A non-probabilistic programming approach enabling risk-aversion analysis for supporting sustainable watershed development

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A B S T R A C T
Due to insufficiency and ineffectiveness of monitoring facilities, variations in natural conditions and changes of human behaviors, watershed planning is interwoven with imprecise data, resulting in a multitude of complexities. A robust interval fuzzy programming approach with superiority—inferiority and risk-aversion analyses (RIFP-SIRA) was developed for identifying sustainable agricultural and industrial production strategies at the watershed scale in a highly uncertain environment. RIFP-SIRA represented a novel attempt to tackle synergies of uncertain information in the forms of intervals with non-statistical bounds and conventional intervals. The developed method was applied to a Chinese watershed. A RIFP-SIRA model was formulated and analyzed under three scenarios to investigate the effects of different policies and standards on watershed development plans. Sensitivity of the model’s solutions to varied risk-aversion and input-fluctuation levels were analyzed, verifying the superiority of RIFP-SIRA over the existing inexact approaches. This research revealed that RIFP-SIRA could provide local authorities with robust, yet flexible decision plans. It could enable a quantitative analysis over the trade-offs between the economic benefits and environmental risks in the absence of probabilistic information.

1. Introduction

Identification of sustainable development strategies is intricate for many watersheds due to the interactions among constituting components, diversification in temporal and spatial scales, and conflicts among economic, eco-environmental, and social targets. This feature is particularly apparent for many watersheds in developing countries, where the impacts of soil erosion, non-point source pollution, stock farming, unexpected droughts, and eutrophication have continuously deteriorated water quality, while rapid growth of their economies is increasingly driving up water consumptions and land utilization (Chang et al., 1997; Merritt et al., 2004; Panigrahi et al., 2010; Zhou et al., 2013). Moreover, due to insufficiency and ineffectiveness of relevant monitoring facilities, variations in natural conditions and changes of human activities, the relevant decision-making processes are further complicated by multiple forms of uncertainties, resulting in a variety of complexities. This leads to major challenges to decision makers at many fast-developing watersheds that are facing dual pressures for protecting the environment and stimulating the economies. Thus, it is desired to develop effective tools for supporting sustainable management under such complexities in developing watersheds.

Previously, many researchers employed a number of mathematical programming techniques to pursue sustainability issues (such as water pollution mitigation, water resources conservation, and water quality management) at various watersheds that are suffering from incisive conflicts between fast-growing economy and degrading environmental quality. For example, Nazer et al.

Abbreviations: CCP, chance-constrained programming; COD, chemical oxygen demand; FMP, fuzzy mathematical programming; IMP, interval mathematical programming; RIFP-SIRA, robust interval fuzzy programming approach with superiority—inferiority and risk-aversion analyses; SMP, stochastic mathematical programming.

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(2010) examined optimal water allocation strategies for agricultural irrigation in the west bank of Palestine through the employment of a linear programming model. Panigrahi et al. (2010) developed a linear goal programming model for optimally allocating land resources to different crop sequences in Khandamal of India. Based on a water-inflow forecasting model, Choudhury (2010) developed a weighted pre-emptive goal programming approach to derive optimal strategies in the Narmada River Basin of India. Roozbahani et al. (2014) developed a multi-objective mixed-integer model for a large transboundary basin in Iran to maximize the net benefits derived from the agricultural and industrial production under resources and environmental constraints. Although these studies provided a holistic and comprehensive analysis of a variety of system activities and factors, they mostly utilized deterministic linear programming techniques through assuming that parameter values could be precisely known. This can hardly be tenable for many practical problems which are fraught with dynamic and uncertain variations, and are short of solidly supported databases, well-established monitoring facilities, and sufficient technical capacities.

In the past decades, uncertainties represent a long-lasting challenge confronting watershed planners and modelers, which ubiquitously exist in parameters and inherently require treatments to avoid oversimplified and caricatured picture of real-world problems. SMP based on probability theory has been widely applied for tackling parametric uncertainties (Kall and Meyer, 2005; Wets, 1996). For example, Suykynri (2004) developed a CCP model to support long-term planning of water quality management in a basin of eastern Thailand. Kataria et al. (2010) used truncated normal distributions to describe probabilistic variations in water pollution, and then incorporated them into a CCP model for reducing nitrogen loads in rivers. Although SMP could cope with randomness, such a sampling-based approach may be prohibitively expensive as a large number of samples are required to establish statistically significant relationships. Its applications to large-scale cases are thus curbed by the complicated intermediate models and time-consuming computational processes (Li et al., 2008; Tan et al., 2010a,b). Particularly in a developing watershed, due to the fact that data acquisition is highly dependent on expertise and judgments of decision makers and stakeholders, the management process is normally characterized by imprecise, inconsistent, incomplete, ambiguous, and linguistic information. This makes SMP approaches inapplicable, and thus bring non-probabilistic ones to the attention of planners and modelers. As supplements to SMP, typical non-probabilistic methods include FMP, and IMP. FMP founded on fuzzy sets theory aims at dealing with possibilistic distributions, while IMP based on interval analysis focuses on interval numbers with known ranges but unknown distributions (Cai et al., 2011a,b,c; Huang and Chang, 2003; Inuiguchi and Ramik, 2000). When distributions are inaccessible, IMP would outweigh FMP; nevertheless, the utilization of IMP by simplifying distributions into interval numbers may spurrn useful information when extra information other than a range is available. In real-world practices, it appears that the parameter values related to environmental factors and physical/chemical laws may frequently encounter the interval type of messages, while the economic factors and values are usually specified by stakeholders as fuzzy membership functions (Dong et al., 2012; Faybishenko, 2010; Hayashi et al., 2014; Huang and Chang, 2003; Tan et al., 2013; Yue et al., 2014). Systematic approaches with the inclusion of both interval and fuzzy implications are thus of theoretical and practical interests.

However, two major challenges remain unsettled for the existing non-probabilistic programming methods. Firstly, there is a lack of effective tools to manipulate and explicitly reflect system risk-aversion levels in the absence of probability distributions, which could have the advantages of CCP but overcome its short-ages. In practice, decision makers need to be informed about risk levels associated with modeling outputs to formulate decisions confidently. They desire a tool to proactively adjust the decision alternatives according to site-specific features and management expectations. Such a tool is particularly useful in the management of developing watersheds, where decision makers are struggling to achieve the most possible rapid economic growth while guaranteeing environmental risks to acceptable levels. Secondly, the existing programming methods have limitations in reflecting synergies of non-statistical uncertainties which are prevalent in watershed management practices. The qualitative and subjective information provided by professionals and stakeholders is highly uncertain in nature, greatly affecting system performances. For example, the available quantity of water resources may be obtained as an interval number where the two bounds arise from the temporal variability in dry and wet seasons; and the quantities in dry and wet seasons may not be available as probabilistic distributions due to the insufficiency of data and the dynamic interactions of many driving factors (e.g., precipitations and temperatures). By the well-known “garbage in, garbage out” principle, stubbornly simplifying imprecise data would churn out inferior, meaningless, or simply erroneous outcomes (Luhandjula, 2006; Tan et al., 2010b, 2009). It is therefore imperative to contend with the aforementioned dual uncertainties without any probability distributions.

Therefore, the objective of this research is to develop an inexact methodology for identifying sustainable development strategies at watersheds under a highly uncertain environment. RIFP-SIRA as well as its algorithm will be developed to facilitate quantitative adjustment of decision conservativeness (or risk levels) when probabilistic distributions are unavailable. Founded on RIFP-SIRA, an integrated modeling framework embracing a wide spectrum of activities and factors will be proposed to seek a balance among issues such as water and land-resource conservation, water quality management, as well as agricultural and industrial development. Through RIFP-SIRA, a substantial body of uncertain data acquired from field surveys, public participation, and hydrological simulation will be processed and communicated into the modeling process as intervals with fuzzy bounds, intervals with fluctuation radii and crisp intervals corresponding to the quality of information. Such a methodology will be applied to and tested in a southeastern Chinese watershed.

2. Robust interval fuzzy programming approach with superiority–inferiority and risk-aversion analyses

In this research, RIFP-SIRA is developed based on the concepts of intervals with non-statistical information at bounds. Firstly, due to the involvement of multiple levels of jurisdictions and various groups of stakeholders, many parameters that are closely linked with human activities may be obtained as intervals with fuzzy bounds which reflect fuzziness embedded within intervals. An interval with fuzzy bounds can be expressed as \( (\bar{x}, \check{x}) \). \( x \)'s range \( [\bar{x}, \check{x}] \) can be characterized as \( [\bar{x}, \check{x}] = [x - l, x + r] \), where \( x \) and \( x' \) are fuzzy sets with the same sign (Zimmermann, 2001); \( x \) and \( x' \) are the values of \( x \) and \( x' \), respectively, when the membership grade is 1; scalars \( l \) and \( r \) (\( l, r \geq 0; l, r \in \mathbb{R} \)) are named the left spreads of \( x \) and \( x' \), respectively; and scalars \( r' \) and \( r' \) (\( r', r' \geq 0; r', r' \in \mathbb{R} \)) are named the right spreads of \( x \) and \( x' \), respectively. Secondly, many parameters in watershed management problems, such as water resources availabilities, may be merely available as intervals with fluctuation radii without neither
probabilistic nor possibilistic information. A interval with fluctuation radii can be defined as an interval number with each of its bounds being expressed as a nominal value and a fluctuation radius: 

$$\bar{x} = (\bar{x}^-, \bar{x}^+) = (\bar{x}^+ - \varepsilon^+, \bar{x}^- + \varepsilon^-)$$

where $\bar{x}^-$ and $\bar{x}^+$ are random variables that obey a symmetric but unknown distribution and take values within $[\bar{x}^- - \varepsilon^-, \bar{x}^- + \varepsilon^-]$ and $[\bar{x}^+ - \varepsilon^+, \bar{x}^+ + \varepsilon^+]$, respectively; $\bar{x}^-$ and $\bar{x}^+$ are the nominal value and the fluctuation radius of $\bar{x}^-$, respectively; $\bar{x}^+$ and $\varepsilon^+$ are the nominal value and the fluctuation radius of $\bar{x}^+$, respectively, and $\bar{x}^-$ and $\varepsilon^-$ are considered to have the same sign (i.e., $\bar{x}^- - \varepsilon^- \geq 0$, $\bar{x}^+ + \varepsilon^+ \geq 0$, and $\bar{x}^- - \varepsilon^- \leq 0$). In this research, $\bar{x}^-$ and $\varepsilon^-$ are considered to have the same sign (i.e., $\bar{x}^+ - \varepsilon^+ \geq 0$, $\bar{x}^- + \varepsilon^- \leq 0$ when $\bar{x}^- - \varepsilon^- \leq 0$).

Therefore, a RIFP-SIRA approach is proposed in this study to directly communicate such uncertainties into the modeling process. A general formula of RIFP-SIRA can be written as:

$$\text{Max } f^z = \tilde{C}^z X^z$$

subject to:

$$\tilde{A}^z X^z \leq \tilde{B}^z$$

$$\tilde{A}^z X^z \leq \tilde{B}^z$$

$$A^z X^z \leq B^z$$

$$X^z \geq 0$$

where $\tilde{C}^z \in \{\mathbb{R^z}\}^{1 \times n}$, $X^z \in \{\mathbb{R^z}\}^{n \times 1}$, $\tilde{A}^z \in \{\mathbb{A^z}\}^{m \times n}$, $\tilde{B}^z \in \{\mathbb{R}^z\}^{m \times 1}$, $\tilde{A}^z \in \{\mathbb{A^z}\}^{m \times n}$, $\tilde{B}^z \in \{\mathbb{R}^z\}^{m \times 1}$, $\mathbb{R}^z$ denotes a set of intervals with fuzzy bounds, $\mathbb{A^z}$ denotes a set of crisp interval numbers, and $\mathbb{A^z}$ denotes a set of intervals with fluctuation radii.

A protection function is introduced to model (1) as a “buffer” (Bertsimas and Thiele, 2006). The magnitude of the buffer for each constraint depends on the degree of uncertainty of the parameters involved in the constraint (i.e., $\varepsilon^z$) and the degree of protection desired by decision makers. Model (1) can then be converted into the following problem:

$$\text{Max } \theta^z$$

subject to:

$$\sum_{j=1}^{n} \tilde{c}^z_j x^z_j \geq \theta^z$$

$$\tilde{a}^z_i x^z_j + \beta_i(X^z, r_i) \leq \tilde{b}^z_i \quad \forall i \in M$$

$$\tilde{a}^z_i x^z_j \leq \tilde{b}^z_i \quad \forall i \in M$$

$$\tilde{a}^z_i x^z_j \leq \tilde{b}^z_i \quad \forall i \in M$$

$$x^z_j \geq 0 \quad \forall j$$

where $\tilde{c}^z_j, \tilde{a}^z_j, \tilde{b}^z_i$, $\tilde{a}^z_i$, $\tilde{b}^z_i$, and $\tilde{x}^z_j$ are the elements of their corresponding matrices (e.g., $\tilde{a}^z_j$ is the element at the $i$th row and $j$th column of $\tilde{A}^z$); $\theta^z$ is an introduced variable which can be fuzzified as $\theta^z = (\theta^z, 0)$; $M = (1, 2, ..., m)$; $M' = (1, 2, ..., m')$; and $\beta_i(X^z, r_i)$ is the protection function of constraint $i$ which can be written as follows:

$$\beta_i(X^z, r_i) = \max \left\{ \left( \sum_{j \in S_i} \tilde{e}^z_j x^z_j \right) + \left( r_i - r_i \right) \right\}$$

where $r_i$ is the protection level of constraint $i$ which refers to the number of intervals with fluctuation radii in constraint $i$ that are allowed to fluctuate at their bounds while constraint $i$ remains feasible, $r_i \in [0, \text{card}(S_i)]$, $S_i$ is the set of intervals with fluctuation radii in constraint $i$, card $(S_i)$ represents the cardinality or number of elements in a set, $S_i$ is a subset of $I_i$ where $|I_i|$ denotes the integer part of $r_i$, $\beta_i(X^z, r_i)$ is specific for a given solution to $X^z$ and depends on the user-defined $r_i$. When $r_i = 0$, $\beta_i(X^z, r_i) = 0$, and the constraint is the same as a deterministic one without any protection against infeasibility.

Based on the superiority and inferiority concepts for fuzzy sets, model (2) requires a maximized objective function value subject to penalties for any violations of the superiority of the right-hand sides (RHS) over the left-hand sides (LHS) or the inferiority of LHS to RHS (Van Hop, 2007; Tan et al., 2010c). Thus, the RIFP-SIRA model can be reformulated as follows:

$$\text{Max } \theta^z$$

subject to:

$$S_0 \left( \theta^z, \sum_{j=1}^{n} \tilde{c}^z_j x^z_j \right) = \lambda^z_0$$

$$I_0 \left( \sum_{j=1}^{n} \tilde{c}^z_j x^z_j, \theta^z \right) = \lambda^z_0$$

$$S_i \left( \sum_{j=1}^{n} \tilde{a}^z_j x^z_j \tilde{c}^z_i \right) = \lambda^z_i \quad \forall i \in M$$

$$I_i \left( \sum_{j=1}^{n} \tilde{a}^z_j x^z_j \tilde{c}^z_i \right) = \lambda^z_i \quad \forall i \in M'$$

$$a^z_i x^z_j \leq b^z_i \quad \forall i \in M$$

$$a^z_i x^z_j \leq b^z_i \quad \forall i \in M'$$

$$x^z_j \geq 0 \quad \forall j$$

$$\lambda^z_0, \lambda^z_i, \lambda^z'_i \geq 0$$
where $\varepsilon_i$, $\phi_i^+$, $\phi_i^-$ and $\phi_i^\pm > 0$ are penalty coefficients for quantifying adverse impacts caused by the violations of superiority and inferiority relationships between LHS and RHS in equations (2b) and (2d). Higher penalty costs would correspond to stricter policies in constraint violations. Therefore, decision makers can identify suitable penalty levels based on projected applicable conditions. In the most optimistic case, the decision maker can select penalty costs as the minimum value of the cost coefficients. In the most pessimistic case, the penalty costs can be selected as the maximum value of the cost coefficients. $\lambda_i^{S^+}$ and $\lambda_i^{S^-}$ denote superiority degrees between LHS and RHS, whereas $\lambda_i^{I^+}$ and $\lambda_i^{I^-}$ denote inferiority degrees. Given two fuzzy sets $\tilde{u}$ and $\tilde{v}$ ($\tilde{u} \leq \tilde{v}$), the total superiority of $\tilde{v}$ over $\tilde{u}$ is defined as the area of $\tilde{v}$ larger than $\tilde{u}$, which can be mathematically presented as follows (Van Hop, 2007).

$$S(\tilde{v}, \tilde{u}) = \frac{1}{\alpha} \{ \sup \{ x' : \mu_{\tilde{u}}(x') \geq \alpha \} - \sup \{ x : \mu_{\tilde{u}}(x) \geq \alpha \} \} \, \text{d} \alpha$$

(5)

Analogously, the inferiority of $\tilde{u}$ to $\tilde{v}$ can be defined as follows:

$$I(\tilde{u}, \tilde{v}) = \frac{1}{\alpha} \{ \inf \{ x' : \mu_{\tilde{u}}(x') \geq \alpha \} - \inf \{ x : \mu_{\tilde{u}}(x) \geq \alpha \} \} \, \text{d} \alpha$$

(6)

In this study, fuzzy arithmetic conforms to that described in Lai and Hwang (1992). For model (4), the degree of conservativeness in satisfying constraint $i$ (inversely, the expected rate of constraint violation) can be controlled by changing $R_i$. Constraint $i$ will be deterministically satisfied for all of the cases that (a) up to $[R_i]$ (i.e., the integer part of $R_i$) of the interval parameters change within their fluctuation radii, and (b) one extra (i.e., $\check{t}$th) interval parameter fluctuates at its bounds by $(R_i - [R_i])$ times of its radii. Even if more than $[R_i]$ interval parameters change, constraint $i$ will be satisfied with a high probability. The maximum that constraint $i$ is violated can be defined as the probability bound of violation (Bertsimas and Sim, 2004, 2003; Bertsimas and Thiele, 2006).

Deriving from a two-step solution method proposed by Huang et al. (2005), an interactive solution algorithm is proposed to solve the proposed RIFP-SIRA model. Model (4) will be transformed into two submodels: each submodel will then be sequentially converted into its deterministic counterpart and solved as a conventional linear programming model. Since the objective is to be maximized, the submodel corresponding to $f^+$ should be formulated and solved in the first step:

$$\text{Max } \theta^+ - \varepsilon_{\theta}^+ \lambda_{\theta}^0 - \phi_{\theta}^+ \lambda_{\theta}^+ - \sum_{i=1}^{m} \varepsilon_i^{S^+} \lambda_i^{S^+} - \sum_{i=1}^{m} \phi_i^{I^+} \lambda_i^{I^+}$$

subject to:

$$S\left(\theta^+, \sum_{j=1}^{k_i} \check{c}_i^j x_j^+ + \sum_{j=k_i+1}^{n} \check{c}_i^j x_j^- \right) = \lambda_{\theta}^{S^+}$$

(7b)

$$I\left(\sum_{j=1}^{k_i} \check{c}_i^j x_j^+ + \sum_{j=k_i+1}^{n} \check{c}_i^j x_j^- , \theta^+ \right) = \lambda_{\theta}^{I^+}$$

(7c)

$$\begin{align*}
\sum_{j=1}^{k_i} |a_{ij}| \ Sign(a_{ij}) x_j^+ + \sum_{j=k_i+1}^{n} |a_{ij}| \ Sign(a_{ij}) x_j^- + \beta_i^+ + (R_i - 1) x_i^+ + \sum_{j=1}^{n} p_{ij}^+ & \leq \beta_i^+ \quad \forall i \\
|z_i^+ + p_{ij}^+| & \geq \varepsilon_{ij} x_j^+ \quad \forall i, j = 1, \ldots, k_i \\
|z_i^+ + p_{ij}^+| & \geq \varepsilon_{ij} x_j^- \quad \forall i, j = k_i + 1, \ldots, n \\
z_i^+ & \geq 0 \quad \forall i \\
p_{ij}^+ & \geq 0 \quad \forall i, j \\
S_i \left( \sum_{j=1}^{k_i} |a_{ij}| \ Sign(a_{ij}) x_j^+ + \sum_{j=k_i+1}^{n} |a_{ij}| \ Sign(a_{ij}) x_j^- , \beta_i^+ \right) & = \lambda_{\theta}^{S^+} \quad \forall i \\
I_i \left( b_i^+, \sum_{j=1}^{k_i} |a_{ij}| \ Sign(a_{ij}) x_j^+ + \sum_{j=k_i+1}^{n} |a_{ij}| \ Sign(a_{ij}) x_j^- \right) & = \lambda_{\theta}^{I^+} \quad \forall i \\
\sum_{j=1}^{k_i} |a_{ij}| \ Sign(a_{ij}) x_j^+ + \sum_{j=k_i+1}^{n} |a_{ij}| \ Sign(a_{ij}) x_j^- & \leq b_i^- \quad \forall i \\
x_i^+ & \geq 0 \quad \forall j \\
x_i^0, x_i^+, x_i^-, x_i^{S^+}, x_i^{S^-}, x_i^{I^+}, x_i^{I^-} & \geq 0
\end{align*}$$

(7d)

(7e)

(7f)

(7g)

(7h)

(7i)

(7j)

(7k)

(7l)

(7m)

where $x_j^+$ ($j = 1, 2, \ldots, k_1$) are interval variables with positive coefficients in the original objective function; $x_j^-$ ($j = k_1 + 1, k_1 + 2, \ldots, n$) are interval variables with negative coefficients; $\cdot$ and $\cdot^+$ represents the lower and upper bounds of the absolute value of $\cdot$, respectively; $\text{Sign}(\cdot^+)$ is the sign of $\cdot^+$, which takes 1 when $\cdot^+ \geq 0$ and -1 when $\cdot^+ < 0$; and $z_i^+$ and $p_{ij}^+$ are new variables.

Solutions of $x_{ij}^{opt}$ ($j = 1, 2, \ldots, k_i$) and $x_{ij}^{-opt}$ ($j = k_i + 1, k_i + 2, \ldots, n$) can be obtained from model (7). Based on the solutions from model (7), the other submodel can be formulated and solved in the second step. Solutions of $x_{ij}^{opt}$ ($j = 1, 2, \ldots, k_i$, $x_{ij}^{opt} \leq x_{ij}^{-opt}$) and $x_{ij}^{-opt}$ ($j = k_i + 1, k_i + 2, \ldots, n$, $x_{ij}^{opt} \geq x_{ij}^{-opt}$) can then be obtained. By combining the solutions from the two submodels, the final solutions for RIFP-SIRA will be obtained as a set of intervals:

$$x_{ij}^{opt} = [x_{ij}^{opt}, x_{ij}^{-opt}]$$

(8a)

$$f_i^{opt} = [f_i^{opt}, f_i^{opt}]$$

(8b)
3. Integrated framework and modeling formulation for sustainable watershed development

An integrated modeling framework founded on advanced systems analysis methods is proposed in this study to support decision making for sustainable watershed management. It can offer a holistic view and scientific basis for analyzing dynamic interactions among system components, activities and factors, tackling multiple formats of uncertainties, examining tradeoffs among conflicting targets, incorporating perspectives of different groups, reflecting impacts from human behaviors and environmental conditions/standards, and providing policy responses in watersheds. The analytical framework is illustrated in Fig. 1.

As the core of the above framework, a RIFP-SIRA model is proposed in this research for facilitating the identification of long-term management strategies for sustainable development at a watershed scale. The objective of this model is to maximize the total economic revenues obtained in a watershed over the planning horizon, which include those from primary, secondary and tertiary industries. The objective function is restrained by four categories of constraints. They are economic, resources, environmental and technical constraints. The decision variables include areas of crop

![Fig. 1. Methodological framework.](image-url)
farms, areas of fishery farms, areas of expanded forests, populations of bred livestock, production of the secondary industries, and production of the tertiary industries. The formulation of the model is presented as follows:

Objective function

\[
\text{Max } F^* = \sum_{u=1}^{q} \sum_{i=1}^{t} \sum_{j=1}^{l_u} \left( NY_i \cdot \rho_i \cdot AGRINC_{u ij} \cdot AGRAREA_{u ij} \right) \\
+ \sum_{u=1}^{q} \sum_{i=1}^{t} \sum_{j=1}^{l_u} \left( NY_i \cdot \rho_i \cdot LIVINC_{u ij} \cdot LIVAREA_{u ij} \right) \\
+ \sum_{u=1}^{q} \sum_{i=1}^{t} \sum_{j=1}^{l_u} \left( NY_i \cdot \rho_i \cdot FINC_{u ij} \cdot FAREA_{u ij} \right) \\
+ \sum_{u=1}^{q} \sum_{i=1}^{t} \sum_{j=1}^{l_u} \left( NY_i \cdot \rho_i \cdot IND_{u ij} \right) \\
+ \sum_{u=1}^{q} \sum_{i=1}^{t} \sum_{j=1}^{l_u} \left( NY_i \cdot \rho_i \cdot TRD_{u ij} \right) \\
\] (9a)

where \( F \) is the total system revenue; \( U \) is the index for subareas, \( u = 1, 2, ..., q; I \) is the index for periods, \( i = 1, 2, ..., t; J \) is the index for economic activities | For cultivation activities, \( j = 1, 2, ..., l_u; \) for livestock husbandry activities, \( j = 1, 2, ..., l_u; \) for forestry activities, \( j = 1, 2, ..., l_u; \) for fishery activities (i.e., fish and prawn farming), \( j = 1, 2, ..., l_u; \) for secondary industrial activities (e.g., manufacturing, mining, architecture, transportation and others), \( j = 1, 2, ..., l_u; \) and for tertiary industrial activities (e.g., retail, wholesale, tourism, and others), \( j = 1, 2, ..., l_u; \) \( NY_i \) is the net worth of period \( i \) yr; \( \rho_i \) is the discount factor for obtaining the present value of the revenue in period \( i \) [21] in this study, the discount factor for each year was calculated as \( \beta_i = 1/(1 + \alpha - \varepsilon)^i \), where \( \alpha \) and \( \varepsilon \) are the annual interest and inflation rates, respectively, and \( \tau \) denotes the \( \text{th} \) year over the planning horizon. The discount factor for a certain period was thus an average for those of the years involved; \( AGRAREA_{u ij} \) is the land area of crop \( j \) planted in subarea \( u \) in period \( i \) (km²/yr); \( AGRINC_{u ij} \) is the net unit revenue of crop \( j \) for subarea \( u \) in period \( i \) (¥10⁴/ha); \( LIVINC_{u ij} \) is the unit net revenue of livestock \( j \) in subarea \( u \) in period \( i \) (¥10⁴/ha); \( LIVAREA_{u ij} \) is the population of livestock \( j \) in subarea \( u \) in period \( i \) (10⁴ heads/yr); \( FINC_{u ij} \) is the unit net revenue of forest type \( j \) in subarea \( u \) in period \( i \) (¥10⁴/ha²); \( FAREA_{u ij} \) is the extension area of forest type \( j \) in subarea \( u \) in period \( i \) (km²²); \( IND_{u ij} \) is the output value of secondary industry \( j \) in subarea \( u \) in period \( i \) (¥10⁴/yr); \( TRD_{u ij} \) is the output value of tertiary industry \( j \) in subarea \( u \) in period \( i \) (¥10⁴/yr).

subject to:

(1) Production constraints

(1a) Agricultural production constraints

\[
\sum_{u=1}^{q} \sum_{j=1}^{l_u} C_{ZW_{u ij}} \cdot (1 + ARATL_{u ij}) \leq \sum_{u=1}^{q} \sum_{j=1}^{l_u} C_{ZW_{u(i+1)j}} \quad \forall i \quad (9b)
\]

where \( C_{ZW_{u ij}} \) is the net revenue of agriculture \( j \) in subarea \( u \) in period \( i \) (¥10⁴/yr), \( C_{ZW_{u(i+1)j}} \) = \( NY_i * AGRINC_{u ij} * AGRAREA_{u ij} + NY_i * LIVINC_{u ij} * LIVAREA_{u ij} + NY_i * FINC_{u ij} * FAREA_{u ij} \), \( ARATL_{u ij} \) is the minimum increase rate of agricultural output value in subarea \( u \) from period \( i \) to period \( i + 1 \)%; \( ARATL_{u(i+1)j} \) is the minimum increase rate of agricultural output value in subarea \( u \) from period \( i \) to period \( i + 1 \)%.

(1b) Secondary industry scale constraints

\[
\sum_{u=1}^{q} \sum_{j=1}^{l_u} IND_{u ij} \leq CIN_{u ij} \quad \forall i, j \quad (9d)
\]

\[
IND_{u(i+1)j} \geq IND_{u ij} \quad \forall u, i, j \quad (9e)
\]

where \( CIN_{u ij} \) is the maximum allowable production for secondary industry \( j \) in subarea \( u \) in period \( i \) (¥10⁴/yr).

(1c) Secondary industry production constraints

\[
\sum_{u=1}^{q} \sum_{j=1}^{l_u} IND_{u ij} \cdot (1 + IRATL_{u ij}) \leq \sum_{u=1}^{q} \sum_{j=1}^{l_u} IND_{u(i+1)j} \quad \forall i \quad (9f)
\]

\[
\sum_{u=1}^{q} \sum_{j=1}^{l_u} IND_{u ij} \cdot (1 + IRATL_{u ij}) \geq \sum_{u=1}^{q} \sum_{j=1}^{l_u} IND_{u(i+1)j} \quad \forall i \quad (9g)
\]

where \( IRATL_{u ij} \) is the minimum increase rate of secondary industries’ output value in subarea \( u \) from period \( i \) to period \( i + 1 \); \( IRATL_{u(i+1)j} \) is the maximum increase rate of secondary industries’ output value in subarea \( u \) from period \( i \) to period \( i + 1 \)%.

(1d) Tertiary industry production constraints

\[
\sum_{u=1}^{q} \sum_{j=1}^{l_u} TRD_{u ij} \cdot (1 + TRATL_{u ij}) \leq \sum_{u=1}^{q} \sum_{j=1}^{l_u} TRD_{u(i+1)j} \quad \forall i \quad (9h)
\]

\[
\sum_{u=1}^{q} \sum_{j=1}^{l_u} TRD_{u ij} \cdot (1 + TRATL_{u ij}) \geq \sum_{u=1}^{q} \sum_{j=1}^{l_u} TRD_{u(i+1)j} \quad \forall i \quad (9i)
\]

where \( TRATL_{u ij} \) is the minimum increase rate of tertiary industries’ output value in subarea \( u \) from period \( i \) to period \( i + 1 \); \( TRATL_{u(i+1)j} \) is the maximum increase rate of tertiary industries’ output value in subarea \( u \) from period \( i \) to period \( i + 1 \)%.

(2) Resources constraints

(2a) Water supply—demand balance constraints
\[ \sum_{u=1}^{q} \left[ \sum_{j=1}^{l_u} \left( \text{WATAGR}_{uji} \times \text{AGRAREA}_{uji} \right) + \sum_{j=1}^{l_u} \left( \text{WATLIV}_{uji} \times \text{LIV}_{uji} \right) \right] + \text{FLIM}^x_u \leq \text{MAXWAT}_u \quad \forall i \]  

(9j)

where \( \text{WATAGR}_{uji} \) is the unit water demand for irrigating crop \( j \) in subarea \( u \) in period \( i \) (m\(^3\)/km\(^2\)); \( \text{WATLIV}_{uji} \) is the unit water demand of livestock \( j \) in subarea \( u \) in period \( i \) (m\(^3\)/10\(^4\) heads); \( \text{WAT}_{uji} \) is the unit water demand of forest type \( j \) in subarea \( u \) in period \( i \) (m\(^3\)/km\(^2\)); \( \text{WATFIS}_{uji} \) is the unit water demand of fishery type \( j \) in subarea \( u \) in period \( i \) (m\(^3\)/km\(^2\)); \( \text{WATIN}_{uji} \) is the unit water demand of secondary industry \( j \) in subarea \( u \) in period \( i \) (m\(^3\)/km\(^2\)); \( \text{WATTRA}_{uji} \) is the unit water demand of tertiary industry \( j \) in subarea \( u \) in period \( i \) (m\(^3\)/10\(^4\) heads); \( \text{MAXWAT}_u \) is the total available water resources for economic activities in period \( i \) (m\(^3\)/yr).

(2b) Cultivation land constraints

\[ \sum_{j=1}^{l_u} \text{AGRAREA}_{uji} \leq \text{CAGC}_{uji} \quad \forall u, i \]  

(9k)

\[ \sum_{j=1}^{l_u} \text{AGRAREA}_{uji} \geq \text{AGC}_{uji} \quad \forall u, i \]  

(9l)

where \( \text{CAGC}_{uji} \) is the maximum available land area for crop cultivation in subarea \( u \) in period \( i \) (km\(^2\)/yr); \( \text{AGC}_{uji} \) is the basic farmland area for crop cultivation in subarea \( u \) in period \( i \) (km\(^2\)/yr).

(2c) Agricultural land constraints

\[ \sum_{j=1}^{l_u} \text{AGRAREA}_{uji} + \sum_{j=1}^{l_u} \text{FAREA}_{uji} \leq \text{CAF}_{uji} \quad \forall u, i \]  

(9m)

where \( \text{CAF}_{uji} \) is the maximum allowable land area for crop cultivation and forestry in subarea \( u \) in period \( i \) (km\(^2\)/yr).

(2d) Forest expansion area constraints

\[ \sum_{j=1}^{l_u} \left( \text{FAREA}_{uji} \times \text{NY}_{uji} \right) \leq \text{FLEM}^z_u \quad \forall u \]  

(9n)

\[ \sum_{j=1}^{l_u} \text{FAREA}_{uji} \geq \text{FREQ}_{uji} \quad \forall u, i \]  

(9o)

where \( \text{FLEM}^z_u \) is the maximum allowable land area for forest extension in subarea \( u \) over the planning horizon (km\(^2\)); \( \text{FREQ}_{uji} \) is the minimum forest extension area in subarea \( u \) in period \( i \) (km\(^2\)/yr).

(2e) Fishery area constraints

\[ \sum_{j=1}^{l_u} \sum_{i=1}^{q} \text{FISAREA}_{uji} \leq \text{FISLIM}_{uji} \quad \forall u, i \]  

(9p)

\[ \sum_{j=1}^{l_u} \sum_{i=1}^{q} \text{FISAREA}_{uji} \geq \text{FISREQ}_{uji} \quad \forall u, i \]  

(9q)

where \( \text{FISLIM}_{uji} \) is the maximum allowable fishery area in period \( i \) (km\(^2\)/yr); \( \text{FISREQ}_{uji} \) is the minimum fishery area in subarea \( u \) in period \( i \) (km\(^2\)/yr).

(2f) Livestock husbandry constraints

\[ \sum_{u=1}^{q} \sum_{i=1}^{q} \text{LIV}_{uji} \leq \text{LIVCAP}_{uji} \quad \forall i, j \]  

(9r)

\[ \sum_{u=1}^{q} \sum_{i=1}^{q} \text{LIV}_{uji} \geq \text{LIVREQ}_{uji} \quad \forall i, j \]  

(9s)

where \( \text{LIVCAP}_{uji} \) is the husbandry capacity of livestock \( j \) in period \( i \) (heads/yr); \( \text{LIVREQ}_{uji} \) is the minimum requirements for livestock \( j \) in period \( i \) (heads/yr).

(3) Environmental constraints

(3a) Soil-loss-related nitrogen loss constraints

\[ \sum_{j=1}^{l_u} \left( \text{AN}^z_{ui} \times \text{AS}_{uij} \times \text{AGRAREA}_{uji} \right) \leq \text{CAN}_{ui} \quad \forall u, i \]  

(9t)

where \( \text{AN}^z_{ui} \) is the nitrogen content of soil in subarea \( u \) in period \( i \) (%); \( \text{AS}_{uij} \) is the soil loss caused by agricultural activity \( j \) in subarea \( u \) in period \( i \) (kg/km\(^2\)); \( \text{CAN}_{ui} \) is the maximum allowable nitrogen loss from agricultural activities in subarea \( u \) in period \( i \) (kg/yr).

(3b) Soil-loss-related phosphorus loss constraints

\[ \sum_{j=1}^{l_u} \left( \text{AP}^z_{ui} \times \text{AS}_{uij} \times \text{AGRAREA}_{uji} \right) \leq \text{CAP}_{ui} \quad \forall u, i \]  

(9u)

where \( \text{AP}^z_{ui} \) is the phosphorus content of soil in subarea \( u \) in period \( i \) (%); \( \text{AS}_{uij} \) is the soil loss caused by agricultural activity \( j \) in subarea \( u \) in period \( i \) (kg/km\(^2\)); \( \text{CAP}_{ui} \) is the maximum allowable phosphorus loss from agricultural activities in subarea \( u \) in period \( i \) (kg/yr).

(3c) Dissolved nitrogen loss constraints:

\[ \sum_{j=1}^{l_u} \left( \text{AGRAREA}_{uji} \times \text{RN}_{uji} \right) + \sum_{j=1}^{l_u} \left( \text{FISAREA}_{uji} \times \text{FN}_{uji} \right) \leq \text{DISN}_{ui} \quad \forall u, i \]  

(9v)

where \( \text{RN}_{uji} \) is the dissolved nitrogen loss with agricultural runoff from the land planted with crop \( j \) in subarea \( u \) in period \( i \) (kg/km\(^2\)/yr); \( \text{DISN}_{ui} \) is the dissolved nitrogen loss from fishery type \( j \) in subarea \( u \) in period \( i \) (kg/km\(^2\)/yr); \( \text{DISN}_{ui} \) is the maximum allowable dissolved nitrogen loss in subarea \( u \) in period \( i \) (kg/yr).

(3d) Dissolved phosphorus loss constraints:

\[ \sum_{j=1}^{l_u} \left( \text{AGRAREA}_{uji} \times \text{RP}_{uji} \right) + \sum_{j=1}^{l_u} \left( \text{FISAREA}_{uji} \times \text{FP}_{uji} \right) \leq \text{DISP}_{ui} \quad \forall u, i \]  

(9w)

where \( \text{RP}_{uji} \) is the dissolved phosphorous loss with agricultural runoff from the land planted with crop \( j \) in subarea \( u \) in period \( i \) (kg/km\(^2\)/yr); \( \text{DISP}_{ui} \) is the dissolved phosphorous loss from fishery type \( j \) in subarea \( u \) in period \( i \) (kg/km\(^2\)/yr); \( \text{DISP}_{ui} \) is the maximum
allowable dissolved phosphorus loss in subarea $u$ in period $i$ (kg/yr):

(3e) COD discharge constraints

$$
\sum_{i=1}^{g} \sum_{j=1}^{l} \left( IC_{ij}^{\pm} * IND_{uij}^{\pm} \right) + \sum_{j=1}^{l} \left( TC_{ij}^{\pm} * TRD_{uij}^{\pm} \right) $$

$$+ \sum_{j=1}^{l} \left( FISC_{ij}^{\pm} * FISAREA_{uij}^{\pm} \right) + \sum_{j=1}^{l} \left( LIVC_{ij}^{\pm} * LIV_{uij}^{\pm} \right)$$

$$\leq MAXCOD_{ij} \forall i$$

(9x)

where $IC_{ij}$ is the COD discharge from secondary industry $j$ in period $i$ (kg/10^4); $TC_{ij}$ is the COD discharge from tertiary industry $j$ (kg/10^4); $FISC_{ij}$ COD discharge from fishery type $j$ (kg/km²); $LIVC_{ij}$ COD discharge from livestock $j$ (kg/10^4 head); $MAXCOD_{ij}$ maximum allowable COD discharge from economic activities in period $i$ (kg/yr).

(4) Technical constraints

$$AGRAREA_{uij}^{\pm} \geq 0 \forall u, i, j$$

(9y)

$$LIV_{uij}^{\pm} \geq 0 \forall u, i, j$$

(9z)

$$FAREA_{uij}^{\pm} \geq 0 \forall u, i, j$$

(9a)

$$FISAREA_{uij}^{\pm} \geq 0 \forall u, i, j$$

(9ab)

4. Application to the He River Basin

4.1. Overview of the study area

The study area, Yongxin County, is located in the southwestern part of China’s Jiangxi Province, ranging from 113°50’ to 114°19’ in longitude, and from 26°47’ to 27°14’ in latitude (Fig. 2). With a total area of 2194.6 km², Yongxin County is located at the middle and upper reaches of the He River Basin. As a tributary of the Ganjiang River, the He River has a total length of 225.0 km, with 77.0 km flowing from west to east across Yongxin County. The majority of water in the Yongxin County comes from the He River. The annual surface water yield in the River is 1.8 billion m³, and annual groundwater storage is 286.0 million m³. The study area has subtropical monsoon humid climate with an average annual temperature of 18.2°C. The average annual evaporation for the area is 1089.6 mm. The County is occasionally subject to natural disasters such as droughts and floods. Of the total land within the County, 71.4% belongs to mountainous terrain. There are several major soil types in this County, including paddy, meadow, red, limestone, purple, mountain yellow, mountain red, mountain red-brown, and mountain meadow soil. As a combination of several types of soil, paddy accounts for the majority of the County’s farmland.

The total population of Yongxin County reached 0.51 million, which is expected to grow at a rate of 7.0‰ per year in the future. Economy booming was considered as the top priority in the provincial strategic plans over the past ten years, and the development
of secondary and tertiary industries has been accelerated. The rapid urbanization process and population growth have been exerting great pressures on local environment and ecosystems due to water resources extraction and environmental pollution. The two major environmental issues are soil erosion and water pollution. A total of 434.0 km² of land in the County has been subject to soil erosion, and pollutant discharge credits) among varied economic activities to obtain the most economic profitability.

Thus, many challenging questions arise, such as "how to achieve sustainable development in Yongxin County. Notwithstanding a number of effective solutions to issues such as economic structure adjustment and land use optimization from a systematic point of view. Effective measures (e.g., restricting fertilizer applications) could be implemented to address these problems, the most effective and fundamental way to achieve sustainable development is to identify effective solutions to issues such as economic structure adjustment and land use optimization from a systematic point of view. Thus, many challenging questions arise, such as "how to achieve certain water quality standards, while minimizing the possible impairments to the economical and social benefits of water use?", "how to optimally allocate limited resources (e.g., water resources, land, and pollutant discharge credits) among varied economic activities to obtain the most economic profits?", "what if an
Table 2
Water demands by various economic activities.

<table>
<thead>
<tr>
<th>Economic Activity</th>
<th>Period 1</th>
<th>Period 2</th>
<th>Period 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farming (10^3 m^3/km^2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paddy</td>
<td>(698 ± 56), (789 ± 63)</td>
<td>(646 ± 58), (729 ± 66)</td>
<td>(596 ± 60), (673 ± 67)</td>
</tr>
<tr>
<td>Dry</td>
<td>(144 ± 12), (163 ± 13)</td>
<td>(136 ± 12), (153 ± 14)</td>
<td>(128 ± 13), (144 ± 14)</td>
</tr>
<tr>
<td>Fruit/vegetable</td>
<td>(209 ± 17), (236 ± 19)</td>
<td>(204 ± 18), (230 ± 21)</td>
<td>(185 ± 18), (209 ± 21)</td>
</tr>
<tr>
<td>Livestock (10^2 m^3/10^4 heads)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hogs</td>
<td>(450 ± 36), (540 ± 43)</td>
<td>(450 ± 41), (540 ± 49)</td>
<td>(450 ± 45), (540 ± 54)</td>
</tr>
<tr>
<td>Cattle</td>
<td>(750 ± 60), (900 ± 72)</td>
<td>(750 ± 68), (900 ± 81)</td>
<td>(750 ± 73), (900 ± 90)</td>
</tr>
<tr>
<td>Poultry</td>
<td>(38 ± 3), (45 ± 4)</td>
<td>(38 ± 4), (45 ± 5)</td>
<td>(38 ± 4), (45 ± 5)</td>
</tr>
<tr>
<td>Forestry (m^3/km^2)</td>
<td>(942 ± 75), (1140 ± 91)</td>
<td>(936 ± 84), (1113 ± 102)</td>
<td>(930 ± 93), (1125 ± 113)</td>
</tr>
<tr>
<td>Fishery (10^2 m^3/km^2)</td>
<td>(900 ± 72), (1161 ± 93)</td>
<td>(899 ± 81), (1160 ± 104)</td>
<td>(898 ± 90), (1159 ± 116)</td>
</tr>
<tr>
<td>Industrial activities (m^3/10^4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mining</td>
<td>(98 ± 8), (111 ± 9)</td>
<td>(91 ± 8), (103 ± 9)</td>
<td>(79 ± 8), (90 ± 9)</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>(117 ± 9), (132 ± 11)</td>
<td>(109 ± 10), (121 ± 11)</td>
<td>(95 ± 10), (107 ± 11)</td>
</tr>
<tr>
<td>Construction</td>
<td>(88 ± 7), (99 ± 8)</td>
<td>(82 ± 7), (92 ± 8)</td>
<td>(71 ± 7), (80 ± 8)</td>
</tr>
<tr>
<td>Transportation</td>
<td>(52 ± 4), (59 ± 5)</td>
<td>(48 ± 4), (55 ± 5)</td>
<td>(42 ± 4), (48 ± 5)</td>
</tr>
<tr>
<td>Others</td>
<td>(73 ± 6), (82 ± 7)</td>
<td>(68 ± 6), (77 ± 7)</td>
<td>(59 ± 6), (67 ± 7)</td>
</tr>
<tr>
<td>Tertiary (m^3/10^4)</td>
<td>(29 ± 2), (33 ± 3)</td>
<td>(27 ± 2), (31 ± 3)</td>
<td>(25 ± 3), (28 ± 3)</td>
</tr>
</tbody>
</table>

4.2. Data collection and processing

Extensive data with social, economic, physical, chemical, biological, legal, water quantity/quality, resources, land availability, and planning implications were collected through a variety of means, including field investigation, public participation, literature review, and hydrological simulation. Experts, officials and analysts were widely consulted. Questionnaire surveys were undertaken to reflect varied opinions, interests, and objectives from different stakeholder groups, such as decision makers and farmers. Economic and technical data used in analysis were also supplemented by a comprehensive review of governmental reports, local authorities’ technical documents, as well as representative published articles focusing on the County (Chen et al., 2009; JBQTS, 2011; Mance, 2007; Murray and Ray, 2010; SEPA, 2002; Yan et al., 1999; Zhang and Wang, 2002). Meanwhile, the University of Regina Hydrological Model (URHM) was utilized to aid in the forecasting of available water resources in the study watershed over the planning horizon. URHM is a simulation model particularly developed for the study watershed by the Environmental Informatics Laboratory (EIL) at the University of Regina, Canada (Huang et al., 2006). The model aims at hydrologic forecasting and long-term hydrological simulation using distributed precipitation data. The processes modeled evapotranspiration, interception, infiltration, snow accumulation and ablation, interflow, groundwater flow, and overland and channel routing.

The quality of collected data could not allow the parameters to be determined either precisely or with exact probabilistic distributions. To closely reflect real-world complexities and avoid losses of valuable information, all of the parameters were thus inputted with uncertain values. Corresponding to the varieties in data source and quality, these uncertain parameters were categorized into different formats. The study area was divided into five subareas for the planning based on natural and socio-economic similarities and administrative jurisdictions, as shown in Fig. 2. The entire planning horizon involves fifteen years which fall within three periods. The collected data were thus synthesized pertaining to the five subareas and three periods.

Table 1 presents the revenues gained from varied economic activities. The economic data listed in the table are the net values (i.e., Chinese yuan). Tables 2–6 present the parameters regarding environmental impacts and resources consumptions of various economic activities. These parameters are associated with factors that are related to climatic and hydrological conditions, soil properties, erosion, and nutrient transport. Specifically, Table 2 displays the water demands by various economic activities. Table 3 presents the total amount of available water resources in the planning period. Subarea 4 would have the least water among the five subareas due to its largest and densest population and serious water pollution problems. The maximum available land areas for crop cultivation and forest expansion in each period are presented in Table 3 below:

Table 3
Total available water resources (10^5 m^3/yr).

<table>
<thead>
<tr>
<th>Subarea</th>
<th>Period 1</th>
<th>Period 2</th>
<th>Period 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subarea 1</td>
<td>(277 ± 17), (294 ± 18)</td>
<td>(258 ± 18), (274 ± 19)</td>
<td>(250 ± 20), (264 ± 21)</td>
</tr>
<tr>
<td>Subarea 2</td>
<td>(499 ± 30), (530 ± 32)</td>
<td>(464 ± 32), (493 ± 35)</td>
<td>(449 ± 36), (476 ± 38)</td>
</tr>
<tr>
<td>Subarea 3</td>
<td>(480 ± 29), (510 ± 31)</td>
<td>(447 ± 31), (475 ± 33)</td>
<td>(433 ± 35), (458 ± 37)</td>
</tr>
<tr>
<td>Subarea 4</td>
<td>(185 ± 11), (196 ± 12)</td>
<td>(172 ± 12), (183 ± 13)</td>
<td>(166 ± 13), (176 ± 14)</td>
</tr>
<tr>
<td>Subarea 5</td>
<td>(406 ± 24), (431 ± 26)</td>
<td>(378 ± 26), (402 ± 28)</td>
<td>(366 ± 29), (388 ± 31)</td>
</tr>
<tr>
<td>Total Subarea 4</td>
<td>(1847 ± 111), (1961 ± 118)</td>
<td>(1719 ± 120), (1827 ± 128)</td>
<td>(1664 ± 133), (1762 ± 141)</td>
</tr>
</tbody>
</table>
respectively. In the entire study area, a total area of 76.0 km² was
This planning problem, the proposed RIFP-SIRA approach was
secondary and tertiary industrial activities. Tables 7 and 8 present
properties, and are not significantly affected by cropping,
manuring, and fertilizing patterns (Haith, 1982; Yoshinaga et al.,
2007). In the study area, the amounts of nitrogen and phosphorus
released into water bodies account for 0.22, 0.25 and 0.09, 0.13%
of the total lost soil mass, respectively. The concentrations of dis-
solved nutrients in agricultural runoff are primarily affected by crop
types, as shown in Table 5. The dissolved nutrient discharges from
fishery activities are also listed in this table. Table 6 shows the COD
discharging coefficients in fish farming, livestock husbandry, and
secondary and tertiary industrial activities. Tables 7 and 8 present
the environmental restraints of the study area. These controlling
parameters depend on water quality management objectives, dis-
charging regulations, pollution loads, assimilative capacities of the
receiving water bodies, and capacities of the treatment facilities. For example, corresponding to different surface water quality
standards adopted in the study area, these restraint parameters
would take different values. In detail, Table 7 shows the maximum
allowable nitrogen and phosphorus losses over the planning hori-
zon. The maximum amounts of COD discharges allowed for the
subareas in the three periods are shown in Table 8.

4.3. Policy analysis

Given the variety of uncertainties and complexities involved in
this planning problem, the proposed RIFP-SIRA approach was
deemed applicable. It allowed the direct communication of a variety of uncertainties (i.e., intervals with fuzzy bounds/fluxuation
radii and crisp intervals) into the optimization process and
resulting solutions. Three scenarios were identified according to
varied development priorities of the study area as well as different
policies regarding the trade-offs between agricultural/industrial
production and eco-environmental protection. They are: (a) Scen-
ario 1 — the improvement of water quality is considered to be a
priority in the study area in the upcoming fifteen years. Under this
scenario, targets of high standard water quality are to be set. Also,
various policies and regulations for controlling soil loss and mitig-
gating pollutant discharge would be implemented. Since environ-
mental protection is to be emphasized under this scenario, only
passive economic development schemes would be allowed. At the
same time, the development of high-pollution economic activities
would probably be hindered, with economic returns being possibly reduced; (b) Scenario 2 — decision makers have no preferences on
either environmental protection or economic development, rep-
resenting a neutral policy. This scenario targets at maintaining a
balance between economic and eco-environmental objectives.
Moderate schemes on both pollution control and economic growth
can be expected; and (c) Scenario 3 — economic development ac-
celeration would still be the priority in the future, while eco-
environmental conservation has to be placed in a less important
position. Under this scenario, preferential policies on issues such as
emission credits are to be adopted, and some resources and cap-
sules of system feasibility are elaborated. The results obtained under
other scenarios can be similarly interpreted. Under scenario 2, the
total revenue gained from the economic activities in the fifteen years
would be $[36.80, 51.16] billion. All of the sectors would have an
increase in the revenues over the planning horizon. Fig. 3(a) exhib-
its that the contribution of the agricultural sector to the total
value would slightly decrease as time lapses, while those of the
other sectors would be on the rise. Fig. 4 shows the land-use plans
for crop cultivation at the five subareas over the planning horizon.
Paddy farm would remain to be the main type of farmland over the
planning horizon. In the entire County, the areas of paddy and fruit/
vegetable farm would gradually decrease over periods 1—3. In
contrast, the total cultivated area of dry farm would be on the rise.
Increasing livestock populations and revenues could be expected
over the planning horizon. In the entire study area, the total pop-
ulation of hogs would moderately ascend over the planning hori-
zon, while the populations of cattle and poultry would be greatly
raised. A sharp decline followed by a moderate climb would be
observed for the total area of expanded forest as well as the asso-
ciated revenues. Among the five subareas, subareas 2 and 3 would
play the most important role in forestry expansions over the
planning years, whereas subarea 4 would have the least new for-
estlands. As for fishery farming, the total area of fishery farm as well as the revenues from fishery would be on the rise over the planning horizon. Detailed production patterns in the secondary industrial
sector of each subarea are illustrated in Fig. 5. Among the five
subareas, subarea 2 would have the highest industrial production
over the planning horizon. In the tertiary industrial sector, an
increasing trend for the production of tertiary industries would be
observed over the planning horizon in all of the five subareas under

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**Table 4.** The total areas of land in the five subareas that can be used for forest expansion over the planning horizon are [93.4, 105.9], [125.1, 140.7], [170.1, 195.2], [46.7, 53.0] and [93.4, 105.9] km², respectively. In the entire study area, a total area of [76.0, 85.0] km² of water surface can be used for fishery per year. Contents of solid-phase nitrogen and phosphorus in soil mainly depend on soil properties, and are not significantly affected by cropping, manuring, and fertilizing patterns (Haith, 1982; Yoshinaga et al., 2007). In the study area, the amounts of nitrogen and phosphorus released into water bodies account for [0.22, 0.25] and [0.09, 0.13]% of the total lost soil mass, respectively. The concentrations of dissolved nutrients in agricultural runoff are primarily affected by crop types, as shown in Table 5. The dissolved nutrient discharges from fishery activities are also listed in this table. Table 6 shows the COD discharging coefficients in fish farming, livestock husbandry, and secondary and tertiary industrial activities. Tables 7 and 8 present the environmental restraints of the study area. These controlling parameters depend on water quality management objectives, discharging regulations, pollution loads, assimilative capacities of the receiving water bodies, and capacities of the treatment facilities. For example, corresponding to different surface water quality standards adopted in the study area, these restraint parameters would take different values. In detail, Table 7 shows the maximum allowable nitrogen and phosphorus losses over the planning horizon. The maximum amounts of COD discharges allowed for the subareas in the three periods are shown in Table 8.

**Table 5.** Dissolved nitrogen and phosphorus discharge coefficient (kg/km²/yr).

<table>
<thead>
<tr>
<th></th>
<th>Period 1</th>
<th>Period 2</th>
<th>Period 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disolved nitrogen discharge coefficient</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paddy farm</td>
<td>[550, 715]</td>
<td>[519, 674]</td>
<td>[496, 644]</td>
</tr>
<tr>
<td>Dry farm</td>
<td>[800, 1039]</td>
<td>[754, 980]</td>
<td>[721, 936]</td>
</tr>
<tr>
<td>Fruit/vegetable farm</td>
<td>[400, 520]</td>
<td>[377, 490]</td>
<td>[360, 468]</td>
</tr>
<tr>
<td>Fishery farming</td>
<td>[417, 559]</td>
<td>[4035, 5484]</td>
<td>[3952, 5337]</td>
</tr>
<tr>
<td>Disolved phosphorus discharge coefficient</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paddy farm</td>
<td>[50, 65]</td>
<td>[47, 61]</td>
<td>[45, 59]</td>
</tr>
<tr>
<td>Dry farm</td>
<td>[125, 162]</td>
<td>[118, 153]</td>
<td>[113, 146]</td>
</tr>
<tr>
<td>Fruit/vegetable farm</td>
<td>[60, 78]</td>
<td>[57, 74]</td>
<td>[54, 70]</td>
</tr>
<tr>
<td>Fishery farming</td>
<td>[580, 783]</td>
<td>[568, 767]</td>
<td>[557, 752]</td>
</tr>
</tbody>
</table>

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advantageous conditions. However, under disadvantageous condition, there would be a number of differences among the subareas. For example, from periods 2 to 3, subareas 1 and 2 would have increased production value from tertiary industries; comparatively, the tertiary industrial production value would descend in the other subareas.

The three scenarios corresponding to varied priorities and policies would differ in the total economic revenue gained within the upcoming fifteen years. Scenarios 1 and 3 would be associated with the lowest and highest total system revenue due to the most and least rigorous environmental policies, respectively. In period 3, the differences under scenarios 1 and 3 would be the most apparent. Such a climb from scenarios 1 to 3 also applies to the output of each economic sector (Fig. 3(b)). Among the three sectors, the tertiary industrial sector would have the most increase in output values as the environmental regulations gradually relax under scenarios 1—3. This is probably because that the control of COD discharges in the industrial sector have gained great success in recent years, while the mitigation of discharges from the tertiary industrial sector would be more difficult due to its scattering patterns and the associated geographical disparity. Moreover, the high pollutant discharge coefficients of the tertiary industries make them be strictly restricted by the environmental restraints and thus be sensitive to scenario changes.

In terms of the economic structure, contribution ratios of the primary, secondary, and tertiary industries to the total revenue would be different under the three scenarios. The breakdown of the total revenue over the entire planning horizon under each scenario is graphically presented in Fig. 6. Under disadvantageous conditions, the relationship of the three sectors in terms of output contributions would be “agricultures > secondary industries > tertiary industries” under scenario 1, and “secondary industries > tertiary industries > agriculture” under scenarios 2 and 3. Correspondingly, the output value ratio of the primary, secondary, and tertiary sectors would be 4:2:2:1, which is consistent with the decreasing contribution ratio under scenarios 1—3.

Table 6
COD discharge coefficients.

<table>
<thead>
<tr>
<th>Sub-area</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
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<tbody>
<tr>
<td></td>
<td>Period 1</td>
<td>Period 2</td>
<td>Period 3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish farming (10^3 kg/km²)</td>
<td>[74.12 ± 5.93, (96.35 ± 7.71)]</td>
<td>[73.37 ± 6.60, (95.39 ± 8.58)]</td>
<td>[72.63 ± 7.26, (94.42 ± 9.44)]</td>
</tr>
<tr>
<td>Livestock husbandry (10^4 kg/10^4 head)</td>
<td>[48.80 ± 3.90, (54.62 ± 4.37)]</td>
<td>[47.82 ± 4.30, (53.53 ± 4.82)]</td>
<td>[46.85 ± 4.68, (52.43 ± 5.24)]</td>
</tr>
<tr>
<td>Cattle</td>
<td>[69.00 ± 5.52, (8.29 ± 6.04)]</td>
<td>[67.62 ± 6.09, (81.28 ± 7.32)]</td>
<td>[66.24 ± 6.62, (79.62 ± 7.96)]</td>
</tr>
<tr>
<td>Poultry</td>
<td>[0.50 ± 0.04, (0.60 ± 0.05)]</td>
<td>[0.49 ± 0.04, (0.59 ± 0.05)]</td>
<td>[0.48 ± 0.05, (0.58 ± 0.06)]</td>
</tr>
<tr>
<td>Industrial activities (kg/10^8)</td>
<td>[2.16 ± 0.17, (2.92 ± 0.23)]</td>
<td>[2.10 ± 0.19, (2.83 ± 0.25)]</td>
<td>[2.03 ± 0.20, (2.74 ± 0.27)]</td>
</tr>
<tr>
<td>Mining</td>
<td>[1.31 ± 0.26, (4.47 ± 0.36)]</td>
<td>[3.21 ± 0.29, (4.34 ± 0.39)]</td>
<td>[3.11 ± 0.31, (4.20 ± 0.42)]</td>
</tr>
<tr>
<td>Construction</td>
<td>[1.32 ± 0.11, (1.78 ± 0.14)]</td>
<td>[1.28 ± 0.12, (1.73 ± 0.16)]</td>
<td>[1.24 ± 0.12, (1.67 ± 0.17)]</td>
</tr>
<tr>
<td>Transportation</td>
<td>[0.19 ± 0.02, (0.26 ± 0.02)]</td>
<td>[0.17 ± 0.02, (0.24 ± 0.02)]</td>
<td>[0.16 ± 0.02, (0.23 ± 0.02)]</td>
</tr>
<tr>
<td>Others</td>
<td>[0.19 ± 0.02, (0.26 ± 0.02)]</td>
<td>[0.17 ± 0.02, (0.24 ± 0.02)]</td>
<td>[0.16 ± 0.02, (0.23 ± 0.02)]</td>
</tr>
<tr>
<td>Tertiary industry (kg/10^8)</td>
<td>[15.17 ± 1.21, (18.13 ± 1.45)]</td>
<td>[14.78 ± 1.33, (17.69 ± 1.59)]</td>
<td>[13.92 ± 1.39, (17.06 ± 1.71)]</td>
</tr>
</tbody>
</table>

Table 7
Maximum allowable nitrogen and phosphorus losses (10^3 kg/yr).

<table>
<thead>
<tr>
<th>Sub-area</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
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<tbody>
<tr>
<td></td>
<td>Period 1</td>
<td>Period 2</td>
<td>Period 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowable soil-loss-related nitrogen loss</td>
<td>[38.7, 39.8]</td>
<td>[37.9, 39.0]</td>
<td>[37.2, 38.2]</td>
</tr>
<tr>
<td>1</td>
<td>[42.6, 43.8]</td>
<td>[41.7, 42.9]</td>
<td>[40.9, 42.0]</td>
</tr>
<tr>
<td>2</td>
<td>[70.4, 73.3]</td>
<td>[68.9, 75.7]</td>
<td>[78.3, 86.0]</td>
</tr>
<tr>
<td>3</td>
<td>[93.3, 112.1]</td>
<td>[112.8, 127.4]</td>
<td>[110.5, 124.9]</td>
</tr>
<tr>
<td>4</td>
<td>[29.3, 30.1]</td>
<td>[28.7, 29.5]</td>
<td>[32.6, 33.5]</td>
</tr>
<tr>
<td>5</td>
<td>[34.8, 39.1]</td>
<td>[43.6, 44.2]</td>
<td>[42.8, 43.5]</td>
</tr>
<tr>
<td>Allowable soil-loss-related phosphorus loss</td>
<td>[16.8, 18.7]</td>
<td>[16.5, 18.3]</td>
<td>[16.1, 17.9]</td>
</tr>
<tr>
<td>1</td>
<td>[18.5, 20.5]</td>
<td>[18.1, 20.1]</td>
<td>[17.7, 19.7]</td>
</tr>
<tr>
<td>2</td>
<td>[35.5, 39.5]</td>
<td>[34.8, 38.7]</td>
<td>[34.1, 37.9]</td>
</tr>
<tr>
<td>3</td>
<td>[54.0, 60.0]</td>
<td>[52.9, 58.8]</td>
<td>[51.8, 57.6]</td>
</tr>
<tr>
<td>4</td>
<td>[9.7, 10.7]</td>
<td>[10.8, 12.0]</td>
<td>[10.6, 11.8]</td>
</tr>
<tr>
<td>5</td>
<td>[14.8, 16.4]</td>
<td>[17.0, 18.8]</td>
<td>[16.3, 18.1]</td>
</tr>
<tr>
<td>Allowable dissolved nitrogen loss</td>
<td>[41.9, 47.9]</td>
<td>[39.0, 45.6]</td>
<td>[37.0, 43.3]</td>
</tr>
<tr>
<td>1</td>
<td>[45.1, 52.7]</td>
<td>[42.8, 50.1]</td>
<td>[40.7, 47.7]</td>
</tr>
<tr>
<td>2</td>
<td>[92.0, 107.7]</td>
<td>[87.5, 102.4]</td>
<td>[104.4, 122.2]</td>
</tr>
<tr>
<td>3</td>
<td>[64.8, 75.8]</td>
<td>[61.6, 72.1]</td>
<td>[70.7, 82.7]</td>
</tr>
<tr>
<td>4</td>
<td>[76.0, 85.0]</td>
<td>[72.3, 84.6]</td>
<td>[78.9, 92.3]</td>
</tr>
<tr>
<td>5</td>
<td>[140.8, 164.7]</td>
<td>[133.9, 156.7]</td>
<td>[127.3, 149.0]</td>
</tr>
<tr>
<td>Allowable dissolved phosphorus loss</td>
<td>[3.8, 4.2]</td>
<td>[3.3, 4.6]</td>
<td>[2.8, 4.1]</td>
</tr>
<tr>
<td>1</td>
<td>[42.5, 58.0]</td>
<td>[36.5, 41.5]</td>
<td>[31.4, 3.5]</td>
</tr>
<tr>
<td>2</td>
<td>[179.2, 217.9]</td>
<td>[167.1, 197.7]</td>
<td>[155.5, 184.1]</td>
</tr>
<tr>
<td>3</td>
<td>[8.7, 10.7]</td>
<td>[9.8, 11.8]</td>
<td>[8.7, 10.8]</td>
</tr>
<tr>
<td>4</td>
<td>[12.6, 15.2]</td>
<td>[11.6, 14.0]</td>
<td>[10.6, 13.0]</td>
</tr>
<tr>
<td>5</td>
<td>[24.1, 28.0]</td>
<td>[28.2, 32.8]</td>
<td>[26.5, 30.8]</td>
</tr>
</tbody>
</table>
industries would be 39:37:24, 27:44:29, and 26:39:16 under scenarios 1–3, respectively. Under advantageous conditions, the output value ratio of the primary, secondary, and tertiary industries would be 35:41:24, 32:36:32, and 29:32:39 under scenarios 1–3, respectively. When pollutant discharge restraints become less rigid, the production scales of heavy pollution industries would make up increased shares.

The total cultivation areas would increase under scenarios 1–3, as shown in Fig. 7(a). Paddy farm would be the main farmland type under all of the three scenarios. However, as the soil and nutrient constraints become more relaxed, paddy farm would account for a less portion in the total industrial production as was expected; in comparison, construction, transportation and other industries would play a more important role. The changes in livestock husbandry activities with scenarios are displayed in Fig. 7(b). Poultry would have the largest population among the three types of livestock under the three scenarios, and its percentage in the total livestock population would increase as environmental constraints relax. On the contrary, hog would represent a decreasing portion in the total livestock population in the study area under scenarios 1–3. Fig. 7(c) shows the variations in the total forestry and fishery areas under the three scenarios. Fig. 7(d) illustrates the variations in the internal structure of secondary industrial sector under varied scenarios. When pollutant discharge constraints are relaxed, the production scales of heavy pollution industries such as mining and manufacturing would be allowed to expand; in comparison, construction, transportation and other industries that have relatively less pollution problems would tend to account for a reduced portion in the total industrial production as discharge caps are raised at the study area. Under almost all of the cases, manufacturing and construction would be the pillar industries in the study area, which are closely followed by the transportation industry. Other and mining industries would merely share a minor portion in the total production of the secondary industrial sector. The only exception is the case under disadvantageous conditions of scenario 1, where transportation and construction would be the most important industries in the study area.

4.4. Sensitivity analyses

Sensitivity analyses are conducted by changing the level of protection (i.e., risk-aversion level) and the fluctuation level of input parameters. In order to investigate the effects of protection level \( \gamma \) on the modeling results, three sets of \( \gamma \) values at low, medium, and high levels are examined. These sets correspond to different probabilities of system feasibility that are desired in various practical applications. In this study, the low, medium and high protection levels are associated with a probability bound of violation (i.e., the maximum chance that a constraint is violated) at 10, 5, and 1%, respectively. Under the three levels, \( G \) applied to a water supply--demand constraint should be 11.6, 14.5, and 19.3, respectively; and a COD discharge constraint should have a \( G \) value of 9.5, 11.9, and 15.6, respectively, to reach the three protection levels. The specific values of \( G \) indicate the numbers of intervals with fluctuation radii in a constraint that are allowed to fluctuate at their bounds while the constraint remains feasible. Through the proposed RIFF-SIRA model, a high probability of system feasibility could be achieved by merely protecting a minor portion of the interval coefficients in a constraint against uncertain fluctuations. For example, a \( G \) value of 11.6 for the water supply--demand constraints suggests that, merely 16.3% of the total 71 intervals with fluctuation radii in such a constraint need to be protected to make the violation risk be no more than 10%. For all of the cases when up to 11 intervals with fluctuation radii in such a constraint fluctuate around their nominal values, and one more fluctuations at each of its bounds within 0.6 times of the corresponding radius, the model would be deterministically feasible without any system-violation risk. Even if such a limit is exceeded, the constraint would still be satisfied with a no less than 90% chance.

Fig. 8 graphically compares the solutions of objective function value \( f^* \) obtained under the low, medium, and high protection levels. As the level of protection increases, a decline in \( f^* \) would be observed under each scenario. This implies a trade-off between system robustness and benefit. A higher level of protection would increase the chance of system feasibility, but paying a cost of lower system benefit. Specifically, under scenario 1, when the level of protection increases from low to high, \( f^* \) would gradually descend from [23.84, 43.49] billion to [19.53, 43.28] billion and then to [19.12, 43.27] billion. Under scenario 2, \( f^* \) would be [36.80, 51.16], [36.61, 50.94], and [36.61, 50.93] billion when the level of protection is low, medium and high, respectively. Under scenario 3, these values would be [43.24, 59.18], [43.04, 58.74], and [43.04, 58.72] billion corresponding to a low, medium, and high level of protection, respectively. Although trade-offs exist between system robustness and optimality, it is interesting to note that the reduction in system benefit would be minor compared to the significant enhancement in system robustness. For example, when the level of protection increases from low to high under scenario 1, the violation risk of the system could be dramatically reduced by 90% (i.e., the probability bound of violation would drop from 10% to 1% and then to 1%). However, the side effect on system benefit would merely be minor, representing by a [0.51, 19.78]% reduction in \( f^* \) (i.e., from \([23.84, 43.49]\) to \([19.12, 43.27]\) billion). This verifies that

<table>
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<tr>
<th>Subarea</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
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<tbody>
<tr>
<td>Period 1</td>
<td>Period 2</td>
<td>Period 3</td>
<td>Period 1</td>
</tr>
<tr>
<td>1</td>
<td>[1945 ± 117]</td>
<td>[2322 ± 156]</td>
<td>[2353 ± 203]</td>
</tr>
<tr>
<td>2</td>
<td>[825 ± 50]</td>
<td>[946 ± 66]</td>
<td>[1077 ± 86]</td>
</tr>
<tr>
<td>3</td>
<td>[886 ± 53]</td>
<td>[1058 ± 74]</td>
<td>[1306 ± 104]</td>
</tr>
<tr>
<td>4</td>
<td>[1105 ± 66]</td>
<td>[1269 ± 89]</td>
<td>[1441 ± 115]</td>
</tr>
<tr>
<td>5</td>
<td>[1186 ± 71]</td>
<td>[1417 ± 99]</td>
<td>[1747 ± 140]</td>
</tr>
<tr>
<td>Total</td>
<td>[562 ± 34]</td>
<td>[675 ± 47]</td>
<td>[878 ± 67]</td>
</tr>
</tbody>
</table>

Note: high fluctuation.
(a) Breakdown of the total annual revenue (S: scenario).

(b) Comparisons of the sectors’ outputs among the three scenarios

Fig. 3. Annual outputs (AGR: agricultures; IND: secondary industries; TER: tertiary industries).

(b) Upper Bound

Fig. 5. Production patterns in the secondary industrial sector.

Legend:
- Paddy - Lower bound
- Paddy - Upper bound
- Dry - Lower bound
- Dry - Upper bound
- Fruit/Vegetable - Lower bound
- Fruit/Vegetable - Upper bound

Fig. 4. Cropping patterns (A: subarea; P: period).
RIFP-SIRA is able to greatly reduce system-violation risk without a significant deterioration of the system benefit.

Due to the above trade-offs, protection levels could be set to reflect decision makers' preferences and attitudes toward system-violation risks and economic benefits. When decision makers and stakeholders are risk averse, higher protection levels should be adopted to generate conservative watershed development plans, resulting in reduced agricultural profits but increased chances of system feasibility. On the contrary, when decision makers and stakeholders desire to earn more profits due to a tight budget, they would become risk-prone through assigning lower protection levels and adopting aggressive watershed development plans, and thus the risk of impairing water quality and ecological integrity would be raised.

Aside from the sensitivity analysis regarding the level of protection, the sensitivity of the optimal solutions toward the fluctuation level of interval bounds is also investigated. Three fluctuation levels, namely low, medium and high, are involved. A lower fluctuation level implies the circumstances where the lower and upper bounds of an interval coefficient fluctuate around their nominal values within a smaller extent (i.e., a smaller percentage of the respective nominal value), while a higher fluctuation level corresponds to wider fluctuations (e.g., a greater percentage of the respective nominal value). In this study, increasing fluctuation radii of parameters are also taken into account over the planning horizon, considering that future parameter values would be harder and harder to be precisely estimated as time elapses from periods 1 to 3. Fig. 9 shows the variations in the total system benefit with varying fluctuation levels. It is indicated that $f^\pm$ would be higher when the fluctuation level of interval parameters becomes lower. Under scenario 1, $f^\pm$ would be \$[31.75, 46.76], [30.00, 45.10]$ and $[23.84, 43.49]$ billion when the fluctuation level is low, medium and high, respectively. Under scenario 2, $f^\pm$ would decrease from \$[39.80, 54.95]$ to \$[38.28, 53.05]$ billion when the fluctuation level ascends from low to medium, and further drop to \$[36.80, 51.16]$ billion under the low fluctuation level. When the fluctuation level gradually increases from low to high under scenario 3, there would a steady climb in $f^\pm$ from \$[46.73, 63.21]$ to \$[43.24, 59.18]$ billion. Corresponding to the changes in the objective function value, the specific economic activities under these scenarios would also vary among different fluctuation levels. Such results reveal that the fluctuations at the bounds of interval parameters have non-negligible impacts on the model's optimal solutions, which further justify that it is imperative to communicate such intervals with fluctuation radii into the optimization process for generating useful decision schemes.

![Diagram](image1.png)

**Fig. 6.** Breakdown of the total revenue in the fifteen years (Left: lower bound; Right: upper bound).
4.5. Discussions

To sum up, to investigate the effects of different policies on watershed development plans, three scenarios with varied priorities were considered. The results indicated that aggressive economic development policies would be associated with high profits, while paying significant costs of eco-environmental deterioration. In contrast, passive development policies would lead to reduced eco-environmental risks, but might spurn development opportunities. Moreover, three sets of protection levels corresponding to low, medium, and high conservativeness toward system-violation risk in face of uncertainty were exerted to the model. Such sensitivity analyses indicated a trade-off between system feasibility and optimality. It also verified that RIFP-SIRA could be capable of highly enhancing the robustness of solutions without significantly affecting system benefit. Furthermore, the sensitivity of solutions toward low, medium, and high fluctuation levels of interval bounds was also analyzed. The results revealed that the solutions were quite sensitive to such fluctuations, verifying the necessity of tackling such uncertainties and the superiority of RIFP-SIRA.

The outputs of the RIFP-SIRA model could be used by the local authorities in the He River Basin to make well-informed decisions with regard to resources utilization, pollution mitigation and industrial development that could commendably serve local economies and simultaneously reduce the impairments to local eco-environment. They could also provide a scientific basis for economic structure adjustment in the area, and facilitate the initiation of new environmental policies and the improvement of existing measures. Not only the economic benefit, but also the system-violation risk, was quantified for each set of the interval solutions obtained from the RIFP-SIRA model. Such interval solutions could provide local authorities with robust, yet flexible decision plans. These decision plans are robust as they would be resilient to the natural and subjective variability of inputs, and remain optimal under numerous input fluctuation cases. Moreover, they can be adopted with flexibility in executions. Such flexibility is reflected not only throughout scenario development and protection level setting, but also by the tuning of a decision deprived from interval solutions. In general, planning for higher economic revenue over the planning horizon would be associated with intensive development activities in the primary, secondary and tertiary industries in the basin, more resources consumptions, lower pollution abatement targets, more pollutant discharges into the water, and lower water quality objectives. At the same time, such aggressive policies are accompanied by an increased probability of exceeding the acceptable waste-loading levels, impairing water quality, and endangering aquatic ecosystems. On the contrary, conservative policies would lower eco-environmental risks, but lead to less economic revenues and may waste development opportunities when there are spare resources, discharge credits and environmental capacities. With sufficient information on both benefits and risks, decision makers could thus identify a desired development alternative according to system conditions as well as their preferences, management expectations and risk tolerance levels. It is also required that the planning scheme be updated whenever system conditions change significantly. By renewing the modeling inputs according to varied conditions changing with factors such as...
climate change, updated planning schemes for the subsequent periods can be obtained conveniently.

5. Concluding remarks

RIFP-SIRA was developed for supporting the identification of sustainable development strategies in a highly uncertain environment. The developed RIFP-SIRA approach has two major merits that make it unique compared to the other inexact optimization techniques as follows:

Firstly, RIFP-SIRA represented a novel attempt to tackle synergies of non-statistical uncertainties that can be expressed as intervals with fuzzy bounds/ fluctuation radii. Superior to the sensitivity analysis method which could merely provide an individual response to one of the numerous potential input variations, the developed RIFP-SIRA approach could reflect the interactions of uncertain inputs and their synergistic effects on the system. It could remain linear and computationally tractable, although additional constraints and variables would be introduced. This makes it outperform SMP methods which either produce enormous linear problems with only a fraction of uncertain data being considered or generate nonlinear models that are typically intractable. RIFP-SIRA also has advantages over conventional FMP methods in the following two aspects: (i) it has a lower computational burden by utilizing the superiority and inferiority measures instead of various discrete intervals under different α-cut levels to compare fuzzy sets, and (ii) it could enhance system robustness through penalizing the objective for possible constraint violations arising from possibilistic uncertainties. In addition, improving upon conventional IMP methods which tackled a fixed set of interval inputs, RIFP-SIRA could cover numerous interval fluctuation cases. More importantly, RIFP-SIRA could view uncertain parameters from both individual and holistic perspectives, since that not only numerous realizations of an individual uncertain parameter, but also unlimited combinations of different parameters could be included.

Secondly, RIFP-SIRA enabled a quantitative analysis over the trade-offs between the system benefit and system violation-risk in the absence of probability density functions. In large-scale watershed planning problems, the accuracy of a multitude of parameters may vary to a great extent, which means that the estimates of some parameters may be more accurate than the others. Moreover, watershed management is not a zero-tolerance issue since the joint elimination of pollution sources and their environmental impacts is technically impossible. Based on these considerations, a protection function was introduced into RIFP-SIRA to provide a protection against data perturbations, while not causing ultra conservativeness and unnecessary deterioration in system benefits. Improving upon conventional IMP methods, the potential risk of the RIFP-SIRA results could be quantified through changing the protection levels. It could thus allow decision makers to proactively adjust the violation risk of the generated interval solutions to an acceptable level according to site-specific characteristics and stakeholders’ requirements.

Moreover, an integrated modeling framework based on RIFP-SIRA was proposed in this research for supporting sustainable watershed management under uncertainties, particularly within the context of watersheds dominated by agriculture. Social, economic, environmental, hydrologic, physical, chemical, institutional and resources considerations were tied together to constitute an intellectually appealing analytical framework. Elements including systems characterization, data analysis, uncertainty analysis, stakeholder participation, inexact modeling, and scenario and sensitivity analyses were integrated into a general modeling framework. Such a framework is of particular significance for developing countries which are confronted with high population density, fast economic growth, inadequate fund availability, and limited land space. Also, the grasp of non-statistical uncertainties is important for the success of watershed management models which depend on diverse data sources and stakeholder participation, and are characterized with highly imprecise economic and environmental parameters.

The developed methodology has been applied to Yongxin County located in the He River Basin of China. The interrelationships among various watershed system components and driven factors, and the impacts of different policies, human behaviors and environmental standards, as well as their interactions and accompanying uncertainties were analyzed via the proposed RIFP-SIRA framework. Three scenarios were analyzed to investigate the impacts of different policies and standards on watershed development plans. Sensitivity of the model’s solutions to varied risk-aversion and input-fluctuation levels were also analyzed, verifying the superiority of RIFP-SIRA over the existing inexact programming approaches. Interval solutions corresponding to varied policy scenarios and protection levels were generated from the RIFP-SIRA model. With quantitative economic revenues and environmental risks of these interval solutions, the flexibility to tune the decision variable was considerably demonstrated. Decision makers could easily identify the most desired development alternatives according to system conditions as well as their preferences, management expectations and risk tolerance levels.

The model may require modification and customization with the inclusion of site-specific features and data, especially when being applied to other contexts. For example, the absence of a labor

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total Revenue (¥billion)</th>
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<tbody>
<tr>
<td>S1-L</td>
<td>45.00</td>
</tr>
<tr>
<td>S1-U</td>
<td>55.00</td>
</tr>
<tr>
<td>S2-L</td>
<td>25.00</td>
</tr>
<tr>
<td>S2-U</td>
<td>15.00</td>
</tr>
<tr>
<td>S3-L</td>
<td>10.00</td>
</tr>
<tr>
<td>S3-U</td>
<td>60.00</td>
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</table>

Fig. 8. Comparisons of objective function value under varied levels of protection (fluctuation level: high).

Fig. 9. Comparison of objective function value under varied fluctuation levels (protection level: low).
constraint is a simplification of the model. This could be justified in the context of watersheds in developing countries, where labor resources are abundant and normally not the limiting factor in terms of development choices. However, in other regions such as developed countries, the cost of, and access to, labor might be a binding constraint which has to be included. In future research, RIFF-SIRA could be embedded within a decision support system as an ineffect module for facilitating decision making in watershed development.

In general, the results of this case study demonstrate the practicability of the developed RIFF-SIRA approach. In the future, data quality improvement through further investigation, and input data updating under varied climate change impacts, would both be helpful for improving this study. Moreover, customization of the constraints would be necessary for tailoring the RIFF-SIRA model to the site-specific characteristics of other watershed management cases. The RIFF-SIRA approach can also be extended to address many other planning problems containing complex uncertainties.

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