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An Interval Fuzzy Multiobjective Watershed Management Model for the Lake Qionghai Watershed, China

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Abstract. Integrated watershed management is required to ensure the reasonable use of resources and reconcile interactions among natural and human systems. In the present study, an interval fuzzy multiobjective programming (IFMOP) method was used to solve an integrated watershed management problem. Based on system analysis, an IFMOP model suitable for a lake watershed system (IFMOPLWS) was developed and applied to the Lake Qionghai watershed in China. Scenario analysis and an interactive approach were used in the solution process. In this manner, various system components were incorporated into one framework for holistic consideration and optimization. Integrality and uncertainty, as well as the multiobjective and dynamic characteristics of the watershed system, were well addressed. Using two scenarios, two planning schemes were generated. Agriculture, tourism, macroeconomics, cropland use, water supply, forest coverage, soil erosion, and water pollution were fully interpreted and compared to identify a preferable planning alternative for local agencies. This study showed that the IFMOPLWS is a powerful tool for integrated watershed management planning and can provide a solid base for sustainable watershed management.

Key words: fuzzy, interval, Lake Qionghai watershed, multiobjective programming, scenario analysis, uncertainty, watershed management

1. Introduction

Watersheds are considered the most appropriate units for the management of water resources, water quality, and interactions among natural and human systems (Heathcote, 1998). Watersheds are complex systems (Newson, 1992) incorporating many components, including natural, economic, demographic, and political factors. These subsystems interconnect and interact, leading to four main characteristics of watershed systems: integrality, multiobjectiveness, dynamism, and uncertainty (Zou, 2000; Zhang *et al.*, 2001).

Watershed management planning can be traced back to dam construction to mediate conflicts between upper and lower watersheds and better fulfill demands for irrigation and power (Newson, 1992). In recent decades, watershed management planning has been strongly influenced by the wide recognition of and concern for sustainable development (Bulkley, 1995; Slocombe, 1998; Radif, 1999). In contrast to conventional watershed planning that aims primarily to exploit and utilize water and land resources, a more holistic approach is needed in modern watershed management (Viessman, 1996). Ecosystem conservation and interactions among socioeconomic–environmental entities must be integrated (Ballweber, 1995; Bulkley, 1995; Slocombe, 1998; Matondo, 2002). Thus, a proper method or framework is essential to integrate all system factors, effectively reflect the above characteristics of watershed systems, and reconcile conflicting activities within watersheds.

Multiobjective programming (MOP) is a reliable tool for working with complicated systems. It can incorporate various system components in a single framework and efficiently coordinate and optimize objectives. Many studies have examined MOP theories and applications (e.g., Cohen, 1978; Chang *et al.*, 1995; Lee and Wen, 1996; Cho, 1999). Based on the deterministic MOP, stochastic MOP (SMOP) and fuzzy MOP (FMOP) methods were proposed to address uncertain system features, especially the uncertainty of system parameters (Zimmermann, 1978; Lai and Hwang, 1994; Chang *et al.*, 1997). However, indispensable possibilistic or probabilistic information is usually unavailable for practical problems using SMOP and FMOP methods; for many system factors, only intervals can be identified. Therefore these methods have not been widely used and better ways for considering uncertainties are required (Huang *et al.*, 1993; Wu *et al.*, 1997; Zou *et al.*, 2000).

Interval fuzzy multiobjective programming (IFMOP), a hybrid of inexact fuzzy linear programming (IFLP; Huang *et al.*, 1993) and multiobjective optimization, is superior to the former MOP methods in its data requirements, solution algorithms, computational requirements, and results interpretation (Wu *et al.*, 1997). IFMOP allows uncertainties presented as intervals to be directly communicated into planning processes through an interval linear programming algorithm (Huang, 1996; Wu *et al.*, 1997). The interactive approach of this method helps account for the indispensable involvement of stakeholders. IFMOP has been successfully used in municipal solid waste management (Huang *et al.*, 2002; Cheng *et al.*, 2003), regional new-zone development planning (Zou *et al.*, 2000), and optimal tourism management (Guo *et al.*, 2001). IFMOP also incorporates some practices effective for watershed management. However, most practices focus on one or two aspects, such as water quality, land resources, or water resource planning (Huang, 1996; Wu *et al.*, 1997; Zou *et al.*, 1999). As the components considered in previous studies have been relatively simple, a more comprehensive IFMOP model is required for optimal management at a watershed scale. While such modeling has seen little use to date in watershed management, increased applications are expected as the method is developed further.

Integrated watershed planning and management are important to ensure the reasonable use of resources and harmonious socioeconomic–environmental development in China. Lake Qionghai is located in southwestern China and is the primary water source in its watershed. The Lake Qionghai area is also a designated national scenic location. Hence, protection of the watershed ecosystem and comprehensive planning of human activities in the watershed are crucial for sustainable development.

The present study developed an IFMOP model for comprehensive lake watershed management. Combining the model with methods of system analysis, scenario analysis, and interactive approaches, schemes for optimum watershed management were developed. The Lake Qionghai watershed was chosen as a case study to verify the practicality of the methods and to support local sustainable development, with the intention of applying the model to other watersheds in China.

2. System Analysis of the Study Area

Lake Qionghai is the second-largest freshwater lake in Sichuan Province and part of the Yangtze River system (Figure 1). At normal water levels, the lake has an area of 27.88 km^2 and a volume of 2.89×10^8 m^3. The Lake Qionghai watershed, located between 102°16′–102°20′E and 27°47′–27°51′N, with an area of 307.67 km^2, includes part of the city of Xichang and the counties of Xide and Zhaojue. This watershed houses a complicated system of intimately interacting social, economic, and environmental components. In this study the lake watershed system was roughly

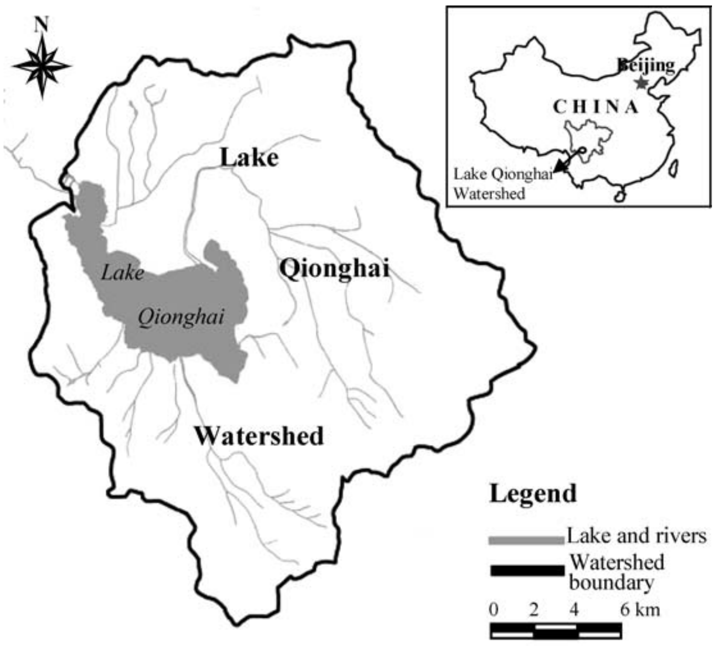

Figure 1. Location map of the Lake Qionghai Watershed, Sichuan Province, China.

simplified into six subsystems for specific analysis: human population, agriculture, industry, tourism, natural resources, and pollution.

2.1. THE HUMAN POPULATION SUBSYSTEM

The size, structure, and variation of the human population directly impact other subsystems. In 2003, approximately 84,153 permanent residents lived in the watershed, with 80.5% living in rural areas, indicating a low urbanization level. However, the permanent population is rapidly expanding with a natural growth rate of 8.9%, which is much higher than the average national level of 7.6%. The population of temporary residents is also growing rapidly at an annual rate of 9.5%. The high ratio of rural residents imposes pressure on farmland use because of the watershed's abundance of highlands and relative shortage of prepared farmland. Meanwhile, rapid population growth has caused serious stress on wastewater discharge, water supply, and solid waste disposal systems.

2.2. THE AGRICULTURE SUBSYSTEM

Agricultural activities in the watershed, including crop farming, forestry, livestock husbandry, and fishing, dominate the local economy, currently accounting for 53% of total production. Within this subsystem, crop farming dominates, and the main crops are wheat, rice, corn, vegetables, and fruit. Because of the local policy of returning hilly lands to forest, as well as the great irrigation demands, crop-farming development will confront land and water limitations in the future. In comparison, livestock husbandry is a promising industry relying on modern intensive breeding technology, but the pollution associated with this industry cannot be ignored.

2.3. THE INDUSTRY SUBSYSTEM

Industry can be both a main source of pollution and a major source of economic benefit. Chemical and food industries are the principle industries in the Lake Qionghai watershed. The wastewater and solid waste produced threaten water quality. Local development planning will prohibit new contaminative corporations in the region to some extent, though existing factories will be allowed to continue, if properly permitted. The industrial subsystem conflicts with the water supply and water pollution; its structure should be considered holistically and effectively optimized.

2.4. THE TOURISM SUBSYSTEM

As a nationally recognized scenic location, Lake Qionghai draws numerous tourists annually. The tourism industry has developed rapidly; for example, the growth rate of the total income from tourism was 13.5% in 2002. Local governments have already designated tourism, with its tremendous development potential, as the leading future industry of the watershed. Improvements in facilities as well as the development of new scenic spots should spur tourism growth. However, increases in the number of visitors will also affect water consumption, wastewater discharge, and environmental investments. The construction of tourist facilities will interfere with already existing land and capital contests, sharpening conflicts among various land uses and capital-demanding activities.

2.5. THE NATURE RESOURCE SUBSYSTEM

Water and land were the major resources considered in this subsystem. Six main water-consumption sectors were examined: crop farming, livestock husbandry, fishing, industry, tourism, residential use, and ecological use. Land-consumption uses considered were paddies, dry land, horticultural land, woodland, water areas, and unused land. Water and land are essential for all social and economic activities but are limited resources within the watershed. Hence, their rational allocation and use must be considered and resolved to achieve maximum profit and maintain a healthy environment.

2.6. THE POLLUTION SUBSYSTEM

Water pollution is currently the primary threat to the watershed. In 1997, a local environmental assessment report gave Lake Qionghai's integrated water quality a level-two rating based on the China Environmental Quality Standards for Surface Water. In 2003, water quality had deteriorated to the third level. The present state of eutrophication is in the middle to high range, and there is a strong tendency towards deterioration. Pollution has also resulted in a potential water crisis. This unsustainable cycle must be halted through integrated planning to meet water and environmental capacity requirements. Further, soil erosion and plans for new sewage treatment plant construction directly relate to water quality and will affect the subsystem. Municipal authorities have planned to transport and dispose of solid wastes outside the watershed, and therefore this factor was not addressed in this study.

3. Model Description and Formulation

3.1. GENERAL IFMOP MODEL

A general MOP model with discrete interval parameters can be formulated as follows:

$$\text{Min} \quad f_k^{\pm} = C_k^{\pm} X^{\pm}, \quad k = 1, 2, \ldots, p \tag{1a}$$

$$\text{Max} \quad f_l^{\pm} = C_l^{\pm} X^{\pm}, \quad l = p+1, p+2, \ldots, q \tag{1b}$$

$$A_i^{\pm} X^{\pm} \leq b_i^{\pm}, \quad i = 1, 2, \ldots, m \tag{1c}$$

$$A_j^{\pm} X^{\pm} \geq b_j^{\pm}, \quad j = m+1, m+2, \ldots, n \tag{1d}$$

$$X^{\pm} \geq 0 \tag{1e}$$

where $X^{\pm} \in \{\Re^{\pm}\}^{t\times 1}$, $C_k^{\pm} \in \{\Re^{\pm}\}^{1\times t}$, $C_l^{\pm} \in \{\Re^{\pm}\}^{1\times t}$, $A_i^{\pm} \in \{\Re^{\pm}\}^{1\times t}$, $A_j^{\pm} \in \{\Re^{\pm}\}^{1\times t}$, and $\Re^{\pm}$ denote a set of inexact interval numbers. All parameters are known as intervals without distribution information. When some of the parameters are assigned membership functions, the model becomes an interval-fuzzy MOP (IFMOP) model. In this study, the IFLP algorithm was used to address uncertainties in the model (Huang *et al.*, 1993; Wu *et al.*, 1997). Thus, coefficients in the objective functions and the left-hand sides of constraints were handled as discrete intervals, while linear membership functions were assigned to fuzzy goals for system objectives and the right-hand sides of constraints.

The solution process was as follows: (a) optimizing each single objective, (b) building the pay-off matrix, (c) decomposing the objective functions, (d) introducing the minimum operator and conducting the IFLP transform action, and (e) formulating and solving the generated sub-models (Huang *et al.*, 1993; Wu *et al.*, 1997).

3.2. IFMOPLWS MODEL

Based on system analysis and the IFMOP method, an Interval Fuzzy Multiobjective Programming for a Lake Watershed System (IFMOPLWS) was developed. The subsystems were effectively incorporated in the IFMOPLWS; feedback and correlations of various system components were well expressed by objectives and constraints. The detailed formulation follows.

3.2.1. *Objective Functions*

(1) Economic objective:

(a) Maximum net social benefits

$$\begin{aligned}\text{Max } F_1 = & \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(FRB_{ij}^{\pm})FR_{ij}^{\pm} + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)\big(FRB_{ij}^{s}\pm FR_{ij}^{\pm} \\ & + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(LKB_{ij}^{\pm})(LKRO_{ij}^{\pm})LK_{ij}^{\pm} \\ & + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(FIB_{ij}^{\pm})FI_{ij}^{\pm} + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)IN_{ij}^{\pm} \\ & + \sum_{i=1}^{n}(NY_i)(TRB_i^{\pm})TR_i^{\pm} - \sum_{i=1}^{n}\sum_{u=1}^{h}(INEXP_{iu}^{\pm})YI_{iu}^{\pm} \\ & - \sum_{i=1}^{n}(TREXP_i^{\pm})YTR_i^{\pm}\end{aligned}$$

$$-\sum_{i=1}^{n}\sum_{u=1}^{h}(WPCEXC_{iu}^{\pm})(WPCEX_{iu}^{\pm})YWP_{iu}^{\pm}$$
$$-\sum_{i=1}^{n}\sum_{u=1}^{h}(NY_i)(WWC_{iu}^{\pm})WWM_{iu}^{\pm}$$
$$-\sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(FRC_{ij}^{\pm})FR_{ij}^{\pm}$$
$$-\sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(FREC_{ij}^{\pm})FREA_{ij}^{\pm}$$

(2) Ecological objective:

(a) Minimum soil loss

$$\text{Min } F_2 = \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(CRS_{ij}^{\pm})\ CR_{ij}^{\pm} + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(FRS_{ij}^{\pm})FR_{ij}^{\pm} + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(RSDS_{ij}^{\pm})RSD_{ij}^{\pm}$$

(3) Environmental objective:

(a) Minimum total nitrogen (TN) loss

$$\text{Min } F_3 = \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(CRN_{ij}^{\pm})(CRF_{ij}^{\pm})CR_{ij}^{\pm} + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(LKN_{ij}^{\pm})LK_{ij}^{\pm} + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(FIN_{ij}^{\pm})FI_{ij}^{\pm} + \sum_{i=1}^{n}(NY_i)(TRN_{i}^{\pm})TR_{i}^{\pm} + \sum_{i=1}^{n}(NY_i)(PN_{ij}^{\pm})P_{ij}^{\pm}$$

(b) Minimum total phosphorous (TP) loss

$$\text{Min } F_4 = \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(CRP_{ij}^{\pm})(CRF_{ij}^{\pm})CR_{ij}^{\pm} + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(LKP_{ij}^{\pm})LK_{ij}^{\pm} + \sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(FIP_{ij}^{\pm})FI_{ij}^{\pm} + \sum_{i=1}^{n}(NY_i)(TRP_{i}^{\pm})TR_{i}^{\pm} + \sum_{i=1}^{n}(NY_i)(PP_{ij}^{\pm})P_{ij}^{\pm}$$

(c) Minimum chemical oxygen demand (COD) discharge

$$\begin{aligned}\text{Min } F_5 = &\sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(LKCOD_{ij}^{\pm})LK_{ij}^{\pm}\\ &+\sum_{i=1}^{n}\sum_{j=1}^{m}(NY_i)(INCOD_{ij}^{\pm})IN_{ij}^{\pm}+\sum_{i=1}^{n}(NY_i)(TRCOD_i^{\pm})TR_i^{\pm}\\ &+\sum_{i=1}^{n}(NY_i)(PCOD_{ij}^{\pm})P_{ij}^{\pm}\end{aligned}$$

3.2.2. *Constraints*

(1) Cropland constraint:

$$\sum_{j=1}^{m} CR_{ij}^{\pm} = CRL_i^{\pm}; \quad \sum_{j=1}^{m} CR_{ij}^{\pm} \geq CRLL_i^{\pm}$$

(2) Fishpond constraint:

$$\sum_{j=1}^{m} FI_{ij}^{\pm} \leq FIL_i^{\pm}$$

(3) Forest area constraint:

$$\sum_{j=1}^{m} FR_{ij}^{\pm} \leq FRL_i^{\pm}; \quad \sum_{j=1}^{m} FR_{(i+1)j}^{\pm} \geq \sum_{j=1}^{m} FR_{ij}^{\pm}; \quad \sum_{j=1}^{m} FREA_{ij}^{\pm} \leq FREL_i^{\pm}$$

(4) Tourism capacity constraint:

$$TR_i^{\pm} \leq TRC_i^{\pm}$$

(5) Water supply constraint:

$$\begin{aligned}&\sum_{j=1}^{m}(WDCR_{ij}^{\pm})CR_{ij}^{\pm}+\sum_{j=1}^{m}(WDLK_{ij}^{\pm})LK_{ij}^{\pm}+\sum_{j=1}^{m}(WDFR_{ij}^{\pm})FR_{ij}^{\pm}\\ &\quad+\sum_{j=1}^{m}(WDFI_{ij}^{\pm})FI_{ij}^{\pm}+\sum_{j=1}^{m}(WDIN_{ij}^{\pm})IN_{ij}^{\pm}\\ &\quad+(WDTR_i^{\pm})TR_i^{\pm}+(WDP_{ij}^{\pm})P_{ij}^{\pm} \leq \text{WSL}_i^{\pm}\end{aligned}$$

(6) Sewage plant augmented control:

$$WPCEX_{iu}^{\pm} \leq WPCEXL_{iu}^{\pm}$$

(7) Sewage water discharge constraint:

$$\begin{aligned}&(INW_{ij}^{\pm})IN_{ij}^{\pm}+(TRW_i^{\pm})TR_i^{\pm}+(PW_{ij}^{\pm})P_{ij}^{\pm} \leq \sum_{u=1}^{h}(WPC_{iu}^{\pm})YW_{iu}^{\pm}\\ &\quad+(TRCOD_i^{\pm})TR_i^{\pm}+(PCOD_{ij}^{\pm})P_{ij}^{\pm}-\sum_{u=1}^{h}(REMCOD_{iu}^{\pm})WWM_{iu}^{\pm}\end{aligned}$$

(8) COD discharge constraint:

$$\sum_{j=1}^{m} (LKCOD_{ij}^{\pm})LK_{ij}^{\pm} + \sum_{j=1}^{m} (FICOD_{ij}^{\pm})FI_{ij}^{\pm}$$
$$+\sum_{j=1}^{m} (INCOD_{ij}^{\pm})IN_{ij}^{\pm}(TRCOD_{i}^{\pm})TR_{i}^{\pm} + (PCOD_{ij}^{\pm})P_{ij}^{\pm}$$
$$-\sum_{u=1}^{h} (REMCOD_{iu}^{\pm})WWM_{iu}^{\pm} \leq CAPCOD_{i}^{\pm}$$

(9) TN loss constraint:

$$\sum_{j=1}^{m} (CRN_{ij}^{\pm})(CRF_{ij}^{\pm})CR_{ij}^{\pm} + \sum_{j=1}^{m} (LKN_{ij}^{\pm})LK_{ij}^{\pm}$$
$$+\sum_{j=1}^{m} (FIN_{ij}^{\pm})FI_{ij}^{\pm} + (TRN_{i}^{\pm})TR_{i}^{\pm} + (PN_{ij}^{\pm})P_{ij}^{\pm}$$
$$-\sum_{u=1}^{h} (REMN_{iu}^{\pm})WWM_{iu}^{\pm} \leq CAPN_{i}^{\pm}$$

(10) TP loss constraint:

$$\sum_{j=1}^{m} (CRP_{ij}^{\pm})(CRF_{ij}^{\pm})CR_{ij}^{\pm} + \sum_{j=1}^{m} (LKP_{ij}^{\pm})LK_{ij}^{\pm} + \sum_{j=1}^{m} (FIP_{ij}^{\pm})FI_{ij}^{\pm}$$
$$+ (TRP_{i}^{\pm})TR_{i}^{\pm} + (PP_{ij}^{\pm})P_{ij}^{\pm} - \sum_{u=1}^{h} (REMP_{iu}^{\pm})WWM_{iu}^{\pm} CAPP_{i}^{\pm}$$

(11) Capital constraint:

$$\sum_{u=1}^{h} (INEXP_{iu}^{\pm})YI_{iu}^{\pm} + (TREXP_{i}^{\pm})YTR_{i}^{\pm} + \sum_{u=l}^{h} (WWC_{iu}^{\pm})WWM_{iu}^{\pm}$$
$$+\sum_{u=l}^{h} (WPCEXC_{iu}^{\pm})(WPCEX_{iu}^{\pm})YWP_{iu}^{\pm} + \sum_{j=1}^{m} (FRC_{ij}^{\pm})FR_{ij}^{\pm}$$
$$+\sum_{j=1}^{m} (FREC_{ij}^{\pm})FREA_{ij}^{\pm} \leq FUNDL_{i}^{\pm}$$

(12) Technical constraint:

$$CR_{ij}^{\pm} \geq 0; \quad LK_{ij}^{\pm} \geq 0; \quad FI_{ij}^{\pm} \geq 0; \quad FR_{ij}^{\pm} \geq 0; \quad IN_{ij}^{\pm} \geq 0;$$
$$TR_{ij}^{\pm} \geq 0; \quad WPC_{iu}^{\pm} \geq 0; \quad FREA_{ij}^{\pm} \geq 0; \quad 0 \leq YI_{ij}^{\pm} \leq 1;$$
$$0 \leq YTR_{ij}^{\pm} \leq 1; \quad 0 \leq YW_{ij}^{\pm} \leq 1; \quad 0 \leq YWP_{iu}^{\pm} \leq 1$$

Notations for the model parameters and variables are provided in the appendix.

4. Results

The model was solved for two periods, 2005–2010 and 2011–2015, considering actual situations in the Lake Qionghai watershed and related primary planning; the base year was chosen to be 2001. Some supporting research materials and incomplete data are also available for 2002, 2003, and 2004. Data for all parameters came from field investigations, previous research reports, statistical yearbooks, and local agencies. The primary constraint parameters are given in Table I.

Scenario analysis was introduced into the interactive solution process to ensure the practicality and operability of the planning alternatives (Zhang *et al.*, 2001; Guo *et al.*, 2004). Two scenarios were identified in this study. One addressed concern for harmonious environmental sustainability and economic growth with a tendency toward environmental protection. This solution was achieved directly through the model. The other scenario incorporated interactive processes in an attempt to reach favored objectives. The preferences of stakeholders and decision makers, determined through questionnaires and discussions, were included throughout the programming process. In general, this scenario put more emphasis on economic objectives. Constraints and parameters were also adjusted to acknowledge preferences. For example, although vegetable growing is the most competitive of all the cropland uses, local experts preferred to ensure space for paddy and dry fields to meet local food demands. In this scenario, the original water constraint parameter was loosened to maintain the water demand of paddies. In addition, the water consumption parameter was adjusted because experts expect that water conserving irrigation technologies will become more prevalent in upcoming years. Other constraints, such as COD, were also loosened given the strong preferences for ensuring economic benefits and maintaining a balanced industrial structure. These two

Table I. The primary constraint parameters in the IFMOPLWS model for the Lake Qionghai Watershed

	Period I		Period II	
Constraint item	Lower bound	Upper bound	Lower bound	Upper bound
Cropland area (km^2)	30.9	35.3	33.0	36.5
Fishpond area (km^2)	4.4	4.8	7.0	7.7
Forest area (km^2)	119.5	132.8	135.9	149.1
Tourism capacity (10^4 person-day/a)	987.1	987.1	1161.3	1161.3
Maximum water supply (10^8 m^3)	0.309	0.395	0.309	0.395
Maximum COD discharge (t/a)	1034	1034	1034	1034
Maximum TN discharge (kg/a)	6530	6530	6530	6530
Maximum TP discharge (kg/a)	96600	96600	96600	96600
Total invested capital (10^4 USD/a)	495.7	576.1	510.1	592.8

scenarios were thoroughly analyzed and compared; the main results and analyses follow.

4.1. ECONOMY STRUCTURE OPTIMIZATION

4.1.1. *Agricultural structure*

The IFMOPLWS represented the agricultural structure well (see Table II). Increases in crop farming, forestry, and livestock husbandry were shown under both scenarios. Livestock husbandry expanded especially rapidly because of its relatively higher profits, lower water consumption, and lower land occupation. By 2015, its proportion of total agricultural production reached 57.9–61.1% under scenario I and 62.5–62.8% under scenario II, compared with 41.4% in 2001. Thus, its leading function in the future agricultural structure should be noted. Compared with livestock husbandry, crop farming was predicted to encounter land and water limitations in coming years, although it plays a dominant role in the present agricultural structure. The production value of crop farming in 2001 was 1490.9 $\times$ 10^4 USD, accounting for 46.9% of the total value of agricultural production. scenario II predicted that this value will drop in 2015 to 1527.1–1929.2 $\times$ 10^4 USD or only 24.9–25.5%. The role of the local fishery differed greatly under the two scenarios. Under scenario I, the fishery disappeared by 2015 because of the extraordinarily high water consumption coefficient and the strict constraint on the water supply. Under scenario II, the actual demand was incorporated through interactive processes, and the constraint was properly loosened. Model optimization maintained certain areas for fishery development.

4.1.2. *Tourism structure*

As shown in Figure 2, tourism developed quickly under both scenarios within the tourist-scale capacity. Tourism's intrinsically low pollution and high production factors explain the rapid development. By 2015 scenarios I and II predicted tourist flows of 949.6–1035.6 $\times$ 10^4 and 952.1–990.5 $\times$ 10^4 person days, respectively, more than 4.5 times the values in 2001. The upper bound of tourist numbers in

Table II. The agricultural benefits of the Lake Qionghai Watershed (Unit: 10^4 USD/a)

Item	2001	2010		2015	
		Scenario I	Scenario II	Scenario I	Scenario II
Crop farming	1490.9	[1362.4, 1951.2]	[1325.6, 1889.3]	[1535.6, 1914.5]	[1527.1, 1929.2]
Forestry	318.2	[535.4, 687.3]	[527.3, 702.8]	[617.3, 800.7]	[614.4, 811.8]
Livestock husbandry	1316.9	[1676.7, 2124]	[3283.6, 3617]	[3384.3, 4027.4]	[3747.5, 4856]
Fishery	53.3	[76.9, 90.8]	[79.6, 95.7]	[0, 0]	[104.3, 132.7]

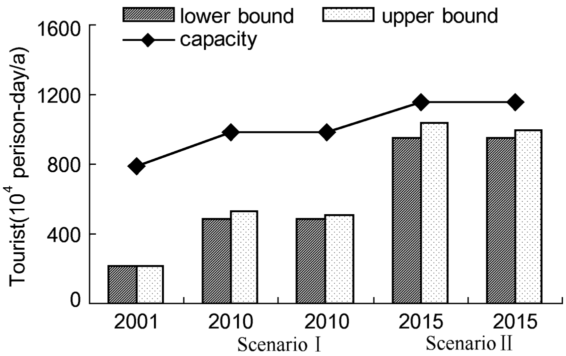

Figure 2. The tourism structure of the Lake Qionghai Watershed.

scenario II was rather conservative, relative to that in scenario I. For example, the upper value in 2010 was 505.4×10^4 person days compared with 526.4×10^4 person days under scenario I. This occurred because the rate of increase was restricted under scenario II, as local experts desired to maintain a balance among different industries and to avoid domination by a single industry. By limiting tourism growth, other industries could be maintained despite the vigorous competition from tourism. Meanwhile, capital for ecosystem conservation was further guaranteed in the allocative competition with the cost-effective tourism industry.

4.1.3. *Macroeconomic Structure*

The optimum integral structure is shown in Figure 3. A clear economic development tendency was shown by the model, i.e., tourism will expand rapidly while agriculture and industry will be greatly curtailed. In 2001, agriculture, industry, and tourism accounted for 37, 36, and 27% of the economy, respectively. By 2015, these percentages changed to 25, 17, and 58% under scenario I and 25, 24, and 51% under scenario II. Tourism is a powerful industry highly interrelated with food and beverage supply, communication, architecture, trade, and insurance, and its development can lead to growth in these other industries. However, presently, scenic spot facilities, the transportation system, and tourist services in the watershed are not strong enough to support such rapid future development. Effective investment, integral tourism development planning, and related incentive measures are required to ensure sustainable tourism development.

4.2. RESOURCE ALLOCATION OPTIMIZATION

4.2.1. *Cropland Use*

Four categories of cropland, i.e., paddies, dry fields, vegetable lands, and horticultural lands, were determined based on distinctions in crops, profits, and irrigation (Table III). The model indicated that the area of vegetable production would increases the most, from 9% of the total area in 2001 to the lower-bound ratio of

Table III. The cropland structure of the Lake Qionghai Watershed (Unit: km^2)

		2010		2015	
Item	2001	Scenario I	Scenario II	Scenario I	Scenario II
Paddy field	19.6	[15.4, 16.5]	[15.1, 16.7]	[4.3, 9.4]	[13.2, 14.2]
Dry field	7.07	[0, 0]	[2.5, 2.8]	[3.7, 9.8]	[2.4, 5.7]
Vegetable land	2.08	[9.1, 11.1]	[6.9, 8.4]	[10.8, 11.6]	[8.4, 8.5]
Horticulture land	2.39	[0.7, 1.3]	[2.6, 3.5]	[1.2, 1.6]	[3.8, 4.6]

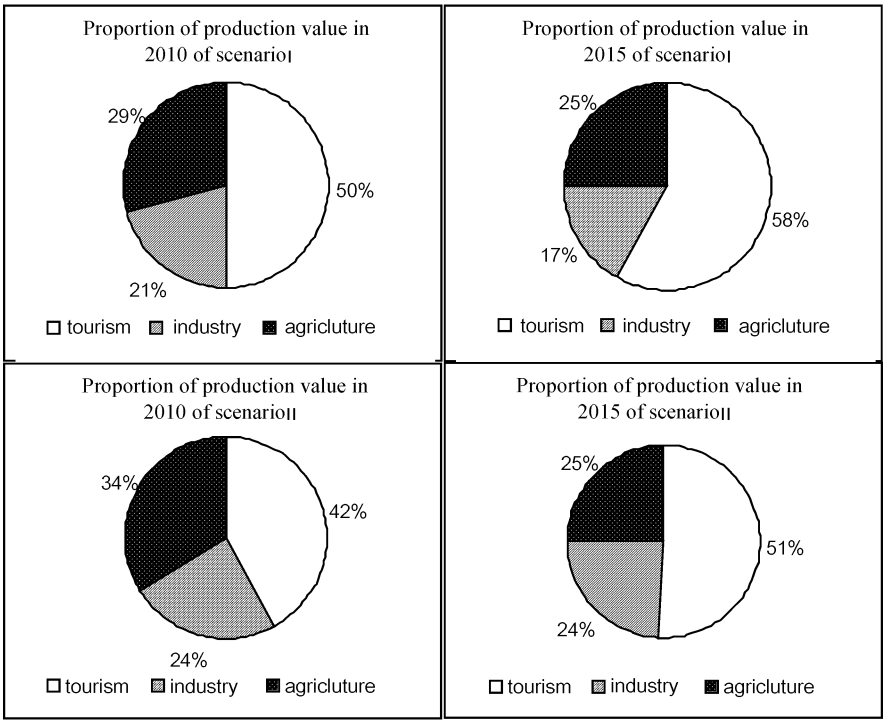

Figure 3. The macroeconomic structure of the Lake Qionghai Watershed.

35.8 and 25.8% in scenarios I and II, respectively, in 2015. The competitiveness of vegetable growing in land allocation was directly related to the considerable benefits derived from this land use. The water efficiency of modern vegetable planting technology was also considered in the model's constraints and further facilitated the increase. Thus, the potential prosperity of vegetable production demands the promotion of water conserving technologies such as sprinkling and drip irrigation and the encouragement of vegetable production bases. Paddies had water consumption coefficients 1.9 to 3.7 times those of other crop types. In the second planning period with fierce water-resource stress under scenario I, the paddy area decreased sharply. For example, its upper bound was 16.5 km^2 in 2010, but only 9.4 km^2

in 2015. Under scenario II, the water supply constraint was reduced. Therefore, paddy area varied little, in accordance with the local experts' desire for foodstuff provisions. Dry fields, with the lowest water consumption and relatively lower benefits than the other cropland uses, showed the opposite results. In both scenarios, allocations to horticultural land increased steadily because of moderate water consumption coefficients, among other benefits. Moreover, horticulture was the recommended cultivation type, supporting the policy of returning fields to woodlands. Therefore, environmentally friendly and scientifically tested cropping patterns should be applied to simultaneously raise productivity and protect the environment.

4.2.2. *Water Supply*

Figure 4 indicates that agriculture and residential uses remained the main consumers of water. In 2001, agricultural sectors (e.g., crops, livestock husbandry, and fishing) and residential living sectors consumed 86.4 and 9.1% of the total water supply, respectively. By 2015, these two sectors consumed less at 64.9 and 26.9% in scenario I and 71.5 and 21.5% in scenario II, respectively. Among the agriculture uses, livestock industry water use increased under both scenarios, while water use by crop farming and fisheries decreased. Despite the relative changes among the agricultural sectors, total agricultural water use decreased, in accord with the structural adaptation described above. Population expansion, as well as the improving living standard in China, accounted for the increased residential water use. Tourism

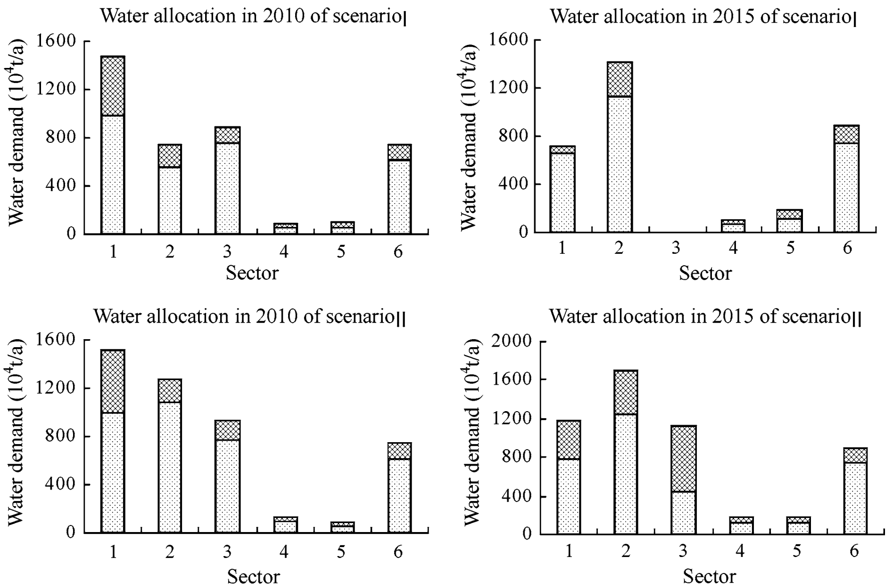

Figure 4. The water allocation of the Lake Qionghai Watershed. 1-cropfarming, 2-livestock husbandry, 3-fishery, 4-industry, 5-tourism, 6-living. The shadow area is the gap between upper bound and lower bound.

and industry only accounted for a small percentage of water use, although these sectors contributed greatly to economic production.

The total water usage under scenario II was far greater than that under scenario I because the water constraint under scenario II was loosened to ensure fast and balanced industrial development. In 2010 and 2015, the upper bounds of water consumption were 46.6×10^6 m^3 and 52.2×10^6 m^3, respectively.

4.3. ECOSYSTEM MAINTENANCE AND POLLUTION CONTROL

4.3.1. *Forest Coverage*

Forest coverage continually increased relative to the forested area in 2001 of 80.6 km^2 (Table IV). Both scenarios produced generally similar results. In 2010, the forested area was 118.2–126.4 km^2 and 116.7–125.5 km^2 under scenarios I and II, respectively. The predicted forested area under scenario II was slightly less than that under scenario I owing to stricter capital and land constraints caused by faster-growing industries. By 2015, the forested area extended greatly under both scenarios, reaching 133.4–144.1 km^2 under scenario I and 132.8–142.1 km^2 under scenario II. However, the coverage under scenario II remained somewhat less because it reached an optimum level at 43.17–46.17% of the total watershed area. Further forest extension would only result in more maintenance and forestation expenses.

4.3.2. *Soil Erosion*

Soil erosion is affected by geology, physiography, climate, vegetation, and human use. For the purposes of this study, soil erosion caused by vegetation factors and human activities was considered; unusual impacts caused by abnormal weather, earthquakes, or debris flows were not included. Thus, soil erosion associated with crop cultivation, forestry, and the barren-zone reservation for forestation was specifically planned (Table IV). Under scenario I, the amount of soil erosion in 2010 was $20.9–26.4 \times 10^4$ tons per annum, a relatively small amount compared with the erosion predicted under scenario II. This result reflects the greater degree of forestation and the reduction in the area of reserved barren land, which is highly subject to erosion, under scenario I. By 2015, although the forested area was larger, soil erosion status had deteriorated somewhat. The main reason for this was the cropland structure (such as dry fields) that led to an increase in easily eroded areas. Under

Table IV. The forest coverage and soil erosion of the Lake Qionghai Watershed

Item	2001	2010 Scenario I	2010 Scenario II	2015 Scenario I	2015 Scenario II
Forest coverage (km^2)	80.6	[118.2, 126.4]	[116.7, 125.5]	[133.4, 144.1]	[132.8, 142.1]
Soil erosion (10^4t/a)	28.4	[20.9, 26.4]	[21.1, 27.1]	[21.1, 28.6]	[20.4, 26.9]

scenario II, erosion levels continued to decrease due to the balanced agricultural structure and the local preference for vegetation protection.

Soil erosion mitigation is generally a difficult and long-term task. Except when surfaces are improved by vegetation, various methods should be applied together, such as ecological engineering techniques, disaster warning information systems, scientific planning for construction, industrial structure adaptation, and the regulation of sloped land use.

4.3.3. *Pollution Control*

COD, TN, and TP are critical elements inducing water quality deterioration and were calculated in the model. Here COD discharge served as an example. Four sectors, agriculture, industry, tourism, and residential use, were the leading sources of COD. Figure 5 shows the discharge allocation among these sectors, but it should be noted that the discharge amounts were based on the expected treatment of sewage from industry, tourism and living sources. Sewage plants are supposed to provide secondary treatment, and the COD removal efficiency should be 85–89%. In 2010, residential and agriculture sources, especially livestock, were the largest dischargers of COD. Industry and tourism contributed a small amount. In 2015, discharge from all sectors increased, especially that of tourism. Under scenario I, tourism produced much COD, despite its reputation as a low-pollution sector. Under scenario II, tourism pollutants were reduced together with the reorganized economical structure. However, under both scenarios the total discharge rose over the planning period. For example, by 2015 discharge reached 3446–4380 and 3593–4796 tons per annum under scenarios I and II, respectively, far more than the amount in 2001 of 1775 tons per annum. Thus, enormous pressures would be imposed on sewage plants or other treatment facilities, and the environmental investment needs to be guaranteed. Other countermeasures, such as clean-production technology for companies and biogas engineering for livestock farming are required to alleviate the contamination.

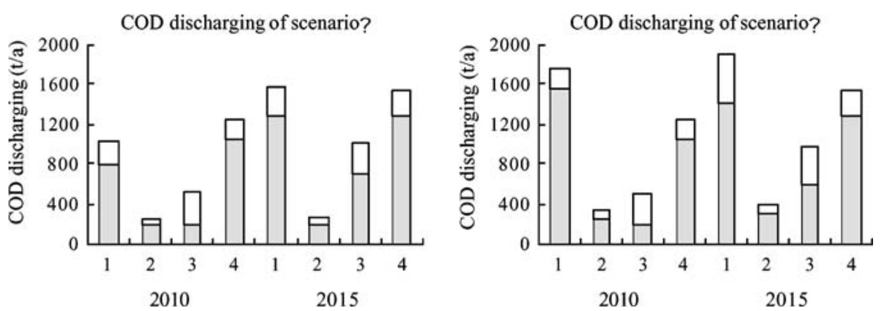

Figure 5. The COD discharging allocation of the Lake Qionghai Watershed. 1-agriculture, 2-industry, 3-tourism, 4-living. The shadow is the gap between the upper and lower bound.

4.4. COMPREHENSIVE ANALYSIS

Through the IFMOPLWS, two planning scenarios were presented and compared in Sections 4.1 through 4.3. Both results were theoretically informative because the model integrally reconciled various activities. However, in terms of economic benefit, resource use, environmental and ecosystem protection, and especially the practicality or operability of the schemes, a single scenario is preferable.

With regard to economic factors, total social net benefits progressed rapidly in both periods: under scenario I,642.5–799.6 $\times$ 10^6 USD in period I and 1117.0–1264.3 $\times$ 10^6 USD in period II; under scenario II, 744.0–9043.6 $\times$ 10^6 and 1216.8–1359.3 $\times$ 10^6 USD in periods I and II, respectively. Therefore, both scenarios ensured the watershed economic objective, but the benefits of scenario II were greater than those of scenario I. With regard to resource use, the total amount of water usage under scenario II was far more than that under scenario I. For example, in 2010 the upper bound of consumption in scenario II was 4.66 $\times$ 10^7 m^3 while it was 3.99 $\times$ 10^7 m^3 in scenario I. Concerning the ecosystem reservation, forest coverage reached satisfying levels in both scenarios; however, the coverage ratio was smaller in scenario II. With the extension of the forested area, soil loss from erosion decreased. The environmental pollution control constraints could be achieved by both scenarios, but the pollutant load under scenario II was higher than that under scenario I, as presented in Section 4.3.

Scenario I fully considered environmental protection and strictly curtailed related activities to be within the constraint. It provided a development mode with a lower ecological risk and sufficient flexibility regarding environmental conservation. However, the economic structure was unbalanced; for example, industries were too readily abandoned or promoted extremely. In particular, dry-land use was totally restricted by 2010 and fishing was abandoned in 2015 under this scenario. On the other hand, scenario II delivered a more stable and considerate pattern under which the economic structure was more balanced and better reflected the preferences of stakeholders. This scenario incorporated the will of stakeholders and experts, making the theoretical mathematical model more suitable for operation and more compatible with reality.

Based on the above interpretation, scenario I was relatively idealistic. Scenario II was more practical and operable, and attained the economic goals while still achieving the environmental objectives. Thus, scenario II was deemed preferable for integrated planning schemes for the Lake Qionghai watershed.

5. Conclusions

In this study, an interval fuzzy multiobjective programming method was introduced to create an integrated watershed plan. Based on a system analysis of the lake watershed, a new model suitable for lake watershed planning, IFMOPLWS, was developed. The model, together with scenario analysis and interactive process methods, was applied to a case study: a sustainable management plan for the Lake

Qionghai watershed. The following conclusions were reached:

- The IFMOPLWS model can coordinate interactions among system components and effectively address uncertainty in interval parameters.
- The model can incorporate the preferences of experts and stakeholders in the planning process by scenario analysis and interactive approaches and can thereby improve planning.
- Tourism should be treated as the leading industry in the Lake Qionghai watershed and could result in the growth of other industries as well. The presently limited facilities, transportation systems, and service systems, as well as the reputation of tourism in the area, should be improved to facilitate tourism development.
- Livestock husbandry, one of the agricultural categories, should be regarded as a competitive contributor to future agricultural growth. Construction of large-scale livestock farms is strongly recommended to bring about rapid progress in this sector.
- The water supply constraint was a key factor affecting solutions under different scenarios. Water resource shortages may present the greatest barrier for future development. Incentives, technologies, and concepts related to water conservation are required.
- Under the optimal scenario, forest coverage reached a favorable level by 2015. Soil erosion was mitigated somewhat. As soil erosion is affected by various factors, various mitigating methods should be applied together to tackle this problem.
- Water pollution was a big obstacle to future development. Sewage plants and other facilities such as constructed wetlands will play an increasingly important role in reducing pollution. Related measures, such as biogas engineering, clean-production technology, and changes in consumer behavior, are required simultaneously.
- Of the two integrated planning scenarios, one scenario created balanced economic and environmental development, and the other led to preferred economic development. The second scenario was finally recommended to local authorities after detailed comparison.
- This study demonstrated that IFMOPLWS is a powerful tool for integrated lake watershed planning that incorporates economic and environmental systems. The optimum alternative could provide a solid base for future sustainable management of the watershed.

Appendix: Notation

Notations for the modeling parameters and variables: $i =$ symbol for planning periods, $i = 1, 2, \ldots n$; $j =$ symbol for different activities of industry and agriculture, $j = 1, 2, \ldots m$; $u =$ symbol for industry expansion alternatives and sewage treatment expansion alternatives, $u = 1, 2, \ldots h$; $NY_i =$ length of period i; $CRB_{ij}^{\pm} =$ net benefit of crop type *j* in period *i* (\$10^4/km^2/a); $CRF_{ij}^{\pm}$ = runoff volume in unit area of cropland type *j* in period *i* (m^3/km^2/a); $CR_{ij}^{\pm}$ = land area of crop type *j* in period *i* (km^2); $CRL_i^{\pm}$ = maximum allowable crop land area in period *i* (km^2/a); $CRLL_i^{\pm}$ = least cropland area in period *i* (km^2/a); $CRN_{ij}^{\pm}$ = total nitrogen content in the runoff of cropland type *j* in period *i* (kg/m^3); $CRP_{ij}^{\pm}$ = total phosphorous content in the runoff of cropland type *j* in period *i* (kg/m^3); $CRS_{ij}^{\pm}$ = soil loss of crop activities *j* in period *i* (t/km^2/a); $FUNDL_i^{\pm}$ = maximum capital in period *i* (\$10^4/a); $CAPCOD_i^{\pm}$ = maximum discharge of COD in period *i* (kg/a); $CAPN_i^{\pm}$ = maximum discharge of nitrogen in period *i* (kg/a); $CAPP_i^{\pm}$ = maximum discharge of phosphorous in period *i* (kg/a); $RSD_{ij}^{\pm}$ = area of reserved land type *i* in period *j* (km^2); $RSDS_{ij}^{\pm}$ = soil loss in reserved land type *j* in period *i* (*t*/km^2/a); $FIB_{ij}^{\pm}$ = net benefit of fishery type *j* in period *i* (\$10^4/km^2/a); $FI_{ij}^{\pm}$ = area of fishpond type *j* in period *i* (km^2); $FIL_i^{\pm}$ = maximum allowable fishpond area in period *i* (km^2/a); $FIN_{ij}^{\pm}$ = total nitrogen loss of fishery activities *j* in period *i* (kg/km^2/a); $FIP_{ij}^{\pm}$ = total phosphorous loss of fishery activities *j* in period *i* (kg/km^2/a); $FRB_{ij}^{\pm}$ = net benefit of forestry activities *j* in period *i* (\$10^4/km^2/a); $FRC_{ij}^{\pm}$ = maintenance cost of forest type *j* in period *i* (\$10^4/km^2/a); $FREA_{ij}^{\pm}$ = extending area of forest type *j* in period *i* (km^2); $FREC_{ij}^{\pm}$ = extending cost of forest type *j* in period *i* (\$10^4/km^2); $FREL_i^{\pm}$ = maximum allowable area of forest extending in period *i* (km^2/a); $FR_{ij}^{\pm}$ = land area of forest type *j* in period *i* (km^2); $FRL_i^{\pm}$ = maximum forest area in period *i* (km^2/a); $FRS_{ij}^{\pm}$ = soil loss of forest type *j* in period *i* (t/km^2/a); $IN_{ij}^{\pm}$ = net benefits of industry type *j* in period *i* (\$10^4); $INCOD_{ij}^{\pm}$ = COD discharging of industry type *j* in period *i* (kg/\$10^4); $INEXP_{iu}^{\pm}$ = invested capital for industrial expanding scheme *u* in period *i* (\$10^4); $INW_{ij}^{\pm}$ = sewage discharging of industry type *j* in period *i* (t/\$10^4); $LKB_{ij}^{\pm}$ = net benefits of livestock husbandry activities *j* in period *i* (\$/head(unit of livestock amount)); $LKCOD_{ij}^{\pm}$ = COD discharging of livestock husbandry activities *j* in period *i* (kg/10^4 head/a); $LK_{ij}^{\pm}$ = year-end amount of livestock type *j* on hand in period *i* (10^4 head/a); $LKN_{ij}^{\pm}$ = total nitrogen discharging of livestock husbandry activities *j* in period *i* (kg/10^4 head/a); $LKP_{ij}^{\pm}$ = total phosphorous discharging of livestock husbandry activities *j* in period *i* (kg/10^4 head/a); $LKRO_{ij}^{\pm}$ = turnoff rate of livestock type *j* in period *i* (%); $PCOD_{ij}^{\pm}$ = COD discharging for living of residents type *j* (urban or rural) in period *i* (kg/10^4 person/a); $P_{ij}^{\pm}$ = predicted population of residents type *j* in period *i* (10^4 person/a); $PN_{ij}^{\pm}$ = total nitrogen discharging by living of residents type *j* in period *i* (kg/ 10^4 person/a); $PP_{ij}^{\pm}$ = total phosphorous discharging by living of residents type *j* in period *i* (kg/10^4 person/a); $PW_{ij}^{\pm}$ = sewage discharging by living of residents type *j* in period *i* (t/10^4 person/a); $REMCOD_{iu}^{\pm}$ = reduced COD under sewage plant augment scheme *u* in period *i* (kg/10^{4}t); $REMN_{iu}^{\pm}$ = reduced total nitrogen under sewage plant augment scheme *u* in period *i* (kg/10^{4}t); $REMP_{iu}^{\pm}$ = reduced total phosphorous under sewage plant augment scheme *u* in period *i* (kg/10^{4}t); $TRB_i^{\pm}$ = net benefit of tourism in period *i* (\$10^4/10^{4}perison-day); $TRC_i^{\pm}$ = tourism capacity in period *i* (10^4 person-day/a);

$TRCOD_i^{\pm}$ = COD discharging by tourism activities in period i (kg/10^4 person-day); $TREXP_i^{\pm}$ = invested capital for tourism expanding in period i (\$$10^4$/a); $TR_i^{\pm}$ = tourist flux in period i (10^4 person-day/a); $TRN_i^{\pm}$ = total nitrogen discharging by tourism activities in period i (kg/10^4 person-day); $TRP_i^{\pm}$ = total phosphorous discharging by tourism activities in period i (kg/10^4 person-day); $TRW_i^{\pm}$ = sewage discharging by tourism activities in period i (t/10^4 person-day); $WDCR_{ij}^{\pm}$ = water consumption of cropping type j in period i (t/km^2); $WDFI_{ij}^{\pm}$ = water consumption of fishery type j in period i (t/km^2); $WDFR_{ij}^{\pm}$ = water consumption of forestry activities j in period i (t/km^2); $WDIN_{ij}^{\pm}$ = water consumption of industry type j in period i (t/\$$10^4$); $WDP_{ij}^{\pm}$ = water consumption for living of residents type j in period i (t/10^4 person); $WDLK_{ij}^{\pm}$ = water consumption of livestock husbandry activities j in period i (t/10^4 head); $WDTR_{ij}^{\pm}$ = water consumption of tourism activities in period i (t/10^4 person-day); $WPC_{iu}^{\pm}$ = accumulative capacity under sewage plant augment scheme u in period i ($10^4 t$/a); $WPCEX_{iu}^{\pm}$ = expanding capacity under sewage plant augment scheme u in period i ($10^4 t$/d); $WPCEXC_{iu}^{\pm}$ = cost of sewage plant augment scheme u in period i (\$ /t/d); $WPCEXL_{iu}^{\pm}$ = limitation of sewage plant augment scale in scheme u in period i (10^4t/d); $WSL_i^{\pm}$ = maximum water supply in period i (t/a); $WWC_{iu}^{\pm}$ = cost of sewage treatment in scheme u in period i (\$ /t); $WWM_{iu}^{\pm}$ = actually treated sewage under scheme u in period i (10^4t/a); $YI_{ij}^{\pm}$, $YTR_i^{\pm}$, $YW_{iu}^{\pm}$, $YWP_{iu}^{\pm}$ = modulating variable, between 0 and 1.

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