Journal of Environmental Informatics 16(2) 43-56 (2010)

Journal of Environmental Informatics

www.iseis.org/jei

Planning Regional Water Resources System Using an Interval Fuzzy Bi-Level Programming Method

Y. Lv[1], G. H. Huang[2,*], Y. P. Li[2], Z. F. Yang[1], Y. Liu[2] and G. H. Cheng[2]

[1]*State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China*
[2]*S-C Energy and Environmental Research Academy, North China Electric Power University, Beijing 102206, China*

Received 1 Februray 2010; revised 5 August 2010; accepted 25 August 2010; published online 10 October 2010

ABSTRACT. An interval fuzzy bi-level programming (IFBP) approach is developed for planning water resources management system. The developed IFBP improves upon the existing bi-level programming by introducing interval mathematical programming (IMP) into its framework. The IFBP can handle uncertainties expressed as interval values in the constraints' left- and right-hand sides, as well as in the upper- and lower-level objective functions. Moreover, the decision dimensions of objective functions can be addressed through setting different tolerance levels based on the fuzzy set theory, such that tradeoffs corresponding to different upper- and lower-level objectives as well as varied system optimality and reliability can be generated. A case study is provided for an application to planning a water resources management system, where a number of scenarios are analyzed. For all scenarios under consideration, the IFBP method has advantages over the conventional programming methods with single decision maker in reflecting the interactions among multi-level objectives and strategies as well as encouraging co-operations among multiple parties under uncertainty.

Keywords: bi-level programming, decision making, fuzzy, interval, planning, uncertainty water resources

1. Introduction

Water resources scarcity related to both water quantity and quality is increasing on a global scale. The main determinant of this scarcity is the increasing water use by a steadily increasing world population (Uitto and Duda, 2002). Since most economic activities consume water, it is desired for the authorities to make integrated strategies for effective water resources development and utilization among multiple competing sectors. Generally, decision making problems are often compounded by uncertainties related to benefits/costs, water availabilities, environmental capacities and objectives. Such uncertainties can affect the related optimization processes and the generated decision schemes, which should be taken into account (Huang et al., 1993; Li et al., 2008; Yeomans, 2008).

Many methods have been proposed to handle uncertainties existing in water resources management systems (Huang, 1998; Huang and Loucks, 2000; Sethi et al., 2002; Sen and Altunkaynak, 2009; Zarghami and Szidarovszky, 2009; Li et al., 2010; Lu et al., 2010; Verderame et al., 2010). Most of them can be categorized into fuzzy, stochastic and interval mathematical programming methods, abbreviated as FMP, SMP and IMP, respectively (Ping et al., 2010; Yan et al., 2010). Among them, FMP is effective in dealing with decision problems under fuzzy goal and constraints (Jairaj and Vedula, 2000; Zimmermann, 2001; Mujumdar and Sasikumar, 2002; Nasiri et al., 2007; Li and Huang, 2009; Li et al., 2009; Liu et al., 2009; Guo et al., 2010). In the conventional FMP methods, the problem is converted to a single-decision-maker one with a single composite objective for the whole system such as an overall economic or social welfare function or a weighted constrained multi-objective function, by encouraging perfect cooperation of all parties (Madani, 2010); however, they often ignore the tolerances among interest obtainments without giving priority to any parties, and fail to recognize how the individual decisions affect other parties' payoffs and actions within the system. Therefore, it is more challenging to illustrate the strategic interactions with respect to the preferences of stakeholders, and to suggest innovative solutions accepted broadly by parties within the system.

Fuzzy bi-level programming (FBP) with a structure of two levels (the upper-level: leader and lower-level: followers) can be introduced to deal with the above decision making problems (Sakawa et al., 1998; Sinha, 2003; Ahlatcioglu and Tiryaki, 2007; Roghanian et al., 2008; Gao et al., 2009). Due to the combination of fuzzy tolerance membership functions, FBP cannot only reflect the reactions of the lower level decision makers (DMs) when the impacts of their decisions are too important to be ignored, but also provide satisfactory solutions that the upper and lower DMs essentially cooperate with each other (Wen and Hsu, 1991; Benayed, 1993; Gao and Liu, 2005; Pramanik and Roy, 2007). Lai (1996) developed a

* Corresponding author. Tel.: +86 10 51971255; fax: +86 10 51971255.
E-mail address: huang@iseis.org (G. H. Huang).

ISSN: 1726-2135 print/1684-8799 online

fuzzy programming approach, for the re-evaluation of problem through redefining the elicited membership values that were essentially needed in the solution search process to obtain a satisfactory solution for all DMs, which was different from that of the Stackelberg solutions where the possibility of rejecting the solutions was given by the upper-level decision maker. Shih et al. (1996; 2000) extended Lai's concept by using compensatory or non-compensatory max-min aggregation operators for solving FBP problems. Sakawa et al. (2000) presented an interactive method for solving a linear bi-level programming problem with fuzzy parameters, where the solution was derived by updating the satisfactory degrees of DMs with considerations of overall satisfactory balance after fuzzy goals were determined. More recently, Zhang et al. (2009) developed a FBP model for day-ahead electricity market strategy making through analyzing the strategic bidding behavior of generating companies. Aviso et al. (2010) proposed a FBP method with the park authority as the upper-level decision-maker, which could help the eco-industrial park to explore the effect of charging fees for the purchase of freshwater and the treatment of wastewater in optimizing the water exchange network of plants.

One main advantage of the FBP method is that it can be solved sequentially through linear submodels, which can make the original problem much more simplified and easier to be implemented. Nevertheless, few studies have been reported on the application of FBP methods to water resources management and planning. Besides, the conventional FBP methods are effective for addressing fuzzy information in decision-making problems; however, when it is typically much harder to specify uncertain parameters as probability density functions (PDFs) or membership functions than to present them as intervals, interval mathematical programming (IMP) with the lower requirements for data collection and solution generation is imperative for many practical applications (Huang et al., 1992; Lv et al., 2009; Lv et al., 2010). Thus, coupling IMP with FBP is promising since uncertainties in left- and/or right-hand sides of constraints as well as lower- and upper- level objective functions can be handled.

Thus, an interval-fuzzy bi-level programming (IFBP) approach will be developed in response to the above challenges, through coupling the interval mathematical programming (IMP) with fuzzy bi-level programming (FBP). The developed method can handle uncertainties expressed as interval values in the constraints' left- and right-hand sides as well as in the upper and lower-level objective functions. It will help generate a range of decision alternatives between the upper- and lower-level objectives and between system optimality and reliability. A case study will then be provided for an application to planning a water resources management system with the bi-level and hierarchical configurations among multiple decision makers. A number of cases based on different solution scenarios will be analyzed to demonstrate the advantages of the developed method over the conventional single decision-maker and/or deterministic programming methods. The strategies associated with acceptable solutions through cooperation will result in optimal outcomes for all regions within the study system.

2. Interval Fuzzy Bi-level Programming

Bi-level programming (BLP) is described as a nested optimization model involving two problems that are upper and lower ones. Let $x_i \in \Re^{n_i}\left(i=1,2\right)$ be a vector of decision variables indicating the first-decision and the second-decision level choices, respectively, and $n_i \geq 1\left(i=1,2\right)$. Let f_i: $\Re^{n_i} \rightarrow \Re^{N_i}\left(i=1,2\right)$ be the first- and the second-level objective functions, respectively. Let the upper- and lower-level decision makers (DMs) have N_i and N_2 objective functions which are linear and bounded, respectively. Therefore, the linear BLP can be formulated as follows (Lai et al., 1996; Bard, 1998; Emam, 2006):

[Upper-level]

$$\max_{x_1} f_1\left(x_1, x_2\right) \tag{1a}$$

where x_2 can be solved from:

[Lower-level]

$$\max_{x_2} f_2\left(x_1, x_2\right) \tag{1b}$$

subject to:

$$G=\left\{\left(x_1, x_2\right) \middle| g_i\left(x_1, x_2\right) \leq 0,\ i=1,2,\ldots,m,\ x_1, x_2 \geq 0\right\} \tag{1c}$$

where the upper-level decision maker (ULDM) has control over vector x_1 and the lower-level decision maker (LLDM) has control over vector x_2. The decision mechanism of BLP problem is that the ULDM and LLDM adopt the leader-follower Stackelberg game, so that fuzzy approach can be used to solve the BLP problem (Sakawa, 1993).

In the decision making context, both ULDM and LLDM are interested in maximizing their own objective functions. However, the optimal solution of each DM calculated in isolation will not be accepted by each other due to the conflicting nature of the objectives. In order to obtain satisfactory solutions, the ULDM should specify preferred values of his/her control variables and the associated objective value with allowable tolerances through membership functions. The LLDM then should not only optimize his/her objective but also try to satisfy the ULDM's goal and preference as much as possible (Lai et al., 1996; Sakawa and Nishizaki, 2001; Pramanik and Roy, 2007). Mathematically, the following ULDM problem can be first solved:

$$\max_{x_1} f_1\left(x_1, x_2\right) \tag{2a}$$

subject to:

$$x \in G \tag{2b}$$

where the solution of model (2) is assumed to be (x_1^U, x_2^U, f_1^U) and the LLDM problem can be independently solved:

$$\max_{x_2} f_2(x_1, x_2) \tag{3a}$$

subject to:

$$x \in G \tag{3b}$$

where the solution of model (3) is assumed to be (x_1^L, x_2^L, f_2^L). The range of the decision on x_1 should be around x_1^U with its maximum tolerance p_1. The following membership function can specify x_1 as follows (Lai et al., 1996; Sakawa and Nishizaki, 2001; Pramanik and Roy, 2007):

$$\mu_{x_1}(x_1) = \begin{cases} \dfrac{x_1 - (x_1^U - p_1)}{p_1}, & if\ x_1^U - p_1 < x_1 \le x_1^U \\ \dfrac{(x_1^U + p_1) - x_1}{p_1}, & if\ x_1^U \le x_1 \le x_1^U + p_1 \\ 0, & if \text{ otherwise} \end{cases} \tag{4}$$

where x_1^U is the most preferred decision; the $(x_1^U - p_1)$ and $(x_1^U + p_1)$ are the worst acceptable decisions; satisfaction or preference can be linearly increased within the interval of $[x_1^U - p_1, x_1]$ and linearly decreased within $[x_1^U, x_1 + p_1]$, even though the other DMs are not acceptable.

For the ULDM, the objective function can be considered under all $f_1 \ge f_1^U$ being acceptable and all $f_1 < f_1^{'} = f_1(x_1^L, x_2^L)$ being unacceptable, and thus the preference might be fluctuated within $[f_1^{'}, f_1^U]$. The LLDM can obtain the optimum at (x_1^L, x_2^L), which in turn provides the ULDM with the objective value of $f_1^{'}$, leading to any $f_1 < f_1^{'}$ unattractive in practice. The following membership function can then be stated as:

$$\mu_{f_1}[f_1(x)] = \begin{cases} 1, & if\ f_1(x) > f_1^U \\ \dfrac{f_1(x) - f_1^{'}}{f_1^U - f_1^{'}}, & if\ f_1^{'} \le f_1(x) \le f_1^U \\ 0, & if\ f_1(x) < f_1^{'} \end{cases} \tag{5}$$

The LLDM may be willing to build a membership function for his/her objective so that he/she can assess the satisfaction of each potential solution. Since f_2^L is the maximum objective value of ULDM, $f_2(x) > f_2^L$ is impossible while the ULDM provides more constraints to the LLDM. Meanwhile, the LLDM will not accept any $f_2(x) < f_2^{'}$ due to the same reason as the ULDM discussed above. The LLDM then has the following membership function for his/her goal:

$$\mu_{f_2}[f_2(x)] = \begin{cases} 1, & if\ f_2(x) > f_2^L \\ \dfrac{f_2(x) - f_2^{'}}{f_2^L - f_2^{'}}, & if\ f_2^{'} \le f_2(x) \le f_2^L \\ 0, & if\ f_2(x) < f_2^{'} \end{cases} \tag{6}$$

where $f_2^{'} = f_2(x_1^U, x_2^U)$. Obviously, the above membership function is a one-to-one mapping within a compact interval of $[f_2^{'}, f_2^L]$. Consequently, the satisfactory solution of model (1) that is a Pareto optimal solution with overall satisfaction for both the ULDM and LLDM can be obtained. Thus, we have:

$$\max \lambda \tag{7a}$$

subject to:

$$x \in G \tag{7b}$$

$$\mu_{x_1}(x_1) \ge \lambda I \tag{7c}$$

$$\mu_{f_1}[f_1(x)] \ge \lambda \tag{7d}$$

$$\mu_{f_2}[f_2(x)] \ge \lambda \tag{7e}$$

$$x_1, x_2 \ge 0 \tag{7f}$$

$$\lambda \in [0,1] \tag{7g}$$

where λ is the overall satisfactory degree, and I is a column vector with all elements equal to ls and the same dimension as μ_{x_1} or x_1.

Obviously, the above approach can address the fuzzy decisions and the associated objective of the upper-level model through possible tolerances, which are described as constraints for the feasible space of the LLDM. Furthermore, an extended consideration is for uncertainties in other parameters. For example, it may be difficult for the authorities to investigate the economic data of the planning horizon in practical decision making problems. Moreover, the quality of obtained information is often not satisfactory enough to be presented as probabilistic distributions or membership functions; besides, even if such functions are available, their reflections in large-scale optimization models could be extremely challenging (Lai and Hwang, 1994). Therefore, to deal with uncertainties in the constraints and cost/revenue parameters in the objective function, interval-parameter programming (IPP) is introduced into the BLP framework, which will lead to an interval fuzzy bi-level programming (IFBP) model as follows:

[Upper-level]

$$\max_{x_1^{\pm}} f_1^{\pm}(x_1, x_2) \tag{8a}$$

where $x_2^{\pm}$ can be solved from:

[Lower-level]

$$\max_{x_2^{\pm}} f_2^{\pm}(x_1, x_2) \tag{8b}$$

subject to:

$$G^{\pm} = \left\{ (x_1^{\pm}, x_2^{\pm}) \middle| g_i^{\pm}(x_1^{\pm}, x_2^{\pm}) \le 0,\ i = 1, 2, \ldots, m,\ x_1^{\pm}, x_2^{\pm} \ge 0 \right\} \tag{8c}$$

Then, an interactive solution algorithm can be used to solve the above problem through analyzing the interrelationships between parameters and variables and between objective functions and constraints. For the objective functions of both ULDM and LLDM are to be maximized, the submodel corresponding to the upper bounds of f_1^+ and f_2^+ can be formulated firstly, where x_1^+ and x_2^+ can be obtained from the following model:

[Upper-level]

$$\max_{x_1^+} f_1^+\left(x_1^+, x_2^+\right) \tag{9a}$$

[Lower-level]

$$\max_{x_2^+} f_2^+\left(x_1^+, x_2^+\right) \tag{9b}$$

subject to:

$$G^+ = \left\{\left(x_1^+, x_2^+\right) \middle| g_i^+\left(x_1^+, x_2^+\right) \le 0,\ i = 1, 2, \ldots, m,\ x_1^+, x_2^+ \ge 0\right\} \tag{9c}$$

Let $\left(x_1^{U+}, x_2^{U+}, f_1^{U+}\right)$ be the solutions from Equations (9a) and (9c), and $\left(x_1^{L+}, x_2^{L+}, f_2^{L+}\right)$ be the solutions from Equations (9a) and (9c), respectively. Accordingly, $f_2^{'+}$ and $f_1^{'+}$ can also be obtained. Therefore, x_1^+ and x_2^+ can be solved based on model (7) with details shown as follows:

$$\max \lambda^+ \tag{10a}$$

subject to:

$$x_1^+, x_2^+ \in G^+ \tag{10b}$$

$$\mu_{x_1^+}\left(x_1^+\right) \ge \lambda^+ I \tag{10c}$$

$$\mu_{f_1^+}\left[f_1^+\left(x_1^+, x_2^+\right)\right] \ge \lambda^+ \tag{10d}$$

$$\mu_{f_2^+}\left[f_2^+\left(x_1^+, x_2^+\right)\right] \ge \lambda^+ \tag{10e}$$

$$x_1^+, x_2^+ \ge 0 \tag{10f}$$

$$\lambda^+ \in [0,1] \tag{10g}$$

where:

$$\mu_{x_1^+}\left(x_1^+\right) = \begin{cases} \dfrac{x_1^+ - \left(x_1^{U+} - p_1^+\right)}{p_1^+}, & if\ x_1^{U+} - p_1^+ < x_1^+ \le x_1^{U+} \\ \dfrac{\left(x_1^{U+} + p_1^+\right) - x_1^+}{p_1^+}, & if\ x_1^{U+} \le x_1^+ \le x_1^{U+} + p_1^+ \\ 0, & if\ \text{otherwise} \end{cases} \tag{10h}$$

$$\mu_{f_1^+}\left[f_1^+\left(x_1^+, x_2^+\right)\right] = \begin{cases} 1, & if\ f_1^+\left(x_1^+, x_2^+\right) > f_1^{U+} \\ \dfrac{f_1^+\left(x_1^+, x_2^+\right) - f_1^{'+}}{f_1^{U+} - f_1^{'+}}, & if\ f_1^{'+} \le f_1^+\left(x_1^+, x_2^+\right) \le f_1^{U+} \\ 0, & if\ f_1^+\left(x_1^+, x_2^+\right) < f_1^{'+} \end{cases} \tag{10i}$$

$$\mu_{f_2^+}\left[f_2^+\left(x_1^+, x_2^+\right)\right] = \begin{cases} 1, & if\ f_2^+\left(x_1^+, x_2^+\right) > f_2^{L+} \\ \dfrac{f_2^+\left(x_1^+, x_2^+\right) - f_2^{'+}}{f_2^{L+} - f_2^{'+}}, & if\ f_2^{'+} \le f_2^+\left(x_1^+, x_2^+\right) \le f_2^{L+} \\ 0, & if\ f_2^+\left(x_1^+, x_2^+\right) < f_2^{'+} \end{cases} \tag{10j}$$

Thus, solutions of x_{1opt}^+ and x_{2opt}^+ can be obtained through submodel (10), and the objective values of the upper and lower levels are f_{1opt}^+ and f_{2opt}^+, respectively. Correspondingly, the submodel corresponding to f_1^+ and f_2^+ can be formulated as follows:

[Upper-level]

$$\max_{x_1^-} f_1^-\left(x_1^-, x_2^-\right) \tag{11a}$$

[Lower-level]

$$\max_{x_2^-} f_2^-\left(x_1^-, x_2^-\right) \tag{11b}$$

subject to:

$$G^- = \left\{\left(x_1^-, x_2^-\right) \middle| g_i^-\left(x_1^-, x_2^-\right) \le 0,\ i = 1, 2, \ldots, m,\ x_1^-, x_2^- \ge 0\right\} \tag{11c}$$

$$x_1^- \le x_{1opt}^+ \tag{11d}$$

$$x_2^- \le x_{2opt}^+ \tag{11e}$$

Similarly, by calculating $\left(x_1^{U-}, x_2^{U-}, f_1^{U-}\right)$, $f_2^{'-}$, $(x_1^{L-}, x_2^{L-}, f_2^{L-})$ and $f_1^{'-}$, the submodel corresponding to lower bounds of the objectives can be formulated sequentially as shown in the following model:

$$\max \lambda^- \tag{12a}$$

subject to:

$$x_1^-, x_2^- \in G^- \tag{12b}$$

$$\mu_{x_1^-}\left(x_1^-\right) \ge \lambda^- I \tag{12c}$$

$$\mu_{f_1^-}\left[f_1^-\left(x_1^-,x_2^-\right)\right] \ge \lambda^- \tag{12d}$$

$$\mu_{f_2^-}\left[f_2^-\left(x_1^-,x_2^-\right)\right] \ge \lambda^- \tag{12e}$$

$$x_1^-, x_2^- \ge 0 \tag{12f}$$

$$x_1^- \le x_{1opt}^+ \tag{12g}$$

$$x_2^- \le x_{2opt}^+ \tag{12h}$$

$$\lambda^- \in [0,1] \tag{12i}$$

where $\mu_{x_1^-}\left(x_1^-\right)$, $\mu_{f_1^-}\left[f_1^-\left(x_1^-,x_2^-\right)\right]$ and $\mu_{f_2^-}\left[f_2^-\left(x_1^-,x_2^-\right)\right]$ can be specified as:

$$\mu_{x_1^-}\left(x_1^-\right)=\begin{cases}\dfrac{x_1^- -\left(x_1^{U-}-p_1^-\right)}{p_1^-}, & if\ x_1^{U-}-p_1^- < x_1^- \le x_1^{U-} \\ \dfrac{\left(x_1^{U-}+p_1^-\right)-x_1^-}{p_1^-}, & if\ x_1^{U-} \le x_1^- \le x_1^{U-}+p_1^- \\ 0, & if\ \text{otherwise}\end{cases} \tag{12j}$$

$$\mu_{f_1^-}\left[f_1^-\left(x_1^-,x_2^-\right)\right]=\begin{cases}1, & if\ f_1^-\left(x_1^-,x_2^-\right) > f_1^{U-} \\ \dfrac{f_1^-\left(x_1^-,x_2^-\right)-f_1^{'-}}{f_1^{U-}-f_1^{'-}}, & if\ f_1^{'-} \le f_1^-\left(x_1^-,x_2^-\right) \le f_1^{U-} \\ 0, & if\ f_1^-\left(x_1^-,x_2^-\right) < f_1^{'-}\end{cases} \tag{12k}$$

$$\mu_{f_2^-}\left[f_2^-\left(x_1^-,x_2^-\right)\right]=\begin{cases}1, & if\ f_2^-\left(x_1^-,x_2^-\right) > f_2^{L-} \\ \dfrac{f_2^-\left(x_1^-,x_2^-\right)-f_2^{'-}}{f_2^{L-}-f_2^{'-}}, & if\ f_2^{'-} \le f_2^-\left(x_1^-,x_2^-\right) \le f_2^{L-} \\ 0, & if\ f_2^-\left(x_1^-,x_2^-\right) < f_2^{'-}\end{cases} \tag{12l}$$

Solutions of x_{1opt}^- and x_{2opt}^- can be obtained through sub-model (12), and the associated objective values are f_{1opt}^- and f_{2opt}^-. Therefore, we can obtain the general solutions for the IFBP model as follows:

$$x_{1opt}^\pm = \left[x_{1opt}^-, x_{1opt}^+\right] \tag{13a}$$

$$x_{2opt}^\pm = \left[x_{2opt}^-, x_{2opt}^+\right] \tag{13b}$$

$$f_{1opt}^\pm = \left[f_{1opt}^-, f_{1opt}^+\right] \tag{13c}$$

$$f_{2opt}^\pm = \left[f_{2opt}^-, f_{2opt}^+\right] \tag{13d}$$

Table 1. Stream Inflows and Technical Data

	Value	Unit
Stream inflow and the associated probability		
Region A: i = 1		
Dry period (probability = 30%)	218.8	10^6 m^3
Normal period (probability = 50%)	273.6	10^6 m^3
Wet period (probability = 20%)	328.3	10^6 m^3
Region A: i = 2		
Dry period (probability = 30%)	104.6	10^6 m^3
Normal period (probability = 50%)	149.4	10^6 m^3
Wet period (probability = 20%)	194.3	10^6 m^3
Other regions: i = 3		
Dry period (probability = 30%)	437. 8	10^6 m^3
Normal period (probability = 50%)	515.1	10^6 m^3
Wet period (probability = 20%)	597.5	10^6 m^3
Maximum storage volume of the reservoir		
Region A: i = 1	31.2	10^6 m^3
Region A: i = 2	22.8	10^6 m^3
Other regions: i = 3	115.2	10^6 m^3
Development capacity of groundwater		
Region A : m = 1	[15.0, 18.0]	10^6 m^3
Other regions: m = 2	[89.0, 106.8]	10^6 m^3
Minimum size of the embankment	[20.0, 24.0]	10^6 m^3
Flood-warning water level	[1800.0,2160.0]	10^6 m^3
Downstream water requirement	[600.0, 720.0]	10^6 m^3
Depth of groundwater removed	4.0	m
Proportion of surface runoff	0.2	m
Size of turbine (portion of storage)	0.4	m

3. Application to Water Resources Management

3.1. Overview of the Study System

Consider a water resources system consisting of multiple regions, wherein the local authority is willing to make a water resources management scheme from an overall viewpoint over the planning horizon. Water supplies to different regions are used for irrigation and hydroelectric power, by which benefits of water usages can be gained. In addition, the retaining water level should be adequate to satisfy ship navigation. Meanwhile, when the stream flow is high, flood control is required to avoid the water exceeding the predefined flood-warning level. Among all regions, Region A which plays a significant role in facilitating economic development of the study area from a long-term consideration, will invest two reservoirs and one groundwater well. For the other regions, they will pay the development costs for surface water storage, groundwater exploitation and embankment construction. Since the total water resources are limited, the shortage will become the major obstacle to the regional economic development. Consequently, conflicts arise in the allocation of water resources among multiple competing interests, because each region prefers to maximize its own net benefit (net benefits = total benefits – investment costs). It is particularly critical for the local authority to contemplate and propose ever more comprehensive decisions on the capacities of the reservoirs, the size of the embankment construction, and the amounts of pumped groundwater; at the same time, the demands for flood control at the critical reach and navigation on the stream can be satisfied. Thus, the system can receive the maximum net benefits of the irrigation water and of power produced at the surface storage sites, in which Region A should be given priority for its prominent contribution to economy.

Table 2. Intervals of Benefit and Cost Coefficients

Benefit		Value
Net benefit of irrigation water from the reservoir ($\$10^6$ m^{-3}):		
Region A	(*i* = 1)	[56.5, 67.8]
Region A	(*i* = 2)	[68.0, 81.6]
Other regions	(*i* = 3)	[75.0, 90.0]
Net benefit of groundwater for irrigation ($\$10^6$ m^{-3}):		
Region A	(*m* = 1)	[59.0, 70.8]
Other regions	(*m* = 2)	[63.0, 75.6]
Hydroelectric benefit ($\$10^6$ m^{-3})		[144.0, 172.8]
Cost		
Water storage cost at the reservoir ($\$10^6$ m^{-3})		[20.4, 24.5]
Development cost of groundwater ($\$10^6$ m^{-2})		
Region A	(*m* = 1)	[9.0, 10.8]
Other regions	(*m* = 2)	[8.3, 10.0]
Embankment construction cost ($\$10^6$ m^{-3})		[20.0, 24.0]

Systems analysis techniques could be used for planning water resources system in a more efficient and environmentally benign way, which may be helpful for generating a desired compromise between the overall economic objective and individual development requirements. Moreover, it is indicated that a variety of complexities exist in the study system, such as uncertainties in parameter inputs, allowances in environmental capacities, and limitations in available resources. These complexities could become further compounded by not only interactions among system components but also their economic implications, which may affect the relevant analysis of water resources management scheme and thus the associated decision making. Therefore, it is deemed necessary to develop effective methods to deal with these problems, and to support developing water resources management plans with a maximized system benefit.

The schematic study system is presented in Figure 1. The modeling parameters are provided in Table 1. The stream inflows with the associated probabilities of occurrence can fluctuate with seasonal variations due to the uneven distributions of precipitation. According to the availabilities of water resources, three inflow seasons (dry, normal and wet) are considered. Meanwhile, the capacity constraints and predefined development requirements, as well as system parameters are tabulated in Table 1. Table 2 shows the related benefit and cost coefficients in intervals. These data mainly come from governmental reports and public surveys (Rogers, 1969; Anandalingam, 1991).

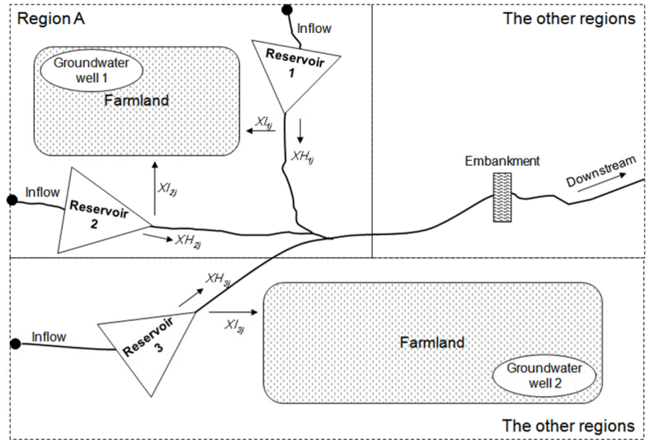

Figure 1. Schematic of the study system.

3.2. Modeling Formulation

The problem under consideration is how to allocate water resources and plan reasonable investments to maximize the expected net benefits over the entire system. The system planner acting as the leader controls the capacities of reservoirs, the size of the embankment, the amounts of surface water and groundwater resources use (i.e., for irrigation and hydro-electricity). The decisions made by Region A (the follower) are on how much water to use for local irrigation (both from surface and groundwater) and how much electricity to generate. Since Region A both plays an important role in economic development of the system and can hardly monopolize water resources of the system, the leader has to incorporate the follower's reaction and maximize its benefits as much as possible. Therefore, the IFBP model can be formulated for the above problem as follows:

Upper level:

$$\max_{V_i^\pm, B^\pm, XG_{2j}^\pm} f_1^\pm = -\sum_{i=1}^{3} CRS_i^\pm \times V_i^\pm - \sum_{m=1}^{2} CG_m^\pm \times G_m^\pm - CD^\pm \times B^\pm + \sum_{i=1}^{3}\left(NB\_I_i^\pm \sum_{j=1}^{3} p_j XI_{ij}^\pm \right) + \sum_{m=1}^{2}\left(NB\_G_m^\pm \sum_{j=1}^{3} p_j XG_{mj}^\pm \right) + NB\_H^\pm \times \sum_{i=1}^{3}\sum_{j=1}^{3} p_j \times XH_{ij}^\pm \tag{14a}$$

Lower level:

$$\max_{XI_{1j}^\pm, XI_{2j}^\pm, XH_{1j}^\pm, XH_{2j}^\pm, XG_{1j}^\pm} f_2^\pm = \sum_{i=1}^{2}\left(NB\_I_i^\pm \sum_{j=1}^{3} p_j XI_{ij}^\pm \right) + NB\_G_1^\pm \times \sum_{j=1}^{3} p_j XG_{1j}^\pm + NB\_H^\pm \sum_{i=1}^{2}\sum_{j=1}^{3} p_j XH_{ij}^\pm - \sum_{i=1}^{2} CRS_i^\pm \times V_i^\pm - CG_1^\pm \times G_1^\pm \tag{14b}$$

subject to:

(1) Release from storage less than inflows:

$$\sum R_{ij} \le \sum I_{ij}, \ \forall j \tag{14c}$$

(2) Storage less than capacity:

$$R_{ij} + V_i^{\pm} \ge I_{ij}, \ \forall i, j \tag{14d}$$

(3) Flood control:

$$\sum R_{ij} - B^{\pm} \le F^{\pm}, \ \forall j \tag{14e}$$

(4) Water amount requirement:

$$\sum R_{ij} - (1-\eta)\sum XI_{ij}^{\pm} + \eta \sum XG_{mj}^{\pm} \ge N^{\pm}, \ \forall j \tag{14f}$$

(5) Flow for surface irrigation:

$$R_{ij} - XI_{ij}^{\pm} \ge 0, \ \forall i, j \tag{14g}$$

(6) Flow through turbines less than or equal to capacity of turbines:

$$\varepsilon_i V_i^{\pm} - XH_{ij}^{\pm} \ge 0, \ \forall i, j \tag{14h}$$

(7) Flow through turbines constrained by water releases:

$$R_{ij} - XH_{ij}^{\pm} \ge 0, \ \forall i, j \tag{14i}$$

(8) Groundwater pumped constrained by recharge:

$$XG_{mj}^{\pm} - \gamma G_m^{\pm} \le 0, \ \forall m, j \tag{14j}$$

(9) Upper limit on surface water storage:

$$V_i^{\pm} \le V_{i\,\max}, \ \forall i \tag{14k}$$

(11) Upper limit on size of groundwater field:

$$G_m^{\pm} \le G_{m\,\max}^{\pm}, \forall m \tag{14l}$$

(12) Requirement for building the embankment:

$$B^{\pm} \ge B_{\min}^{\pm} \tag{14m}$$

where:

i = name of reservoir, i = 1 and 2 for Region A, and i = 3 for the other regions;

m = name of groundwater location;

j = number of period, j = 1, 2 and 3 representing dry, normal and wet periods, respectively;

p_j = occurrence probability of period j;

R_{ij} = release from reservoir i in period j (m^3);

I_{ij} = inflow into reservoir i in period j (m^3);

$F^{\pm}$ = flood capacity at control on river system (m^3);

η = proportion of irrigation water returning to stream;

$N^{\pm}$ = water amount required by the downstream user in terms of flow units (m^3);

ε_i = capacity of turbines at reservoir i expressed as a proportion of storage;

γ = depth of groundwater removed, in meter of water (m);

$V_{i\,max}$ = maximum volume of reservoir i in terms of flow units (m^3);

$G_{m\,\max}^{\pm}$ = maximum size of tube well field of location m (m^2);

$B_{\min}^{\pm}$ = minimum size of embankment in terms of flow units (m^3);

$NB\_I_i^{\pm}$ = net benefit of irrigation water per unit of flow from reservoir i ($\$10^6 \cdot m^{-3}$);

$NB\_G_m^{\pm}$ = net benefit per unit of pumped groundwater from location m for irrigation ($\$10^6 \cdot m^{-3}$);

$NB\_H^{\pm}$ = net benefit of hydropower per unit of flow ($\$10^6 \cdot m^{-3}$);

$CRS_i^{\pm}$ = regular cost per unit volume of storage at reservoir i ($\$10^6 \cdot m^{-3}$);

$CD^{\pm}$ = investment per unit of building the embankment ($\$10^6 \cdot m^{-3}$);

$CG_m^{\pm}$ = cost per unit of groundwater development at location m ($\$10^6 \cdot m^{-2}$);

$G_m^{\pm}$ = size of tube well field of location m (m^2);

$V_i^{\pm}$ = volume of reservoir i in terms of flow units (m^3);

$B^{\pm}$ = size of embankment at flood control point in terms of flow units (m^3);

$XI_{ij}^{\pm}$ = agricultural diversion from reservoir i in period j (m^3);

$XG_{mj}^{\pm}$ = pumped groundwater at location m in period j (m^3);

$XH_{ij}^{\pm}$ = flow through turbines at site i in period j (m^3);

In model (14), the $V_i^{\pm}$, $B^{\pm}$, $XI_{ij}^{\pm}$, $XG_{mj}^{\pm}$ and $XH_{ij}^{\pm}$ are decision variables. The objective function equals benefits from water usages for hydroelectricity generation and agricultural irrigation minus the costs for reservoir investment. For example, the upper-level objective includes the payments from the regions that are assumed to tied to the hydroelectricity generated ($XH_{ij}^{\pm}$), amounts of surface water ($XI_{ij}^{\pm}$) and groundwater ($XG_{mj}^{\pm}$) used for irrigation, and the investment costs for the surface water storage ($V_i^{\pm}$), groundwater well development ($G_m^{\pm}$) and the embankment construction ($B^{\pm}$).

3.3. Solution Method

The above IFBP model can be transformed into two deterministic submodels through the proposed interactive algorithm, which correspond to the upper and lower bounds of the desired objective function values, respectively (Huang et al., 1992, 1993, 1995). The resulting solution can provide stable intervals for the objective function values and decision variables, and can be easily interpreted for generating decision alternatives. The submodel corresponding to f_1^+ and f_2^+ can be formulated in the first step when the system objectives are to be maximized; another submodel (corresponding to f_1^- and f_2^-) can then be formulated based on the solution of the first submodel. Thus, the upper-bound submodel is formulated as follows:

Upper level:

$$\max_{V_i^-, B^-, XG_{2j}^+} f_1^+ = -\sum_{i=1}^{3} CRS_i^- \times V_i^- - \sum_{m=1}^{2} CG_m^- \times G_m^- - CD^- \times B^- + \sum_{i=1}^{3}\left(NB\_I_i^+ \sum_{j=1}^{3} p_j XI_{ij}^+\right) + \sum_{m=1}^{2}\left(NB\_G_m^+ \sum_{j=1}^{3} p_j XG_{mj}^+\right) + NB\_H^+ \times \sum_{i=1}^{3}\sum_{j=1}^{3} p_j \times XH_{ij}^+ \quad (15a)$$

Lower level:

$$\max_{XI_{1j}^+, XI_{2j}^+, XH_{1j}^+, XH_{2j}^+, XG_{1j}^+} f_2^+ = \sum_{i=1}^{2}\left(NB\_I_i^+ \sum_{j=1}^{3} p_j XI_{ij}^+\right) + NB\_G_1^+ \times \sum_{j=1}^{3} p_j XG_{1j}^+ + NB\_H^+ \sum_{i=1}^{2}\sum_{j=1}^{3} p_j XH_{ij}^+ - \sum_{i=1}^{2} CRS_i^- \times V_i^- - CG_1^- \times G_1^- \quad (15b)$$

subject to

$$\sum R_{ij} \le \sum I_{ij}, \ \forall j \quad (15c)$$

$$R_{ij} + V_i^- \ge I_{ij}, \ \forall i, j \quad (15d)$$

$$\sum R_{ij} - B^- \le F^+, \ \forall j \quad (15e)$$

$$\sum R_{ij} - (1-\eta)\sum XI_{ij}^+ + \eta \sum XG_{mj}^+ \ge N^-, \ \forall j \quad (15f)$$

$$R_{ij} - XI_{ij}^+ \ge 0, \ \forall i, j \quad (15g)$$

$$\varepsilon_i V_i^- - XH_{ij}^+ \ge 0, \ \forall i, j \quad (15h)$$

$$R_{ij} - XH_{ij}^+ \ge 0, \ \forall i, j \quad (15i)$$

$$XG_{mj}^+ - \gamma G_m^- \le 0, \ \forall m, j \quad (15j)$$

$$V_i^- \le V_{i\,\max}, \ \forall i \quad (15k)$$

$$G_m^- \le G_{m\,\max}^+, \forall m \quad (15l)$$

$$B^- \ge B_{\min}^- \quad (15m)$$

$$V_i^- \ge 0, \ \forall i \quad (15n)$$

$$B^- \ge 0 \quad (15o)$$

$$XI_{ij}^+ \ge 0, \ \forall i, j \quad (15p)$$

$$XH_{ij}^+ \ge 0, \ \forall i, j \quad (15q)$$

$$XG_{mj}^+ \ge 0, \ \forall m, j \quad (15r)$$

Model (15) can be solved through the fuzzy approach as described from models (9) to (12). Solutions for the objective function values of both ULDM and LLDM (f_1^+ and f_2^+) provide the extreme upper bounds of expected benefits. Let $V_{i\,opt}^-$, B_{opt}^-, $XI_{ij\,opt}^+$, $XH_{ij\,opt}^+$ and $XG_{mj\,opt}^+$ be the solutions of model (15). Then, the second submodel corresponding to f_1^- and f_2^- can be established as follows:

Upper level:

$$\max_{V_i^+, B^+, XG_{2j}^-} f_1^- = -\sum_{i=1}^{3} CRS_i^+ \times V_i^+ - \sum_{m=1}^{2} CG_m^+ \times G_m^+ - CD^+ \times B^+ + \sum_{i=1}^{3}\left(NB\_I_i^- \sum_{j=1}^{3} p_j XI_{ij}^-\right) + \sum_{m=1}^{2}\left(NB\_G_m^- \sum_{j=1}^{3} p_j XG_{mj}^-\right) + NB\_H^- \times \sum_{i=1}^{3}\sum_{j=1}^{3} p_j \times XH_{ij}^- \quad (16a)$$

Lower level:

$$\max_{XI_{1j}^-, XI_{2j}^-, XH_{1j}^-, XH_{2j}^-, XG_{1j}^-} f_2^- = \sum_{i=1}^{2}\left(NB\_I_i^- \sum_{j=1}^{3} p_j XI_{ij}^-\right) + NB\_G_1^- \times \sum_{j=1}^{3} p_j XG_{1j}^- + NB\_H^- \sum_{i=1}^{2}\sum_{j=1}^{3} p_j XH_{ij}^- - \sum_{i=1}^{2} CRS_i^+ \times V_i^+ - CG_1^+ \times G_1^+ \quad (16b)$$

subject to

$$\sum R_{ij} \le \sum I_{ij}, \ \forall j \quad (16c)$$

$$R_{ij} + V_i^+ \ge I_{ij}, \ \forall i, j \quad (16d)$$

$$\sum R_{ij} - B^+ \le F^-, \ \forall j \quad (16e)$$

$$\sum R_{ij} - (1-\eta)\sum XI_{ij}^- + \eta \sum XG_{mj}^- \ge N^+, \ \forall j \quad (16f)$$

$$R_{ij} - XI_{ij}^{-} \geq 0, \quad \forall i, j \tag{16g}$$

$$\varepsilon_i V_i^{+} - XH_{ij}^{-} \geq 0, \quad \forall i, j \tag{16h}$$

$$R_{ij} - XH_{ij}^{-} \geq 0, \quad \forall i, j \tag{16i}$$

$$XG_{mj}^{-} - \gamma G_m^{+} \leq 0, \quad \forall m, j \tag{16j}$$

$$V_i^{+} \leq V_{i\,\max}, \quad \forall i \tag{16k}$$

$$G_m^{+} \leq G_{m\,\max}^{-}, \forall m \tag{16l}$$

$$B^{+} \geq B_{\min}^{+} \tag{16m}$$

$$V_i^{+} \geq V_{i\,opt}^{-}, \ \forall i \tag{16n}$$

$$B^{+} \geq B_{opt}^{-} \tag{16o}$$

$$0 \leq XI_{ij}^{-} \leq XI_{ij\,opt}^{+}, \ \forall i, j \tag{16p}$$

$$0 \leq XH_{ij}^{-} \leq XH_{ij\,opt}^{+}, \ \forall i, j \tag{16q}$$

$$0 \leq XG_{mj}^{-} \leq XG_{mj\,opt}^{+}, \ \forall m, j \tag{16r}$$

where V_i^{+}, B^{+}, XI_{ij}^{-}, XH_{ij}^{-} and XG_{mj}^{-} are decision variables. Let $V_{i\,opt}^{+}$, B_{opt}^{+}, $XI_{ij\,opt}^{-}$, $XH_{ij\,opt}^{-}$ and $XG_{mj\,opt}^{-}$ be solutions of model (16).

Thus, the final solution for the primal problem [i.e. model (14)] is:

$$V_{i\,opt}^{\pm} = \left[V_{i\,opt}^{-}, V_{i\,opt}^{+}\right], \ \forall i \tag{17a}$$

$$B_{opt}^{\pm} = \left[B_{opt}^{-}, B_{opt}^{+}\right] \tag{17b}$$

$$XI_{ij\,opt}^{\pm} = \left[XI_{ij\,opt}^{-}, XI_{ij\,opt}^{+}\right], \ \forall i, j \tag{17c}$$

$$XH_{ij\,opt}^{\pm} = \left[XH_{ij\,opt}^{-}, XH_{ij\,opt}^{+}\right], \ \forall i, j \tag{17d}$$

$$XG_{mj\,opt}^{\pm} = \left[XG_{mj\,opt}^{-}, XG_{mj\,opt}^{+}\right], \ \forall m, j \tag{17e}$$

The objective function values for the ULDM and LLDM are $f_{1opt}^{\pm} = \left[f_{1opt}^{-}, f_{1opt}^{+}\right]$ and $f_{2opt}^{\pm} = \left[f_{2opt}^{-}, f_{2opt}^{+}\right]$, respectively. In detail, the solution process for model (14) with both the upper- and lower-level objectives being maximized can be summarized as shown in Figure 2.

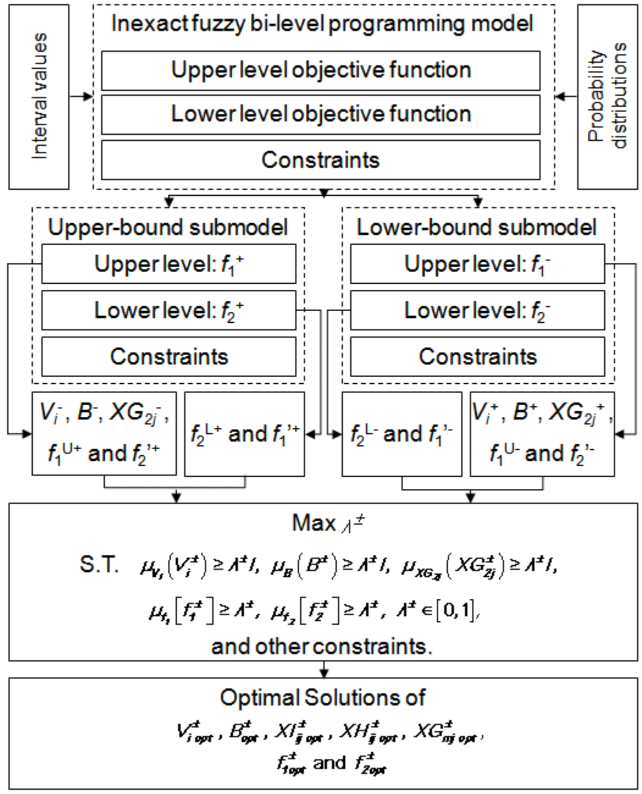

Figure 2. Flowchart of solving the IFBP model.

4. Result Analysis

The nine scenarios related to the study system are investigated through solving the water resources allocation problem (Table 3). The obtained optimal solutions under each scenario can provide the local authorities possible options for water resources development strategies. For example, Scenario 1 (the basic one) represents the optimal scheme generated through the IFBP method as solved through models (15) and (16) subsequently. In detail, the upper-bound submodel is given priority to be solved and then the lower-bound submodel, while the objectives are to maximize the net benefits of the upper and lower levels. Scenarios 2 and 3 show the situations of planning a water resources system with conventional methods related to single decision maker. Scenarios 4, 5 and 6 present the solutions corresponding to different sets of tolerances which are decided by the authorities. Meanwhile, several extreme scenarios such as best/worst case analysis are presented as Scenarios 7 and 8. Under Scenario 9, model (14) is converted to a deterministic one by letting interval parameters be their mid-values.

The results indicate that the optimal water resources allocations to parties would vary with the interval inputs under Scenario 1 (as shown in Table 4). The reservoir capacities decided by the local authorities appear to reach their maximum sizes, which would be 31.2 × 10^6 m^3 for reservoir 1 and 22.8

Table 3. Descriptions of Solution Scenarios

Scenario	Description
1	Obtaining the interval solutions from the IFBP method
2	Optimizing Region A separately to gain the maximum expected benefits
3	Optimizing the whole system to gain the maximum expected benefits without negotiation with Region A
4	Solving the IFBP model by letting the tolerances be 2% of the decision variables controlled by the ULDM
5	Solving the IFBP model by letting the tolerances be 5% of the decision variables controlled by the ULDM
6	Solving the IFBP model by letting the tolerances be 20% of the decision variables controlled by the ULDM
7	Obtaining the deterministic solutions under worst case analysis
8	Obtaining the deterministic solutions under best case analysis
9	Obtaining the deterministic solutions through the conventional fuzzy bi-level programming (FBP) method

Table 4. Solutions Obtained from the IFBP Model

	By local authority	By Region A	Bi-level solutions
Reservoir capacity (10^6 m^3):			
V_1	31.2	31.2	31.2
V_2	22.8	22.8	22.8
V_3	115.2	115.2	115.2
Size of embankment B (10^6 m^3):			
	[20.0, 24.0]	[20.0, 24.0]	[20.0, 24.0]
Pumped groundwater XG (m^3):			
m = 1, Dry	[60.0, 72.0]	[60.0, 72.0]	[60.0, 72.0]
Normal	[60.0, 72.0]	[60.0, 72.0]	[60.0, 72.0]
Wet	[60.0, 72.0]	[60.0, 72.0]	[60.0, 72.0]
m = 2, Dry	[356.0, 427.2]	[356.0,427.2]	[356.0,427.2]
Normal	[356.0, 427.2]	[356.0, 427.2]	[356.0, 427.2]
Wet	[356.0, 427.2]	[356.0, 427.2]	[356.0, 427.2]
Irrigation water from reservoir XI (10^6 m^3):			
m = 1, Dry	0	[0, 75.4]	0
Normal	0	[80.8, 242.4]	[0, 18.0]
Wet	0	[263.4, 297.1]	[126.3, 297.1]
m = 2, Dry	0	[155.6, 251.0]	[80.2, 251.0]
Normal	0	295.8	[271.7, 295.8]
Wet	[0, 123.3]	340.7	340.7
m = 3, Dry	[155.6, 326.4]	0	75.4
Normal	[376.6, 547.4]	0	[104.9, 233.6]
Wet	[604.1, 651.5]	0	137.1
Water resources for hydroelectricity XH (10^6 m^3):			
m = 1, Dry	7.8	7.8	7.8
Normal	7.8	7.8	7.8
Wet	7.8	7.8	7.8
m = 2, Dry	5.7	5.7	5.7
Normal	5.7	5.7	5.7
Wet	5.7	5.7	5.7
m = 3, Dry	28.8	0	28.8
Normal	28.8	0	28.8
Wet	28.8	0	28.8
Benefit from Region A ($\$10^6$):			
	[4,000.1, 8,179.7]	[27,123.6, 43,718.2]	[20,933.4, 34,577.0]
Expected system benefit ($\$10^6$):			
	[52,977.1, 86,989.3]	[45.269.1, 72,378.0]	[50,913.7, 83,231.0]

× 10^6 m^3 for Reservoir 2 in Region A; Reservoir 3 for the other regions would be 115.2 × 10^6 m^3. The construction of the embankment at the flood control point would be at least [20.0, 24.0] ×10^6 m^3 to prevent the river overflowing, which would be particularly crucial in the wet season. Irrigation water is supplied by the conjunctive use of surface and ground water resources. For example, the agricultural area in Region A is surrounded by two surface water sources (i.e., reservoirs 1 and 2) and one groundwater well. During the dry season, there would be [80.2, 251.0] × 10^6 m^3 of the surface water for irrigation released from reservoir 2. No water would be available from reservoir 1. In comparison, with the increase of stream inflows, the irrigation water from the two reservoirs would be [126.3, 297.1] × 10^6 m^3 and 340.7 × 10^6 m^3 during the wet season, respectively. The groundwater is profitable so that there would be [60.0, 72.0] × 10^6 m^3 of groundwater pumped in Region A for irrigation (despite of inflow levels). Meanwhile, the surface water resources can also be used for hydroelectricity generation, which would be 7.8 × 10^6 m^3, 5.7 × 10^6 m^3 and 28.8 × 10^6 m^3 for the three reservoirs respectively, despite of inflow levels.

Table 4 also presents the results obtained under Scenarios 2 and 3. Under Scenario 2, Region A could make an optimal plan of full utilization of available resources. For example, the irrigation water from reservoir 1 would be [0, 75.4] × 10^6 m^3 in the dry season, [80.8, 242.4] × 10^6 m^3 in the normal season and [263.4, 297.1] × 10^6 m^3 in the wet season, respectively. For reservoir 2, the allocations of irrigation water during the three seasons would be [155.6, 251.0] × 10^6, 295.8 × 10^6 and 340.7 × 10^6 m^3, respectively. Under such a situation, the other regions can be allocated little water from reservoir 3. In fact, the increasing possession of water for any individual regions would definitely entail losses for the other regions. Apparently, the local authorities can optimize the entire system independently through conventional single-objective programming methods by assuming that all the regions will develop equally in the future. Their actions thus would form the final development scheme as described under Scenario 3. It is indicated that resource allocations among parties within the system are motivated by economic benefits from the water utilizations. The surface water assigned to Region A for irrigation would be [0, 123.3] × 10^6 m^3 from Reservoir 2 only during the wet season due to lower benefits of both Reservoirs 1 and 2. Comparatively, the flows for irrigation from reservoir 3 would be [155.6, 326.4] × 10^6 m^3 in the dry season, [376.6, 547.4] × 10^6 m^3 in the normal season and [604.1, 651.5] × 10^6 m^3 in the wet season. However, since Region A plays a significant role in promoting the local economic growth from a long-term viewpoint, it should be given priority while making development plans. Decisions under Scenario 3 would hamper Region A's use of water resources, and would lead to a low benefit to the entire system.

Moreover, different water resources management strategies under different scenarios (i.e., Scenarios 1, 2 and 3) would result in varying system benefits. Under Scenario 2, Region A would obtain the maximum net benefit of \$[27,123.6, 43,718.2] × 10^6 by implementing the optimum plan regardless of what the other regions do. The whole system would then obtain a net benefit of \$[45,269.1, 72,378.0] × 10^6 over the planning horizon. Under Scenario 3, the expected system benefit would be \$[52,977.1, 86,989.3] × 10^6 which is higher than that under Scenario 2. However, benefit losses would occur to Region A, which would restrict economic growth within this region. Thus, Region A can only gain the net benefit of \$[4,000.1, 8,179.7] × 10^6. Comparatively, the optimum solutions under Scenario 1 would be generated after all parties could discuss their strategies and make binding agreements. Then, the beneficial objective function values would be \$ [50,913.7, 83,231.0] × 10^6 for the entire system and \$ [20,933.4, 34,577.0] × 10^6 for Region A, respectively, with a satisfactory level λ of [0.732, 0.743]. Since the local authority would take on the leadership role presented as the upper-level objective function, it would be ensured that the water resources for irrigation (e.g., surface or groundwater) and hydroelectricity would be distributed scientifically among the parties throughout the system. The resources could not be monopolized by any parties as in the case of a single decision maker for the entire system (e.g., Scenario 2). Indeed, the bi-level management structure would result in a better system behavior than those under any other situations, especially if the leader would also subsidize the project investments of building reservoirs, developing groundwater wells, as well as the construction of the embankment.

Different tolerance levels would lead to slight variations of solutions for the study case. Solving the problem under Scenarios 4, 5 and 6 demonstrates the influences of tolerance levels on the model outputs. Under Scenario 1, the capacities of reservoirs, the size of embankment and the amount of groundwater development for the other regions can be obtained through solving the upper-level optimizing problem independently. Then the related tolerances assigned in the fuzzy bi-level programming model would be 10% of the above variables, respectively. For example, in the upper bound submodel [i.e. model (15)], the capacities of reservoirs optimized by the ULDM (the local authority) would be 31.2 × 10^6 m^3 for reservoir 1, 22.8 × 10^6 m^3 for reservoir 2, and 115.2 × 10^6 m^3 for reservoir 3. Accordingly, the tolerances for the three reservoirs would be 3.12 × 10^6 m^3, 2.28 × 10^6 m^3 and 11.52 × 10^6 m^3, respectively. The values of tolerances in the lower bound submodel [i.e. model (16)] can be obtained in the similar way. In Scenarios 4, 5 and 6, different tolerances that are 2%, 5% and 20% of the upper-level decision variables are considered. Under Scenarios 4 and 6, only slightly changes would happen to the amounts of irrigation water received from reservoirs ($XI_{ij}^{\pm}$); while the values of objective functions and the other decision variables would remain the same as those under Scenario 1. For example, in the wet season under Scenario 4, the allocated irrigation water would be 0 from reservoir 1, 340.7 × 10^6 m^3 from Reservoir 2, and [263.4, 434.2] × 10^6 m^3 from reservoir 3; whereas, in the same season under Scenario 6, the allotments of irrigation water from the three reservoirs would be [126.3, 297.1] × 10^6, 340.7 × 10^6 and 137.1 × 10^6 m^3, respectively. The solutions obtained under Scenario 5 would not be affected by the inputs of the tolerances (same as those under Scenario 1). The result comparisons for the amounts of surface irrigation water ($XI_{ij}^{\pm}$) obtained under Scenarios 1, 5, 6 and 7 are shown in Figure 3. The tolerances representing the domains for the decision variables would be set subjectively, and the variations of tolerances might influence the model outputs. However, the differences of results among scenarios would be tiny and occur on some

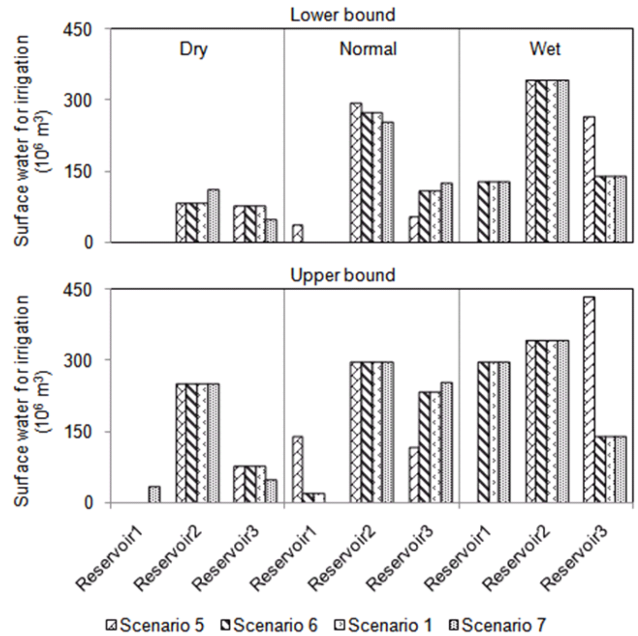

Figure 3. Comparisons of solutions for surface water irrigation under several scenarios.

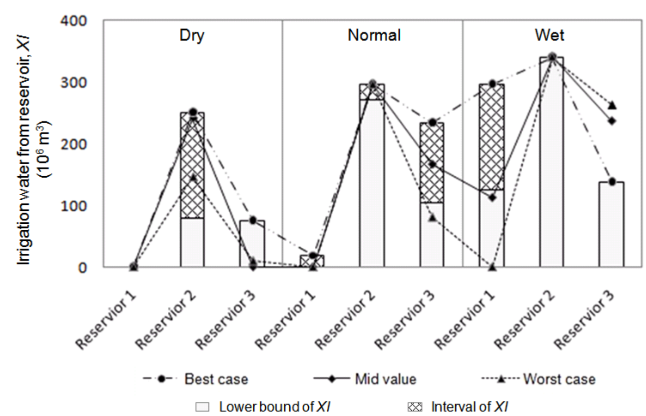

Figure 4. Amounts of irrigation water released from reservoirs under different cases.

of the decision variables. Moreover, the objectives of both ULDM and LLDM would not be changed despite of various inputs of the tolerances. It is indicated that the proposed IFBP can provide compromising solutions for the study problem.

The study problem can be solved under worst/best case analysis, where two extreme decisions would be generated through conventional fuzzy bi-level programming models corresponding to the most pessimistic and optimistic system benefits, respectively. For example, under the normal season, the optimal flows to irrigation from Reservoirs 1, 2 and 3 would respectively be (i) 0, 295.8×10^6 and 80.8×10^6 m^3 under the worst case (Scenario 7), and (ii) 18.0×10^6, 295.8×10^6 and 233.6×10^6 m^3 under the best case (Scenario 8). Accordingly, the objective functions values of the upper and lower levels would be (i) \$$51,158.4 \times 10^6$ and \$$21,667.6 \times 10^6$ with $\lambda = 0.764$ under Scenario 7, (ii) \$$83,231.0 \times 10^6$ and \$$34,577.0 \times 10^6$ with $\lambda = 0.743$ under Scenario 8, respectively. Decisions at the worst case would lead to an increased satisfactory level in fulfilling the system conditions but with a low system benefit; decisions at the best case would result in a high benefit, but the risk of violating the system constraints would be high (i.e. a relative low reliability level of satisfying system constraints). Although the best/worst case analysis is useful for judging the system's capability to realize the desired goals, the obtained solutions could only reflect extreme decision situations which might not be attained in real-world problems.

Let the uncertain inputs of Scenario 1 be a set of mid values of the intervals, and the problem could be converted into a deterministic bi-level programming model. Under Scenario 9, inexact information in the capacities of groundwater development, the size of the embankment, the requirements for the flood control and downstream water amounts, as well as the benefit/cost coefficients were ignored, which would lead to different water resources development pattern from that under Scenario 1. For instance, during the normal season, the surface water amounts allocated from Reservoirs 1 and 2 would be 0 and 295.8×10^6 m^3, respectively, which would be used for irrigation in Region A. While the irrigation water supplied by reservoir 3 for the other regions would be 166.2×10^6 m^3 over the planning horizon. Accordingly, the expected system benefit would be \$$66,505.0 \times 10^6$; meanwhile, Region A could obtain the net benefit of \$$28,009.4 \times 10^6$ under Scenario 9. Figure 4 presents the comparisons of irrigation water amounts from reservoirs (*XI*) obtained under Scenarios 1, 7, 8 and 9. The methods according to Scenarios 7, 8 and 9 oversimplified the interval information into deterministic values (i.e., the extreme or mid values), such that the solutions representing one of many potential responses to the uncertain parameters could be generated. In comparison, IFBP has advantages over the conventional bi-level programming methods in terms of its capacity for reflecting uncertainties presented as intervals.

5. Conclusions

An interval fuzzy bi-level approach (IFBP) has been developed for the planning of water resources management system. The IFBP method improves upon the existing fuzzy bi-level programming by introducing interval mathematical programming (IMP) into its framework, such that uncertainties presented as interval values and fuzzy sets can be handled. A two-step interactive fuzzy approach has been proposed to solve the IFBP model. Interval solutions have been obtained through solving the upper- and lower-bound submodels sequentially with maximizing the objective-function values of both ULDM and LLDM. It can help generate a range of decision alternatives between the upper- and lower-level objectives as well as between system optimality and reliability. The IFBP method can deal with the water resources management problem by addressing the specific factors to formulate the bi-level and hierarchical configurations among multiple decision makers. A case study has been provided for an application to planning a water resources management system. Moreover, a number of scenarios have been analyzed. For all scenarios under consideration, the IFBP method has advantages over the conventional single decision-maker and/or deterministic programming methods not only in respecting the strategic interacttions and encouraging cooperation among parties, but also in tackling uncertain information; this can easily reach a win–win situation for decision-makers and lead to optimal solutions for the system.

Although this study is the first attempt for planning water resources management through development of such an IFBP method, there are several assumptions to be taken into account in a practical application of the IFBP method. Firstly, the study focuses on planning a water resources management system where the increasing desire for agricultural water utilization is considered as main reason for making the scheme because of its dominant status in local economic activities. If the development proceeds piecemeal as at present, the agricultural production will not be able to keep pace with the population increase, which would bring serious crises for the entire system. Moreover, benefits from the generation of hydroelectricity are also taken into account while making decisions. Secondly, Region A can be considered as one of the representatives which should be given priorities while making a development scheme due to the prominent contributions in promoting economic development. Thus, a bi-level management structure can be formulated where the decision variables are controlled by the upper and lower objective functions together. In detail, the local authority (the leader) can only control a subset of the decision variables in the hierarchical system, but that it would be affected by those variables that are controlled by the follower (i.e., Region A in the study), and Region A has its own objective function, which would in turn be affected by the leader's variables. Since the water resources are shared by all regions within the system, cooperation between parties are encouraged to support the sustainable development. The benefit tradeoff should be made between the ULDM and LLDM through collaboration from a long-term point of view, so that the system will not lead to development restrictions and poor behavior in the future. Thirdly, inexact information is reflected as random variables and interval parameters in the method. For example, the availabilities of water resources are quantified as discrete random variables and assumed to be taken on discrete distributions, such that the IFBP model can be solved through linear programming method. As to the other uncertain inputs, they can only be expressed as intervals, which will lead to a lack of the specification of distribution information in the obtained solutions. Generally, although there are some assumptions and limitations in the model's development and implementation, the proposed IFBP method can provide insight into identifying engineering designs for the development of a water recourses management system, and reaching significant benefits for the parties under existing conditions.

Acknowledgments. This research was supported by the Major State Basic Research Development Program of MOST (2005CB724207) and the Special Water Project of China (2009ZX07104-004). The authors are grateful to the editor and the anonymous reviewers for their insightful comments and suggestions.

References

Ahlatcioglu, M., and Tiryaki, F. (2007). Interactive fuzzy programming for decentralized two-level linear fractional programming (DTLLFP) problems, *Omega-Int. J. Manage. Sci.*, 35(4), 432-450. doi:10.1016/j.omega.2005.08.005

Anandalingam, G. (1991). Multi-level programming and conflict resolution, *Eur. J. Oper. Res.*, 51(2), 233-247. doi:10.1016/0377-2217(91)90253-R

Aviso, K.B., Tan, R.R., Culaba, A.B., and Cruz, J.B. (2010). Bi- level fuzzy optimization approach for water exchange in eco-industrial parks, *Process Saf. Environ. Prot.*, 88(1), 31-40. doi: 10.1016 /j. psep.2009.11.003

Bard, J. (1998). *Practical bilevel optimization: algorithms and applications*, Kluwer Academic Pub, USA.

Benayed, O. (1993). Bilevel Linear-Programming, *Comput. Oper. Res.*, 20(5), 485-501. doi:10.1016/0305-0548(93)90013-9

Emam, O.E. (2006). A fuzzy approach for bi-level integer non- linear programming problem, *Appl. Math. Comput*., 172(1), 62-71. doi: 10.1016/j.amc.2005.01.149

Gao, J.W., and Liu, B.D. (2005). Fuzzy multilevel programming with a hybrid intelligent algorithm, Comput. Math. Appl., 49 (9-10), 1539-1548. doi:10.1016/j.camwa.2004.07.027

Gao, Y., Zhang, G.Q., and Lu, J. (2009). A Fuzzy Multi-Objective Bilevel Decision Support System, *Int. J. Inf. Tech. Decis. Making*, 8(1), 93-108. doi:10.1142/S0219622009003284

Guo, P., Huang, G.H., and Li, Y.P. (2010). An inexact fuzzy-chance-constrained two-stage mixed-integer linear programming approach for flood diversion planning under multiple uncertainties, *Adv. Water Resour.*, 33(1), 81-91, doi:10.10 16/j.advwatres. 2009.10.009

Huang, G.H. (1998). A hybrid inexact-stochastic water management model, *Eur. J. Oper. Res.*, 107(1), 137-158. doi:10.1016/ S0377-2217 (97)00144-6

Huang, G.H., Baetz, B.W., and Patry, G.G. (1992). A Gray Linear-Programming Approach For Municipal Solid-Waste Management Planning Under Uncertainty, *Civ. Eng. Syst.*, 9(4), 319-335. doi: 10.1080/02630259208970657

Huang, G.H., Baetz, B.W., and Patry, G.G. (1993). A Gray Fuzzy Linear-Programming Approach for Municipal Solid-Waste Management Planning Under Uncertainty, *Civ. Eng. Syst.*, 10 (2), 123-146. doi:10.1080/02630259308970119

Huang, G.H., Baetz, B.W., and Patry, G.G. (1995). Grey Integer Programming - an Application to Waste Management Planning under Uncertainty. *Eur. J. Oper. Res.*, 83(3), 594-620. doi:10. 1016 /0377-2217(94)00093-R

Huang, G.H., and Loucks, D.P. (2000). An inexact two-stage stochastic programming model for water resources management under uncertainty, *Civ. Eng. Env. Syst.,* 17(2), 95-118. doi: 10.1080 /02630250008970277

Jairaj, P.G., and Vedula, S. (2000). Multireservoir system optimazation using fuzzy mathematical programming, Water Resour. Manage., 14(6), 457-472. doi:10.1023/A:1011117918943

Lai, Y.J. (1996). Hierarchical optimization: A satisfactory solution, *Fuzzy Sets Syst.*77(3), 321-335, doi:10.1016/0165-0114(95)000 86-0

Lai, Y.J., and Hwang, C.L. (1994). *Fuzzy multiple objective decision making:(methods and applications)*, Berlin, Springer.

Li, Y.P., and Huang, G.H. (2009). Fuzzy-stochastic-based violation analysis method for planning water resources management systems with uncertain information, *Inf. Sci.,* 179(24), 4261-4276. doi:10. 1016/j.ins.2009.09.001

Li, Y.P., Huang, G.H., Wang, G.Q., and Huang, Y.F. (2009). FSWM: A hybrid fuzzy-stochastic water-management model for agricultural sustainability under uncertainty, *Agric. Water Manage.*, 96(12), 1807-1818. doi:10.1016/j.agwat.2009.07.0 19

Li, Y.P., Huang, G.H., and Xiao, H.N. (2008). Municipal Solid Waste Management under Uncertainty: An Interval-Fuzzy Two-Stage Stochastic Programming Approach, *J. Env. Inform.*, 12(2), 96-104. doi:10.3808/jei.200800128

Li, Y.P., Huang, G.H., Zhang, N., Mo, D.W., and Nie, S.L. (2010). ISIP: capacity planning for flood management systems under uncertainty, *Civ. Eng. Env. Syst.*, 27(1), 33-52. doi:10.1080/102866 00802284373

Liu, K.F.R., Liang, H.H., Yeh, K., and Chen, C.W. (2009). A Qualitative Decision Support for Environmental Impact Assessment Using Fuzzy Logic, *J. Env. Inform.*, 13(2), 93-103. doi:10. 3808 /jei.200900144

Lu, H.W., Huang, G.H., and He, L. (2010). Development of an interval-valued fuzzy linear-programming method based on infinite alpha-cuts for water resources management, *Env. Model. Software,* 25(3), 354-361. doi:10.1016/j.envsoft.2009. 08.007

Lv, Y., Huang, G.H., Li, Y.P., Yang, Z.F., and Li, C.H. (2009). Interval-Based Air Quality Index Optimization Model for Regional Environmental Management under Uncertainty. *Env. Eng. Sci.*, 26(11), 1585-1597. doi:10.1089/ees.2009.0017

Lv, Y., Huang, G.H., Li, Y.P., Yang, Z.F., and Sun W. (2010). A two-stage inexact joint-probabilistic programming me- thod for air quality management under uncertainty, *J. Env. Manage.*, doi:10. 1016/j.jenvman.2010.10.027

Madani, K. (2010). Game theory and water resources, *J. Hydrol.*, 381, 225-238. doi:10.1016/j.jhydrol.2009.11.045

Mujumdar, P.P., and Sasikumar, K. (2002). A fuzzy risk approach for seasonal water quality management of a river system, *Water Resour. Res.*, 38(1), 1004-1013. doi:10.1029/2000WR00 0126

Nasiri, F., Maqsood, I., Huang, G.H., and Fuller, N. (2007). Water quality index: A fuzzy river-pollution decision support expert system, *J. Water Resour. Plann. Manage.*, 133, 95-105. doi:10. 1061/(ASCE)0733-9496(2007)133:2(95)

Ping, J., Chen, Y., Chen, B., and Howboldt, K. (2010). A Robust Statistical Analysis Approach for Pollutant Loadings in Urban Rivers, *J. Env. Inform.*, 16(1), 35-42. doi:10.3808/jei.2010001 76

Pramanik, S., and Roy, T.K. (2007). Fuzzy goal programming approach to multilevel programming problems, *Eur. J. Oper. Res.*, 176(2), 1151-1166. doi:10.1016/j.ejor.2005.08.024

Rogers, P. (1969). A game theory approach to the problems of international river basins, *Water Resour. Res.*, 5(4), 749-760.doi:10. 1029/WR005i004p00749

Roghanian, E., Aryanezhad, M.B., and Sadjadi, S.J. (2008). Integrating goal programming, Kuhn-Tucker conditions, and penalty function approaches to solve linear bi-level programming problems, *Appl. Math. Comput*., 195(2), 585-590. doi:10.1016/j.amc.

2007.05.004

Sakawa, M. (1993). *Fuzzy sets and interactive multiobjective optimization,* Plenum, USA.

Sakawa, M., and Nishizaki, I. (2001). Interactive fuzzy programming for two-level linear fractional programming problems, *Fuzzy Sets Syst.,* 119(1), 31-40. doi:10.1016/S0165-01 14(99)000 66-4

Sakawa, M., Nishizaki, I., and Uemura, Y. (1998). Interactive fuzzy programming for multilevel linear programming problems, *Comput. Math. Appl.* 36(2), 71-86. doi:10.1016/S0898-1221(98)00118-7

Sakawa, M., Nishizaki, I., and Uemura, Y. (2000). Interactive fuzzy programming for multi-level linear programming problems with fuzzy parameters, *Fuzzy Sets Syst.,* 109(1), 3-19. doi:10.1016/S0165-0114(98)00130-4

Sen, Z., and Altunkaynak, A. (2009). Fuzzy system modelling of drinking water consumption prediction, *Expert Syst. Appl.*, 36(9), 11745-11752. doi:10.1016/j.eswa.2009.04.028

Sethi, L.N., Kumar, D.N., Panda, S.N.. and Mal, B.C. (2002). Optimal crop planning and conjunctive use of water resources in a coastal river basin, *Water Resour. Manage.,* 16(2), 145-169. doi:10.1023/A:1016137726131

Shih, H.S., Lai, Y.J., and Stanley Lee, E. (1996). Fuzzy approach for multi-level programming problems, *Comput. Oper. Res.,* 23(1), 73-91. doi:10.1016/0305-0548(95)00007-9

Shih, H.S., and Lee, E.S. (2000). Compensatory fuzzy multiple level decision making, *Fuzzy Sets Syst.*, 114(1), 71-87. doi:10.1016/S0165-0114(98)00409-6

Sinha, S. (2003). Fuzzy mathematical programming applied to multi-level programming problems, *Comput. Oper. Res.*, 30(9), 1259-1268. doi:10.1016/S0305-0548(02)00061-8

Sinha, S. (2003). Fuzzy programming approach to multi-level programming problems, *Fuzzy Sets Syst.,* 136(2), 189-202. doi:10.1016/S0165-0114(02)00362-7

Uitto, J.I., and Duda, A.M. (2002). Management of trans- boundary water resources: lessons from international cooperation for conflict prevention, *Geogr. J.*, 168(4), 365-378. doi:10.1111/j. 0016-7398.2002.00062.x

Verderame, P.M., Elia, J.A., Li, J., and Floudas, C.A. (2010). Planning and Scheduling under Uncertainty: A Review Across Multiple Sectors, *Ind. Eng. Chem. Res.*, 49(9), 3993-4017. doi:10.1021/ie902009k

Wen, U.P., and Hsu, S.T. (1991). Linear Bi-Level Programming-Problems - A Review, *J. Oper. Res. Soc.*, 42(2), 125-133.

Yan, X.P., Ma, X.F., Huang, G.H., and Wu, C.Z. (2010). An Inexact Transportation Planning Model for Supporting Vehicle Emissions Management, *J. Env. Inform.*, 15(2), 87-98.

Yeomans, J.S. (2008). Applications of Simulation-Optimization Methods in Environmental Policy Planning Under Uncertainty. *J. Env. Inform.,* 12(2), 174-186. doi:10. 3808/jei.200800135

Zarghami, M., and Szidarovszky, F. (2009). Stochastic-fuzzy multi criteria decision making for robust water resources management. *Stochastic Environ. Res. Risk Assess.*, 23(3), 329-339. doi:10.1007/s00477-008-0218-6

Zhang, G.Q., Zhang, G.L., Gao, Y., and Lu, J. (2009). A Fuzzy Bilevel Model and a PSO-Based Algorithm for Day-Ahead Electricity Market Strategy Making. *Knowledge-Based and Intelligent Information and Engineering Systems, Pt Ii, Proceedings*. J. D. Velasquez, S. A. Rios, R. J. Howlett and L. C. Jain. Berlin, Springer-Verlag Berlin. 5712: 736-744.

Zimmermann, H.J. (2001). *Fuzzy set theory and its applications*, Springer Netherlands.