. Results from the case study showed that groundwater would make up for the water shortage in terms of the shrinking surface water and rising water demand, and the optimized total pumpage of groundwater from both alluvial and karst aquifers would exceed 90% of its maximum allowable levels when credibility level is higher than or equal to 0.9. It is also indicated that an increase in credibility level would induce a reduction in cost for surface water acquisition, a rise in cost from groundwater withdrawal, and negligible variation in cost for water pollution control.

1. Introduction

Issues of sustainable development are of significant concerns in rural areas, particularly under pressures of poverty reduction, environmental protection and economic development (Davies and Simonovic, 2011; Singh, 2014). The authorities are concerned of supporting agricultural production to feed a rapidly growing population and identifying an economic engine to stimulate economic growth (Sousa et al., 2013; Safavi et al., 2015). However, it is challenging to maintain rapid economic development under depleting natural resources and the degrading environmental conditions. Problems in water pollution, soil erosion and ecological deterioration could further hinder economic growth. It is thus desired that effective water resources planning be undertaken to help support sustainable regional development.

Environmental management has been facing new challenges due to increasing changes and their associated uncertainties which can be represented by stochastic, possibility and fuzzy information (He et al., 2008; Pouget et al., 2012; Ki and Ray, 2014; Fernández-Camacho et al., 2015). Among these, possibility theory is a mathematical counterpart of probability theory that deals with uncertainties by means of fuzzy sets (Dubois, 2004). Credibility theory which was advanced from possibility theory would be useful in the presence of other weak sources of information, although possibilistic representation is weaker than probability. Similar to possibility and necessity, computation of credibility is more convenient than that of probability, especially in a large scale case, as the no complex nonlinear terms need to be incorporated in the computation (Jamison and Lodwick, 2002).

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Credibility constrained programming, initially introduced by Liu and Iwamura (1998), is useful in the presence of other weak sources of information; computing with possibilities is much simpler than with probabilities (Zhang et al., 2012). Analogous to chance constrained programming with stochastic parameters, it is assumed that the constraints will hold with at least possibility α in a fuzzy environment, and the chance is represented by the possibility that the constraints are satisfied. Generally, the credibility constrained programming is proposed based upon credibility measure. The most-used credibility measure was proposed by Liu and Liu (2002) which can only simulate fuzzy relationships between a fuzzy variable and a deterministic parameter. Thus, the derived credibility programming methods can be grouped into two types, which can solve models with credibility constraints and/or credibility objectives. As for the fuzzy model with credibility constraint, most credibility programming model can only handle fuzzy parameters in one-side of the constraints ($\mathrm{Cr}\left\{\sum_{j=1}^{n}\tilde{\tilde{a}}'_{ij}x_j \geq b_i\right\} \geq \lambda_i$ or $\mathrm{Cr}\left\{\sum_{j=1}^{n}\tilde{\tilde{a}}_{ij}x_j \geq b'_i\right\} \geq \lambda_i$). For example, Gurav and Regulwar (2012) presented a multiobjective fuzzy linear programming (MOFLP) model, which deals with the fuzziness in resources and decision variables; it focuses on the four objectives namely maximization of net benefits, maximization of crop production, maximization of employment generation and maximization of manure utilization. Pishvaee et al. (2012) developed credibility-based fuzzy mathematical programming model for green logistics design with fuzzy right-hand side parameters. As for the credibility objectives, Lan et al. (2010) proposed an approximation-based approach for multi-period production planning problem with fuzzy objective by credibility measure. Whenever there are fuzzy parameters in both sides of the constraints, one most used method is to transform the fuzzy equation to several deterministic constraints by using alpha-cut. Lau et al. (2010) proposed a credibility-based fuzzy location model for the design of distribution systems, where both market supply and customer demand were treated as fuzzy variables. Rong and Lahdelma (2008) presented the fuzzy credibility constrained model for scrap charge optimization by using this method.

A key issue facing the abovementioned studies is to address the vague parametric-information represented as fuzzy sets, particularly when they appear concurrently in the objective and the left- and right-hand-side of the constraints. Since such vague information is involved in the inputs, the associated outputs (i.e. optimal management polices) should also be uncertain. Although robust programming could an available tool, it fails to provide uncertain level of the outputs. Possibility-based chance-constrained programming (PCP) has been proven to be useful for addressing vague parametric-information and offering satisfactory level of generated optimal water management strategies (He et al., 2008). Nonetheless, Liu and Liu (2002) suggested that credibility should be a more reasonable indicator measuring fuzzy inequality (or fuzzy event) than possibility and necessity, since it makes up both of their disadvantages. Unfortunately, no previous effort was found using the concept of credibility to solve optimal water management problems under complex parametric vagueness.

Therefore, this study attempts to develop a full credibility-based chance-constrained programming (FCCP) model for supporting the planning of water resources and quality management. In the model, the objective is to maximize the system benefit subject to a set of constraints such as water availability, water balance and pollution control. In particular, conjunctive use of surface and groundwaters will be allowed for in the water management process. The model will be applied to Heshui River watershed, China to help the local agricultural sector to accomplish sustainable water resources management and pollution. Tradeoffs among satisfaction of constraints (indicated by the measure of credibility) and system benefit will be analyzed.

2. Methodology

There are three types of measures for handling of vague parametric-information: possibility, necessity, and credibility. Zadeh (1978) proposed the concept of possibility measure to indicate how much one can believe a fuzzy event would occur. The concept has been widely used in solving fuzzy problems. As a dual part of possibility measure, the concept of necessity measure can also be used to address fuzzy problems. Since both of the measures are not self-dual, Liu and Liu (2002) present the concept of credibility measure by combining possibility and necessity measures. It has been proven to be a more reasonable indicator measuring fuzzy events than possibility and necessity because it can make up their disadvantages. Therefore, credibility measure is selected in this modeling formulation instead of possibility and necessity. Therefore, an FCCP problem is formulated to deal with those coefficients and parameters represented as fuzzy sets. Through the concept of credibility, the chance of a fuzzy event that will occur can be quantified (Zhao and Liu, 2005). The problem is shown as follows:

$$Max\sum_{j=1}^{n}\tilde{c}_j x_j \tag{1a}$$

$$\text{s.t.}\quad \mathrm{Cr}\left\{\sum_{j=1}^{n}\tilde{a}_{ij}x_j \leq \tilde{b}_i\right\} \geq \lambda_i, \quad i = 1,\ldots,m, \tag{1b}$$

$$x_j \geq 0,\ \ i = 1,\ldots,\ n. \tag{1c}$$

where $(x_1,x_1,\ldots,x_n)$ is a vector of non-fuzzy decision variables, $\tilde{c}_j$ is coefficient in the objective; $\tilde{a}_{ij}$, $\tilde{b}_i$ are fuzzy coefficients in the constraints; Cr represents credibility level; i and j represent the index of the constraint decision variables, respectively. Formula (1a) is the objective function to be optimized. Formula (1b) shows that the credibility of constraint ($\sum_{j=1}^{n}\tilde{a}_{ij}x_j \leq \tilde{b}_i$) should be greater than or equal to level λ_i. Consider two fuzzy variables ($\tilde{a}$ and $\tilde{b}$) with membership function μ. The credibility of a fuzzy event, characterized by $\tilde{a} \leq \tilde{b}$, can be defined as follows:

$$\mathrm{Cr}\left\{\tilde{a} \leq \tilde{b}\right\} = \begin{cases} 1 & \text{if } a_3 \leq b_1 \\ \dfrac{a_3 - 2a_2 + 2b_2 - b_1}{2(a_3 -{}^3 a_2 + b_2 -{}^2 b_1)} & \text{if } a_2 \leq b_2,\ a_3 > b_1 \\ \dfrac{b_3 - a_1}{2(b_3 -{}^3 b_2 + a_2 -{}^2 a_1)} & \text{if } a_2 > b_2,\ a_1 < b_3 \\ 0 & \text{if } a_1 \geq b_3 \end{cases}. \tag{2}$$

Fig. 1 shows four credibility situations for the two fuzzy sets. Credibility measure can present the credibility satisfaction level of an event when input information is presented as fuzzy sets. For example, if the waste generation rate is 50, 60, and 75 t/day and if the normal time waste collecting capability is 62, 68, and 82 t/day, then the credibility degree of the event wherein all the waste is collected on the same day (Cr(50,60,75) ≤ Cr(62,68,82)) would be 0.691. Thus the credibility degree of its complement event (not all the waste is collected on the same day) would be 1 − 0.691 = 0.309. In water resources management, if the water demand is 300, 360, and 420 m^3/day and the available water is 340, 410, and 465 m^3/day, then the credibility degree of the event wherein the water resources can meet the need would be 0.717. Hence, the credibility degree of its complement event (water shortage occurs) would be 0.283. The advantage of credibility measure over possibility and necessity ones is that when the credibility of a fuzzy event reaches 1, this fuzzy event will certainly occur and when the credibility reaches 0, the event will certainly not occur (Huang, 2006). As