Agricultural Water Management 156 (2015) 79–89

Contents lists available at ScienceDirect

Agricultural Water Management

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

A modified fuzzy credibility constrained programming approach for agricultural water resources management—A case study in Urumqi, China

X.M. Li [a], H.W. Lu [a], J. Li [a], P. Du [a], M. Xu [b], L. He [a,*]

[a] College of Renewable Energy, North China Electric Power University, Beijing 102206, China
[b] Water Environment Institute, Chinese Academy for Environmental Planning, Beijing 100012, China

ARTICLE INFO

Article history:
Received 10 June 2014
Accepted 7 March 2015
Available online 24 April 2015

Keywords:
Fuzzy
Groundwater
Agricultural systems
Water resources management
Credibility
Uncertainty

ABSTRACT

In this study, a modified fuzzy credibility constrained programming (MFCCP) model is developed for agricultural irrigation systems management under uncertainty. The developed MFCCP model incorporates fuzzy programming and credibility constrained programming into a modelling framework, which can solve the problems associated with uncertain parameters in fuzzy decision space when their stochastic distribution information are unavailable. Optimal schemes can be obtained in the combination of different credibility levels and various contributions from possibility and necessity to credibility. The MFCCP model is applied to a real case study in the agricultural areas of Wulabo lowland in Urumqi, which is a typical arid region in Northwest China. The results indicate that the credibility level intensely affects system net benefit, especially when it varies from 1 to 0.9. Water allocation to all crops decreases with the increasing credibility level, which is the major reason for the total benefit's shrink. The developed model can effectively specify the variety of uncertainties through provision of additional λ information, which represents the possibility of satisfying the objective and constraints and corresponds to the decision makers' preference regarding the tradeoffs between system benefits and reliability levels. Moreover, significantly different management strategies exist under various contribution rates of possibility and necessity to credibility, therefore the model can be adjusted according to various considerations, besides, much optimal and applicable management strategies can be expected through identifying the most appropriate contribution rate for possibility and necessity to credibility.

1. Introduction

Scientific and effective water resources management has been increasingly being one of crucial solutions for global water crisis. Over the past decades, controversial and conflict-laden issues in water resources became serious, particularly water shortage (Beck, 1987; Davies and Simonovic, 2011). Excessive resource exploitation, unreasonable industrial, agricultural, municipal and domestic utilization, as well as negative natural response to human activities (e.g. reduced flows of rivers, streams and lakes, groundwater depletion) all contribute to the above problems (Sarker et al., 2008; Zeng et al., 2010; Shi et al., 2014). The conflict between reduced water supplies and increased water demands has led to severe obstacle to socio-economic development. Water-saving and beneficial water resources management systems are thus important for tackling water crisis problems and promoting sustainable development (Komakech et al., 2011).

However, multiple uncertainties exist in water resources management problems, presented as hardly-identified system components including natural, social, environmental, technical and political factors (Lavee, 2010; Singh, 2014). Random characteristics of natural conditions, such as climate change, geographic feature, hydrological conditions, simulation errors and complexities of system operations, are all potential sources of uncertainties (Sousa et al., 2013). Inefficient acknowledgement of such uncertainties would lead to the inapplicability of water management policies, and further disturb the system balance. In the past decades, many inexact optimization methods were proposed to deal with uncertainties in water resources management (Pallottino et al., 2005; He et al., 2010; Lu et al., 2011, 2012; Li et al., 2014; Zhang et al., 2014; Fan et al., 2015). Among them, the fuzzy credibility constrained programming (FCCP) method has been proved as an effective approach to tackle uncertainties.

FCCP was proposed as a measure of confidence level in fuzzy environment, based on the uncertainty theory (Dubois and Prade,

* Corresponding author. Tel.: +86 10 61772416.
E-mail address: li.he@ncepu.edu.cn (L. He).

http://dx.doi.org/10.1016/j.agwat.2015.03.005
0378-3774/

1992). It can tackle uncertain parameters identified as various kinds of fuzzy membership functions, such as triangular and trapezoidal forms (Liu and Iwamura, 1998). Currently, FCCP has been used for solving various uncertain problems in real world practices (Huang, 2006). For example, Zhang and Huang (2010) proposed an FCCP approach by integrating credibility constrained programming into the framework of robust programming; it was superior when all of the imprecise parameters were presented as distributed fuzzy membership functions. The developed approach was then applied to a solid waste management problem, and useful solutions were obtained for supporting long-term decision making. Rong and Lahdelma (2008) also presented an FCCP model for steel production optimization, where the uncertainty in chemical composition of the scrap was addressed; it was found that the failure risk in the system can be managed by proper combination of aspiration levels and confidence factors for defining fuzzy numbers, while the local decision makers need to gaining insights into the tradeoff between failure risk and material cost. Zhang et al. (2012) applied an FCCP method to deal with parameter uncertainty in a regional power system by incorporating the concepts of credibility based chance constrained programming and mixed integer programming within an optimization framework, which can explicitly address planning problems and systematic uncertainties without unrealistic simplifications. According to these efforts, FCCP has showed its effectiveness with uncertain parameters whose stochastic distribution information is unavailable. In general, the aforementioned FCCP methods were effective for solving the problems associated with uncertain parameters in fuzzy decision space when their stochastic distribution information is unavailable.

In the previous FCCP approaches, credibility was set to be the average of possibility and necessity; this assumed that possibility and necessity had the equal contribution to the credibility that an event would occur. However, a truth is that a different decision maker would pay dissimilar proportions (or weights) to possibility and necessity when estimating credibility. Since the weights may be variable case by case, it is desired that the existing FCCP be modified to account for the impact of the proportions assigned by different decision makers on the estimated credibility. Therefore, the objective of this study is to improve conventional FCCP approaches, through analyzing different contributions of possibility and necessity to credibility as well as their effects on real problems. The modified FCCP (i.e. MFCCP) is developed in which different proportions for possibility and necessity are studied compared with the equal assumption in FCCP. In real decision problems, possibility and necessity are usually not presented as equality relation. Moreover, different proportions for possibility and necessity have advantages in analyzing the systematic reliability when input parameters are presented as uncertain information. Inexact parameters will be used to reflect parameter uncertainty. Trade-offs between water allocation and resources shortage will then be analysed under different credibility levels and possibility/necessity contributions. The MFCCP will be applied to a real-world water resources management problem in Urumqi, which is one of the most arid regions in Northwest China. The obtained results can help decision makers generate management alternatives for cropping pattern and water supply, with consideration of groundwater resources utilization.

2. Development of modified fuzzy credibility constrained programming

2.1. Conventional FCCP

FCCP is effective under situations where system analysis is desired and the uncertain information can be well identified as fuzzy sets (Zhao and Liu, 2005). Generally, a conventional FCCP model can be formulated as follows:

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

subject to

$$\text{Cr}\left\{ \sum_{j=1}^{n} \tilde{a}_{ij} x_j \le \tilde{b}_i \right\} \ge \lambda_i, \quad i = 1, \ldots, m, \tag{1b}$$

$$x_j \ge 0, \quad j = 1, \ldots, n. \tag{1c}$$

where $\mathbf{x} = (x_1, x_2, \ldots, x_n,)$ is a vector of non-fuzzy decision variables, $\tilde{c}_j$ is coefficient in objective; $\tilde{a}_{ij}$, $\tilde{b}_i$ are fuzzy coefficients in constraints. Here, i is the number of constraints and j is the number of variables. Formula (1a) is the objective function in the optimal framework. Formula (1b) shows that the credibility of constraint $(\sum_{j=1}^{n} \tilde{a}_{ij} x_j \le \tilde{b}_i)$ should be greater than or equal to level λ_i.

Consider two fuzzy variables $\tilde{a}$ and $\widetilde{b}$ (i.e. $\tilde{a} = (a_1, a_2, a_3)$, $\widetilde{b} = (b_1, b_2, b_3)$) with membership function $\mu(x)$, where the membership function can be denoted by:

$$\mu(x) = \begin{cases} \dfrac{x - t_1}{t_2 - t_1} & \text{if} \quad t_1 \le x < t_2, \\ \dfrac{x - t_3}{t_2 - t_3} & \text{if} \quad t_2 \le x < t_3, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

The membership function $\mu(x)$ is denoted with a triangle fuzzy variable which is determined by a triplet (t_1, t_2, t_3) of deterministic numbers.

The possibility of a fuzzy event, characterized by $\tilde{a} \le \widetilde{b}$, is defined as follows:

$$\text{Pos}\left\{ \tilde{a} \le \widetilde{b} \right\} = \sup\left\{ \min(\mu_a(x), \mu_b(y)) \,|\, x, y \in \Re, x \le y \right\} \tag{3}$$

Based on the definition in Eqs. (1) and (3), the possibility of $\tilde{a} \le \tilde{b}$ can be calculated as follows:

$$\text{Pos}\left\{ \tilde{a} \le \tilde{b} \right\} = \begin{cases} 1 & \text{if} \quad a_2 \le b_2 \\ \dfrac{b_3 - a_1}{b_3 - b_2 + a_2 - a_1} & \text{if} \quad a_2 > b_2, a_1 \le b_3 \\ 0 & \text{if} \quad a_1 > b_3 \end{cases} \tag{4}$$

The necessity of $\tilde{a} \le \widetilde{b}$ presents the impossibility of the opposite event, i.e. proposition "$\tilde{a}$ is less than or equal to $\widetilde{b}$" is true, and can be defined as

$$\text{Nec}\left\{ \tilde{a} \le \widetilde{b} \right\} = \inf\left\{ \max(\mu_a(x), 1 - \mu_b(y)) \,|\, x, y \in \Re, x < y \right\} \tag{5}$$

Similarly, the necessity can be calculated as follow:

$$\text{Nec}\left\{ \tilde{a} \le \tilde{b} \right\} = \begin{cases} 1 & \text{if} \quad a_3 \le b_1 \\ \dfrac{b_2 - a_2}{a_3 - a_2 + b_2 - b_1} & \text{if} \quad a_2 < b_2, a_3 > b_1 \\ 0 & \text{if} \quad a_2 \ge b_2 \end{cases} \tag{6}$$

Liu and Liu (2002) advanced an integrated credibility measure, which is the average of the possibility and necessity measures as follows:

$$\text{Cr}\left\{ \tilde{a} \le \tilde{b} \right\} = \frac{1}{2}\left(\text{Pos}\left\{ \tilde{a} \le \tilde{b} \right\} + \text{Nec}\left\{ \tilde{a} \le \tilde{b} \right\} \right) \tag{7}$$