

Water quality management in a wetland system using an inexact left-hand-side chance-constrained fuzzy multi-objective approach

Yao Ji¹ · Guohe Huang¹ · Wei Sun² · Yanfeng Li¹

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Abstract Water quality management is a significant item in the sustainable development of wetland system, since the environmental influences from the economic development are becoming more and more obvious. In this study, an inexact left-hand-side chance-constrained fuzzy multi-objective programming (ILCFMOP) approach was proposed and applied to water quality management in a wetland system to analyze the tradeoffs among multiple objectives of total net benefit, water quality, water resource utilization and water treatment cost. The ILCFMOP integrates interval programming, left-hand-side chance-constrained programming, and fuzzy multi-objective programming within an optimization framework. It can both handle multiple objectives and quantify multiple uncertainties, including fuzziness (aspiration level of objectives), randomness (pollutant release limitation), and interval parameters (e.g. water resources, and wastewater treatment costs). A representative water pollution control case study in a wetland system is employed for demonstration. The optimal schemes were analyzed under scenarios at different probabilities (p_i , denotes the admissible probability of violating the constraint i). The optimal solutions indicated that, most of the objectives would decrease with increasing

probability levels from scenarios 1 to 3, since a higher constraint satisfaction probability would lead to stricter decision scopes. This study is the first application of the ILCFMOP model to water quality management in a wetland system, which indicates that it is applicable to other environmental problems under uncertainties.

Keywords Inexact chance-constrained programming · Multi-objective programming · Water quality · Wetland · Uncertainty

1 Introduction

As the “kidneys” of the earth, a wetland can provide ecosystem services such as carbon sinks, clean water supply, flood abatement, food, esthetic beauty and recreational benefits (Zedler 2003). Tropical wetlands are complicated and huge natural ecosystems for ecological balance protection and biological diversity maintenance, based on a mixture of vegetation, soil, and water components (Qin et al. 2011; Gao et al. 2013). Degradation of wetland ecosystems is primarily by eutrophication or contamination problems, which are caused by discharges of nutrients or pollutants into the aquatic environment of wetland due to industrial, agricultural, and other human-induced activities (Jing et al. 2008; Huang et al. 2003). More than 52 % of the lakes in China are undergoing severe eutrophication problems. Thus, implementation of water quality management for wetland systems is necessary and imperative.

In view of the wetland system’s complexity, a multitude of techniques were applied to water quality management (Huang et al. 1992; Huang and Xia 2001; Lischeid 2008; Cai et al. 2011; Zhang et al. 2011; Lv et al. 2013; Li et al. 2014; Xie and Huang 2014). Ham et al. (2010) proposed an

✉ Guohe Huang
guohe.huang@hotmail.com

✉ Wei Sun
sunwei@iseis.org

¹ MOE Key Laboratory of Regional Energy and Environmental Systems Optimization, S-C Resources and Environmental Research Academy, North China Electric Power University, Beijing 102206, China

² Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, SK S4S 0A2, Canada

integrated model to manage the size and the operation of wetlands to maximize the improvement of reservoir water-quality at a catchment scale. Zhang and Huang (2011) presented a multi-criteria method to assess the nitrogen loss potential and the water quality classification of rivers. Bai et al. (2013) carried out a research on land-use effects on soil carbon and nitrogen in typical wetland of China, and suggest that TN and SOC contents in top 20 cm soils of wetlands can be reduced significantly by cultivation, but they are restored slowly after abandonment. Cools et al. (2013) uses rapid assessment tools to promote understanding and achieve an integrated assessment of the management of the wetland system.

Although many systematic modeling technologies were developed for water pollution control in wetlands, few studies mentioned the links between the external and internal systems (Zedler and Kercher 2005; Helton et al. 2014; Hargalani et al. 2014). Water pollution may be caused by several human activities, such as agricultural or industrial production, soil erosion, tree plantations. Since multiple processes and activities need to be taken into account, holistic and interactive objectives, such as ecological protection, economic benefits and resource conservation, should be satisfied simultaneously (Füederer 1999; Ferguson and Mudd 2011; Tan et al. 2011). Meanwhile, uncertainties are also complicated in the wetland system due to data availability and results computation. Most of data can hardly be expressed as deterministic values but intervals and probability distributions (Wei et al. 2012). For example, water resource can be expressed as a random variable, which is determined by dry/wet summers, extreme weather, and climatic disasters. The socio-economic factors can be presented as intervals, because their probability density functions (PDFs) are impractically obtained (Huang et al. 1992; Beck 1987).

Hence, the objective of this study is to develop an inexact left-hand-side chance-constrained fuzzy multi-objective programming (ILCFMOP) model and apply it to water quality control in a wetland system. The ILCFMOP integrates interval programming, left-hand-side chance-constrained programming, and fuzzy multi-objective programming within an optimization framework. It can analyze the tradeoffs among multiple objectives of total net benefit (TNB), water resource utilization and water pollution control. It can also provide scientific optimal schemes under various human activity conditions, such as tourism flows, agricultural areas and livestock numbers. In addition, multiple uncertainties in water quality management can be quantified, including fuzziness (aspiration level of objectives), randomness (pollutant release limitation), and interval parameters [e.g. water resources, and wastewater treatment costs (WTC)].

2 Model development

2.1 Multi-objective programming model (MOP)

A MOP can be expressed as follows (Slowinski and Teghem 1990):

$$\min f_k = c_{kj}x_j, \quad k = 1, 2, \dots, p; \quad j = 1, 2, \dots, t \quad (1a)$$

$$\max f_l = c_{lj}x_j, \quad l = p + 1, p + 2, \dots, p + q; \quad j = 1, 2, \dots, t \quad (1b)$$

subject to:

$$a_{ij}x_j \leq b_i, \quad i = 1, 2, \dots, m \quad (1c)$$

$$x_j \geq 0 \quad (1d)$$

where f is the objective function, x are decision variables, b_i and c are real-number parameters. $x_j \in R^{t \times 1}$, $c_{kj} \in R^{p \times t}$, $c_{lj} \in R^{q \times t}$, $a_{ij} \in R^{m \times t}$, R denote a set of real numbers.

2.2 Inexact left-hand-side chance-constrained programming (ILCCP)

When the left-hand-side parameter (a_{ij}) in (1c) is expressed in the term of random variables with normal distributions (η_{ij} is expectation and τ_{ij}^2 is standard variation), the constraints (1c) can be written as follows:

$$\Pr \left\{ \sum_{i=1}^n a_{ij}(\omega)x_j^\pm \leq b_i^\pm \right\} \geq 1 - p_i, \quad i = 1, 2, \dots, m \quad (2)$$

a_{ij} are random variables, and $a_{ij}(\omega) \sim N(\eta_{ij}, \tau_{ij}^2)$. Since the CCP method does not require that all the constraints should be totally satisfied, two important definitions should be introduced, which are p_i and $(1 - p_i)$. p_i is the significance level, which represents the admissible probability of violating the constraint; $1 - p_i$ is the confidence coefficient, which represents the probability of satisfying the constraint. The linearization form of ILCCP can be transferred as follows (Ji et al. 2014):

$$\sum_{j=1}^n \left[x_j^\pm (\eta_{ij} + \tau_{ij} \Phi^{-1}(1 - p_i)) \right] \leq b_i^\pm, \quad \forall i \quad (3)$$

2.3 Inexact left-hand-side chance-constrained multi-objective programming (ILCMOP)

When some parameters are expressed as random variables in the left-hand-side constraints of model (1), the ILCCP method should be incorporated into a MOP model. An inexact left-hand-side chance-constrained MOP can be written as follows:

$$\min f_k^\pm = c_{kj}^\pm x_j^\pm, \quad k = 1, 2, \dots, p; \quad j = 1, 2, \dots, t \quad (4a)$$

$$\max f_l^\pm = c_{lj}^\pm x_j^\pm, \quad l = p + 1, p + 2, \dots, p + q; \quad j = 1, 2, \dots, t \quad (4b)$$

subject to:

$$\sum_{j=1}^n [x_j^\pm (\eta_i + \tau_i \Phi^{-1}(1 - p_i))] \leq b_i^\pm, \quad i = 1, 2, \dots, n \quad (4c)$$

$$a_{ij}^\pm x_j^\pm \leq b_i^\pm, \quad i = n + 1, n + 2, \dots, m \quad (4d)$$

$$x_j^\pm \geq 0 \quad (4e)$$

2.4 Inexact left-hand-side chance-constrained fuzzy multi-objective programming (ILCFMOP)

On the basis of fuzzy flexible programming (Charnes et al. 1972), fuzziness in the constraints and objectives (represented by fuzzy sets and denoted as “fuzzy goal” and “fuzzy constraints”) can be presented as membership grades (λ^\pm). Through incorporating the fuzzy programming into ILCMOP, an ILCFMOP model can be formulated as follows:

$$\max \lambda^\pm \quad (5a)$$

subject to:

$$c^\pm x^\pm \leq f^- + (1 - \lambda^\pm)(f^+ - f^-) \quad (5b)$$

$$a^\pm x^\pm \leq d^- + (1 - \lambda^\pm)(d^+ - d^-) \quad (5c)$$

$$\sum_{j=1}^n [x_j^\pm (\eta_i + \tau_i \Phi^{-1}(1 - p_i))] \leq b_i^\pm, \quad i = 1, 2, \dots, n \quad (5d)$$

$$x_j^\pm \geq 0 \quad (5e)$$

$$0 \leq \lambda^\pm \leq 1 \quad (5f)$$

f^+ and f^- are the upper and lower bounds of the aspiration level of objectives. λ^\pm is the control decision variable corresponding to the membership grade of satisfaction for the fuzzy decision. According to Huang et al. (1993), the ILCFMOP model can be converted into two deterministic sub-models.

2.4.1 Sub-model 1

$$\max \lambda^+ \quad (6a)$$

subject to:

$$\sum_{j=1}^{k_1} c_j^- x_j^- + \sum_{j=k_1+1}^n c_j^- x_j^+ \leq f^- + (1 - \lambda^+)(f^+ - f^-) \quad (6b)$$

$$\sum_{j=1}^{k_1} |a_{ij}|^+ \text{Sign}(a_{ij}^+) x_j^- + \sum_{j=k_1+1}^n |a_{ij}|^- \text{Sign}(a_{ij}^-) x_j^+ \leq d_i^- + (1 - \lambda^+)(d_i^+ - d_i^-) \quad (6c)$$

$$\sum_{j=1}^n [x_j^+ (\eta_i + \tau_i \Phi^{-1}(1 - p_i))] \leq b_i^+, \quad i = 1, 2, \dots, n \quad (6d)$$

$$0 \leq \lambda^+ \leq 1 \quad (6e)$$

$$x_j^- \geq 0, \quad j = 1, 2, \dots, k_1 \quad (6f)$$

$$x_j^+ \geq 0, \quad j = k_1 + 1, k_1 + 2, \dots, t \quad (6g)$$

2.4.2 Sub-model 2

$$\max \lambda^- \quad (7a)$$

subject to:

$$\sum_{j=1}^{k_1} c_j^+ x_j^+ + \sum_{j=k_1+1}^n c_j^+ x_j^- \leq f^- - (1 - \lambda^-)(f^+ - f^-), \quad k = 1, 2, \dots, p \quad (7b)$$

$$\sum_{j=1}^n [x_j^- (\eta_i + \tau_i \Phi^{-1}(1 - p_i))] \leq b_i^-, \quad i = 1, 2, \dots, n \quad (7c)$$

$$\sum_{j=1}^{k_1} |a_{ij}|^- \text{Sign}(a_{ij}^-) x_j^+ + \sum_{j=k_1+1}^n |a_{ij}|^+ \text{Sign}(a_{ij}^+) x_j^- \leq d_i^+ - \lambda^- (d_i^+ - d_i^-) \quad (7d)$$

$$0 \leq x_{jopt}^- \leq x_j^+, \quad j = 1, 2, \dots, k_1 \quad (7e)$$

$$0 \leq x_j^- \leq x_{jopt}^+, \quad j = k_1 + 1, k_1 + 2, \dots, t \quad (7f)$$

$$0 \leq \lambda^- \leq 1 \quad (7g)$$

Decision variables $x_{jopt}^\pm = [x_{jopt}^-, x_{jopt}^+]$ can be obtained by solving submodels (6) and (7). Accordingly, the objective values for the ILCFMOP model ($f_{kopt}^\pm = [f_{kopt}^-, f_{kopt}^+]$ and $f_{lopt}^\pm = [f_{lopt}^-, f_{lopt}^+]$) can be generated through x_{jopt}^\pm using model (4).

3 Case study

3.1 Problem statement

To demonstrate application of the proposed ILCFMOP model, a water quality management problem within a wetland system is employed (Liu et al. 2012). A great number of social, economic, and ecological factors and related processes are included. Deterioration of water

quality has been considered the primary concern resulting in degradation of wetland ecosystems.

In the study wetland system, several human activities, such as agricultural/industrial/aquacultural production, forest plantations, livestock husbandry, soil erosion, tourism, have contributed to water pollution. Thus, issues of water supply and demand, wastewater treatment, pollutant discharge limitation, biodiversity, agricultural/industrial development and tourism activities are incorporated. Multiple interactive and holistic objectives, such as economic benefits, environmental protection and resource conservation need to be satisfied (Tan et al. 2011). Therefore, the prominent problem in the wetland is the conflict between achievement of total net system benefit and protection of water resources (including a water quality objective, a WTC objective and a water resources demand objective). The local economy is mainly based on crop/forest farming, animal (land-livestock and waterfowl) husbandry, regional industry, aquaculture and tourism. Thus, the decision variables are determined to be agricultural areas, forestry areas, aquacultural areas, industry scales, numbers of land-livestock and waterfowl, tourism flows and resident numbers; the objectives are to maximize TNB, to minimize WTC, to minimize water resource demand, and to minimize water quality. Tables 1 and 2 list the parameters of water resources/quality requirements and

the water quality management system. Especially, the “treatment efficiency for COD in period k ” is chosen as random variables with normal distributions, while most of the other parameters are interval numbers. In this study, the primary problem is how to allocate the resources to maximize the total benefit of the wetland system under constraints of water quality management and water resources protection/limitation.

3.2 Application of the ILCFMOP

A hybrid ILCFMOP model was developed to deal with the water quality management problem in a wetland system. Four major objectives were taken into account, which are the highest TNB, the lowest cost on wastewater treatment, the lowest water resources demand and the lowest water pollutant discharge into the system [minimize the chemical oxygen demand (COD), nitrogen/phosphorous discharge (PD) and soil loss (SL)]. Constraints related to water resource balance, such as water mass balance, pollutant release limits, forest cover balance, and land area balance, were included. In detail, the ILCFMOP model was as follows:

(1) Objectives

(a) Total net system benefit

$$\max f_1 = \left(\begin{aligned} & \sum_{i=1}^I \sum_{k=1}^K A_{ik}^{\pm} \cdot BA_{ik}^{\pm} + \sum_{j=1}^J \sum_{k=1}^K AF_{jk}^{\pm} \cdot BF_{jk}^{\pm} + \sum_{m=1}^M \sum_{k=1}^K W_{mk}^{\pm} \cdot BW_{mk}^{\pm} + \\ & \sum_{n=1}^N \sum_{k=1}^K L_{nk}^{\pm} \cdot BL_{nk}^{\pm} + \sum_{s=1}^S \sum_{k=1}^K A_{sk}^{\pm} \cdot BA_{sk}^{\pm} + \sum_{u=1}^U \sum_{k=1}^K I_{uk}^{\pm} + \sum_{k=1}^K T_k^{\pm} \cdot BT_k^{\pm} \end{aligned} \right) \cdot \Delta L_k \tag{8a}$$

(b) Water quality

$$\text{COD discharge: } \min f_2 = \left(\begin{aligned} & \left(\sum_{i=1}^I \sum_{k=1}^K A_{ik}^{\pm} \cdot SA_{ik}^{\pm} + \sum_{j=1}^J \sum_{k=1}^K AF_{jk}^{\pm} \cdot SF_{jk}^{\pm} \right) \cdot CS_k^{\pm} + \\ & \sum_{m=1}^M \sum_{k=1}^K W_{mk}^{\pm} \cdot WC_{mk}^{\pm} + \sum_{n=1}^N \sum_{k=1}^K L_{nk}^{\pm} \cdot LC_{nk}^{\pm} + \sum_{s=1}^S \sum_{k=1}^K A_{sk}^{\pm} \cdot AQC_{sk}^{\pm} + \\ & \sum_{u=1}^U \sum_{k=1}^K I_{uk}^{\pm} \cdot IC_{uk}^{\pm} + \sum_{k=1}^K (T_k^{\pm} + R_k^{\pm}) \cdot HC_k^{\pm} \end{aligned} \right) \cdot \Delta L_k \tag{8b}$$

$$\text{Nitrogen discharge (ND): } \min f_3 = \left(\begin{aligned} & \sum_{i=1}^I \sum_{k=1}^K A_{ik}^{\pm} \cdot (SA_{ik}^{\pm} \cdot NS_k^{\pm} + NA_{ik}^{\pm}) + \sum_{j=1}^J \sum_{k=1}^K AF_{jk}^{\pm} \cdot SF_{jk}^{\pm} \cdot NS_k^{\pm} + \\ & \sum_{m=1}^M \sum_{k=1}^K W_{mk}^{\pm} \cdot NW_{mk}^{\pm} + \sum_{n=1}^N \sum_{k=1}^K L_{nk}^{\pm} \cdot NL_{nk}^{\pm} + \sum_{s=1}^S \sum_{k=1}^K A_{sk}^{\pm} \cdot NAQ_{sk}^{\pm} + \\ & \sum_{u=1}^U \sum_{k=1}^K I_{uk}^{\pm} \cdot NI_{uk}^{\pm} + \sum_{k=1}^K (T_k^{\pm} + R_k^{\pm}) \cdot NH_k^{\pm} \end{aligned} \right) \cdot \Delta L_k \quad (8c)$$

$$\text{Phosphorous discharge: } \min f_4 = \left(\begin{aligned} & \sum_{i=1}^I \sum_{k=1}^K A_{ik}^{\pm} \cdot (SA_{ik}^{\pm} \cdot SA_{ik}^{\pm} \cdot PS_k^{\pm} + PA_{ik}^{\pm}) + \sum_{j=1}^J \sum_{k=1}^K AF_{jk}^{\pm} \cdot SF_{jk}^{\pm} \cdot PS_k^{\pm} + \\ & \sum_{m=1}^M \sum_{k=1}^K W_{mk}^{\pm} \cdot PW_{mk}^{\pm} + \sum_{n=1}^N \sum_{k=1}^K L_{nk}^{\pm} \cdot PL_{nk}^{\pm} + \sum_{s=1}^S \sum_{k=1}^K A_{sk}^{\pm} \cdot PA_{sk}^{\pm} + \\ & \sum_{u=1}^U \sum_{k=1}^K I_{uk}^{\pm} \cdot I_{uk}^{\pm} + \sum_{k=1}^K (T_k^{\pm} + R_k^{\pm}) \cdot PH_k^{\pm} \end{aligned} \right) \cdot \Delta L_k \quad (8d)$$

$$\text{Soil loss: } \min f_5 = \left(\sum_{i=1}^I \sum_{k=1}^K A_{ik}^{\pm} \cdot SA_{ik}^{\pm} + \sum_{j=1}^J \sum_{k=1}^K AF_{jk}^{\pm} \cdot SF_{jk}^{\pm} \right) \cdot \Delta L_k \quad (8e)$$

(c) Wastewater treatment cost

$$\min f_6 = \left(\sum_{u=1}^U \sum_{k=1}^K I_{uk}^{\pm} \cdot CWI_{uk}^{\pm} \cdot WI_u^{\pm} + \sum_{k=1}^K (T_k^{\pm} + R_k^{\pm}) \cdot WH^{\pm} \cdot CWH_k^{\pm} \right) \cdot \Delta L_k \quad (8f)$$

(d) Water resources demand

$$\min f_7 = \left(\begin{aligned} & \sum_{i=1}^I \sum_{k=1}^K A_{ik}^{\pm} \cdot DA_{ik}^{\pm} + \sum_{j=1}^J \sum_{k=1}^K AF_{jk}^{\pm} \cdot DF_{jk}^{\pm} + \\ & \sum_{m=1}^M \sum_{k=1}^K W_{mk}^{\pm} \cdot DW_{mk}^{\pm} + \sum_{n=1}^N \sum_{k=1}^K L_{nk}^{\pm} \cdot DL_{nk}^{\pm} + \\ & \sum_{s=1}^S \sum_{k=1}^K A_{sk}^{\pm} \cdot DA_{sk}^{\pm} + \sum_{u=1}^U \sum_{k=1}^K I_{uk}^{\pm} \cdot DI_{uk}^{\pm} + \sum_{k=1}^K (T_k^{\pm} + R_k^{\pm}) \cdot DTS_k^{\pm} \end{aligned} \right) \cdot \Delta L_k \quad (8g)$$

(2) Constraints

(a) Water resource availability

$$\begin{aligned} & \sum_{i=1}^I A_{ik}^{\pm} \cdot DA_{ik}^{\pm} + \sum_{j=1}^J AF_{jk}^{\pm} \cdot DF_{jk}^{\pm} + \sum_{m=1}^M W_{mk}^{\pm} \cdot DW_{mk}^{\pm} + \sum_{n=1}^N L_{nk}^{\pm} \cdot DL_{nk}^{\pm} \\ & + \sum_{s=1}^S A_{sk}^{\pm} \cdot DA_{sk}^{\pm} + \sum_{u=1}^U I_{uk}^{\pm} \cdot DI_{uk}^{\pm} + \sum_{k=1}^K ((T_k^{\pm} + R_k^{\pm}) \cdot DTS_k^{\pm} - DP_k^{\pm}) \leq RE_k, \quad \forall k \end{aligned} \quad (9a)$$

(b) Pollutant release limitation

$$\text{COD discharge: } \Pr \left\{ \begin{aligned} & \sum_{m=1}^M W_{mk}^{\pm} \cdot WC_{mk} + \sum_{n=1}^N L_{nk}^{\pm} \cdot LC_{nk}^{\pm} + \sum_{s=1}^S A_{sk}^{\pm} \cdot AQC_{sk}^{\pm} + \\ & \left[\sum_{u=1}^U I_{uk}^{\pm} \cdot IC_{uk}^{\pm} + (T_k^{\pm} + R_k^{\pm}) \cdot HC_k^{\pm} \right] [1 - EC(\varpi)_k] \leq MC_k^{\pm} \end{aligned} \right\} \geq 1 - p_i \tag{9b}$$

$$\begin{aligned} & \sum_{i=1}^I (A_{ik}^{\pm} \cdot SA_{ik}^{\pm} \cdot NS_k^{\pm} + A_{ik}^{\pm} \cdot NA_{ik}^{\pm}) + \sum_{j=1}^J AF_{jk}^{\pm} \cdot SF_{jk}^{\pm} \cdot NS_k^{\pm} \\ \text{Nitrogen discharge: } & + \sum_{m=1}^M W_{mk}^{\pm} \cdot DW_{mk}^{\pm} + \sum_{n=1}^N L_{nk}^{\pm} \cdot NL_{nk}^{\pm} + \sum_{s=1}^S A_{sk}^{\pm} \cdot NAQ_{sk}^{\pm} \end{aligned} \tag{9c}$$

$$+ \left[\sum_{u=1}^U I_{uk}^{\pm} \cdot NI_{uk}^{\pm} + (T_k^{\pm} + R_k^{\pm}) \cdot NH_k^{\pm} \right] [1 - EN_k] \leq MN_k^{\pm}, \quad \forall k$$

$$\begin{aligned} & \sum_{i=1}^I (A_{ik}^{\pm} \cdot SA_{ik}^{\pm} \cdot PS_k^{\pm} + A_{ik}^{\pm} \cdot PA_{ik}^{\pm}) + \sum_{j=1}^J AF_{jk}^{\pm} \cdot SF_{jk}^{\pm} \cdot PS_k^{\pm} \\ \text{Phosphorous discharge: } & + \sum_{m=1}^M W_{mk}^{\pm} \cdot PW_{mk}^{\pm} + \sum_{n=1}^N L_{nk}^{\pm} \cdot PL_{nk}^{\pm} + \sum_{s=1}^S A_{sk}^{\pm} \cdot PA_{sk}^{\pm} \end{aligned} \tag{9d}$$

$$+ \left[\sum_{u=1}^U I_{uk}^{\pm} \cdot PI_{uk}^{\pm} + (T_k^{\pm} + R_k^{\pm}) \cdot PH_k^{\pm} \right] [1 - EP_k] \leq MP_k^{\pm}, \quad \forall k$$

(c) Wastewater treatment

$$\begin{aligned} & \sum_{u=1}^U I_{uk}^{\pm} \cdot WI_{uk}^{\pm} \cdot CWI_{uk}^{\pm} + (T_k^{\pm} + R_k^{\pm}) \cdot WH_k^{\pm} \\ & \cdot CWH_k^{\pm} \leq MW_k^{\pm}, \quad \forall k \end{aligned} \tag{9e}$$

(d) Land area availability

$$\sum_{i=1}^I A_{ik}^{\pm} + \sum_{j=1}^J AF_{jk}^{\pm} \leq AGF_k^{\pm}, \quad \forall k \tag{9f}$$

(e) Water area availability

$$\sum_{s=1}^S A_{sk}^{\pm} \leq AAQ_k^{\pm}, \quad \forall k \tag{9g}$$

(f) Soil erosion

$$\sum_{i=1}^I (A_{ik}^{\pm} \cdot SA_{ik}^{\pm}) + \sum_{j=1}^J AF_{jk}^{\pm} \cdot SF_{jk}^{\pm} \leq MS_k^{\pm}, \quad \forall k \tag{9h}$$

(g) Forest cover

$$\sum_{j=1}^J AF_{jk}^{\pm} \geq AGF_k^{\pm} \cdot MF_k^{\pm}, \quad \forall k \tag{9i}$$

(i) Agriculture

$$\sum_{i=1}^I A_{ik}^{\pm} \geq MiA_k^{\pm}, \quad \forall k \tag{9j}$$

(j) Livestock

$$\sum_{n=1}^N L_{nk}^{\pm} \cdot BL_{nk}^{\pm} + \sum_{m=1}^M W_{mk}^{\pm} \cdot BW_{mk}^{\pm} \geq MiL_k^{\pm}, \quad \forall k \tag{9k}$$

(k) Industry

$$\sum_{u=1}^U I_{uk}^{\pm} \geq MiI_k^{\pm}, \quad \forall k \tag{9l}$$

(l) Population

$$R_k^{\pm} \geq IR_k^{\pm}, \quad \forall k \tag{9m}$$

(m) Tourism

$$IF^{\pm} \leq T_k^{\pm} \leq IF_k^{\pm}, \quad \forall k \tag{9n}$$

(n) Non-negativity and technical constraints

$$\begin{aligned} & A_{ik}^{\pm}, AF_{jk}^{\pm}, W_{mk}^{\pm}, L_{nk}^{\pm}, A_{sk}^{\pm}, I_{uk}^{\pm}, T_k^{\pm}, R_k^{\pm} \geq 0, \\ & \forall i, j, m, n, s, u, k \end{aligned} \tag{9o}$$

Table 1 Parameters of water resources and water quality requirements

Parameters	Period		
	$k = 1$	$k = 2$	$k = 3$
Maximum available water resource (10^7 m^3)	[4.94, 5.52]	[5.30, 6.21]	[5.64, 6.71]
Maximum allowable COD discharge (10^7 kg)	[62.00, 64.00]	[66.00, 68.00]	[70.00, 72.00]
Maximum allowable nitrogen discharge (10^5 kg)	[56.00, 58.00]	[61.00, 63.00]	[65.00, 67.00]
Maximum allowable phosphorus discharge (10^5 kg)	[12.00, 14.00]	[13.00, 15.00]	[14.00, 16.00]
Maximum allowable soil loss (10^7 kg)	[1.90, 2.10]	[2.05, 2.25]	[2.20, 2.35]

Table 2 Parameters of the water quality management system

	Net benefit		Water demand		Nitrogen discharge	
	Unit	Value	Unit	Value	Unit	Value
Agricultural activities	10^6 RMB/km^2	[1.82, 1.80]	$10^5 \text{ m}^3/\text{km}^2$	[7.50, 7.55]	10^3 kg/km^2	[31.32, 31.48]
Forestry activities	10^4 RMB/km^2	[10.00, 3.00]	m^3/km^2	[190.00, 210.00]		
Livestock rearing	RMB/head	[480.00, 520.00]	m^3/head	[3.60, 3.90]	kg/head	[15.00, 17.00]
Poultry raising	RMB/head	[3.00, 5.00]	m^3/head	[0.15, 0.21]	kg/head	[0.31, 0.37]
Fish farming	10^6 RMB/km^2	[2.80, 2.85]	$10^5 \text{ m}^3/\text{km}^2$	[50.00, 53.00]	10^5 kg/km^2	[60.00, 63.00]
Industrial production			m^3/RMB	[0.011, 0.013]	10^{-3} kg/RMB	[0.18, 0.21]
Tourism flow	RMB/people	[730.00, 745.00]	m^3/people	[1.80, 2.20]	kg/people	[0.06, 0.07]
Residential population			m^3/people	[102.00, 116.00]	kg/people	[0.23, 0.34]

where $A_{ik}^\pm, AF_{jk}^\pm, W_{mk}^\pm, L_{nk}^\pm, A_{sk}^\pm, I_{uk}^\pm, T_k^\pm, R_k^\pm$ are decision variables. The nomenclatures and values for the parameters are provided in Tables 1, 2, and 3.

Based on in Eqs. (2) and (3), the linearization form of inequalities (9b) can be transformed to the following inequalities:

$$\begin{aligned}
 & \sum_{m=1}^M W_{mk}^\pm + \sum_{n=1}^N L_{nk}^\pm \cdot LC_{nk}^\pm + \sum_{s=1}^S A_{sk}^\pm \cdot AQC_{sk}^\pm \\
 & + \left[\sum_{u=1}^U I_{uk}^\pm \cdot IC_{uk}^\pm + (TUX_k^\pm + PPX_k^\pm) \cdot HC_k^\pm \right] \\
 & + [-\eta_{EC,k} + \tau_{EC,k} \Phi^{-1}(1 - p_i)] \\
 & \times \left[\sum_{u=1}^U I_{uk}^\pm \cdot IC_{uk}^\pm + (TUX_k^\pm + PPX_k^\pm) \cdot HC_k^\pm \right] \\
 & \leq MC_k^\pm, \quad \forall k \tag{10}
 \end{aligned}$$

To demonstrate the advantage of ILCFMOP, a corresponding inexact chance-constrained fuzzy multi-objective programming (ICFMOP) model was introduced. Through replacing both the left-hand-side random parameters $EC(\varpi)_i$ with the interval numbers, and the interval parameters MC with the random variables in the ILCFMOP model, an ICFMOP model was formulated. Accordingly, the inequalities (9b) can be reformulated as follows:

$$\begin{aligned}
 & \sum_{m=1}^M W_{mk}^\pm \cdot WC_{mk} + \sum_{n=1}^N L_{nk}^\pm \cdot LC_{nk}^\pm + \sum_{s=1}^S A_{sk}^\pm \cdot AQC_{sk}^\pm \\
 & + \left[\sum_{u=1}^U I_{uk}^\pm \cdot IC_{uk}^\pm + (T_k^\pm + R_k^\pm) \cdot HC_k^\pm \right] [1 - EC_k^\pm] \leq MC_k^{p_i} \tag{11}
 \end{aligned}$$

4 Results analysis

The solutions for the ILCFMOP model under three scenarios are displayed in the figures. The three scenarios were designed at increasing probabilities ($p_i = 0.1$ in scenario 1, $p_i = 0.05$ in scenario 2, and $p_i = 0.01$ in scenario 3), which represent the different risk levels of environmental constraint violations. The levels of p_i imply that the constraints would be satisfied with a probability of at least 90, 95 and 99 %.

The three scenarios represent the changes of TNB, WTC, water resource demand (WRD), COD discharge (COD), ND, PD and SL of the system under various uncertain conditions (shown in Figs. 1, 2, 3). In detail, the TNB of the system in scenarios 1–3 are $[10.77, 12.28] \times 10^9 \text{ RMB}$, $[9.30, 10.57] \times 10^9 \text{ RMB}$, $[8.89, 9.36] \times 10^9 \text{ RMB}$, respectively. Both of the upper and lower bounds of the total benefit show a downtrend from scenarios 1 to 3, which indicates that lower p_i level could result in a narrower decision space, corresponding to a higher system reliability and lower total benefit.

Table 3 Definitions and interpretations of the parameters

Symbols	Interpretation	Unit
A_{ik}	Area of agricultural land cultivated with crop i in period k	km ² /year
BA_{ik}	Net benefit from agricultural cultivation of crop i in period k	RMB/km ²
AF_{jk}	Area of forestry land planted with tree j in period k	km ² /year
BF_{jk}	Net benefit from forestry planted with tree j in period k	RMB/km ²
W_{mk}	Number of waterfowl m raised in the system during period k	head/year
BW_{mk}	Net benefit from raised waterfowl m in period k	RMB/head
L_{nk}	Number of livestock n raised in the system during period k	head/year
BL_{nk}	Net benefit from raised livestock n in period k	RMB/head
A_{sk}	$A = \pi r^2$ of aquaculture farmed with aquatic animal s in period k	km ² /year
BA_{sk}	Net benefit from aquaculture farmed with aquatic animal s in period k	RMB/km ²
ΔL_k	Planning period	year
I_{uk}	Industrial production with industry type u in period k	RMB/year
T_k	Tourism flow in the system during period k	people/year
BT_k	Net benefit from tourism in period k	RMB/people
SA_{ik}	Soil lose from agricultural land cultivated with crop i in period k	kg/km ²
SF_{jk}	Soil lose from forestry land planted with tree j in period k	kg/km ²
CS_k	COD content of soil in period k	%
WC_{mk}	Amount of COD generated by waterfowl m in period k	kg/head
LC_{nk}	Amount of COD generated by livestock n in period k	kg/head
AQC_{sk}	Amount of COD generated by aquatic animal s in period k	kg/km ²
IC_{uk}	Amount of COD generated from industrial production with industry type u in period k	kg/km ²
R_k	Number of residents in the system during period k	people/year
HC_k	Amount of COD generated from human activities	kg/people
NS_k	Nitrogen content of soil in period k	%
NA_{ik}	Amount of nitrogen generated from agricultural activities with crop i in period k	kg/km ²
NW_{mk}	Amount of nitrogen generated by waterfowl m in period k	kg/head
NL_{nk}	Amount of nitrogen generated by livestock n in period k	kg/head
NAQ_{sk}	Amount of nitrogen generated by aquatic animal s in period k	kg/km ²
NI_{uk}	Amount of nitrogen generated from industrial production with industry type u in period k	kg/km ²
NH_k	Amount of nitrogen generated from human activities	kg/people
PA_{ik}	Amount of phosphorus generated by agricultural activities with crop i in period k	kg/km ²
PW_{mk}	Amount of phosphorus generated by waterfowl m in period k	kg/head
PL_{nk}	Amount of phosphorus generated by livestock n in period k	kg/head
PA_{sk}	Amount of phosphorus generated by aquatic animal s in period k	kg/km ²
PI_{uk}	Amount of phosphorus generated from industrial production with industry type u in period k	kg/km ²
WI_u	Wastewater generated from industrial production with industry type u	m ³ /RMB
WH	Municipal wastewater generated by human activities	m ³ /people
CWH_k	Treatment cost for municipal wastewater generated by human activities in period k	RMB/m ³
DA_{ik}	Water demand for agricultural land cultivated with crop i in period k	m ³ /km ²
DF_{jk}	Water demand for forestry land planted with tree j in period k	m ³ /km ²
DW_{mk}	Water demand for raised waterfowl m in period k	m ³ /head
DL_{nk}	Water demand for livestock n raised in period k	m ³ /km ²
DA_{sk}	Water demand for aquaculture farmed with aquatic animal s in period k	m ³ /km ²
DI_{uk}	Water demand for industrial production with industry type u during period k	m ³ /RMB
DTS_k	Water demands for tourists and residents in period k	m ³ /people
DP_k	Water demand for ecological protection in period k	m ³ /head
RE_k	Amount of water resources available in period k	m ³
PS_k	Phosphorus content of soil in period k	%

Table 3 continued

Symbols	Interpretation	Unit
PH_k	Amount of phosphorus generated from human activities	kg/people
EC_k	Treatment efficiency for COD with a probability level of p_i in period k	%
MC_k	Maximum allowable amount of COD in the system during period k	kg
EN_k	Treatment efficiency for nitrogen in period k	%
MN_k	Maximum allowable amount of nitrogen in the system during period k	kg
EP_k	Treatment efficiency for phosphorus in period k	%
MP_k	Maximum allowable amount of phosphorus in the system during period k	kg
CWI_{uk}	Treatment cost for wastewater generated from industrial production with industry type u in period k	RMB/m ³
MW_k	Maximum capacity of wastewater treatment facilities in period k	m ³
MiA_k	Minimum area of agricultural land required in period k	km ²
AGF_k	Available area of land for agriculture and forestry during period k	km ²
AAQ_k	Available area of water for aquaculture during period k	km ²
MS_k	Maximum allowable soil erosion in the system during period k	kg
MF_k	Minimum allowance of forest cover in period k	%
MiL_k	Minimum number of livestock required in period k	head
MiI_k	Minimum level of industry required during period k	RMB
IR_k	Initial number of residents in the system during period k	people
IF_k	Initial tourism flow in the system during period k	people/year
i	Index for type of crop	
j	Index for type of tree	
n	Index for type of livestock	
m	Index for type of waterfowl	
u	Index for type of industry	
s	Index for type of aquatic animal	

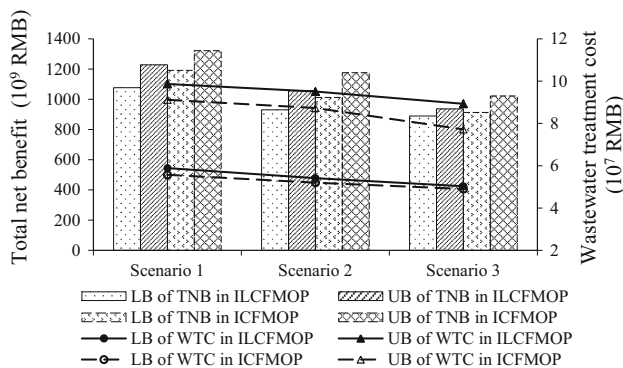


Fig. 1 Solutions for total net benefit and wastewater treatment cost for the three periods in different scenarios (*LB* and *UB* represent lower and upper bounds)

Accordingly, the degrees of satisfaction (λ_{opt}^{\pm}) for the three scenarios are obtained, which are [0.48, 0.90], [0.42, 0.90] and [0.39, 0.86], respectively. The λ_{opt}^{\pm} level depends on the decision makers' preference to economic and environmental tradeoffs. For example, in scenario 1, $\lambda_{opt}^{-} = 0.48$ corresponds to the lower total system benefit ($f_{opt}^{-} = 10.77 \times 10^9$ RMB), which represents a lowest

degree of satisfaction under demanding conditions. By contrast, $\lambda_{opt}^{+} = 0.90$ corresponds to a higher total system benefit ($f_{opt}^{+} = 12.28 \times 10^9$ RMB), representing a highest degree of satisfaction under beneficial conditions. Therefore, the solution of λ_{opt}^{\pm} represents the degree of satisfying the system objective/constraints would decrease in Scenarios 1 to 3.

Similarly, water resource demand would also decline as p_i decreases, corresponding to $[42.69, 53.21] \times 10^7$ m³, $[40.08, 50.20] \times 10^7$ m³, $[38.27, 47.09] \times 10^7$ m³ when p_i equals 0.1, 0.05 and 0.01 (Fig. 2). Figure 3 presents the minimized discharge of COD, nitrogen, phosphorous and SL. For example, the lowest discharge of COD would be $[26.88, 35.69] \times 10^7$ kg in scenario 3 ($p_i = 0.01$), and the highest discharge would be $[35.58, 46.89] \times 10^7$ kg in scenario 1 ($p_i = 0.1$), which show an obvious downtrend from scenarios 1 to 3. Nitrogen, phosphorous and SL follow the similar trends to COD. Overall, the above results demonstrate that, in the ILCFMOP model, decisions at a lower p_i level lead to lower system net benefit, but the risk of constraints violation would be decreased, and the environmental objective would be more satisfied. In comparison, decisions at a higher p_i level would increase the risk

of environmental system, but the system net benefit would be higher.

In Figs. 1, 2, and 3, the optimal result obtained by the comparison model (ICFMOP) is also included. In comparison, the ICFMOP model has higher net system benefit than the ILCFMOP model among all the scenarios. This is because the left-hand-side random parameters are replaced by interval numbers, which makes the decision domain of ICFMOP more relaxed. However, discharges of COD, nitrogen, phosphorous and SL in the ICFMOP are higher than those in the ILCFMOP. Thus, the ILCFMOP model can reduce the pollutant discharges more effectively under the demanding conditions.

Figure 4 presents the solutions for agricultural and forest areas through the ILCFMOP model under different p_i levels in the three periods. It is indicated that both

agricultural and forest areas had tendencies to increase from periods 1 to 3 in each scenario but obvious downtrends from scenarios 1 to 3. For example, in period 1, agricultural area would be [43.58, 47.34], [41.49, 45.94] and [37.17, 43.73] km² in scenarios 1–3. The decreasing trend demonstrated that agricultural areas should be limited as the risk of constraints violation decreased, since agricultural activities are the most significant factor causing non-point source pollution. On the other side, taking scenario 1 as an example, agricultural area showed an increasing trend from periods 1 to 3 ([43.58, 47.34], [45.26, 50.51] and [46.86, 56.03] km² for periods 1–3). Scenarios 2 and 3 had the same tendency as scenario 1, which indicated that, although resulting in non-point pollutions, agricultural activities were unavoidable for regional population growth and economic development. The forest areas had a similar variation trend to the agricultural areas. Their difference is

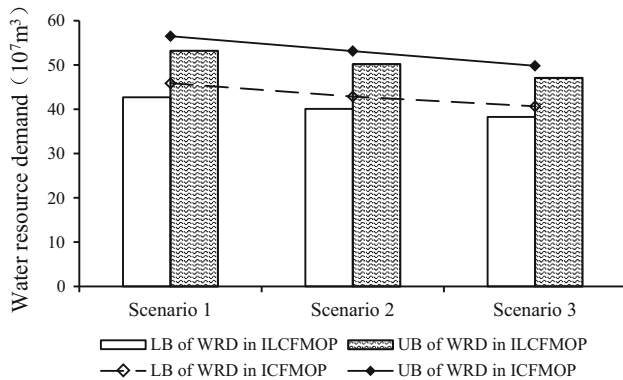


Fig. 2 Solutions for water resource demand for the three periods in different scenarios

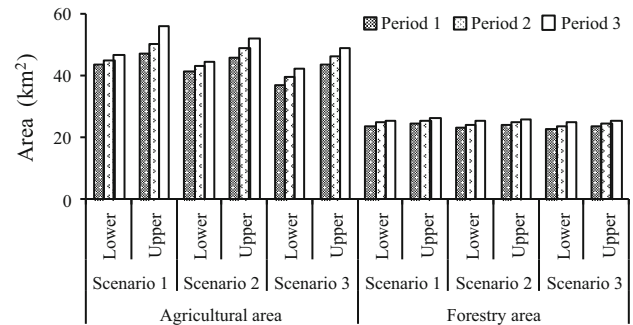
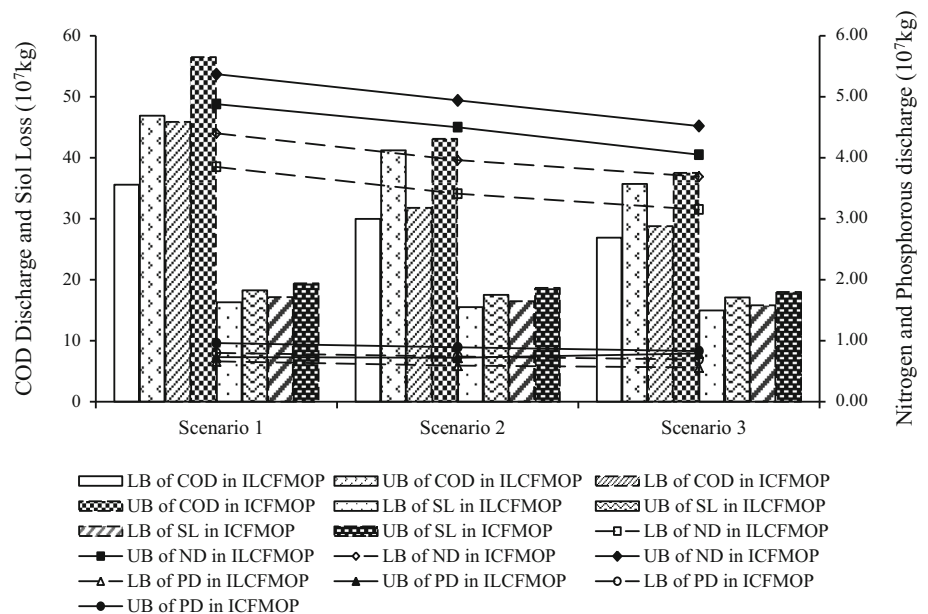


Fig. 4 Solutions for agricultural and forest areas for the three periods in different scenarios

Fig. 3 Solutions for COD, nitrogen and phosphorous discharges (ND and PD) and soil loss (SL) for the three periods in different scenarios



that the forest areas decreased less in different scenarios due to its prominent function of water conservation and ecological service.

Figure 5 presents the aquacultural areas and industrial scale in different scenarios for the three periods. Aquacultural areas showed a downtrend from periods 1 to 3. Taking scenario 2 as an example, aquacultural areas would be [6.89, 7.59], [6.57, 7.39] and [6.01, 6.79] km² from periods 1 to 3. The variations in other scenarios had similar tendencies. In period 1, aquacultural areas would be [7.93, 8.39], [6.89, 7.59] and [6.55, 6.58] km² in scenarios 1 to 3. On the contrary, the industry scale had an uptrend from periods 1 to 3. For instance, industry scale in scenario 2 are [7.01, 8.09], [7.66, 9.29] and [10.30, 11.02] × 10⁸ RMB, respectively. The variations of industry scale in other scenarios had similar tendencies. The aquacultural areas would decline as the levels of violating probabilities decreased over the whole planning period, which demonstrated that its vital function on water pollution is unfavorable. Conversely, industry scale would grow steadily from periods 1 to 3 in each scenario because of its high contribution on economic benefit, but decrease from scenarios 1 to 3 for satisfying environment protection objectives.

Figure 6 shows the optimal solution of land-livestock and waterfowl numbers in the three scenarios during the whole planning period. For example, the land-livestock

number would display an evident uptrend from periods 1 to 3 ([26.78, 28.90], [32.83, 35.09] and [34.49, 36.73] × 10³) in scenario 3. The increasing trend in the whole period indicated that land-livestock feeding would have a significant contribution to the system benefit on account of its high income. In comparison, the decreasing tendency from scenarios 1 to 3 demonstrates the number would also be limited to environmental protection objectives (e.g. water quality objective, water resources demand objective). The waterfowl number would have similar variation tendencies to the land-livestock number.

Figure 7 shows the tourism flow and resident number in the study area. For the tourism flow, there would be an increasing trend in the whole period, especially from periods 1 to 2. Meanwhile, for satisfying the environmental protection constraints, the tourism flow declined as the risk of constraint violation decreases from scenarios 1 to 3. The resident number would be relatively stable than all the other variables for maintaining regional stability. The figure shows that the tourism flow due to its high income would be two or three times the resident number. This indicated that tourism would also be a vital industry in the wetland and had a significant contribution to the regional economic development.

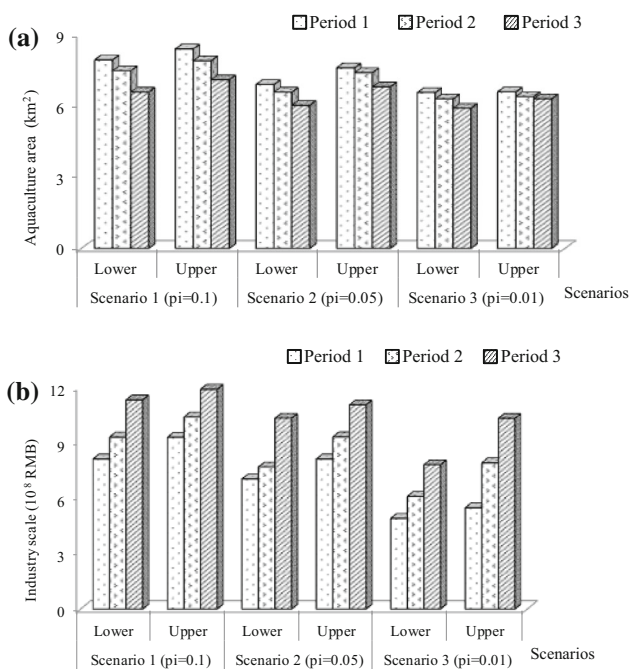


Fig. 5 Aquacultural areas and industrial scale for the three periods in different scenarios

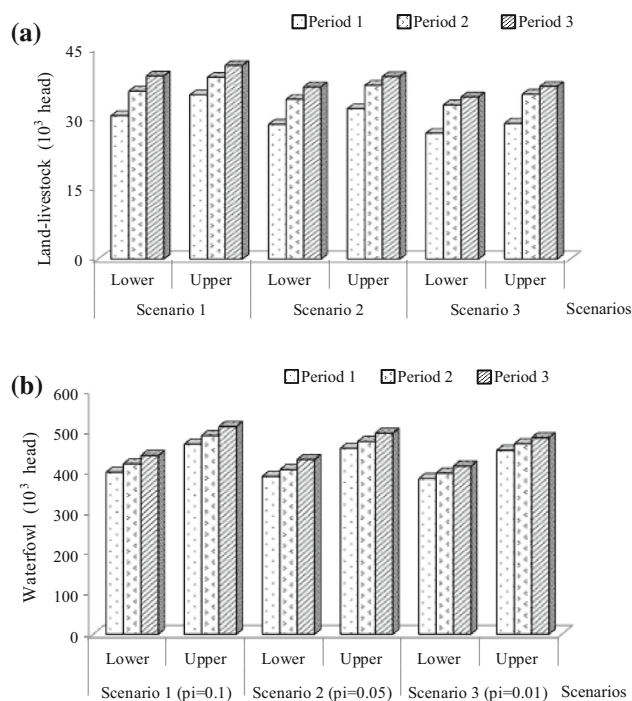


Fig. 6 Numbers of land-livestock and waterfowl for the three periods in different scenarios

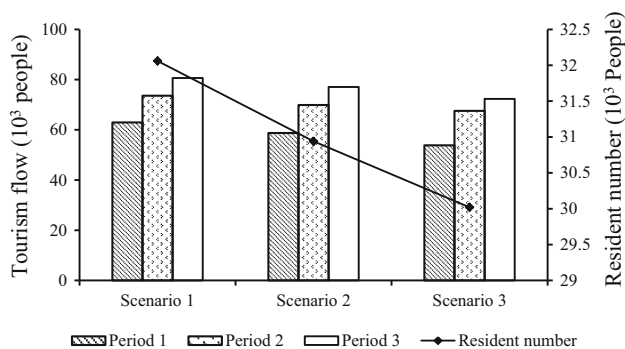


Fig. 7 Tourism flow and resident number for the three sub-areas in different scenarios

5 Discussion

The ILCFMOP model integrates interval programming, left-hand-side chance-constrained programming, and fuzzy multi-objective programming within a general wetland water quality management framework. It can reflect uncertainties presented as fuzziness (aspiration level of objectives), random variables (pollutant release limitation) in the left-hand-side constraints, and interval parameters (e.g. water resources, and WTCs). Also, it can deal with both multiple uncertainties and tradeoff among multiple objectives simultaneously. Meanwhile, compared with the ICFMOP, the optimization scheme by the ILCFMOP would reduce pollutant discharges (e.g. COD, nitrogen, and phosphorous). However, the TNB of ILCFMOP would be higher than that of ICFMOP, since its demanding constraint on pollutant discharge may result in higher cost in environmental protection.

In addition, some limitations still exist in the ILCFMOP. For example, λ is kept the same for every sub-objective in scenarios, which means that individual adjustment is not reflected for different sub-objectives. Moreover, due to data availability, random variables may appear in both sides of constraints while parameters may have dual uncertainties (e.g., random-boundary intervals). In the future, adjustable λ s for different sub-objectives can be further quantified. Besides, the ILCFMOP model can be upgraded to a double-sided chance-constrained model.

6 Conclusions

An ILCFMOP method has been proposed and applied to water quality management in a wetland system under dual uncertainties. The most outstanding advantage of ILCFMOP model is able to reflect uncertainties presented as randomness in left hand side of the decision variables (pollutant release limitation), fuzziness (aspiration level of objectives),

and interval parameters (e.g. water resources, and WTCs) in a multiple objectives model. The innovativeness of the model is to introduce inexact left-hand-side chance-constrained programming (ILCCP) into interval fuzzy multi-objective programming (IFMOP), so the applicability of the traditional IFMOP to more complex condition can be improved. Taking this study as an example, pollutant release limitation is a left-hand-side random parameter, which can hardly be presented and solved by the traditional IFMOP method. In this case, the ILCFMOP shows its superiority by enhancing the model's capability in qualifying left-hand-side random variables.

A water quality management problem in a wetland system has been solved by the proposed ILCFMOP model in this study, which can deal with the water pollution control problem by allocating the resources properly. It can analyze the tradeoffs among multiple objectives of TNB, water resource utilization and water pollution control. A representative water pollution control case study in a wetland system is employed for demonstration. The case shows that the significant advantage of ILCFMOP is to represent and qualify multiple uncertainties in water quality management, including randomness in the left-hand side of constraints (pollutant release limitation), fuzziness (aspiration level of objectives), and interval parameters (e.g. water resources, and WTCs).

The optimal solutions indicated that, most of the objectives (e.g. TNB, water resource demand, COD discharge, and SL) would decrease with increasing probability levels from scenarios 1 to 3, since a higher constraint satisfaction probability would lead to stricter decision scopes. Accordingly, the strictness of the constraints would cause a declining tendency of the optimal scheme from scenarios 1 to 3 (e.g. agricultural areas, aquacultural areas, industry scale, land-livestock numbers). This study is the first application of the ILCFMOP model to water quality management in a wetland system, which can be extended to handling other environmental issues with uncertainties.

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