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Interval-parameter chance-constrained fuzzy multi-objective programming for water pollution control with sustainable wetland management

Y. Liu[a],, Y.P. Cai[b,c*], G.H. Huang[a*], C. Dong[a]

[a] MOE Key Laboratory of Regional Energy Systems Optimization, Sino-Canada Energy and Environmental Research Academy, North China Electric Power University, Beijing 102206, China
[b] CSEE, University of Regina, Regina Sask, S4S 4H4, Canada
[c] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing, 100875, China

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Abstract

Water pollution control plays a significant role in the water quality management of wetland ecosystems. In this study, an interval-parameter chance-constrained fuzzy multi-objective programming (ICFMOP) model for assisting water pollution control within a sustainable wetland management system under uncertainty was developed. The proposed ICFMOP approach not only effectively handled the uncertainties and complexities in the water pollution control management systems, it also allowed decision makers to adjust the fuzzy objective control decision variable to satisfy multiple holistic and interactive objectives. The ICFMOP model developed was then applied to a wetland water pollution control case study to assist the planning of regional wetland eco-environmental sustainability. Interval solutions of the compromise decision alternatives associated with different risk levels of constraint violations were obtained. The results were helpful for decision makers to identify desirable strategies under various social-economic, environmental and system-reliability constraints with the highest system benefits and the lowest water pollutant discharge and eco-environment impact. Moreover, tradeoffs between the multiple objectives and the constraint-violation risks could be evaluated.

Keywords: water quality management; wetland system; optimization; multi-objective, uncerainty

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* Corresponding author. *E-mail address*: yanpeng.cai@iseis.org
Tel.:+86-10-61772981; fax: +86-10-61772982 *E-mail address*: huang@iseis.org

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1. Introduction

Water pollution has been identified as a major contributing factor to the degradation and contamination of wetland ecosystems [1]. Agricultural, industrial and other human activities not only have a high demand on water resources, they also discharge large volumes of agricultural polluted-runoff, industrial wastewater and municipal sewage into the aquatic environment of wetland ecosystem causing eutrophication and water contamination [2]. It has been estimated that more than 52 % of the major lakes in China are undergoing severe eutrophication subject to the excess discharges of nitrogen and phosphorus pollution from municipal sewage [3]. The implementation of water pollution management for wetland systems is therefore necessary and imperative.

Nomenclature

$AX_{ik}^{\pm}$	area of agricultural land cultivated with crop *i* in period *k* (km^2/year)
$FX_{jk}^{\pm}$	area of forestry land planted with tree *j* in period *k* (km^2/year)
$SX_{nk}^{\pm}$	number of livestock *n* raised in the system during period *k* (head/year)
$PX_{mk}^{\pm}$	number of waterfowl *m* raised in the system during period *k* (head/year)
$FIX_{sk}^{\pm}$	area of aquaculture farmed with aquatic animal *s* in period *k* (km^2/year)
$IX_{uk}^{\pm}$	industrial production with industry type *u* in period *k* (RMB/year)
$TUX_{k}^{\pm}$	tourism flow in the system during period *k* (people/year)
$PPX_{k}^{\pm}$	number of residents in the system during period *k*(people/year)
$ACB_{ik}^{\pm}$	net benefit from agricultural cultivation of crop *i* in period *k* (RMB/km^2)
$FCB_{jk}^{\pm}$	net benefit from forestry planted with tree *j* in period *k* (RMB/km^2)
$SCB_{nk}^{\pm}$	net benefit from raised livestock *n* in period *k* (RMB/head)
$PCB_{mk}^{\pm}$	net benefit from raised waterfowl *m* in period *k* (RMB/head)
$FIB_{sk}^{\pm}$	net benefit from aquaculture farmed with aquatic animal *s* in period *k* (RMB/km^2)
$TCB_{k}^{\pm}$	net benefit from tourism in period *k* (RMB/people)
$IWW_{u}^{\pm}$	wastewater generated from industrial production with industry type *u* (m^3/RMB)

$IWC_{uk}^{\pm}$	treatment cost for wastewater generated from industrial production with industry type u in period k (RMB/m^3)
$TPW^{\pm}$	municipal wastewater generated by human activities (m^3/people)
$PWC_{k}^{\pm}$	treatment cost for municipal wastewater generated by human activities in period k (RMB/m^3)
$AWM_{ik}^{\pm}$	water demand for agricultural land cultivated with crop i in period k (m^3/km^2)
$FWM_{jk}^{\pm}$	water demand for forestry land planted with tree j in period k (m^3/km^2)
$SWM_{nk}^{\pm}$	water demand for livestock n raised in period k (m^3/km^2)
$PWM_{mk}^{\pm}$	water demand for raised waterfowl m in period k (m^3/head)
$FIM_{sk}^{\pm}$	water demand for aquaculture farmed with aquatic animal s in period k (m^3/km^2)
$IWM_{uk}^{\pm}$	water demand for industrial production with industry type u during period k (m^3/RMB)
$TPM_{k}^{\pm}$	water demands for tourists and residents in period k (m^3/people)
$ASL_{ik}^{\pm}$	soil lose from agricultural land cultivated with crop i in period k (kg/km^2)
$FSL_{jk}^{\pm}$	soil lose from forestry land planted with tree j in period k (kg/km^2)
$SOD_{k}^{\pm}$	COD content of soil in period k (%)
$SCO_{nk}^{\pm}$	amount of COD generated by livestock n in period k (kg/head)
$PCO_{mk}^{\pm}$	amount of COD generated by waterfowl m in period k (kg/head)
$FCO_{sk}^{\pm}$	amount of COD generated by aquatic animal s in period k (kg/km^2)
$ICO_{uk}^{\pm}$	amount of COD generated from industrial production with industry type u in period k (kg/km^2)
$TCO_{k}^{\pm}$	amount of COD generated from human activities (kg/people)
$SN_{k}^{\pm}$	nitrogen content of soil in period k (%)
$AGN_{ik}^{\pm}$	amount of nitrogen generated from agricultural activities with crop i in period k (kg/ km^2)

$SLN_{nk}^{\pm}$	amount of nitrogen generated by livestock n in period k (kg/head)
$PWN_{mk}^{\pm}$	amount of nitrogen generated by waterfowl m in period k (kg/head)
$FIN_{sk}^{\pm}$	amount of nitrogen generated by aquatic animal s in period k (kg/km^2)
$IDN_{uk}^{\pm}$	amount of nitrogen generated from industrial production with industry type u in period k (kg/km^2)
$TPN_{k}^{\pm}$	amount of nitrogen generated from human activities (kg/people)
$SP_{k}^{\pm}$	phosphorus content of soil in period k (%)
$AGP_{ik}^{\pm}$	amount of phosphorus generated by agricultural activities with crop i in period k (kg/ km^2)
$SLP_{nk}^{\pm}$	amount of phosphorus generated by livestock n in period k (kg/head)
$PWP_{mk}^{\pm}$	amount of phosphorus generated by waterfowl m in period k (kg/head)
$FIP_{sk}^{\pm}$	amount of phosphorus generated by aquatic animal s in period k (kg/km^2)
$IDP_{uk}^{\pm}$	amount of phosphorus generated from industrial production with industry type u in period k (kg/km^2)
$TPP_{k}^{\pm}$	amount of phosphorus generated from human activities (kg/people)
$EWD_{k}^{\pm}$	water demand for ecological protection in period k (m^3/head)
$TW_{k}^{(p_i)}$	amount of water resources available with a probability level of p_i in period k (m^3)
$TLA_{k}^{\pm}$	available area of land for agriculture and forestry during period k (km^2)
$TWA_{k}^{\pm}$	available area of water for aquaculture during period k (km^2)
α_k	average treatment efficiency for COD in period k (%)
β_k	average treatment efficiency for nitrogen in period k (%)
θ_k	average treatment efficiency for phosphorus in period k (%)
$TOD_{k}^{\pm}$	maximum allowable amount of COD in the system during period k (kg)
$TN_{k}^{\pm}$	maximum allowable amount of nitrogen in the system during period k (kg)

$TP_k^{\pm}$	maximum allowable amount of phosphorus in the system during period *k* (kg)
$TWM_k^{\pm}$	maximum capacity of wastewater treatment facilities in period *k* (m^3)
$TSL_k^{\pm}$	maximum allowable soil erosion in the system during period *k* (kg)
$FR_k^{\pm}$	minimum allowance of forest cover in period *k* (%)
$TU^{\pm}$	initial tourism flow in the system during period *k* (people/year)
$TU_k^{\pm}$	maximum allowable tourism flow in the system during period *k* (people)
$TIP_k^{\pm}$	initial number of residents in the system during period *k* (people)
$TIA_k^{\pm}$	minimum area of agricultural land required in period *k* (km^2)
$TLS_k^{\pm}$	minimum number of livestock required in period *k* (head)
$TIS_k^{\pm}$	minimum level of industry required during period *k* (RMB)
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

Note: '±' denotes a set of interval numbers.

In the past decades a number of optimization programming techniques were proposed for water pollution management. For instance, Zhao et al. proposed a plant-level aggregation method to estimate the spatial distribution of regional industrial development and its water pollution emissions [4]. Ham et al. proposed an integrated modelling approach for planning the size and the operation of constructed wetlands to maximize the retention of nonpoint source pollutant loads and the improvement of reservoir water-quality at a catchment scale [5]. Schaffner et al. studied the origins and flow paths of the various point- and non-point pollution sources in the Thachin River Basin (in terms of nitrogen and phosphorus) and quantified their relative importance within the system [6]. Spanou and Chen developed an object-oriented approach for the analysis of point-source pollution control in river basins [7]. Sakai et al discussed the characteristics and application of a multichannel electrode type sensor for detecting water quality and preventing water pollution [8]. Wang et al developed a one-dimensional water quantity and quality model for rivers, and a two-dimensional model for lakes to simulate the hydrodynamic and pollutant transport processes [9]. Cheng et al presented an expert system (ES) to assist the department of environment management team in their efforts to improve municipal water quality [10]. Zhang and Huang proposed a spatial multi-criteria method to evaluate the nitrogen loss potential from river sub-basin and the water quality classification of rivers [11]. Greiner et al developed a multi-criteria based tool for assessing the relative impact of diffuse-source pollution on the Great Barrier Reef (GBR) from the river basins draining into the GBR lagoon [12]. And Unami and Kawachi presented a universal optimization scheme to determine a management strategy for controlling water quality in a generic body of water [13].

Although these studies effectively addressed the problems of water pollution control, most of them hardly reflected the links between the external factors and internal processes of pollution management of wetlands, which are huge and complicated systems that include many subsystems [14]. Wetlands not only could offer a variety of ecosystem functions, but also provide ecosystem services that support human livelihood both directly and indirectly [15]. Thus, the management of water pollution for wetland systems should take into account multiple processes and objectives with complex and dynamic interrelationships. Many objectives need be simultaneously achieved, such as water quality improvement, water resource utilization and net benefit maximization. Meanwhile, the problems with wetland pollution control would be further complicated by the uncertainties and complexities deriving from data availability, modelling simulation and results computation in the system [16-24]. Under this situation, deterministic data are hardly obtained; uncertainties expressed as intervals and probability distributions may exist [25-29]. For instance, the available water resource, which is affected by extreme weather, climatic disasters, drought/wet summers *etc*., can be presented as a probability distribution. Conversely for most of the socio-economic factors and system conditions, it is impractical to acquire their probability density functions (PDFs), and in contrast they can be expressed as intervals [30].

Therefore, the objective of this study is to develop an interval-parameter chance-constrained fuzzy multi-objective programming (ICFMOP) model to couple water quality improvement with sustainable wetland development in an inexact water pollution management system. In detail, this research attempts to (a) handle and achieve competitive and interactive multi-objectives with total net benefit water pollution control and water resource utilization, (b) identify optimal schemes for agricultural and industrial practices and other human activities (e.g., agricultural area, livestock number and tourism flow) while minimizing the corresponding environmental impacts, (c) produce a number of decision alternatives under uncertain conditions, that allow a comprehensive analysis of tradeoffs among multiple objectives that might be in conflict with each other and (d) facilitate the reflection of multiple forms of uncertainties incorporated in systems in terms of PDFs and interval values.

2. Formulation of the ICFMOP model

First, a multi-objective programming model (MOP) can be formulated as follows [31]:

$$\min\ f_k = C_k X\ ,\ k = 1, 2, \ldots, p, \tag{1a}$$

$$\max\ f_l = C_l X\ ,\ l = p+1, p+2, \ldots, q, \tag{1b}$$

$$s.t.\ A_i X \le b_i\ ,\ i = 1, 2, \ldots, m, \tag{1c}$$

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

Where $X \in \boldsymbol{R}^{t\times 1}$, $C_k \in \boldsymbol{R}^{1\times t}$, $C_l \in \boldsymbol{R}^{1\times t}$, $A_i \in \boldsymbol{R}^{1\times t}$, and $\boldsymbol{R}$ denote a set of real numbers. In model (1), all the parameters are known as deterministic numbers. However, when the uncertainties for some parameters on the right-hand side of the constraints are expressed as probabilities, chance-constrained programming (CCP) can be incorporated to deal with them. The models can then be solved by the CCP approach to convert them into a deterministic version by: (i) fixing a certain level of probability $p_i \in [0, 1]$ for each constraint i, and (ii) imposing the condition that the constraint i is satisfied by at least a probability of $1 - p_i$. Then the feasible solution set is subject to the following constraints [32]:

$$\Pr\,[A_i X \le b_i] \ge 1 - p_i,\; i = 1, 2, \ldots, n, \tag{2}$$

Constraint (2) is generally nonlinear, and the set of feasible constraints is convex for some particular cases, one of which is when the left-hand side coefficients A_i are deterministic, and the right-hand side ones of constraints b_i are random. This leads to an equivalent linear constraint that has the same size and structure as a deterministic term, and the only required information about the uncertainty is then p_i for the unconditional distribution of b_i. Thus, constraint (2) becomes linear [33]:

$$A_i X \le b_i^{(p_i)},\; \forall i,\; i = 1, 2, \ldots, n, \tag{3}$$

Where $b_i^{(p_i)} = F_i^{-1}(p_i)$, was given the cumulative distribution function of b_i (i.e., $F_i\ (b_i)$), and the probability of violating constraint i (p_i). Moreover, due to the uncertain features and inaccurate information, multiple parameters are known as intervals without distribution information and difficulties may appear with modeling such a system by a deterministic mathematical programming method, which would cripple the model formulating effort leading to no results. In order to address the uncertainties of the above intervals and/or probability density functions (PDFs), ILP and CCP methods are integrated into the MOP model. Model (1) can be converted to:

$$\min\; f_k^{\pm} = C_k^{\pm} X^{\pm},\; k = 1, 2, \ldots, p, \tag{4a}$$

$$\max\; f_l^{\pm} = C_l^{\pm} X^{\pm},\; l = p+1, p+2, \ldots, q, \tag{4b}$$

$$s.t.\; A_i^{\pm} X^{\pm} \le b_i^{(p_i)},\; i = 1, 2, \ldots, n, \tag{4c}$$

$$A_i^{\pm} X^{\pm} \le b_i^{\pm},\; i = n+1, n+2, \ldots, m, \tag{4d}$$

$$X^{\pm} \ge 0, \tag{4e}$$

Where $X^{\pm} \in \{\boldsymbol{R}^{\pm}\}^{t \times 1}$, $C_k^{\pm} \in \{\boldsymbol{R}^{\pm}\}^{1 \times t}$, $C_l^{\pm} \in \{\boldsymbol{R}^{\pm}\}^{1 \times t}$, $A_i^{\pm} \in \{\boldsymbol{R}^{\pm}\}^{1 \times t}$, and $\boldsymbol{R}^{\pm}$ denote a set of interval numbers. On the basis of the principle of fuzzy flexible programming [34], the parameters and/or interrelationships, the flexibility in the constraints and fuzziness in the system objective can all be assigned membership functions and represented by fuzzy sets. ‘Fuzzy constraints’ and a ‘fuzzy goal’ can then be established by specifying an ‘aspiration level’ and ‘inferior limit’ for each objective function and constraint. By incorporating the $\lambda^{\pm}$ value corresponding to the membership grade of satisfaction for the fuzzy of the constraints/objective into the MOP model the interval-parameter chance-constrained fuzzy multi-objective programming model (ICFMOP) can be reformulated as follows:

$$\max\; \lambda^{\pm} \tag{5a}$$

$$s.t.\; f_k^{\pm}(X^{\pm}) \le f_{kg}^{+} - \lambda^{\pm}(f_{kg}^{+} - f_{kg}^{-}),\; k = 1, 2, \ldots, p, \tag{5b}$$

$$f_l^{\pm}(X^{\pm}) \le f_{lg}^{+} - \lambda^{\pm}(f_{lg}^{+} - f_{lg}^{-}),\; l = p+1, p+2, \ldots, q, \tag{5c}$$

$$A_i^{\pm} X^{\pm} \le b_i^{(p_i)},\; i = 1, 2, \ldots, n, \tag{5d}$$

$$A_i^{\pm} X^{\pm} \le b_i^+ - \lambda^{\pm}(b_i^+ - b_i^-),\ i = n+1, n+2, \ldots, m, \tag{5e}$$

$$X^{\pm} \ge 0, \tag{5f}$$

$$0 \le \lambda^{\pm} \le 1, \tag{5g}$$

$\lambda^{\pm}$ is the control decision variable corresponding to the degree (membership grade) to which $X^{\pm}$ solutions fulfill the fuzzy objective or constraints. f_g^+ and f_g^- are the lower and upper bounds respectively of the objective's aspiration level as designated by the decision makers. According to Huang et al.[35], this ICFMOP model can be transformed into two deterministic sub-models, corresponding to the upper and lower bounds for the desired objective function value.

$$\max \lambda^+ \tag{6a}$$

$$s.t.\ \sum_{j=1}^{k_1} c_{kj}^- x_j^- + \sum_{j=k_1+1}^{n} c_{kj}^- x_j^+ \le f_{kg}^+ - \lambda^+(f_{kg}^+ - f_{kg}^-),\ k = 1, 2, \ldots, p, \tag{6b}$$

$$\sum_{j=1}^{k_1} c_{lj}^- x_j^- + \sum_{j=k_1+1}^{n} c_{lj}^+ x_j^+ \ge f_{lg}^- + \lambda^+(f_{lg}^+ - f_{lg}^-),\ l = p+1, p+2, \ldots, q, \tag{6c}$$

$$\sum_{j=1}^{k_1} \left|a_{ij}\right|^+ Sign(a_{ij}^+) x_j^- + \sum_{j=k_1+1}^{n} \left|a_{ij}\right|^- Sign(a_{ij}^-) x_j^+ \le b_i^{(p_i)},\ \forall i,\ i = 1, 2, \ldots, n, \tag{6d}$$

$$\sum_{j=1}^{k_1} \left|a_{ij}\right|^+ Sign(a_{ij}^+) x_j^- + \sum_{j=k_1+1}^{n} \left|a_{ij}\right|^- Sign(a_{ij}^-) x_j^+ \le b_i^+ - \lambda^+(b_i^+ - b_i^-),\ \forall i,\ i = n+1, n+2, \ldots, m, \tag{6e}$$

$$x_j^- \ge 0,\ j = 1, 2, ..., k_1, \tag{6f}$$

$$x_j^+ \ge 0,\ j = k_1+1, k_1+2, ..., n, \tag{6g}$$

$$0 \le \lambda^+ \le 1, \tag{6h}$$

and:

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

$$s.t.\ \sum_{j=1}^{k_1} c_{kj}^+ x_j^+ + \sum_{j=k_1+1}^{n} c_{kj}^+ x_j^- \le f_{kg}^+ - \lambda^+(f_{kg}^+ - f_{kg}^-),\ k = 1, 2, \ldots, p, \tag{7b}$$

$$\sum_{j=1}^{k_1} c_{lj}^+ x_j^+ + \sum_{j=k_1+1}^{n} c_{lj}^- x_j^- \ge f_{lg}^- + \lambda^-(f_{lg}^+ - f_{lg}^-),\ l = p+1, p+2, \ldots, q, \tag{7c}$$

$$\sum_{j=1}^{k_1} \left|a_{ij}\right|^- Sign(a_{ij}^-) x_j^+ + \sum_{j=k_1+1}^{n} \left|a_{ij}\right|^+ Sign(a_{ij}^+) x_j^- \le b_i^{(p_i)},\ \forall i,\ i = 1, 2, \ldots, n, \tag{7d}$$

$$\sum_{j=1}^{k_1} \left|a_{ij}\right|^- Sign(a_{ij}^-) x_j^+ + \sum_{j=k_1+1}^{n} \left|a_{ij}\right|^+ Sign(a_{ij}^+) x_j^- \le b_i^+ - \lambda^-(b_i^+ - b_i^-),\ \forall i,\ i = n+1, n+2, \ldots, m, \tag{7e}$$

$$x_j^+ \ge x_{jopt}^- \ge 0,\ j = 1, 2, ..., k_1, \tag{7f}$$

$$0 \le x_j^- \le x_{jopt}^+,\ j = k_1+1, k_1+2, ..., n, \tag{7g}$$

$$0 \le \lambda^- \le 1, \tag{7h}$$

For h interval parameters $c_j^{\pm}(j=1,2,\ldots,h,)$ in this objective function, assume that the former k_1 coefficients are positive, i.e. $c_j^{\pm}(j=1,2,\ldots,k_1,)$, and the latter k_1 coefficients are negative, i.e., $c_j^{\pm}(j=k_1+1,k_1+2,\ldots,h,)$, where $k_1+k_2=h$). By solving the two sub-models (6) and (7), interval solutions for all the decision variables $x_{jopt}^{\pm}=[x_{jopt}^{-},\ x_{jopt}^{+}]$ $(x_j^{\pm}\in X^{\pm})$ can be obtained, while the multiple objective functions ($f_{kopt}^{\pm}=[f_{kopt}^{-},\ f_{kopt}^{+}]$ and $f_{lopt}^{\pm}=[f_{lopt}^{-},\ f_{lopt}^{+}]$) can be generated through the range of $x_{jopt}^{\pm}$ using model (4).

3. Application to water pollution management in a wetland system

3.1. Overview of the study system

Wetland is a huge and complicated natural ecosystem. It functions as the “kidneys” of the earth, providing ecological and environmental services and playing an important role in maintaining regional ecological balance and protecting biological diversity. Wetlands also directly and indirectly support people by providing ecosystem services such as flood abatement, carbon sinks, food, clean water supply, esthetic beauty and educational and recreational benefits [36]. A great number of economic, social and ecological sectors and processes associated with environmental concerns are included in this system. Among them, the deterioration of water quality is considered the primary concern regarding the degradation of wetland ecosystems [37]. Several human-induced activities, such as agricultural/industrial production, livestock husbandry, aquaculture, tree plantations, soil erosion as well as tourism, have contributed to the pollution of water. Therefore issues of biodiversity, water supply and demand, wastewater treatment, pollutant discharge limitation, agricultural/industrial development and tourism activities need to be incorporated into any study system. Multiple holistic and interactive objectives, such as environmental, economic and resource-conservation need to be satisfied [38]. Meanwhile, due to the complexities and uncertainties of the system most coefficients of cost and benefit are vogue and can only be expressed as interval numbers (Table 2). In addition, the availability of water resources in wet and dry seasons are random in nature, and the distribution information of which is given in Table 1 The aims of this study were thus to focus on water resources shortage and water pollution control for sustainable management of wetlands, and to identify optimal schemes for land and water use, crop cultivation, forest plantation, livestock rearing and industrial and tourism development under the given economic, environmental, social and technical restrictions. Moreover, the study system was subject to a variety of uncertainties in terms of interval numbers and probability distributions. The ICFMOP approach is considered appropriate for addressing this planning problem.

Table 1. Distribution information of available water resources and water quality requirements

Parameters	Period		
	$k = 1$	$k = 2$	$k = 3$
Maximum available water resource (10^7 m^3)			
$p_i = 0.01$	[4.60, 5.33]	[5.03, 5.87]	[5.42, 6.35]
$p_i = 0.05$	[4.94, 5.70]	[5.23, 6.19]	[5.62, 6.74]
$p_i = 0.1$	[5.27, 6.16]	[5.64, 6.58]	[5.87, 7.03]
Maximum allowable COD discharge (10^7 kg)			
	[62, 64]	[66, 68]	[70, 72]
Maximum allowable nitrogen discharge (10^5 kg)			
$k = 3$	[56, 58]	[61, 63]	[65, 67]
Maximum allowable phosphorus discharge (10^5 kg)			
	[12, 14]	[13, 15]	[14, 16]
Maximum allowable soil loss (10^7 kg)			
	[1.90, 2.10]	[2.05, 2.25]	[2.20, 2.35]

Table 2. System parameters of net benefit, water demand and nitrogen discharge

	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 m^3/km^2	[7.50, 7.55]	10^3 kg/km^2	[31.32, 31.48]
Forestry activities	10^4 RMB/km^2	[10, 13]	m^3/km^2	[190, 210]		
Livestock rearing	RMB/head	[480, 520]	m^3/head	[3.6, 3.9]	kg/head	[15, 17]
Poultry raising	RMB/head	[3, 5]	m^3/head	[0.15, 0.21]	kg/head	[0.31, 0.37]
Fish farming	10^6 RMB/km^2	[2.80, 2.85]	10^3 m^3/km^2	[50, 53]	10^3 kg/km^2	[60, 63]
Industrial production			m^3/RMB	[0.011, 0.013]	10^{-3} kg/RMB	[0.18, 0.21]]
Tourism flow	RMB/people	[730, 745]	m^3/people	[1.8, 2.2]	kg/people	[0.06, 0.07]
Residential population			m^3/people	[102, 116]	kg/people	[0.23, 0.34]

3.2. Modelling formulation

Based on a detailed analysis of the study system, four major sets of objectives were considered when modeling this system to achieve the following aims: (i) the highest total net benefit, (ii) the lowest wastewater treatment cost, (iii) the lowest water resources demand and (iv) the lowest water pollutant discharge into the wetland system. The water quality objective consisted of four sub-objectives to minimize the chemical oxygen demand (COD), nitrogen, phosphorous and soil loss. Thirteen sets of constraints were included relating to water resource balance, land area balance, forest cover balance, water mass balance, and pollutant release limits *etc*. Non-negativity and technical constraints were also included. In detail, the objective functions and constraints were formulated as follows:

Objectives:

(a) total net benefit objective

$$Max\ \ f_1=\sum_{i=1}^{I}\sum_{k=1}^{K}AX_{ik}^{\pm}*ACB_{ik}^{\pm}*\Delta L_k+\sum_{j=1}^{J}\sum_{k=1}^{K}FX_{jk}^{\pm}*FCB_{jk}^{\pm}*\Delta L_k$$
$$+\sum_{n=1}^{N}\sum_{k=1}^{K}SX_{nk}^{\pm}*SCB_{nk}^{\pm}*\Delta L_k+\sum_{m=1}^{M}\sum_{k=1}^{K}PX_{mk}^{\pm}*PCB_{mk}^{\pm}*\Delta L_k$$
$$+\sum_{s=1}^{S}\sum_{k=1}^{K}FIX_{sk}^{\pm}*FIB_{sk}^{\pm}*\Delta L_k+\sum_{u=1}^{U}\sum_{k=1}^{K}IX_{uk}^{\pm}*\Delta L_k+\sum_{k=1}^{K}TUX_k^{\pm}*TCB_k^{\pm}*\Delta L_k \tag{8a}$$

(b) wastewater treatment cost objective

$$Min\ \ f_2=\sum_{u=1}^{U}\sum_{k=1}^{K}IX_{uk}^{\pm}*IWW_u^{\pm}*IWC_{uk}^{\pm}*\Delta L_k+\sum_{k=1}^{K}(TUX_k^{\pm}+PPX_k^{\pm})*TPW^{\pm}*PWC_k^{\pm}*\Delta L_k \tag{8b}$$

(c) water resources demand objective

$$Min\ \ f_3=\sum_{i=1}^{I}\sum_{k=1}^{K}AX_{ik}^{\pm}*AWM_{ik}^{\pm}*\Delta L_k+\sum_{j=1}^{J}\sum_{k=1}^{K}FX_{jk}^{\pm}*FWM_{jk}^{\pm}*\Delta L_k$$
$$+\sum_{n=1}^{N}\sum_{k=1}^{K}SX_{nk}^{\pm}*SWM_{nk}^{\pm}*\Delta L_k+\sum_{m=1}^{M}\sum_{k=1}^{K}PX_{mk}^{\pm}*PWM_{mk}^{\pm}*\Delta L_k$$
$$+\sum_{s=1}^{S}\sum_{k=1}^{K}FIX_{sk}^{\pm}*FIM_{sk}^{\pm}*\Delta L_k+\sum_{u=1}^{U}\sum_{k=1}^{K}IX_{uk}^{\pm}*IWM_{uk}^{\pm}*\Delta L_k$$
$$+\sum_{k=1}^{K}(TUX_k^{\pm}+PPX_k^{\pm})*TPM_k^{\pm}*\Delta L_k \tag{8c}$$

(d) water quaility objective

$$Min\ \ f_4=\sum_{i=1}^{I}\sum_{k=1}^{K}AX_{ik}^{\pm}*ASL_{ik}^{\pm}*SOD_k^{\pm}*\Delta L_k+\sum_{j=1}^{J}\sum_{k=1}^{K}FX_{jk}^{\pm}*FSL_{jk}^{\pm}*SOD_k^{\pm}*\Delta L_k$$
$$\sum_{n=1}^{N}\sum_{k=1}^{K}SX_{nk}^{\pm}*SCO_{nk}^{\pm}*\Delta L_k+\sum_{m=1}^{M}\sum_{k=1}^{K}PX_{mk}^{\pm}*PCO_{mk}^{\pm}*\Delta L_k+\sum_{s=1}^{S}\sum_{k=1}^{K}FIX_{sk}^{\pm}*FCO_{sk}^{\pm}*\Delta L_k$$
$$+\sum_{u=1}^{U}\sum_{k=1}^{K}IX_{uk}^{\pm}*ICO_{uk}^{\pm}*\Delta L_k+\sum_{k=1}^{K}(TUX_k^{\pm}+PPX_k^{\pm})*TCO_k^{\pm}*\Delta L_k \tag{8d}$$

(COD discharge)

$$Min\ \ f_5=\sum_{i=1}^{I}\sum_{k=1}^{K}AX_{ik}^{\pm}*ASL_{ik}^{\pm}*SN_k^{+}*\Delta L_k+\sum_{j=1}^{J}\sum_{k=1}^{K}FX_{jk}^{\pm}*FSL_{jk}^{\pm}*SN_k^{\pm}*\Delta L_k$$
$$+\sum_{i=1}^{I}\sum_{k=1}^{K}AX_{ik}^{\pm}*AGN_{ik}^{\pm}*\Delta L_k+\sum_{n=1}^{N}\sum_{k=1}^{K}SX_{nk}^{\pm}*SLN_{nk}^{\pm}*\Delta L_k+\sum_{m=1}^{M}\sum_{k=1}^{K}PX_{mk}^{\pm}*PWN_{mk}^{\pm}*\Delta L_k$$
$$+\sum_{s=1}^{S}\sum_{k=1}^{K}FIX_{sk}^{\pm}*FIN_{sk}^{\pm}*\Delta L_k+\sum_{u=1}^{U}\sum_{k=1}^{K}IX_{uk}^{\pm}*IDN_{uk}^{\pm}*\Delta L_k+\sum_{k=1}^{K}(TUX_k^{\pm}+PPX_k^{\pm})*TPN_k^{\pm}*\Delta L_k \tag{8e}$$

(Nitrogen discharge)

$$Min\ \ f_6=\sum_{i=1}^{I}\sum_{k=1}^{K}AX_{ik}^{\pm}*ASL_{ik}^{\pm}*SP_k^{\pm}*\Delta L_k+\sum_{j=1}^{J}\sum_{k=1}^{K}FX_{jk}^{\pm}*FSL_{jk}^{\pm}*SP_k^{\pm}*\Delta L_k$$
$$+\sum_{i=1}^{I}\sum_{k=1}^{K}AX_{ik}^{\pm}*AGP_{ik}*\Delta L_k+\sum_{n=1}^{N}\sum_{k=1}^{K}SX_{nk}^{\pm}*SLP_{nk}^{\pm}*\Delta L_k+\sum_{m=1}^{M}\sum_{k=1}^{K}PX_{mk}^{\pm}*PWP_{mk}^{\pm}*\Delta L_k$$
$$+\sum_{s=1}^{S}\sum_{k=1}^{K}FIX_{sk}^{\pm}*FIP_{sk}^{\pm}*\Delta L_k+\sum_{u=1}^{U}\sum_{k=1}^{K}IX_{uk}^{\pm}*IDP_{uk}^{\pm}*\Delta L_k+\sum_{k=1}^{K}(TUX_k^{\pm}+PPX_k^{\pm})*TPP_k^{\pm}*\Delta L_k \tag{8f}$$

(Phosphorous discharge)

$$Min\ \ f_7=\sum_{i=1}^{I}\sum_{k=1}^{K}AX_{ik}^{\pm}*ASL_{ik}^{\pm}*\Delta L_k+\sum_{j=1}^{J}\sum_{k=1}^{K}FX_{jk}^{\pm}*FSL_{jk}^{\pm}*\Delta L_k \tag{8g}$$

(Soil loss)

The constraints are as follows:

(e) water resource availablity constraint

$$\begin{aligned}&\sum_{i=1}^{I} AX_{ik}^{\pm} * AWM_{ik}^{\pm} + \sum_{j=1}^{J} FX_{jk}^{\pm} * FWM_{jk}^{\pm} + \sum_{n=1}^{N} SX_{nk}^{\pm} * SWM_{nk}^{\pm}\\ &+\sum_{m=1}^{M} PX_{mk}^{\pm} * PWM_{mk}^{\pm} + \sum_{s=1}^{S} FIX_{sk}^{\pm} * FIM_{sk}^{\pm} + \sum_{u=1}^{U} IX_{uk}^{\pm} * IWM_{uk}^{\pm}\\ &+(TUX_{k}^{\pm} + PPX_{k}^{\pm}) * TPM_{k}^{\pm} - EWD_{k}^{\pm} \le TW_{k}^{(p_i)}, \forall k \end{aligned} \quad (8h)$$

(f) land area ayailability consraint

$$\sum_{i=1}^{I} AX_{ik}^{\pm} + \sum_{j=1}^{J} FX_{jk}^{\pm} \le TLA_{k}^{\pm}, \forall k \quad (8i)$$

(g) water area availability constraint

$$\sum_{s=1}^{S} FIX_{sk}^{\pm} \le TWA_{k}^{\pm}, \forall k \quad (8j)$$

(h) pollutant release limitation constraint

$$\begin{aligned}&\sum_{n=1}^{N} SX_{nk}^{\pm} * SCO_{nk}^{\pm} + \sum_{m=1}^{M} PX_{mk}^{\pm} * PCO_{mk}^{\pm} + \sum_{s=1}^{S} FIX_{sk}^{\pm} * FCO_{sk}^{\pm}\\ &+[\sum_{u=1}^{U} IX_{uk}^{\pm} * ICO_{uk}^{\pm} + (TUX_{k}^{\pm} + PPX_{k}^{\pm}) * TCO_{k}^{\pm}] * (1-\alpha_{k}) \le TOD_{k}^{\pm}, \forall k \end{aligned} \quad (8k)$$

(COD discharge)

$$\begin{aligned}&\sum_{i=1}^{I} AX_{ik}^{\pm} * ASL_{ik}^{\pm} * SN_{k}^{\pm} + \sum_{j=1}^{J} FX_{jk}^{\pm} * FSL_{jk}^{\pm} * SN_{k}^{\pm}\\ &+\sum_{i=1}^{I} AX_{ik}^{\pm} * AGN_{ik}^{\pm} + \sum_{n=1}^{N} SX_{nk}^{\pm} * SLN_{nk}^{\pm} + \sum_{m=1}^{M} PX_{mk}^{\pm} * PWN_{mk}^{\pm} + \sum_{s=1}^{S} FIX_{sk}^{\pm} * FIN_{sk}^{\pm}\\ &+[\sum_{u=1}^{U} IX_{uk}^{\pm} * IDN_{uk}^{\pm} + (TUX_{k}^{\pm} + PPX_{k}^{\pm}) * TPN_{k}^{\pm}] * (1-\beta_{k}) \le TN_{k}^{\pm}, \forall k \end{aligned} \quad (8l)$$

(Nitrogen discharge)

$$\begin{aligned}&\sum_{i=1}^{I} AX_{ik}^{\pm} * ASL_{ik}^{\pm} * SP_{k}^{\pm} + \sum_{j=1}^{J} FX_{jk}^{\pm} * FSL_{jk}^{\pm} * SP_{k}^{\pm}\\ &+\sum_{i=1}^{I} AX_{ik}^{\pm} * AGP_{ik}^{\pm} + \sum_{n=1}^{N} SX_{nk}^{\pm} * SLP_{nk}^{\pm} + \sum_{m=1}^{M} PX_{mk}^{\pm} * PWP_{mk}^{\pm} + \sum_{s=1}^{S} FIX_{sk}^{\pm} * FIP_{sk}^{\pm}\\ &+[\sum_{u=1}^{U} IX_{uk}^{\pm} * IDP_{uk}^{\pm} + (TUX_{k}^{\pm} + PPX_{k}^{\pm}) * TPP_{k}^{\pm}] * (1-\theta_{k}) \le TP_{k}^{\pm}, \forall k \end{aligned} \quad (8m)$$

(Phosphorous discharge)

(i) wastewater treatment constraint

$$\sum_{u=1}^{U} IX_{uk}^{\pm} * IWW_{u}^{\pm} * IWC_{uk}^{\pm} + (TUX_{k}^{\pm} + PPX_{k}^{\pm}) * TPW^{\pm} * PWC_{k}^{\pm} \le TWM_{k}^{\pm}, \forall k \quad (8n)$$

(j) soil erosion constraint

$$\sum_{i=1}^{I} AX_{ik}^{\pm} * ASL_{ik}^{\pm} + \sum_{j=1}^{J} FX_{jk}^{\pm} * FSL_{jk}^{\pm} \le TSL_{k}^{\pm}, \forall k \tag{8o}$$

(k) forest cover constraint

$$\sum_{j=1}^{J} FX_{jk}^{\pm} \ge TLA_{k}^{\pm} * FR_{k}^{\pm}, \forall k \tag{8p}$$

(l) tourism constraint

$$TU^{\pm} \le TUX_{k}^{\pm} \le TU_{k}^{\pm}, \forall k \tag{8q}$$

(m) population constraint

$$PPX_{k}^{\pm} \ge TIP_{k}^{\pm}, \forall k \tag{8r}$$

(n) agricutural constraint

$$\sum_{i=1}^{I} AX_{ik}^{\pm} \ge TIA_{k}^{\pm}, \forall k \tag{8s}$$

(o) livestock constraint

$$\sum_{n=1}^{N} SX_{nk}^{\pm} * SCB_{nk}^{\pm} + \sum_{m=1}^{M} PX_{mk}^{\pm} * PCB_{mk}^{\pm} \ge TLS_{k}^{\pm}, \forall k \tag{8t}$$

(p) industry constraint

$$\sum_{u=1}^{U} IX_{uk}^{\pm} \ge TIS_{k}^{\pm}, \forall k \tag{8u}$$

(q) non-negativiity and technical constraint

$$AX_{ik}^{\pm}, FX_{jk}^{\pm}, SX_{nk}^{\pm}, PX_{mk}^{\pm}, FIX_{sk}^{\pm}, IX_{uk}^{\pm}, TUX_{k}^{\pm}, PPX_{k}^{\pm} \ge 0, \forall i, j, n, m, s, u, k \tag{8v}$$

Through applying the algorithm deduced in section 3, we can derive the final solutions of $f_{1opt}^{\pm} = \left[f_{1opt}^{-}, f_{1opt}^{+}\right]$, $f_{2opt}^{\pm} = \left[f_{2opt}^{-}, f_{2opt}^{+}\right]$, $f_{3opt}^{\pm} = \left[f_{3opt}^{-}, f_{3opt}^{+}\right]$, $f_{4opt}^{\pm} = \left[f_{4opt}^{-}, f_{4opt}^{+}\right]$, $f_{5opt}^{\pm} = \left[f_{5opt}^{-}, f_{5opt}^{+}\right]$, $f_{6opt}^{\pm} = \left[f_{6opt}^{-}, f_{6opt}^{+}\right]$, $f_{7opt}^{\pm} = \left[f_{7opt}^{-}, f_{7opt}^{+}\right]$, $(AX_{ik}^{\pm})_{opt} = \left[(AX_{ik}^{-})_{opt}, (AX_{ik}^{+})_{opt}\right]$, $(FX_{jk}^{\pm})_{opt} = \left[(FX_{jk}^{-})_{opt}, (FX_{jk}^{+})_{opt}\right]$, $(SX_{nk}^{\pm})_{opt} = \left[(SX_{nk}^{-})_{opt}, (SX_{nk}^{+})_{opt}\right]$, $(PX_{mk}^{\pm})_{opt} = \left[(PX_{mk}^{-})_{opt}, (PX_{mk}^{+})_{opt}\right]$, $(FIX_{sk}^{\pm})_{opt} = \left[(FIX_{sk}^{-})_{opt}, (FIX_{sk}^{+})_{opt}\right]$, $(IX_{uk}^{\pm})_{opt} = \left[(IX_{uk}^{-})_{opt}, (IX_{uk}^{+})_{opt}\right]$, $(TUX_{k}^{\pm})_{opt} = \left[(TUX_{k}^{-})_{opt}, (TUX_{k}^{+})_{opt}\right]$ and $(PPX_{k}^{\pm})_{opt} = \left[(PPX_{k}^{-})_{opt}, (PPX_{k}^{+})_{opt}\right]$.

4. Results analysis

The solutions of ICFMOP are displayed in Figs 1 - 3 and Table 3. Decision alternatives emphasizing the water quality objectives were generated under different risk levels of environmental constraint violations. A set of significant level (i.e., p_i) including 0.01, 0.05 and 0.1 were selected in this study according to the risk tolerance level of decision makers. The p_i levels imply that the constraints would be satisfied with a probability of at least 99, 95 and 90 % [38].

Fig. 1 provides the results for optimized agricultural area and forestry area under three p_i levels over the entire planning horizon. From Fig. 1 (a) it can be observed that the agricultural area had a tendency to grow during the three periods. In period 1, it would be [41.11, 47.82], [43.87, 48.21] and [45.87, 49.76] km^2 where p_i equals 0.01, 0.05 and 0.1, respectively. In period 2, it would increase from [43.87, 49.44], [45.58, 51.67] and [47.58, 53.17] km^2 under the three p_i levels. Finally in period 3, it would change to [46.54, 52.45], [47.69, 55.37] and [49.19, 58.52] km2 under the three p_i, respectively. Similarly, Fig. 1 (b) shows that the forestry area would also increase gradually over the three periods of the planning horizon, with the values of [22.97, 24.46], [24.72, 26.28] and [25.95, 27.39] km^2, for the three p_i levels during period 1 [24.25, 25.44], [25.73, 27.67] and [26.94, 28.31] km^2 for period 2, and [25.96, 26.35], [26.28, 28.61] and [27.43, 29.27] km^2 for period 3. Although agricultural activities often result in non-point source pollution, planting of crops is an almost unavoidable consequence of population growth and economic development. Conversely the area of forest area would grow because of its prominent ecological service and benefit to water conservation.

Fig. 2 presents the optimal patterns for land-livestock and waterfowl development under the different p_i levels for the three periods. For the land-livestock, the number of heads reared in period 1 would be [30.67, 33.44] × 10^3, [32.85, 35.98] × 10^3 and [38.33, 41.52] × 10^3 when p_i equals to 0.01, 0.05 and 0.1, respectively. In period 2, these values would rise to [34.77, 37.26] × 10^3, [35.92, 38.14] × 10^3 and [39.44, 42.74] × 10^3 heads and finally to [35.49, 39.73] × 10^3, [37.65, 40.85] × 10^3 and [40.72, 43.23] × 10^3 heads in period 3. Similarly, with p_i changing from 0.01, 0.05 to 0.1, the optimized number of waterfowl within the system would be [381.88, 451.23] × 10^3, [387.33, 456.68] × 10^3 and [397.55, 466.90] × 10^3 heads in period 1. But over the period 2, the number of waterfowl would be [395.23, 467.54] × 10^3, [403.73, 473.45] × 10^3 and [418.40, 487.98] × 10^3 heads. And during period 3, it would change to [412.32, 482.55] × 10^3, [428.99, 493.54] × 10^3 and [438.67, 510.24] × 10^3 heads. This data indicates that both land-livestock and waterfowl would have a steady growth over the entire planning period, reflecting their favorable contribution to the course of development.

Fig. 3 shows the optimization solutions for aquaculture area and industry scale over the entire planning period under different p_i levels. Unlike the decision variables considered above, the aquaculture area would decrease over the planning horizon. In period 1, it would decline from [7.58, 8.18] to [8.41, 9.98] and then to [9.17, 10.24] km^2 where p_i equals 0.01, 0.05 and 0.1, respectively. In period 2, it would change from [7.24, 7.93], to [7.97, 8.89] and then [8.94, 9.45] km^2 for the three p_i levels. And in period 3, the optimal area would become [7.04, 7.85], [7.52, 8.36] and [8.61, 9.33] km^2. The optimized industrial scale was programmed and calculated in terms of production value. The data generated indicate that the scale of industrial activities would gradually increase over the entire planning horizon. The detailed values for the three different p_i levels would be [6.42, 7.06] × 10^8, [8.55, 9.62] × 10^8 and [10.41, 11.73] × 10^8 RMB in period 1; [7.67, 9.46] × 10^8, [9.24, 10.83] × 10^8 and [11.47, 12.91] × 10^8 RMB in period 2 and [9.39, 11.85] × 10^8, [11.79, 12.62] × 10^8 and [12.84, 13.26] × 10^8 RMB in period 3. These results indicate that the aquaculture area would decline over the planning period reflecting its unfavorable contribution to achieving the water pollution control objective. Meanwhile, industry would grow steadily because of its high economic benefit.

Besides, the optimized tourism flow and resident number were also predicted by the ICFMOP model, although the data does not appear in any of the figures. During period 1, the optimized tourism flows would be 58.32 ×10^3, 62.47 ×10^3 and 66.71 ×10^3 people for three p_i levels of 0.01, 0.05 and 0.1, respectively. In period 2, the optimized tourism flow would be 68.87 ×10^3, 71.32 ×10^3 and 74.86 ×10^3 people over three p_i levels, respectively. Finally, it would be 76.52 ×10^3, 82.65 ×10^3 and 88.16 ×10^3 people for period 3, when p_i equals to 0.01, 0.05 and 0.1. The number of residents would also increase over the planning horizon but it would not vary with the different p_i levels all of which generate the values of 30.92 ×10^3, 30.94 ×10^3 and 30.96 ×10^3 people for the three periods respectively.

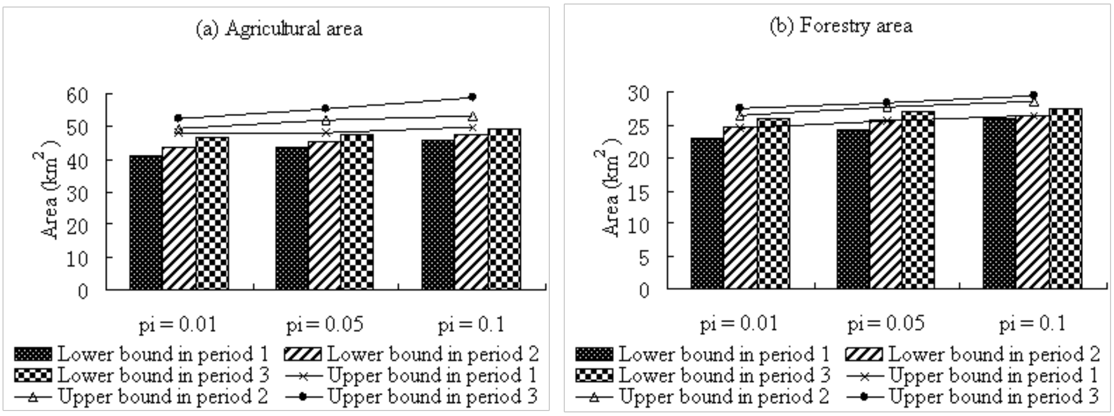

Fig. 1. Solutions for (a) agricultural area and (b) forestry area, under three p_i levels

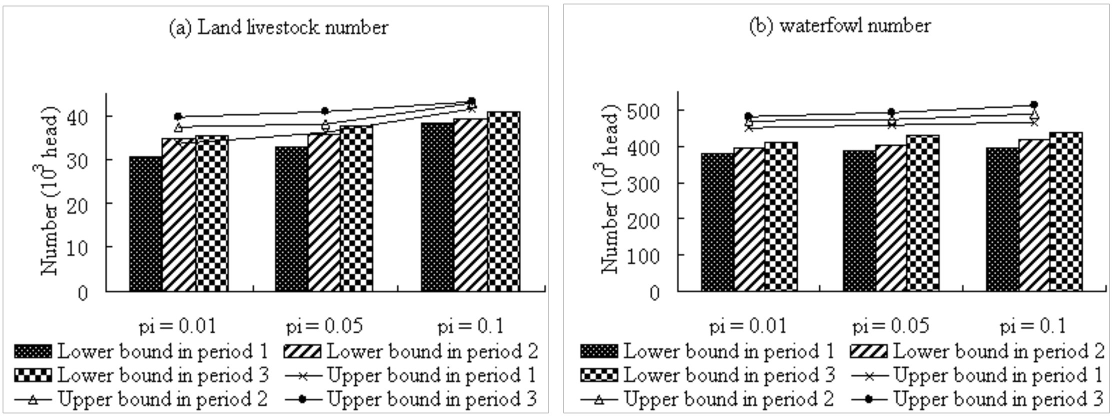

Fig. 2. Solutions for (a) land livestock number and (b) waterfowl number, under three p_i levels

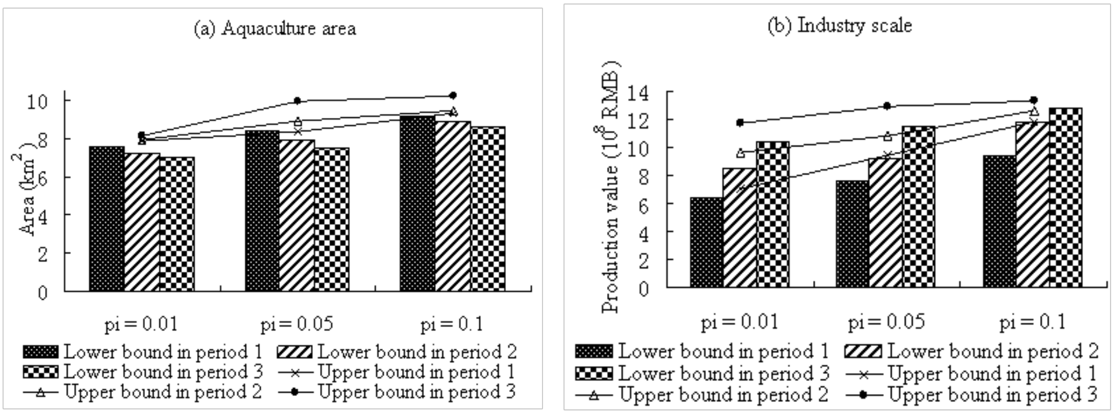

Fig. 3. Solutions for (a) aquaculture area and(b) industry scale, under three p_i levels

The solutions of the objective functions at the three p_i levels are presented in Table 3. It can be observed that all the objective functions would change with different p_i levels, reflecting the tight interrelationships between economic benefit, treatment cost, water demand, water quality, soil loss, water resource availability and system reliability (risks of constraint violation). In detail the total benefit were [9.13, 10.22] × 10^9 RMB, [10.12, 11.76] × 10^9 RMB and [11.91, 13.22] × 10^9 RMB when p_i equals 0.01, 0.05 and 0.1 respectively, which indicates that a lower p_i level corresponds to a higher system reliability and a higher net benefit; in contrast a higher p_i level results in a lower cost but a higher constraint-violation risk. When considering the wastewater treatment cost the values obtained when p_i equals 0.01 were [4.90, 7.72] ×10^7 RMB; [5.20, 8.73] ×10^7 RMB when p_i equals 0.05, and [5.57, 9.12] × 10^7 RMB when p_i equals 0.1. This indicates that a higher p_i level would lead to an increased cost for wastewater treatment. The water resource demand would also grow at a higher p_i level, corresponding to [40.66, 49.80] × 10^7 m^3 when p_i equals 0.01, [42.87, 53.13] × 10^7 m^3 when p_i equals 0.05, and [45.87, 56.49] ×10^7 m^3 when p_i equals 0.1. The minimized water pollutant discharge of COD, nitrogen, phosphorous and soil loss were also predicted by the model (Table 3). The minimized COD discharge of the system would be [28.76, 37.51] × 10^7 kg when p_i equals 0.01, [31.78, 43.08] × 10^7 kg when p_i equals 0.05, and [37.41, 48.52] × 10^7 kg when p_i equals 0.1. This indicates that a higher p_i level would cause an increase in COD discharge. Soil loss would also increase with p_i level changing from [15.79, 17.97] × 10^7 kg when p_i equals 0.01, to [16.47, 18.64] × 10^7 when p_i equals 0.05, and finally [17.13, 19.38] × 10^7 kg when p_i equals 0.1. Although the detailed values have not been analyzed, the data from Table 3 also shows that nitrogen and phosphorus follow similar trends with COD and soil loss. Together these data imply that at a lower p_i level would be more satisfied the environmental objective but leading to a lower net system benefit.

Various forms of uncertainties in terms of intervals and probability were successfully incorporated into the ICFMOP model. Some of the solutions for decision variables were intervals, while others remained as deterministic values. For example, in period 1, the optimized agricultural area was predicted to be [41.11, 47.82], [43.87, 48.21] and [45.87, 49.76] km^2 when p_i equals to 0.01, 0.05 and 0.1 respectively, while for waterfowl the optimal number of heads would be [397.55, 466.90] × 10^3, [418.40, 487.98] × 10^3 and [438.67, 510.24] × 10^3 when p_i equals 0.1 for the three periods respectively. Most of the solutions were presented as intervals, facilitating the reflection of uncertainties during the decision-making process.

Other solutions remained as deterministic values, which might not respond sensitively to the input uncertainties, implying they would reach the maximum allowable levels or reflect their unfavorable situation due to high costs. For example, the optimized tourism flows would remain as 58.32 $\times 10^3$, 68.87 $\times 10^3$ and 76.52 $\times 10^3$ people for the periods 1-3 when p_i levels equals 0.01. Based on such interval solutions, many decision alternatives can be generated. Since the actual values of the variables and/or parameters vary within their boundaries, the expected objective function changes correspondingly between f_{opt}^{-} and f_{opt}^{+} with different reliability levels.

Table 3. Optimized results for the seven objective functions under three p_i levels

Objectives	Different p_i level		
	$p_i = 0.01$	$p_i = 0.05$	$p_i = 0.1$
Total net benefit (10^9 RMB)	[9.13, 10.22]	[10.12, 11.76]	[11.91, 13.22]
Wastewater treatment cost (10^7 RMB)	[4.90, 7.72]	[5.20, 8.73]	[5.57, 9.12]
Water resource demand (10^7 m^3)	[40.66, 49.80]	[42.87, 53.13]	[45.87, 56.49]
COD discharge (10^7 kg)	[28.76, 37.51]	[31.78, 43.08]	[37.41, 48.52]
Nitrogen discharge (10^7 kg)	[3.69, 4.52]	[3.96, 4.94]	[4.40, 5.37]
Phosphorous discharge (10^7 kg)	[0.69, 0.83]	[0.74, 0.89]	[0.80, 0.96]
Soil loss (10^7 kg)	[15.79, 17.97]	[16.47, 18.64]	[17.13, 19.38]

In summary, the ICFMOP model presents that agriculture and industry will continue to grow since they are the major economic contributors to the system. Similarly, the developing pattern and distribution of livestock and waterfowl would tend to increase. The forest cover should also be increased due to its high environmental and ecological value. The residential population would grow slowly while tourism will increase as a result of its high economic efficiency. Conversely aquaculture should be limited as a result of its significant contribution to water pollution. In general the ICFMOP model effectively addressed the water pollution control problems for sustainable wetland management and provided helpful data to plan agricultural and industrial development and other human activities (e.g., agricultural area, livestock number and tourism flow) in accordance with the multiple objectives. The solutions generated by the ICFMOP model can be effectively utilized to assist the formulation of policies and strategies regarding regional socio-economic development and environmental protection according to different violating risk levels. Moreover tradeoffs between economic cost and system reliability can also be considered.

5. Conclusion

An ICFMOP model was developed to aid the planning of water pollution control within a sustainable wetland management system under uncertainty. Through integrating interval linear programming, chance-constrained programming and multi-objective programming methods into a general optimization framework, multi-objective and interactive features originated from a number of sectors/processes could be successfully reflected with the dual uncertainties being expressed as interval values and probability distributions. .The model allows decision makers to adjust the fuzzy objective control decision variable to satisfy multiple holistic and interactive objectives. The probability distributions of water resource availability can be integrated into the optimization process through the CCP method under several p_i levels. The ICFMOP model was then applied to a case study for long-term wetland water pollution management to promote regional wetland eco-environmental sustainability. The interval solutions could be used as compromise decision alternatives associated with different risk levels for water resources availability constraint violations, which are useful for analyzing tradeoffs between objective function and resource availability. Optimal schemes of agricultural, industrial development and other human activities (e.g., agricultural area, livestock number and tourism flow) were generated. These would be very useful for decision makers to identify desirable strategies under various social-economic, environmental and system-reliability constraints with the highest system benefit, and the lowest water pollutant discharge and lowest ecological environment impact. Moreover, tradeoffs between the multiple objectives and constraint-violation risks can also be effectively tackled.

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