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Model-based decision support system for water quality management under hybrid uncertainty

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ABSTRACT

Water quality management is inevitably complicated since it involves a number of environmental, socio-economic, technical, and political factors with dynamic and interactive features. In planning water quality management systems, uncertainties exist in many system components and may affect the system behaviours. It is thus desired that such complexities and uncertainties be effectively addressed for providing decision support for practical water quality management. The objective of this study is to develop a model-based decision support system for supporting water quality management under hybrid uncertainties, named FICMDSS, which is based on a hybrid uncertain programming (HFICP) model with fuzzy and interval coefficients. The system provides an effective tool for the decision makers in dealing with water quality management problems and formulating desired policies and strategies. The user can easily operate the system and obtain the decision support through user-friendly graphical interfaces. The HFICP model improves upon the existing inexact programming methods through incorporation of hybrid fuzzy and interval uncertainties into the optimization management processes and resulting solutions. Results of a water quality management case study indicated that the developed FICMDSS can facilitate the decision making in planning agricultural activities for water quality management in agricultural systems. Feasible decision alternatives for cropping area, amounts of manure and fertilizer application, and sizes of livestock husbandry can be generated for achieving the maximum agricultural system benefit subject to the given water-related constraints. The user can better make the decisions for water quality management under hybrid uncertainties with the help of FICMDSS.

1. Introduction

Water quality management is inevitably complicated since it involves a number of environmental, socio-economic, technical, and political factors with dynamic and interactive features. Nonpoint source (NPS) pollution from agricultural activities is the most significant source of water quality deterioration in agricultural lands (Cho, Park, & Im, 2008; Huang & Xia, 2001; Leóna, Booty, Bowenc, & Lamb, 2004; USEPA, 1992). Due to its diffuse characteristics, NPS contamination is difficult to be controlled since it is hard to isolate and quantify the contribution from individually dispersed sources (Berka, Schreier, & Hall, 2001). One effective means for NPS pollution control is to plan the related agricultural activities for causing the water quality deterioration. In planning of such water quality management systems, uncertainties exist in many system components and may affect the system behaviours. It is thus desired that such complexities and uncertainties be effectively addressed for providing decision support for practical water quality management (Chen et al., 2005; Huang, Chan, & Zhang, 2008; Nie, Huang, Wang, & Li, 2008).

Mathematical models can facilitate in identifying effective decision schemes for water quality management. Previously, a variety of inexact water quality management models have been developed for dealing with various types of uncertainties (Chang, Chen, Shaw, & Yang, 1997; Chen et al., 2005; Huang, 1996, 1998; Karmakar & Mujumdar, 2006; Lee & Wen, 1997; Luo, Li, Huang, & Li, 2006; Nie et al., 2008; Sasikumar & Mujumdar, 1998, 2000; Zhang, Huang, & Zhang, 2009; Zhang, Huang, & Nie, 2010). They could be categorized into fuzzy programming models, stochastic programming models, and interval programming models. Due to the inherent complexities and uncertainties, these mathematical models were highly complicated and involved in a number of mathematical knowledge on uncertainty analysis, modeling formulation and solution algorithms. The decision makers often encounter difficulties in understanding the inexact modeling results and formulation of desired policies and strategies for water quality management.

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A decision support system (DSS) can be helpful for handling the above situations and facilitating the decision making processes. Previously, a number of decision support systems have been developed and applied in the field of environmental management (Loucks & da Costa, 1991; Recknagel, Beuschold, & Petersohn, 1991; Ito, Xu, Jinno, Kojiri, & Kawamura, 2001; Matthies, Berlekamp, Lautenbach, Graf, & Reimer, 2006; Obropta, Niazi, & Kardos, 2008; Quinn, 2009; Simonovic, 1996a, 1996b; Srinivasan & Engel, 1994; Zhang, Huang, Lin, & Yu, 2009). Nasiri, Maqsood, Huang, and Fuller (2007) proposed a fuzzy multiple-attribute decision support expert system to compute the water quality index for assessment and evaluation of water quality policies. Assaf and Saadeh (2008) developed an integrated decision support system to assess and evaluate alternative management plans for sewage induced degradation of surface water quality. Argent, Perraud, Rahman, Grayson, and Podger (2009) described a catchment modeling software system named E2 to improve the flexibility of the specific DSS. Kao, Pan, and Lin (2009) developed a web-based budget allocation system for regional water quality management to improve environmental sustainability. However, there was a lack of research efforts in incorporating the inexact water quality management models into the decision support systems, where the hybrid uncertainties expressed by fuzzy membership functions and interval numbers associated with the coefficients of the objective function and the constraints of the models could be effectively reflected.

Therefore, the objective of this study is to develop a model-based decision support system for supporting water quality management under hybrid uncertainties, named FICMDSS, which is based on a hybrid uncertain programming (HFICP) model with fuzzy and interval coefficients. The different functions are effectively organized and integrated within an integrated decision support framework. The coefficients in the objective function can be modeled as interval numbers, and those in the constraints can be expressed by fuzzy membership functions. The HFICP model can improve upon the existing inexact programming methods through incorporation of hybrid fuzzy and interval uncertainties into the optimization management processes and resulting solutions. An agricultural water management case is proposed for demonstrating the applicability of the developed FICMDSS. Feasible decision alternatives for cropping area, amounts of manure and fertilizer application, and sizes of livestock husbandry can be generated for achieving the maximum agricultural system benefit subject to the given water-related constraints under hybrid uncertainties.

This papers proceeds as follows. Section 2 describes the model development. Section 3 presents the development of FICMDSS. Section 4 describes the implementation of FICMDSS through a water quality management case study, and Section 5 concludes the paper.

2. Model development

2.1. Hybrid uncertain programming model with fuzzy and interval coefficients

A general hybrid uncertain programming (HFICP) model with fuzzy and interval coefficients can be formulated as follows:

$$\text{Max} \quad Z^{\pm} = C^{\pm}X \tag{1a}$$

$$\text{Subject to}: A_k X \leqslant B_k, \quad k \neq l, \tag{1b}$$

$$\widetilde{A}_l X \leqslant \widetilde{B}_l, \quad l \neq k, \tag{1c}$$

$$X \geqslant 0, \tag{1d}$$

where A_k and B_k are deterministic values, $\widetilde{A}_l$ and $\widetilde{B}_l$ are imprecise coefficients and have fuzzy membership functions, $C^{\pm}$ is interval numbers with the lower bound C^- and upper bound C^+.

Since the coefficients of the objective function are interval numbers, the objective function is also an interval value expressed as $Z^{\pm}$. Thus, the objective of model (1) is to maximize an interval number. One effective means of dealing with the above problem is to simultaneously maximize the lower and upper bounds of the interval number so that the compromise between the lower and upper bounds could be achieved. Thus, the original problem with an interval objective will be converted into a bi-objective linear programming problem and rewritten as follows:

$$\text{Max} \quad Z^- = C^- X, \tag{2a}$$

$$\text{Max} \quad Z^+ = C^+ X. \tag{2b}$$

In constraint (1c), both the left-hand side and right-hand side coefficients are of fuzzy features. In order to deal with such uncertainties, fuzzy robust programming is proposed. These fuzzy constraints can be considered as fuzzy inclusive form (Leung, 1988):

$$A_{l1}x_1 \oplus A_{l2}x_2 \oplus \cdots \oplus A_{lp}x_p \subseteq B_l, \quad l = 1, 2, \ldots, m, \tag{3}$$

where A_{lj} ($j = 1, 2, \ldots, p$) and B_l are fuzzy subsets, and symbol denotes the addition of fuzzy subsets. As a result, uncertainties in the coefficients of A_{lj} and B_l carry fuzziness into the decision space. Let $\widetilde{U}_{lj}$ and $\widetilde{V}_l$ be base variables imposed by fuzzy subsets A_{lj} and B_l, then:

$$\mu_{A_{lj}} : \widetilde{U}_{lj} \to [0, 1], \tag{4a}$$

$$\mu_{B_l} : \widetilde{V}_l \to [0, 1], \tag{4b}$$

where $\mu_{A_{lj}}$ indicates the possibility of consuming a specific amount of resource l by activity j, and μ_{B_l} indicates the possible availability of resource B_l. The symmetric triangular fuzzy number N can be determined by a center a^c and a spread a^s, and be represented as (a^c, a^s). Its membership function can be written as follows:

$$\mu_N(x) = \begin{cases} 0, & \text{if } x < a^c - a^s \text{ or } x > a^c + a^s, \\ 1 - \frac{|a^c - x|}{a^s}, & \text{if } a^c - a^s \leqslant x \leqslant a^c + a^s. \end{cases} \tag{5}$$

Based on the concept of level set (fuzzy -cut) and representation theorem, constraints in (3) can be represented in the following format (Negoita, Minoiu, & Stan, 1976):

$$(A_{l1})_\alpha x_1 \oplus (A_{l2})_\alpha x_2 \oplus \cdots \oplus (A_{lp})_\alpha x_p \subseteq B_{l\alpha}, \quad l = 1, 2, \ldots, m, \ \alpha \in (0, 1], \tag{6a}$$

where

$$(A_{lj})_\alpha = \{a_{lj} \in \widetilde{U}_{lj} \big| \mu_{A_{lj}}(a_{lj}) \geqslant \alpha\}, \quad l = 1, 2, \ldots, m, \tag{6b}$$

$$(B_l)_\alpha = \{b_l \in \widetilde{V}_l \big| \mu_{B_l}(b_l) \geqslant \alpha\}, \quad l = 1, 2, \ldots, m. \tag{6c}$$

Assume that the fuzzy subsets in (3) are finite and have the following characteristics:

$$\{\mu_{A_{lj}}(a_{lj}) | a_{lj} \in \widetilde{U}_{lj}\} = \{a_{l1}, a_{l2}, \ldots, a_{lk}\}, \quad l = 1, 2, \ldots, m, \tag{7}$$

where $0 \leqslant \alpha_{l1} \leqslant \alpha_{l2} \leqslant \cdots \leqslant \alpha_{lk} \leqslant 1$. Thus, for each α_{ls} ($s = 1, 2, \ldots, k$), constraints in (6a) become:

$$(\widetilde{A}_{l1})_{\alpha_{ls}} x_1 \oplus (\widetilde{A}_{l2})_{\alpha_{ls}} x_2 \oplus \cdots \oplus (\widetilde{A}_{lp})_{\alpha_{ls}} x_p \subseteq B_{l\alpha_{ls}}, \quad \alpha_{ls} \in (0, 1], \tag{8}$$

where $(A_{lj})_{a_{ls}}$ ($l = 1, 2, \ldots, m$; $j = 1, 2, \ldots, p$; $s = 1, 2, \ldots, k$) and $(B_l)_{a_{ls}}$ constitute convex and non-empty fuzzy sets. Thus, fuzzy constraints in (8) can be replaced by the following $2k$ precise inequalities, in which k denotes k levels of -cut (Leung, 1988; Liu, Huang, Liu, & Fuller, 2003; Nie et al., 2008; Soyster, 1973).