Environ Sci Pollut Res (2017) 24:14980–15000
DOI 10.1007/s11356-017-9106-2

RESEARCH ARTICLE

Identification of water quality management policy of watershed system with multiple uncertain interactions using a multi-level-factorial risk-inference-based possibilistic-probabilistic programming approach

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Received: 13 February 2017 / Accepted: 24 April 2017 / Published online: 9 May 2017

Abstract In this study, a multi-level-factorial risk-inference-based possibilistic-probabilistic programming (MRPP) method is proposed for supporting water quality management under multiple uncertainties. The MRPP method can handle uncertainties expressed as fuzzy-random-boundary intervals, probability distributions, and interval numbers, and analyze the effects of uncertainties as well as their interactions on modeling outputs. It is applied to plan water quality management in the Xiangxihe watershed. Results reveal that a lower probability of satisfying the objective function (θ) as well as a higher probability of violating environmental constraints (q_i) would correspond to a higher system benefit with an increased risk of violating system feasibility. Chemical plants are the major contributors to biological oxygen demand (BOD) and total phosphorus (TP) discharges; total nitrogen (TN) would be mainly discharged by crop farming. It is also discovered that optimistic decision makers should pay more attention to the interactions between chemical plant and water supply, while decision makers who possess a risk-averse attitude would focus on the interactive effect of q_i and benefit of water supply. The findings can help enhance the model's applicability and identify a suitable water quality management policy for environmental sustainability according to the practical situations.

Keywords Multiple uncertainties · Multiple interactions · Optimization · Risk · Water quality management

Responsible editor: Marcus Schulz

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Introduction

Intensive anthropogenic activities (e.g., industrial and municipal wastewater discharges, nutrient losses as well as excessive dam and sluice constructions) generate and release increased waste and wastewater, can irreversibly impair surface water quality of a watershed system since the generated pollution cannot be assimilated (Khadam and Kaluarachchi 2006; Lin and Chen 2016; Romero et al. 2016; Fleifle et al. 2016). Optimization techniques are effective tools to analyze the relevant information, evaluate pollutant mitigation, assess the resulting impact, and generate desired decision alternative (Li et al. 2014; Mishra et al. 2016). In fact, a water quality management system involves a number of components, such as the production scale of economic activities, pollutant discharge allowances, and pollutant discharge rates, these components are inherently uncertain and their latent interactions may lead to the further complexities in decision making processes (Li et al. 2008; Liu et al. 2015).

Previously, a number of techniques handled uncertainties in water quality management problems through fuzzy, stochastic, and interval programming approaches (Kerachian and Karamouz 2007; Kahraman and Kaya 2009; Kataria et al. 2010; Üçler et al. 2015; Bottrel et al. 2015; Martín-Fernández et al. 2016). Singh et al. (2007) presented an interactive fuzzy programming model for water quality management in a river basin, which incorporated the aspirations and conflicting objectives of the decision maker by taking the aspects relevant for pollution control boards and wastewater dischargers into account. Riverol and Pilipovik (2008) developed a fuzzy possibilistic programming for assessing the seasonal influence on the quality of seawater, where the behavior of salinity and total dissolved solids content in different seasons were characterized by possibilistic distributions. Zarghami (2010) advanced a fuzzy-probabilistic programming for integrated urban water management, in which the vagueness in the objective function was handled by fuzzy set theory and the randomness in the constraints (related to environmental hazards) was tackled by chance-constrained programming. Tavakoli et al. (2015) proposed a probabilistic-possibilistic programming to tackle uncertainties described as fuzzy-boundary intervals and probability distributions in decision making of optimal water allocation and pollutant load policies. The above methods successfully handled uncertainties expressed as membership functions, probability distributions, and/or interval numbers.

In fact, some economic coefficients (e.g., benefit/cost of industrial and agricultural activities) in the objective function are often affected by the changing economic conditions; the observed values of them may be ambiguous that can be estimated as fuzzy sets, leading to more complex uncertainties (e.g., intervals with fuzzy-random boundary). For example, decision makers estimate that the benefit from water supply possibly ranges from 44.3 RMB¥/m^3 to 56.9 RMB¥/m^3 or 64.2 RMB¥/m^3 to 76.0 RMB¥/m^3 (i.e., [[44.3, 56.9], [64.2, 76.0]] RMB¥/m^3). The probability of benefit exceeding 51.2 RMB¥/m^3 is less than 5% whereas the probability of benefit exceeding 49.9 RMB¥/m^3 is more than 95% or the probability of benefit exceeding 70.7 RMB¥/m^3 is less than 5% whereas the probability of benefit exceeding 69.5 RMB¥/m^3 is more than 95%, leading to a fuzzy-random-boundary interval (i.e., [($\overline{50.6}$, 6.3, 6.3), ($\overline{70.1}$, 5.9, 5.9)], where $\overline{50.6}\sim N(50.6, 0.1)$ and $\overline{70.1}\sim N(70.1, 0.1)$). Besides, the allowable pollutant discharges may be presented as probability distributions since they can be determined via tests, experiences, and expertise. The conventional optimization methods have difficulty in tackling such multiple uncertainties in decision making processes. Therefore, a risk-inference-based possibilistic-probabilistic programming (RIPP) method for handling multiple uncertainties by improving upon fuzzy-random-boundary programming (FRBP), interval-parameter programming (IPP), and chance-constrained programming (CCP) is advanced for planning water quality management. In the RIPP method, possibility theory can be used to treat the vagueness of subjective estimates by presenting possibility distributions for ambiguous parameter (Wang et al. 2015a, b); fractile criterion approach is a powerful tool to handle the randomness by transforming the objective function into deterministic equivalent function (Kataoka 1963; Kato et al. 2010). The stochastic allowable pollutant discharges can be handled through allowing a set of related constraints to have finite probability of being violated (Li et al. 2009).

In reality, water quality management systems possess complex interactions among many components from the related environment, ecosystem, and socio-economy aspects (Habersack and Samek 2016). Socio-economic activities (e.g., agricultural and industrial activities) are responsible for relevant production generations and pollutant discharges, and conversely have impacts on local environment and ecosystems. For instance, water resources are often transferred from low-value irrigation to high-value industrial uses, putting additional stresses on the performance of agriculture (Li et al. 2010; Wang et al. 2015a; Nematian 2016). A certain degree of environmental-violation risk may exist when pollutant discharges exceed the acceptable amounts, leading to shifts of the existing production patterns of related activities over a long time and induce decreased economic benefit. The RIPP method can effectively handle uncertainties that exist in multiple formats; nevertheless, the effects of multiple uncertainties as well as their interactions on the water quality management system performance should be further disclosed. Multi-level Taguchi method is a fractional factorial design which can effectively identify the important parameters (or factors) through performing a small number of experimental runs, while it has difficulty in reflecting the interactions among these factors. Taguchi method which based on Taguchi's orthogonal arrays (highly fractional orthogonal designs) can help study the effects of factors on the response mean and variations using in a fast and economic way. It can be used to figure out the significant factors from a number of potential factors (Wang and Huang 2015). Full factorial design is a powerful statistical analysis method which has been widely used by researchers to understand the effect of two or more independent variables on an individual dependent variable. Thus, a multi-level full factorial design involving those significant factors can then be employed to detect the interactions. Through combining the Taguchi method with the full factorial design, a multi-level Taguchi-factorial design (MTD) can be advanced to identify influential uncertain factors and gain insight into their interactive effects on system performance.

Thus, this paper proposes to provide a multi-level-factorial risk-inference-based possibilistic-probabilistic programming (MRPP) method to planning water quality management under multiple uncertainties. The MRPP method will introduce MTD into RIPP framework, which can (i) handle uncertainties described as fuzzy-random-boundary intervals, probability distributions, and interval numbers; (ii) analyze the effects of multiple uncertainties and their interactions on modeling outputs. Then, it is applied to support water quality management of the Xiangxihe watershed in China. The related economic activities (i.e., industrial and agricultural) will be optimized, while multiple parameters (or impact factors) and their interactions will then be identified. The results are helpful for generating decision alternatives in response to the reduction of pollutant discharges and maximization of economic objective.

The study system

Study area

In this study, main point sources include five chemical plants (i.e., GF, BSH, PYK, LCP, and XJLY), six phosphorus mining companies (i.e., XL, XH, XC, GP, JJW, and SJS), and four wastewater treatment plants (WTPs) (i.e., Gufu, Nanyang, Gaoyang, and Xiakou); meanwhile, four agricultural zones (AZ1 to AZ4) are the main nonpoint sources (as shown in Fig. 1). A 1-year planning horizon is selected and further sorted into two periods: dry season (i.e., November to May of the following year) and wet season (i.e., June to October) based on the specific growth periods of different crops. Wheat, potato, rapeseed, and alpine rice are identified as crops in dry season; second rice, maize, and vegetables are determined as crops during wet season; citrus and tea grow up over the whole planning horizon. Pig, ox, sheep, and domestic fowl are the main live stocks in animal husbandry for generating manure.

Data collection and analysis

The imprecise inputs are investigated through field surveys, statistical yearbooks, government reports, and literatures. They are presented as fuzzy-random-boundary intervals, probability distributions, and interval numbers. Table 1 displays benefits from

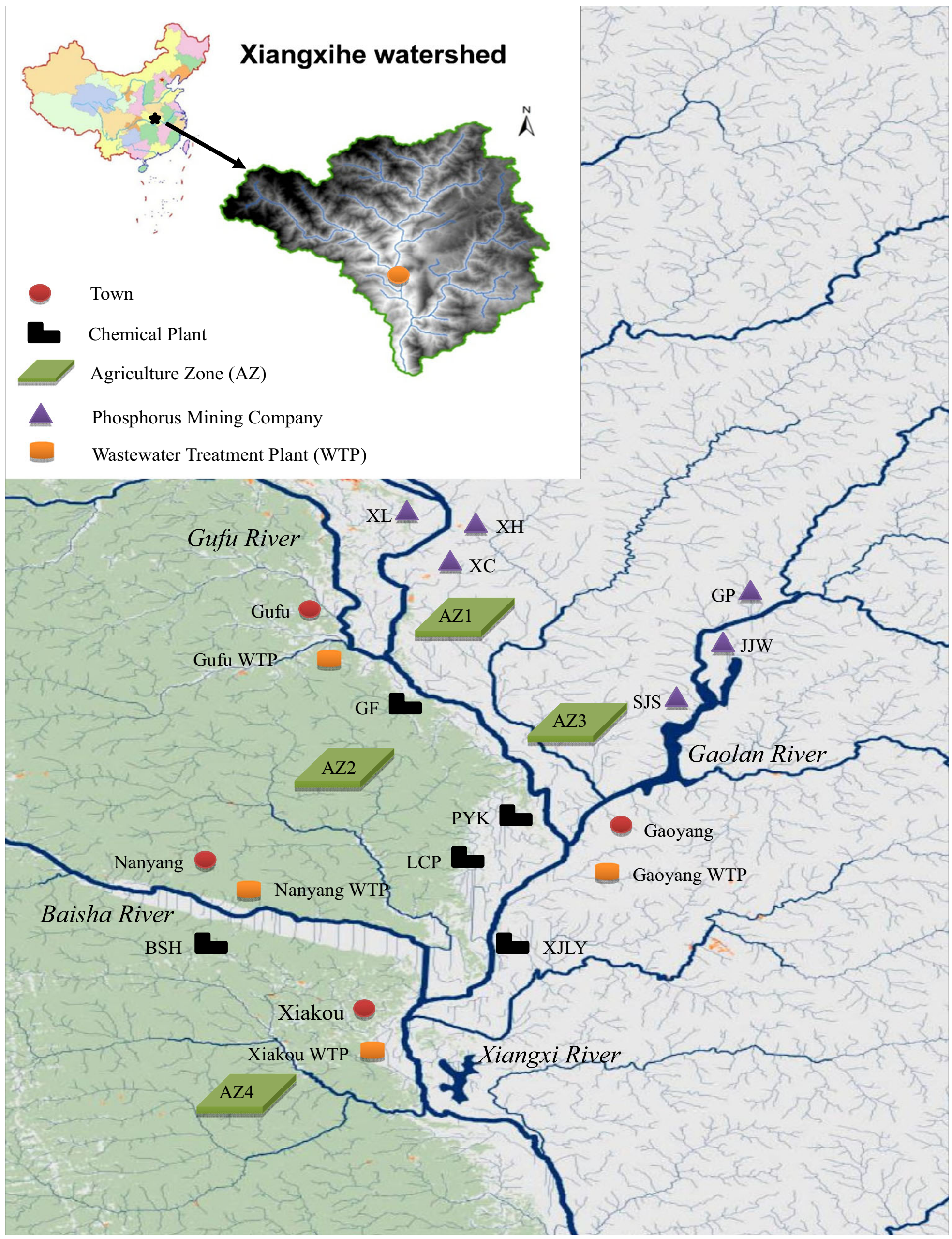


Fig. 1 Study area. Note: *GF*, Gufu chemical plant; *XL*, Xinglong phosphorus mining company; *XH*, Xinghe phosphorus mining company; *XC*, Xingchang phosphorus mining company; *BSH*, Baishahe chemical plant; *PYK*, Pingyikou chemical plant; *LCP*, Liucaopo chemical plant; *GP*, Geping phosphorus mining company; *JJW*, Jiangjiawan phosphorus mining company; *SJS*, Shenjiashan phosphorus mining company; *XJLY*, Xiangjinlianying chemical plant

Table 1 Net benefits, presented as fuzzy-random-boundary intervals, from industrial activities and municipal water usage

	Period	
	t = 1 (dry season)	t = 2 (wet season)
Net benefits from chemical plant (RMB¥/tonne):		
GF	[($\overline{718.6}$, 15.3, 15.3), ($\overline{834.5}$, 17.2, 17.2)]	[($\overline{743.8}$, 16.2, 16.2), ($\overline{876.2}$, 18.4, 18.4)]
BSH	[($\overline{1291.5}$, 21.4, 21.4), ($\overline{1499.7}$, 26.8, 26.8)]	[($\overline{1336.7}$, 24.5, 24.5), ($\overline{1574.8}$, 27.3, 27.3)]
PYK	[($\overline{740.3}$, 15.8, 15.8), ($\overline{862.8}$, 17.9, 17.9)]	[($\overline{769.0}$, 17.4, 17.4), ($\overline{905.9}$, 19.3, 19.3)]
LCP	[($\overline{1324.2}$, 23.7, 23.7), ($\overline{1537.5}$, 27.2, 27.2)]	[($\overline{1370.6}$, 25.2, 25.2), ($\overline{1614.4}$, 27.8, 27.8)]
XJLY	[($\overline{1524.4}$, 26.5, 26.5), ($\overline{1770.0}$, 28.1, 28.1)]	[($\overline{1578.7}$, 27.5, 27.5), ($\overline{1858.5}$, 28.4, 28.4)]
Net benefits from water supply (RMB¥/m^3):		
Gufu	[($\overline{39.1}$, 2.5, 2.5), ($\overline{42.1}$, 2.8, 2.8)]	[($\overline{43.3}$, 2.9, 2.9), ($\overline{47.7}$, 3.1, 3.1)]
Nanyang	[($\overline{29.0}$, 1.9, 1.9), ($\overline{31.2}$, 2.1, 2.1)]	[($\overline{32.2}$, 2.1, 2.1), ($\overline{35.4}$, 2.3, 2.3)]
Gaoyang	[($\overline{35.3}$, 2.3, 2.3), ($\overline{38.0}$, 2.4, 2.4)]	[($\overline{39.2}$, 2.5, 2.5), ($\overline{43.1}$, 2.9, 2.9)]
Xiakou	[($\overline{32.1}$, 2.1, 2.1), ($\overline{34.6}$, 2.2, 2.2)]	[($\overline{35.7}$, 2.3, 2.3), ($\overline{39.3}$, 2.5, 2.5)]
Net benefits from phosphorus mining company (RMB¥/tonne):		
XL	[($\overline{150}$, 7.2, 7.2), ($\overline{173}$, 8.4, 8.4)]	[($\overline{147}$, 7.1, 7.1), ($\overline{180}$, 8.7, 8.7)]
XH	[($\overline{126}$, 5.8, 5.8), ($\overline{145}$, 7.1, 7.1)]	[($\overline{130}$, 5.8, 5.8), ($\overline{156}$, 7.4, 7.4)]
XC	[($\overline{135}$, 6.0, 6.0), ($\overline{155}$, 7.4, 7.4)]	[($\overline{135}$, 6.0, 6.0), ($\overline{162}$, 7.6, 7.6)]
GP	[($\overline{144}$, 7.1, 7.1), ($\overline{166}$, 7.7, 7.7)]	[($\overline{150}$, 7.2, 7.2), ($\overline{180}$, 8.7, 8.7)]
JJW	[($\overline{137}$, 6.1, 6.1), ($\overline{158}$, 7.4, 7.4)]	[($\overline{141}$, 6.9, 6.9), ($\overline{169}$, 8.1, 8.1)]
SJS	[($\overline{140}$, 6.9, 6.9), ($\overline{164}$, 7.6, 7.6)]	[($\overline{145}$, 7.1, 7.1), ($\overline{175}$, 8.4, 8.4)]

The six phosphorus mining companies are abbreviated as their initials in the table. XL, Xinglong, p = 1; XH, Xinghe, p = 2; XC, Xingchang, p = 3; GP, Geping, p = 4; JJW, Jiangjiawan, p = 5; SJS, Shenjiashan, p = 6. The five chemical plants are abbreviated as their initials in the table. GF, Gufu, i = 1; BSH, Baishahe, i = 2; PYK, Pingyikou, i = 3; LCP, Liucaopo, i = 4; XJLY, Xiangjinlianying, i = 5

industrial activities which presented as fuzzy-random-boundary intervals (Environmental Science Research and Design Institute of Zhejiang Province 2014). A fuzzy-random-boundary interval of [($\overline{718.6}$, 15.3, 15.3), ($\overline{834.5}$, 17.2, 17.2)] RMB¥/tonne (i.e., RMB¥/t) denotes the benefit from GF (per unit) when the allowable pollutant discharges are satisfied. Decision makers estimate that the benefit from GF (per unit) possibly ranges from 703.3 to 733.9 RMB¥/t or 817.3 to 851.7 RMB¥/t. The probability of benefit exceeding 728.7 RMB¥/t is less than 5% whereas the probability of benefit exceeding 707.5 RMB¥/t is more than 95% or the probability of benefit exceeding 843.2 RMB¥/t is less than 5% whereas the probability of benefit exceeding 808.8 RMB¥/t is more than 95%, leading to a fuzzy-random-boundary interval; $\overline{718.6}$ means that the benefit follows a normal distribution with an expected value of 718.6 and a standard deviation of 0.1 (i.e., $\overline{718.6} \sim N\left(718.6, 0.1^2\right)$), while 15.3 denotes the left spread and the right spread of the benefit. According to the Annual Bulletin on Environment Situations in Hubei Province (Environment Protection Bureau of Hubei Province 2001–2014) and the Annual Report on the Impact of the Three Gorges Project on the Ecology and Environment (State Environmental Protection Administration 1997–2014), local decision makers can estimate the probability distributions of allowable pollutant discharges and discrete the probability distribution. Table 2 lists the allowable pollutant discharges of different industrial activities with three probability levels (i.e., q_i = 0.01, 0.05, and 0.10).

MRPP for water quality management

Framework of MRPP

In this study, a water quality management system contains identification of multiple uncertainties, exploration of optimal parameters as well as investigation of important parameters and their interactions. The MRPP method covers these tasks through a combination of the RIPP and MTD methods. Each method has a contribution in improving the ability of the MRPP method to cope with uncertainties and complexities in water quality management problems. RIPP method specializes in coping with uncertainties expressed as fuzzy-random-boundary intervals and probability distributions. MTD can qualitatively estimate the individual and interactive effects of design parameters on modeling performance. Figure 2 descripts the general framework of the MRPP method. The first step is to recognize multiple uncertainties related to system components such as economic coefficient, pollutant discharge rate, and pollutant discharge allowance. The

Table 2 Range of allowable pollutant discharge for industrial activities and municipal wastewater treatment under different probability levels (q_i)

	Period 1			Period 2		
	$q_i = 0.01$	$q_i = 0.05$	$q_i = 0.10$	$q_i = 0.01$	$q_i = 0.05$	$q_i = 0.10$
Allowable phosphorus discharge for each chemical plant (kg)						
Gufu (GF)	[173.8, 208.6]	[175.5, 210.6]	[178.5, 214.2]	[139.5, 168.9]	[140.9, 170.6]	[143.3, 173.6]
Baishahe (BSH)	[71,339.5, 86,321.7]	[72,038.9, 87,168.0]	[73,265.7, 88,652.4]	[47,805.0, 57,843.8]	[48,273.7, 58,410.9]	[49,095.8, 59,405.7]
Pingyikou (PYK)	[11,056.4, 13,378.8]	[11,075.1, 13,399.9]	[11,354.9, 13,740.1]	[10,967.5, 13,269.8]	[11,075.1, 13,399.9]	[11,263.7, 13,628.2]
Liucaopo (LCP)	[48,857.4, 59,118.6]	[49,926.9, 60,410.2]	[50,176.6, 60,714.8]	[49,442.3, 59,823.7]	[49,926.9, 60,410.2]	[50,777.2, 61,438.9]
Xiangjinlianying (XJLY)	[47,408, 57,363.2]	[42,967.9, 51,990.4]	[48,688.3, 58,911.9]	[42,550.7, 51,485.7]	[42,967.9, 51,990.4]	[43,699.6, 52,875.8]
Allowable phosphorus discharge for each mine company (kg)						
Xinglong (XL)	[18,249.8, 19,708.9]	[18,432.3, 19,905.9]	[18,523.6, 20,004.5]	[17,166.8, 18,540.9]	[17,338.6, 18,726.4]	[17,424.4, 18,819.1]
Xinghe (XH)	[8715.9, 9412.5]	[8803.1, 9506.6]	[10,478.7, 11,316.4]	[10,323.8, 11,149.2]	[10,427, 11,260.7]	[10,478.7, 11,316.4]
Xingchang (XC)	[9069.5, 9795.8]	[9160.2, 9893.8]	[11,206.9, 12,103.3]	[11,041.2, 11,924.4]	[11,151.7, 12,043.6]	[11,206.9, 12,103.3]
Geping (GP)	[14,743.8, 15,923.8]	[14,891.3, 16,083.1]	[15,995.8, 17,274.7]	[15,759, 17,019.4]	[15,916.9, 17,189.6]	[15,995.7, 17,272.7]
Jiangjiawan (JJW)	[8620.1, 9310.2]	[8706.3, 9403.3]	[8421.7, 9094.8]	[8297.2, 8960.4]	[8380.2, 9050.0]	[8421.7, 9094.8]
Shenjiashan (SJS)	[6532.7, 7054.6]	[6598.0, 7125.1]	[9344.7, 10,091.5]	[9206.6, 9942.3]	[9298.7, 10,041.7]	[9344.7, 10,091.5]
Allowable BOD discharge for each WTP (kg)						
Gufu	[17,040.2, 19,170.3]	[17,551.2, 19,745.1]	[17,738.6, 15,032.4]	[12,920, 14,440]	[13,307.6, 14,873.2]	[13,449.7, 15,032.0]
Nanyang	[639.4, 1065.5]	[658.2, 1096.7]	[665.2, 1108.7]	[608, 912]	[626.4, 939.4]	[632.9, 949.4]
Gaoyang	[2130.7, 3834.4]	[2193.9, 3949.2]	[2217.3, 3991.2]	[1824, 3040]	[1878.7, 3131.2]	[1898.8, 3164.6]
Xiakou	[3195.8, 4899.2]	[3290.9, 5045.9]	[3325.9, 5099.8]	[2584, 3800]	[2661.5, 3914.3]	[2689.9, 3955.8]

sources of data include Government report from Environmental technology verification report-Refinancing Hubei Chemical Group Co., Xingfa, literatures, Document from China Environmental Protection Agency (CEPA), field survey in Xingshan County, and Government report from Bureau of Land Resources of Xingshan. Based on the recognition, the uncertainties are handled by the RIPP optimization method which incorporates interval-parameter programming (Liu et al. 2014), fuzzy-random-boundary programming (Kataoka 1963; Kato et al. 2010), and chance-constrained programming (Huang 1998). Possibility measure (or necessity measure) and fuzzy goal as well as fractile criterion approach can tackle fuzziness and randomness of the objective function based on risk inferences of decision makers, respectively. Chance-constraint is adopted to tackle randomness of the right-hand side parameters (e.g., pollutant discharge allowance). Then, the MTD method is used to detect the influential uncertain parameters and their interactive effects on modeling outputs. A three-level Taguchi method is conducted to explore the effects of variations in individual parameters on the system benefit, and the dominant parameters can thus be identified. A full factorial design containing the dominant parameters can thus be performed to analyze their interactive effects on the system benefit.

Risk-inference-based possibilistic-probabilistic method

Firstly, a fuzzy-random-boundary interval chance-constrained programming method can be presented as:

$$\text{Max } f^{\pm} = \sum_{j=1}^{n} \tilde{c}_j^{\pm}(\omega) x_j^{\pm} \tag{1a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i(\omega)^{q_i}, \quad i = 1, 2, \ldots, m \tag{1b}$$

$$x_j^{\pm} \ge 0, \quad j = 1, 2, \quad \ldots, n \tag{1c}$$

where $\left(x_1^{\pm}, x_2^{\pm}, \ldots, x_n^{\pm}\right)$ is a vector of interval decision variables; $\tilde{c}_j^{\pm}(\omega)$ are fuzzy-random-boundary intervals in numerator and denominator of the objective; $a_{ij}^{\pm}$ are technical coefficients. $b_i(\omega)$ are random variables; q_i is probability of violating constraints ($q_i \in [0, 1]$). The $\tilde{c}_j^{\pm}(\omega)$ can be expressed as triangular fuzzy numbers. The objective function can be characterized as (Sakawa and Matsui 2013):

$$\mu_{\sum_{j=1}^{n} \tilde{c}_j^{\pm}(\omega) x_j^{\pm}}(\varphi^{\pm}) = \begin{cases} L\left(\dfrac{\sum_{j=1}^{n} d_j^{\pm}(\omega) x_j^{\pm} - \varphi^{\pm}}{\sum_{j=1}^{n} \lambda_j^{\pm} x_j^{\pm}}\right), & \text{if } \varphi \le \sum_{j=1}^{n} d_j^{\pm}(\omega) x_j^{\pm} \\ R\left(\dfrac{\varphi^{\pm} - \sum_{j=1}^{n} d_j^{\pm}(\omega) x_j^{\pm}}{\sum_{j=1}^{n} \gamma_j^{\pm} x_j^{\pm}}\right), & \text{otherwise} \end{cases} \tag{2}$$

where $d_j^{\pm}(\omega)$, $\lambda_j^{\pm}$, and $y_j^{\pm}$ represent the mean value, the left spread, and the right spread of $\tilde{c}_j^{\pm}(\omega)$, respectively. $d_j^{\pm}(\omega)$ is assumed to be a Gaussian random vector with expected value $\mu_j^{\pm}$ and standard deviation $\sigma_j^{\pm}$.

Decision makers generally set a goal for the system benefit; they will be totally satisfied if the actual system benefit is higher than the goal. The goal can be quantified by:

$$\mu_G(z^{\pm}) = \begin{cases} 1, & \text{if } z^{\pm} > z_1^{\pm} \\ \dfrac{z^{\pm} - z_0^{\pm}}{z_1^{\pm} - z_0^{\pm}}, & \text{if } z_0^{\pm} \le z^{\pm} \le z_1^{\pm} \\ 0, & \text{if } z^{\pm} < z_0^{\pm} \end{cases} \tag{3}$$

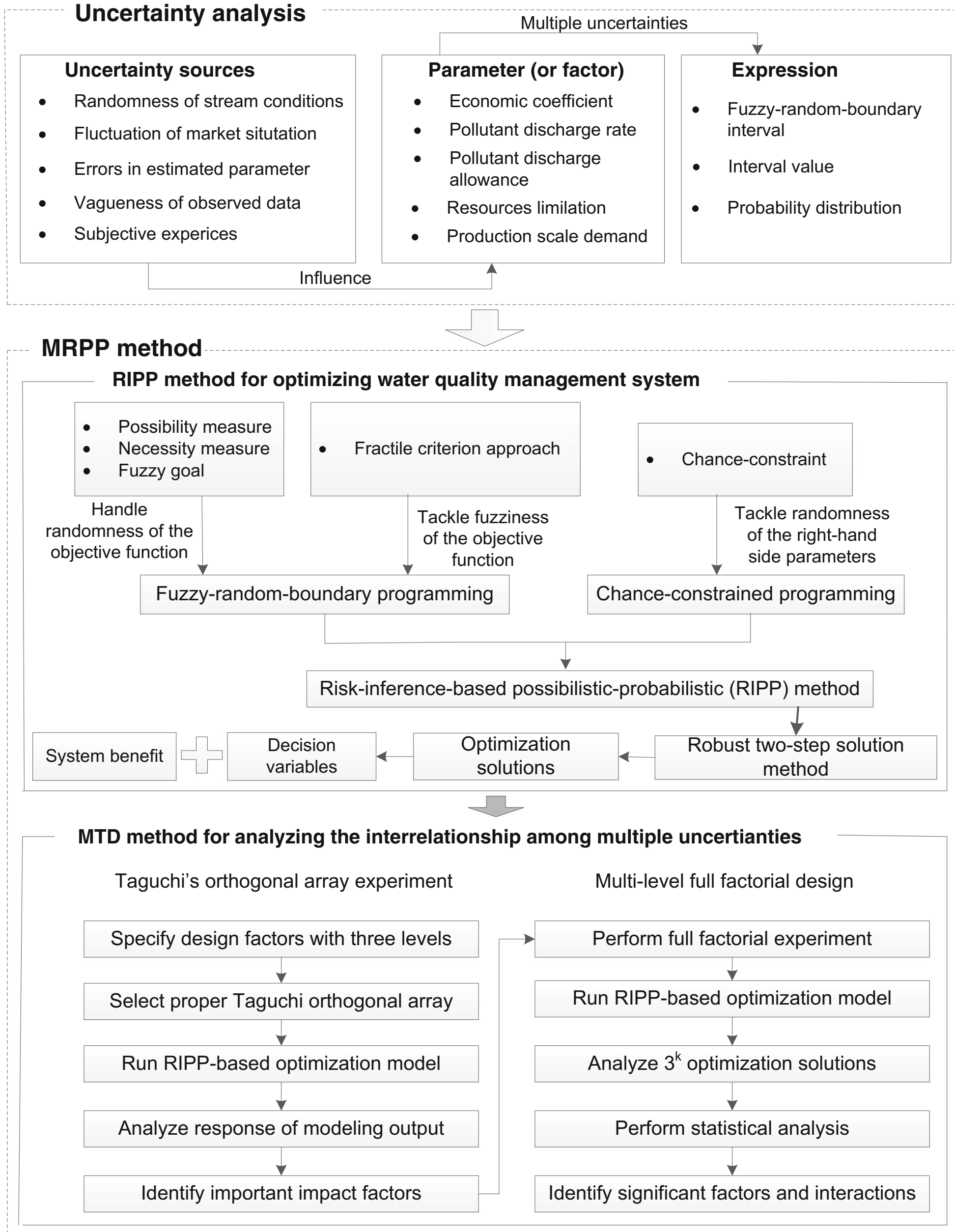


Fig. 2 General framework of MRPP

where $z_0^{\pm}$ and $z_1^{\pm}$ represent the minimum and maximum system benefit that decision makers desire to obtain, respectively. Possibility measure (PM) and necessity measure (NM) are employed to reflect the degree that the objective function fulfills the fuzzy goal. PM and NM are two concepts of possibility theory to handle incomplete information. Let $u^{\pm}$ and $r^{\pm}$ be real numbers for $\tilde{c}_j^{\pm}(\omega)$ with membership function μ. The possibility of $\tilde{c}_j^{\pm}(\omega) > r^{\pm}$ is defined as:

$$\mathrm{Pos}\left(\tilde{c}_j^{\pm}(\omega) \le r^{\pm}\right) = \sup_{u^{\pm} \le r^{\pm}} \mu\left(x^{\pm}\right) \tag{4}$$

where $\mathrm{Pos}\left(\tilde{c}_j^{\pm}(\omega) \le r^{\pm}\right) = 1$ denotes that $\tilde{c}_j^{\pm}(\omega) \le r^{\pm}$ is possible, and $\mathrm{Pos}\left(\tilde{c}_j^{\pm}(\omega) \le r^{\pm}\right) = 0$ denotes that $\tilde{c}_j^{\pm}(\omega) \le r^{\pm}$ is impossible. The necessity of $\tilde{c}_j^{\pm}(\omega) > r^{\pm}$ is defined by:

$$\mathrm{Nec}\left\{\tilde{c}_j^{\pm}(\omega) \le r^{\pm}\right\} = 1 - \mathrm{Pos}\left\{\tilde{c}_j^{\pm}(\omega) > r^{\pm}\right\} = 1 - \sup_{u^{\pm} > r^{\pm}} \mu\left(u^{\pm}\right) \tag{5}$$

where $\tilde{c}_j^{\pm}(\omega) > r^{\pm}$ means the complement of $\tilde{c}_j^{\pm}(\omega) \le r^{\pm}$; that is, the elements that do not belong to $\tilde{c}_j^{\pm}(\omega) \le r^{\pm}$. Nec

$\left\{\tilde{c}_j^{\pm}(\omega)\leq r^{\pm}\right\}=1$ means that $\tilde{c}_j^{\pm}(\omega)\leq r^{\pm}$ is necessary and $\text{Nec}\left\{\tilde{c}_j^{\pm}(\omega)\leq r^{\pm}\right\}=0$ means that $\tilde{c}_j^{\pm}(\omega)\leq r^{\pm}$ is unnecessary. PM is suitable for optimistic decision makers; contrarily, NM is appropriate for decision makers who are risk-averse. On the basis of formula (2) to (5), the degrees of fulfilling the fuzzy goal under the possibility distribution of the objective function (i.e., possibility degree and necessity degree) can be respectively presented as (Katagiri et al. 2008):

$$\text{Pos}_{\sum_{j=1}^{n}\tilde{c}_j^{\pm}(\omega)x_j^{\pm}}\left(\tilde{G}\right)=\sup_{\ell}\ \min\left\{\mu_{\sum_{j=1}^{n}\tilde{c}_j^{\pm}(\omega)x_j^{\pm}}\left(\ell^{\pm}\right),\mu_{\tilde{G}}\left(\ell^{\pm}\right)\right\} \tag{6}$$

$$\text{Nec}_{\sum_{j=1}^{n}\tilde{c}_j^{\pm}(\omega)x_j^{\pm}}\left(\tilde{G}\right)=\inf_{\ell}\ \min\left\{1-\mu^{\pm}_{\sum_{j=1}^{n}\tilde{c}_j^{\pm}(\omega)x_j^{\pm}}\left(\ell^{\pm}\right),\mu_{\tilde{G}}\left(\ell^{\pm}\right)\right\} \tag{7}$$

To handle the randomness in the objective function, the fractile criterion approach can be employed based on a concept of permissible level. Permissible level is defined as the acceptable level that decision makers want the possibility degree is greater than or equal to. The stochastic objective can be handled through transforming the objective function into chance constraints, where the probability of approaching the permissible level is decided by decision makers according to their risk inference (Sakawa and Matsui 2013). Thus, a risk-inference-based possibilistic-probabilistic (RIPP) method can be formulated to tackle the fuzziness and randomness of the objective function. Considering PM, model (1) can be transformed into:

$$\text{Max}\ \ f^{\pm}=h_{\pm} \tag{8a}$$

subject to:

$$\Pr\left\{\omega\left|\text{Pos}_{\sum_{j=1}^{n}\tilde{c}_j^{\pm}(\omega)x_j^{\pm}}\left(\tilde{G}^{\pm}\right)\geq h^{\pm}\right.\right\}\geq\theta \tag{8b}$$

$$\sum_{j=1}^{n}a_{ij}^{\pm}x_j^{\pm}\leq b_i(\omega)^{q_i},\ \ i=1,2,\ldots,m \tag{8c}$$

$$x_j^{\pm}\geq 0,\ \ j=1,2,\ldots,n \tag{8d}$$

where $h^{\pm}$ denotes a permissible level that the possibility degree is greater than or equal to, and $\theta^{\pm}$ represents a probability of satisfying objective function. Constraint (8b) can be transformed as:

$$\frac{\sum_{j=1}^{n}\left(\lambda_j^{\pm}-\mu_j^{\pm}\right)x_j^{\pm}-\Phi^{-1}(1-\theta)\sqrt{\sum_{j=1}^{n}\left(\sigma_j^{\pm}x_j^{\pm}\right)^2}+z_0^{\pm}}{\sum_{j=1}^{n}\lambda_j^{\pm}x_j^{\pm}-z_1^{\pm}+z_0^{\pm}}\geq h_{\pm} \tag{9}$$

Then, model (8) can be reformulated as (The details of solution method are presented in Appendix A):

$$\text{Max}\ \ h^{\pm} \tag{10a}$$

subject to:

$$\frac{\sum_{j=1}^{n}\left(\lambda_j^{\pm}-\mu_j^{\pm}\right)x_j^{\pm}-\Phi^{-1}(1-\theta)\sqrt{\sum_{j=1}^{n}\left(\sigma_j^{\pm}x_j^{\pm}\right)^2}+z_0^{\pm}}{\sum_{j=1}^{n}\lambda_j^{\pm}x_j^{\pm}-z_1^{\pm}+z_0^{\pm}}\geq h_{\pm} \tag{10b}$$

$$\sum_{j=1}^{n}a_{ij}^{\pm}x_j^{\pm}\leq b_i(\omega)^{q_i},\ \ i=1,2,\ldots,m \tag{10c}$$

$$x_j^{\pm}\geq 0,j=1,2,\ \ \ldots,n \tag{10d}$$

Similarly, when the NM is adopted, model (1) can be equivalently transformed into:

$$\text{Max}\ \ h^{\pm} \tag{11a}$$

subject to:

$$\frac{-\sum_{j=1}^{n}\mu_j^{\pm}x_j^{\pm}-\Phi^{-1}(1-\theta)\sqrt{\sum_{j=1}^{n}\left(\sigma_j^{\pm}x_j^{\pm}\right)^2}+z_0^{\pm}}{\sum_{j=1}^{n}\gamma_j^{\pm}x_j^{\pm}-z_1^{\pm}+z_0^{\pm}}\geq h^{\pm} \tag{11b}$$

$$\sum_{j=1}^{n}a_{ij}^{\pm}x_j^{\pm}\leq b_i(\omega)^{q_i},\ \ i=1,2,\ldots,m \tag{11c}$$

$$x_j^{\pm}\geq 0,j=1,2,\ \ \ldots,\ \ n \tag{11d}$$

Application of MRPP approach

Firstly, the RIPP method is applied to formulate model for optimizing economic activities in the Xiangxihe watershed. The objective is to maximize the system benefit through identifying desired industrial and agricultural activities; biological oxygen demand (BOD), total nitrogen (TN), and total phosphorus (TP) are selected as water quality indicators. The constraints involve relationships among economic activity, environmental restriction, and resources availability. The RIPP model (under PM) for supporting water quality management in the Xiangxihe watershed can be represented as follows:

$$\text{Max}\ \ h^{\pm} \tag{12}$$

subject to:

(1) Risk inference of decision maker:

$$\frac{\left\{\begin{aligned}&\sum_{i=1}^{5}\sum_{t=1}^{2}\left[\left(\lambda_{it}^{\pm}-\mu_{it}^{\pm}\right)-\left(\lambda_{it}^{'\pm}-\mu_{it}^{'\pm}\right)\right]PLC_{it}^{\pm}+\sum_{p=1}^{6}\sum_{t=1}^{2}\left(\lambda_{pt}^{\pm}-\mu_{pt}^{\pm}\right)PLM_{pt}^{\pm}\\&+\sum_{s=1}^{4}\sum_{t=1}^{2}\left[\left(\lambda_{st}^{\pm}-\mu_{st}^{\pm}\right)-\left(\lambda_{st}^{'\pm}-\mu_{st}^{'\pm}\right)\right]QW_{st}^{\pm}+\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\left(\lambda_{jkt}^{\pm}-\mu_{jkt}^{\pm}\right)CY_{jkt}^{\pm}PA_{jkt}^{\pm}\\&+\sum_{r=1}^{4}\left(\lambda_{r}^{\pm}-\mu_{r}^{\pm}\right)NL_{r}^{\pm}-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\left(\lambda_{jt}^{\pm}-\mu_{jt}^{\pm}\right)AM_{jkt}^{\pm}-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\left(\lambda_{jt}^{'\pm}-\mu_{jt}^{'\pm}\right)AF_{jkt}^{\pm}\end{aligned}\right\}\\-\Phi^{-1}(1-\theta)\sqrt{\begin{aligned}&\sum_{i=1}^{5}\sum_{t=1}^{2}\left[\left(\sigma_{it}^{\pm}PLC_{it}^{\pm}\right)^2-\left(\sigma_{it}^{'\pm}PLC_{it}^{\pm}\right)^2\right]+\sum_{p=1}^{6}\sum_{t=1}^{2}\left(\sigma_{pt}^{\pm}PLM_{pt}^{\pm}\right)^2\\&+\sum_{s=1}^{4}\sum_{t=1}^{2}\left[\left(\sigma_{st}^{\pm}QW_{st}^{\pm}\right)^2-\left(\sigma_{st}^{'\pm}QW_{st}^{\pm}\right)^2\right]+\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\left(\sigma_{jkt}^{\pm}CY_{jkt}^{\pm}PA_{jkt}^{\pm}\right)^2\\&+\sum_{r=1}^{4}\left(\sigma_{r}^{\pm}NL_{r}^{\pm}\right)^2-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\left(\sigma_{jt}^{\pm}AM_{jkt}^{\pm}\right)^2-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\left(\sigma_{jt}^{'\pm}AF_{jkt}^{\pm}\right)^2\end{aligned}}+z_0^{\pm}}{\begin{aligned}&\sum_{i=1}^{5}\sum_{t=1}^{2}\left(\lambda_{it}^{\pm}-\lambda_{it}^{'\pm}\right)PLC_{it}^{\pm}+\sum_{p=1}^{6}\sum_{t=1}^{2}\lambda_{pt}^{\pm}PLM_{pt}^{\pm}+\sum_{s=1}^{4}\sum_{t=1}^{2}\left(\lambda_{st}^{\pm}-\lambda_{st}^{'\pm}\right)QW_{st}^{\pm}+\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\lambda_{jkt}^{\pm}CY_{jkt}^{\pm}PA_{jkt}^{\pm}\\&+\sum_{r=1}^{4}\lambda_{r}^{\pm}NL_{r}^{\pm}-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\lambda_{jt}^{\pm}AM_{jkt}^{\pm}-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\lambda_{jt}^{'\pm}AF_{jkt}^{\pm}-z_1^{\pm}+z_0^{\pm}\end{aligned}}\geq h^{\pm} \quad (13)$$

(2) Constraints of water supply:

$$QW_{st}^{\pm}\cdot GT_{st}^{\pm}\leq TPC_{st}^{\pm},\quad \forall s,t \quad (14a)$$

$$QW_{st}^{\pm}\cdot GT_{st}^{\pm}\cdot BM_{st}^{\pm}\cdot\left(1-\eta_{BOD,st}^{\pm}\right)\leq ABW_{st}^{q_i},\quad \forall s,t \quad (14b)$$

$$QW_{st}^{\pm}\cdot GT_{st}^{\pm}\cdot PCM_{st}^{\pm}\left(1-\eta_{TP,st}^{\pm}\right)\leq APW_{st}^{\pm},\forall s,t \quad (14c)$$

$$QW_{st,\min}\leq QW_{st}^{\pm}\leq QW_{st,\max},\quad \forall s,t \quad (14d)$$

(3) Constraints of chemical plant production:

$$PLC_{it}^{\pm}\cdot WC_{it}^{\pm}\leq TPD_{it}^{\pm},\quad \forall i,t \quad (15a)$$

$$PLC_{it}^{\pm}\cdot WC_{it}^{\pm}\cdot IC_{it}^{\pm}\cdot\left(1-\eta_{BOD,it}^{\pm}\right)\leq ABC_{it}^{\pm},\quad \forall i,t \quad (15b)$$

$$PLC_{it}^{\pm}\cdot\left[WC_{it}^{\pm}\cdot PCR_{it}^{\pm}\left(1-\eta_{TP,it}^{\pm}\right)+ASC_{it}^{\pm}\cdot SLR_{it}^{\pm}\cdot PSC_{it}^{\pm}\right]\leq APC_{it}^{q_i},\quad \forall i,t \quad (15c)$$

$$PLC_{it,\min}\leq PLC_{it}^{\pm}\leq PLC_{it,\max},\quad \forall i,t \quad (15d)$$

(4) Constraints of phosphorus mining company production:

$$PLM_{pt}^{\pm}\cdot\left[WPM_{pt}^{\pm}\cdot MWC_{pt}^{\pm}\left(1-\eta_{TP,pt}^{\pm}\right)+ASM_{pt}^{\pm}\cdot PCS_{pt}^{\pm}\cdot SLW_{pt}^{\pm}\right]\leq APM_{pt}^{q_i},\quad \forall p,t \quad (16a)$$

$$PLM_{pt,\min}\leq PLM_{pt}^{\pm}\leq PLM_{pt,\max},\quad \forall p,t \quad (16b)$$

(5) Constraints of crop farming:

$$\sum_{k=1}^{9}\left(NS_{jk}^{\pm}\cdot SL_{jkt}^{\pm}+RF_{jkt}^{\pm}\cdot DN_{jkt}^{\pm}\cdot 10^{-5}\right)\cdot PA_{jkt}^{\pm}\leq MNL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\quad \forall j,t \quad (17a)$$

$$\sum_{k=1}^{9}\left(PS_{jkt}^{\pm}\cdot SL_{jkt}^{\pm}+DP_{jkt}^{\pm}\cdot RF_{jkt}^{\pm}\cdot 10^{-5}\right)PA_{jkt}^{\pm}\leq MPL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\forall j,t \quad (17b)$$

$$\sum_{k=1}^{9}SL_{jkt}^{\pm}\cdot PA_{jkt}^{\pm}\leq MSL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\forall j,\quad t \quad (17c)$$

$$\left(1-NVF_{t}^{\pm}\right)\cdot\varepsilon_{NF}^{\pm}\cdot AF_{jkt}^{\pm}+\left(1-NVM_{t}^{\pm}\right)\cdot\varepsilon_{NM}^{\pm}\cdot AM_{jkt}^{\pm}\geq NR_{jkt}^{\pm}\cdot PA_{jkt}^{\pm},\quad \forall j,k,t \quad (17d)$$

$$\varepsilon_{PF}^{\pm}\cdot AF_{jkt}^{\pm}+\varepsilon_{PM}^{\pm}\cdot AM_{jkt}^{\pm}\geq PR_{jkt}^{\pm}\cdot PA_{jkt}^{\pm},\quad \forall j,k,t \quad (17e)$$

$$\sum_{k=1}^{9}\left(\varepsilon_{NF}^{\pm}\cdot AF_{jkt}^{\pm}+\varepsilon_{NM}^{\pm}\cdot AM_{jkt}^{\pm}-NR_{jkt}^{\pm}\cdot PA_{jkt}^{\pm}\right)\leq MNL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\quad \forall j,t \quad (17f)$$

$$\sum_{k=1}^{9}\left(\varepsilon_{PF}^{\pm}\cdot AF_{jkt}^{\pm}+\varepsilon_{PM}^{\pm}\cdot AM_{jkt}^{\pm}-PR_{jkt}^{\pm}\cdot PA_{jkt}^{\pm}\right)\leq MPL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\quad \forall j,t \quad (17g)$$

$$\sum_{j=1}^{4}\sum_{k=1}^{6}PA_{jkt}^{\pm}\geq MFP_{t}^{\pm},\quad t=1 \quad (17h)$$

$$\sum_{j=1}^{4}\sum_{k=1}^{2}PA_{jkt}^{\pm}+\sum_{j=1}^{4}\sum_{k=8}^{9}PA_{jkt}^{\pm}\geq MFP_{t}^{\pm},\quad t=2 \quad (17i)$$

$$PA_{jkt}^{\pm}\leq TAS_{jt}^{\pm},\quad k=6,t=1 \quad (17j)$$

$$\sum_{k=1}^{5}PA_{jkt}^{\pm}\leq TAH_{jt}^{\pm},\quad t=1 \quad (17k)$$

$$PA^{\pm}_{jkt} \leq TAS^{\pm}_{jt}, \quad k = 7, t = 2 \tag{17l}$$

$$\sum_{k=1}^{2} PA^{\pm}_{jkt} + \sum_{k=8}^{9} PA^{\pm}_{jkt} \leq TAH^{\pm}_{jt}, \quad t = 2 \tag{17m}$$

$$TAS^{\pm}_{jt} + TAH^{\pm}_{jt} = TA^{\pm}_{jt}, \quad \forall j, t \tag{17n}$$

(6) Constraints of livestock husbandry:

$$\left(\sum_{r=1}^{4} AML^{\pm}_{rt} \cdot NL^{\pm}_{r} + AMH^{\pm}_{t} \cdot RP^{\pm}_{t} - \sum_{j=1}^{4} \sum_{k=1}^{9} AM^{\pm}_{jkt} \right) \cdot MS^{\pm}_{t} \cdot \varepsilon^{\pm}_{NM} + RP^{\pm}_{t} \cdot ACW^{\pm}_{t} \cdot DNR^{\pm}_{t} \leq ANL^{q_i}_{t}, \quad \forall t \tag{18a}$$

$$\sum_{r=1}^{4} AML^{\pm}_{rt} \cdot NL^{\pm}_{r} + AMH^{\pm}_{t} \cdot RP^{\pm}_{t} \geq \sum_{j=1}^{4} \sum_{k=1}^{9} AM^{\pm}_{jkt}, \quad \forall t \tag{18b}$$

$$NL_{r,\min} \leq NL^{\pm}_{r} \leq NL_{r,\max}, \quad \forall r \tag{18c}$$

(7) Non-negative constraints:

$$PLC^{\pm}_{it}, \; PA^{\pm}_{jkt}, \; NL^{\pm}_{r}, \; QW^{\pm}_{st}, \; PLM^{\pm}_{pt}, \; AM^{\pm}_{jkt}, \; AF^{\pm}_{jkt} \geq 0 \tag{19}$$

The details of nomenclatures and the RIPP model under NM are listed in "Appendix B." Solutions for the RIPP model under a given risk level (i.e., the probability of violating pollutant discharge allowance constraints q_i) can be obtained through integration of solutions of the lower and upper submodels. A set of interval solutions associated with possiblistic and probabilistic information for the objective and decision variables can be obtained by solving the submodels under the other risk levels. The RIPP model under NM can be similarly formulated based on the RIPP method.

Then, based on the optimization results, a set of parameters are selected as impact factors that need to be analyzed. In this study, factorial design involves n factors with each at three levels (i.e., 3^n factorial design). The three levels of factors are represented as low, medium, and high; they are often denoted by −1, 0, and +1, respectively (Wang et al. 2015a, b). Taguchi method uses a set of special orthogonal arrays for laying out the matrix of experiments (Sivasakthivel et al. 2014). This matrix can determine the main effects of factors with minimum number of experiments and the best level of each factor can also be found. The number of experiments can be determined according to $N_{\text{Taguch}} = 1 + \sum_{i=1}^{NV} (L_i - 1)$, where NV is the number of factors; L_i is the number of levels (Sivasakthivel et al. 2014).

In the full factorial design scheme, there are 3^n treatment combinations with $3^n - 1$ degrees of freedom. These treatment combinations allow sums of squares to be computed for n main effects with each having 2 degrees of freedom, and m-factor interaction has 2^m degrees of freedom ($m \leq n$) (Wang et al. 2015b). Any m-factor interaction can be divided into 2^{m-1} orthogonal two-degrees-of-freedom components, which are helpful to construct complex designs (Montgomery 2001). In factorial design analysis, it is essential to build a matrix of orthogonal coefficients following the standard Yates' order (Montgomery and Runger 2003). The following equations are then used to evaluate the individual and interactive effects:

$$EF_x = \frac{\text{Contrast}(x)}{2^{k-1}} \tag{20}$$

$$SS_x = \frac{(\text{Contrast}(x))^2}{2^k} \tag{21}$$

where EF_x is the standardized effect of a factor or joint effects of multi-factors; *Contrast(x)* is calculated according to the Yates' order table; SS_x is the sum of squares for a factor or multi-factor interaction. The importance of factors and their interactions can be ranked by the standardized effect and/or sum of squares.

Result analysis

Possibility/necessity degrees

In this study, 14 θ levels (i.e., probability of satisfying objective function) and 12 q_i levels (i.e., probability of violating pollutant discharge allowance constraints) were examined. The minimum and maximum system benefits that decision makers desire to achieve are [800, 1200] × 10^6 RMB¥ (i.e.,$z_0^{\pm}$) and [1300, 1700] × 10^6 RMB¥ (i.e.,$z_1^{\pm}$), respectively. Figure 3 shows the possibility and necessity degrees (i.e., degrees of possibility and necessity that the fuzzy goal is fulfilled under the possibility distribution of the objective function) under different θ and q_i levels, where possibility and necessity degrees would decrease with the raised θ levels. For example, when q_i = 0.01, they would respectively be [0.1219, 0.1289] and [0.3364, 0.5579] under θ = 0.01; in comparison, they would respectively be [0.0775, 0.1209] and [0.2707, 0.5508] under θ = 0.90. It is implied that decision makers who predetermine a higher probability of satisfying objective function would obtain a lower system benefit, leading to a decreased risk of violating system feasibility. It is also shown that possibility degree would be lower than necessity degree under a given risk level. For instance, when q_i = 0.05 and θ = 0.01, possibility and necessity degrees would be [0.1292, 0.1554] and [0.3493, 0.5886], respectively. This is because decision makers with PM possess a risk-neutral attitude (with desiring a high system benefit); contrarily, decision makers with NM own a risk-averse attitude. Decision makers could choose either PM or NM based on their risk preferences. Moreover, the variation of system benefit based on the

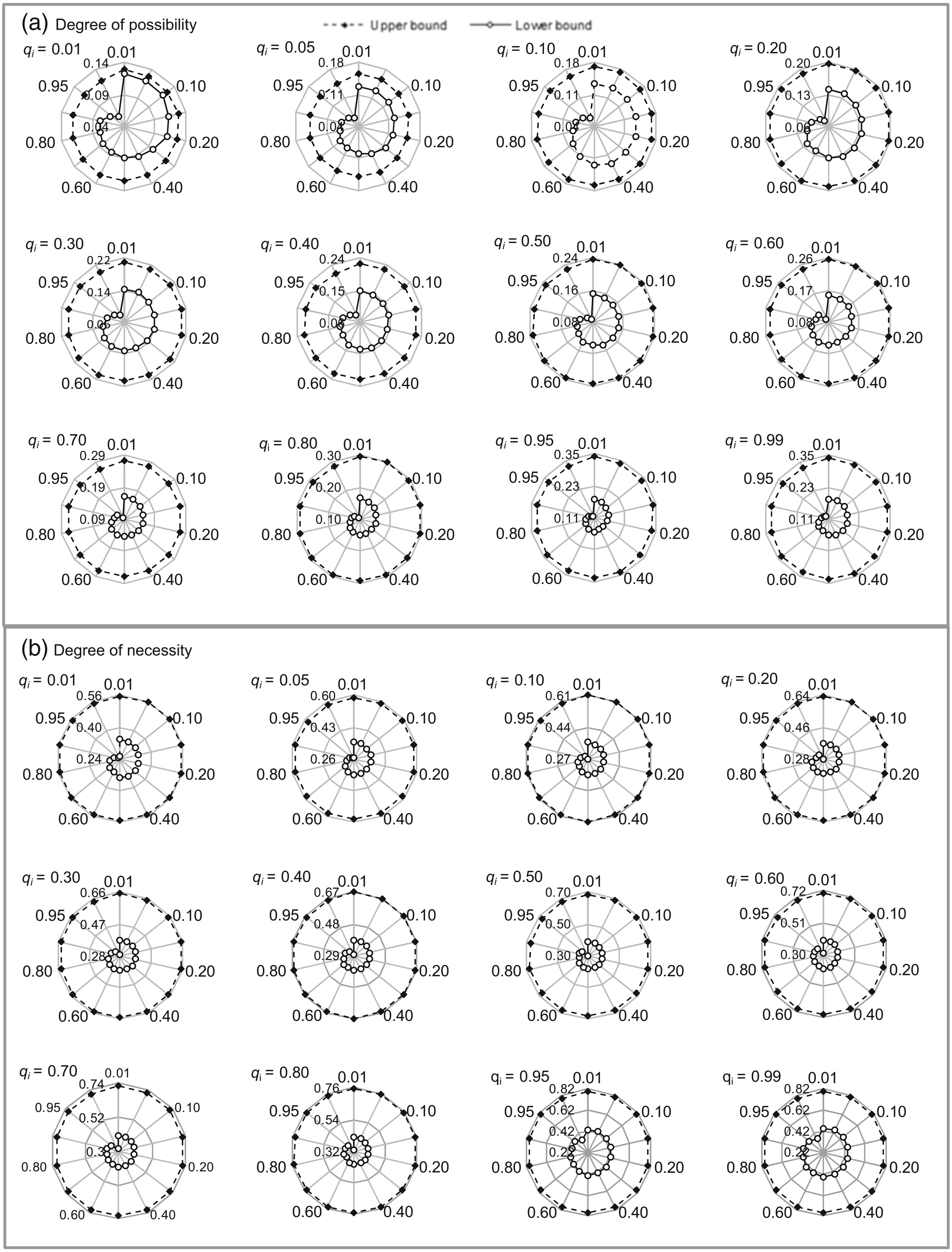


Fig. 3 Possibility and necessity degrees with different θ and q_i levels

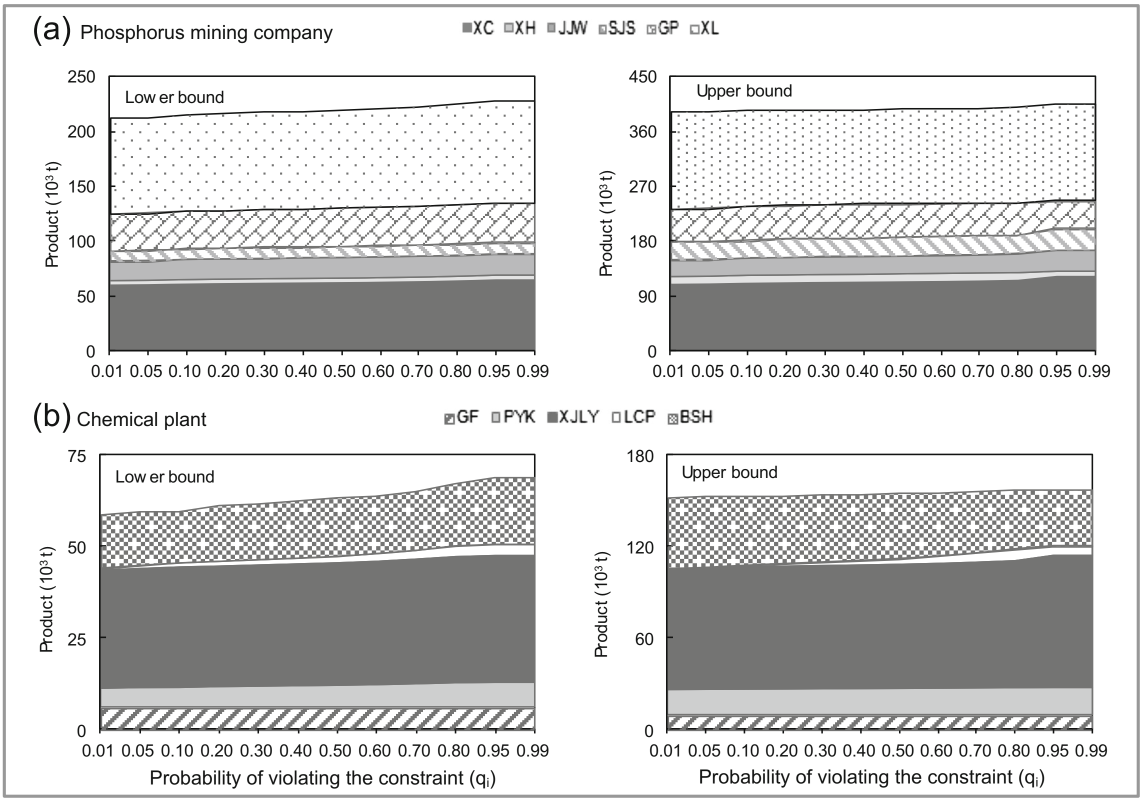


Fig. 4 Production scales of industrial activities under different q_i levels

chance-constraints (related to pollutant discharge allowances) also represents a compromise between economic activity and river protection. For instance, when $\theta = 0.10$, the system benefit would be [859.9, 1263.7] × 10^6 RMB¥ under $q_i = 0.01$ (with PM), while the system benefit would be [863.3, 1276.7] × 10^6 RMB¥ under $q_i = 0.05$ (with PM). Results reveal that decisions associated with a strong desire (corresponding to a high q_i level) to obtain a high system benefit would lead to an increased risk of violating environmental requirements.

Agricultural and industrial activities

Figures 4 and 5 present the production scales of industrial and agricultural activities under different q_i levels over the planning horizon. Production scales would vary as q_i level is raised. This is because the amounts of products are mainly determined by the benefit (per unit), pollutant discharge rate, and pollutant discharge allowance. Generally, XL (occupying [32.8, 33.3]% of the total amount generated by phosphorus mining companies) and BSH (occupying [35.4, 36.9]% of the total amount generated by chemical plants) are the main economic contributors to industrial activities. These may be associated with their high benefits (per unit) and low pollutant discharge rates. In terms of agriculture, it is shown that the areas of potato and wheat would occupy [77.8, 80.6]% of the total farmland in dry season, and [74.4, 76.4]% of the tillable land in wet season would be planted with vegetables. Most amounts of manure would be generated by sheep and domestic fowl, attributing to their high feeding sizes and economic benefits.

Pollutant discharge

Figure 6 displays the distribution of pollutant discharge from each sector under $q_i = 0.05$. Chemical plants discharged [61.6, 85.6]% of BOD and [56.6, 65.7]% of TP. This is attributed to their high production scales and high pollutant discharge rates. Specifically, BSH contributed about [46.0, 67.8]% of BOD. Promotion of centralized treatment of industrial wastewater and wastes would largely reduce BOD and TP discharges. Results also indicate that TN be mainly discharged by crop farming, accounting for [74.8, 86.5]% of the total amount. Soil loss rate would be mainly responsible for the TN discharge since the study area belongs to an intense soil loss region (associated with the special geography and heavy rainfall). Therefore, protection measures such as a combination of broad-base terraces and infiltration strips should be adopted.

Identification of significant factors

Based on the optimization results, six factors such as probability of violating constraint (q_i), probability of satisfying

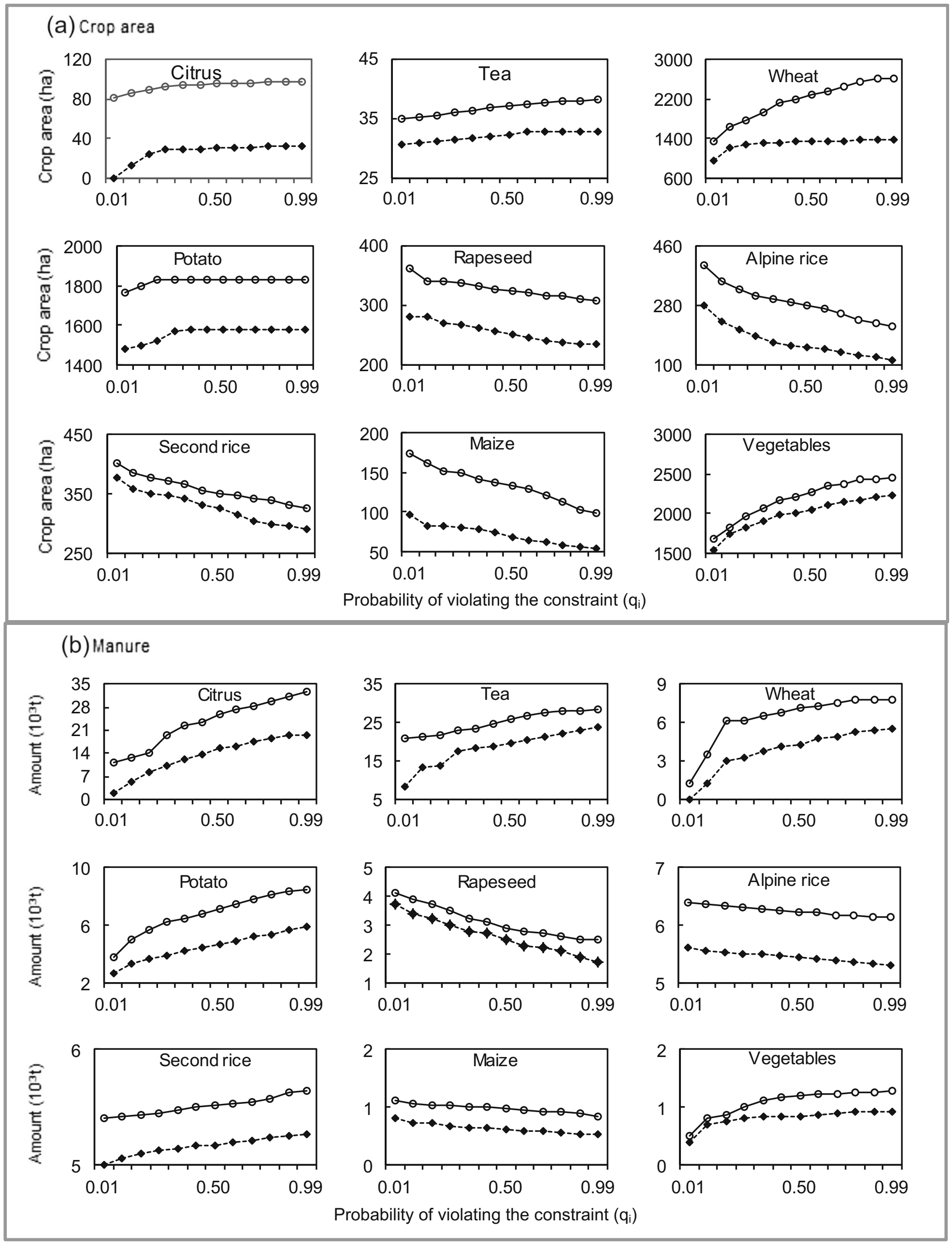


Fig. 5 Solutions for crop area planning and manure application

objective function (θ), benefit from phosphorus mining company ($\lambda_{it}^{\pm}$, $\mu_{it}^{\pm}$), benefit from chemical plant ($\lambda_{pt}^{\pm}$, $\mu_{pt}^{\pm}$), benefit from agricultural product ($\lambda_{st}^{\pm}$, $\mu_{st}^{\pm}$), and benefit of water supply ($\lambda_{jkt}^{\pm}$, $\mu_{jkt}^{\pm}$) are denoted as A, B, C, D, E, and F to carry out the factorial experiment, respectively. They are further divided into three levels with the following: (i) low level (−1) corresponding to $q_i = 0.01$, $\theta = 0.90$, (λ_{it}^{-}, μ_{it}^{-}), (λ_{pt}^{-}, μ_{pt}^{-}), (λ_{st}^{-}, μ_{st}^{-}), and (λ_{jkt}^{-}, μ_{jkt}^{-}); (ii) medium level (0) corresponding to $q_i = 0.05$, $\theta = 0.95$, $((\lambda_{it}^{-} + \lambda_{it}^{+})/2, (\mu_{it}^{-} + \mu_{it}^{+})/2)$, $((\lambda_{pt}^{-} + \lambda_{pt}^{+})/2, (\mu_{pt}^{-} + \mu_{pt}^{+})/2)$, $((\lambda_{st}^{-} + \lambda_{st}^{+})/2, (\mu_{st}^{-} + \mu_{st}^{+})/2)$, and $((\lambda_{jkt}^{-} + \lambda_{jkt}^{+})/2, (\mu_{jkt}^{-} + \mu_{jkt}^{+})/2)$; (iii) high level (+1) corresponding to $q_i = 0.10$, $\theta = 0.99$, (λ_{it}^{+}, μ_{it}^{+}), (λ_{pt}^{+}, μ_{pt}^{+}), (λ_{st}^{+}, μ_{st}^{+}), and (λ_{jkt}^{+}, μ_{jkt}^{+}).The average system benefit (i.e., $f_{\text{ave}} = (f^{-} + f^{+})/2$) is employed to estimate the comprehensive effects of the factors on system performance. The f_{ave} would range from 1220.3 × 10^6 to 1433.1 × 10^6 RMB¥ under PM, and 903.0 × 10^6 to 1060.5 × 10^6 RMB¥ under NM. It is thus necessary to examine the effects of the six factors and figure out the dominant factors due to the noticeable changes of the system benefit result from variations of these factors.

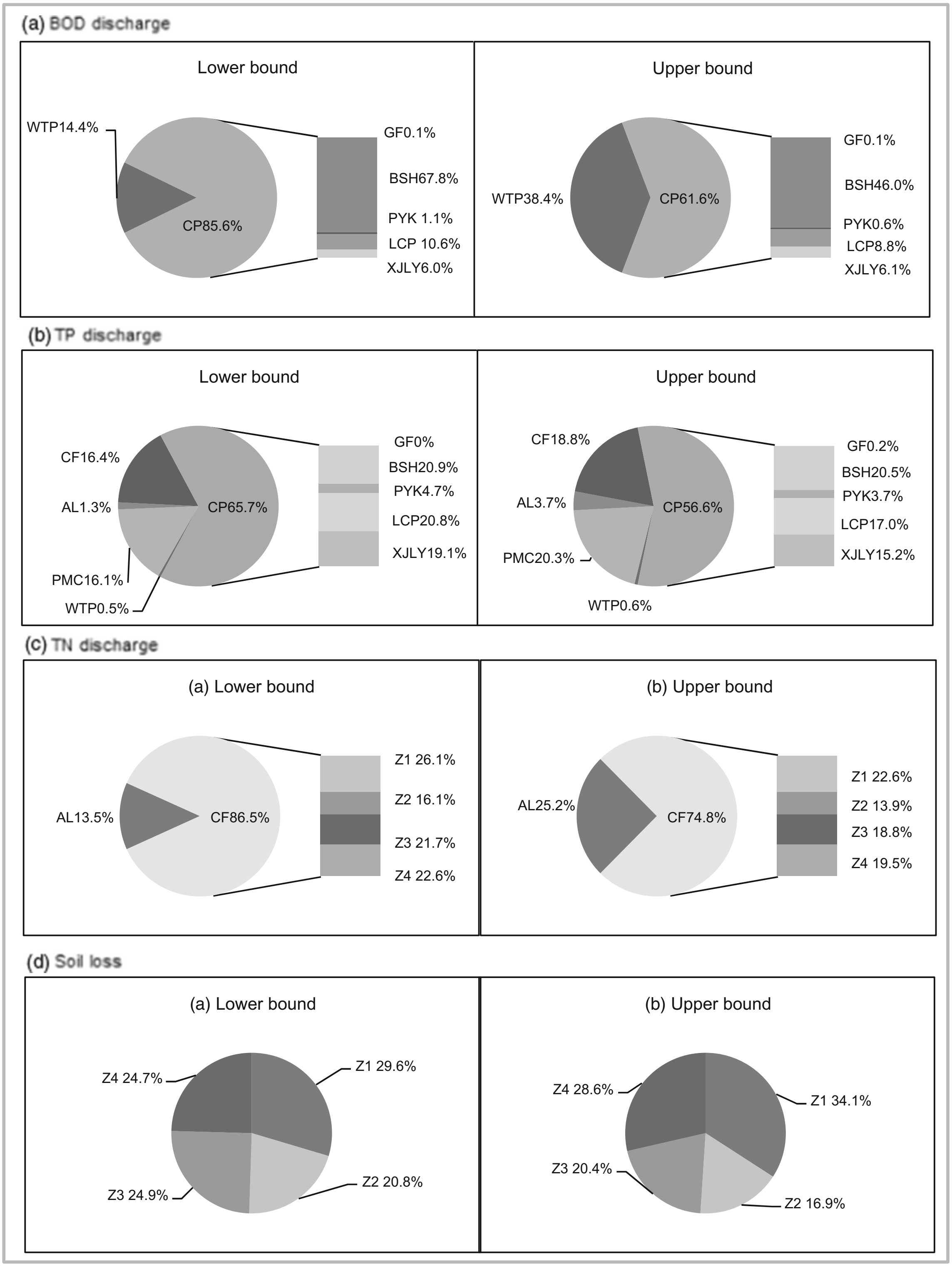


Fig. 6 Distribution of pollutant discharge from each sector ($q_i = 0.05$). Note: *WTP*, wastewater treatment plant; *CP*, chemical plant; *CF*, crop farming; *AL*, agricultural life; *PMC*, phosphorus mining company

Table 3 visualizes the effects of the six factors which estimated based on f_{ave}. All delta values are positive (delta value = maximum value − minimum value), indicating their positive effects on the modeling response. The positive delta value implies that the system benefit would increase with the increased factor level. This is mainly because a higher factor level corresponds to a higher risk and a higher benefit (per unit), leading to a higher system benefit. The factor with higher delta value would

Table 3 Response table for average system benefits (10^6 RMB¥)

Level	Factor					
	A	B	C	D	E	F
PM						
1	1328.74	1339.62	1333.84	1300.09	1336.32	1324.91
2	1349.04	1347.11	1351.05	1351.00	1348.88	1349.24
3	1366.78	1357.82	1359.66	1393.47	1359.36	1374.45
Delta	38.04	18.20	25.82	93.38	23.04	49.54
Rank	3	6	4	1	5	2
NM						
1	983.26	991.32	987.04	962.02	988.88	980.44
2	998.29	996.86	999.78	999.74	998.17	998.43
3	1011.42	1004.79	1006.15	1031.17	1005.92	1017.09
Delta	28.16	13.47	19.11	69.15	17.04	36.65
Rank	3	6	4	1	5	2

Delta value is calculated as the difference between maximum and minimum averages of system benefits

correspond to more significant effect. Results indicate that factor D would have the most significant effect on the system benefit; contrarily, factor B would have the most insignificant effect on the system benefit. Such an effect may be associated with the industrial-oriented pattern of the study area (where mineral resources are abundant, and can bring high economic return). Therefore, A, C, D, and F are important factors, while B and E are unimportant factors and removed from further analysis.

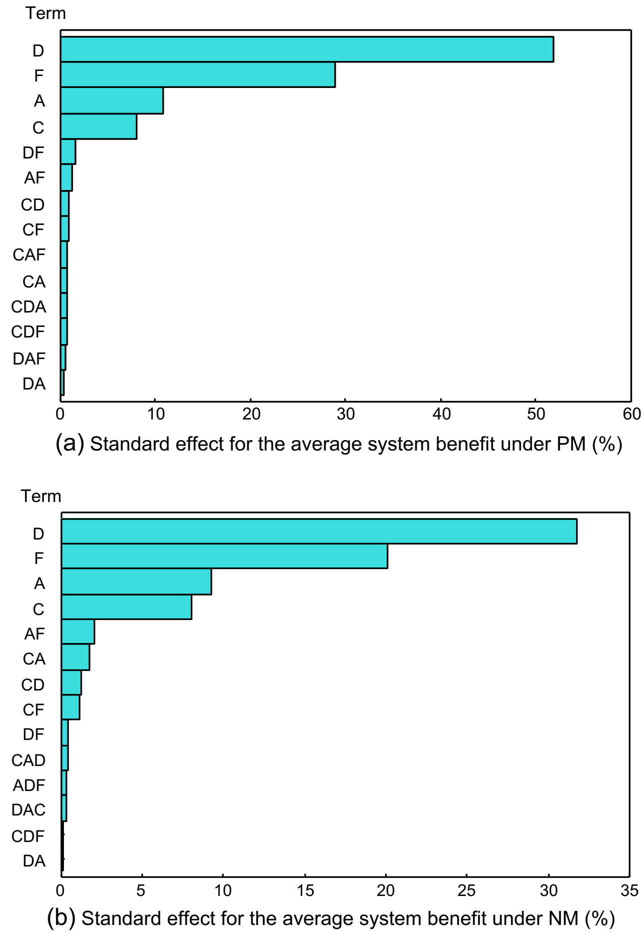


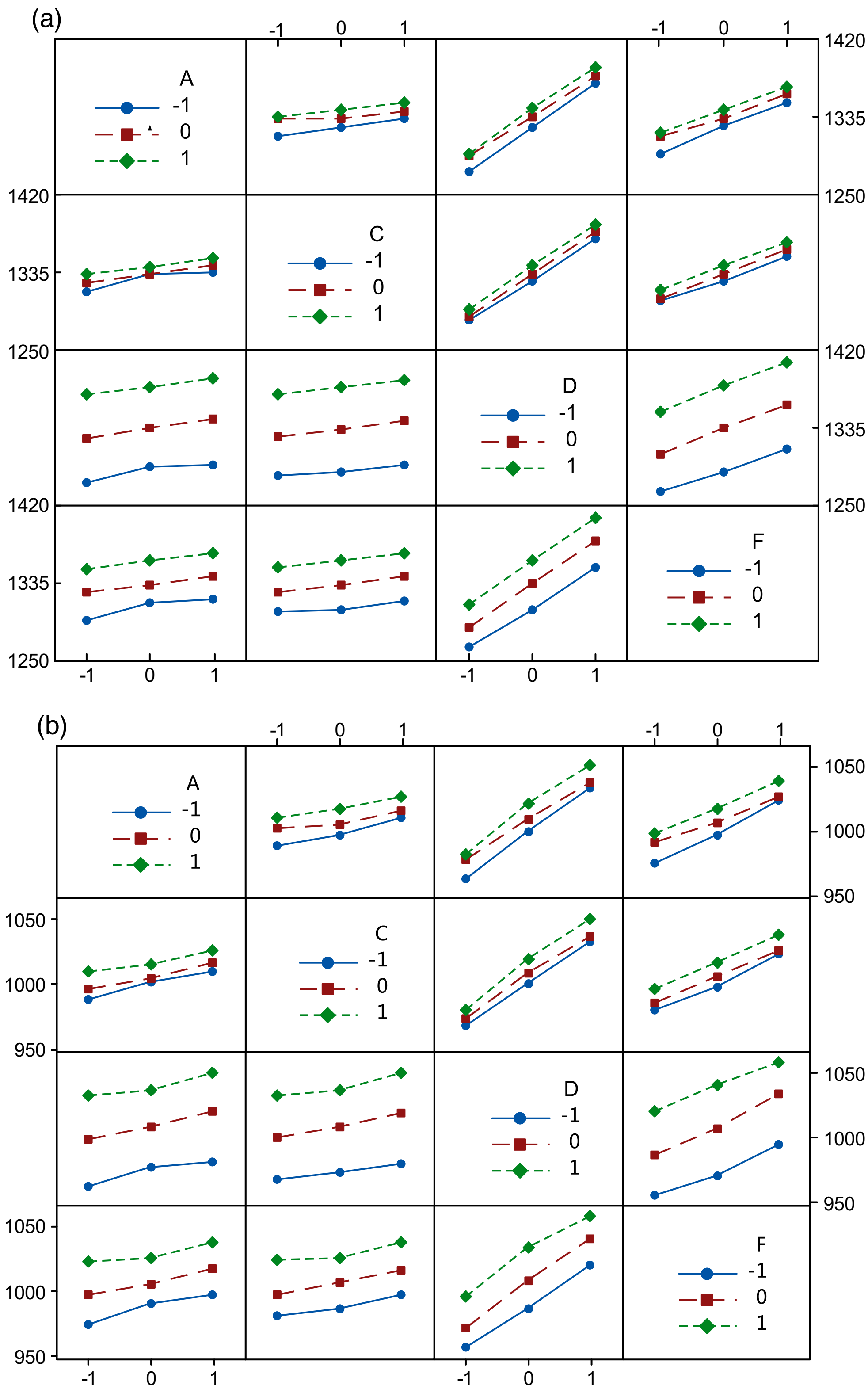
Fig. 7 Pareto chart of the standardized effect under **a** PM and **b** NM

Analyzation of interaction effects

Figure 7 depicts the Pareto chart for the standardized effects of important factors and their interactions on f_{ave} under PM and NM, in which factor effects are ranked in descending order based on their significant levels. Results indicate that benefit from chemical plant (D) would contribute 53.8% of f_{ave} followed by benefit of water supply (F) that comparatively less (29.7%) under PM. In case of NM, the most significant factor (D) would contribute nearly 28.3% of f_{ave} while the second significant factor (F) would contribute around 19.7%. It is also shown that variation of f_{ave} under NM is less than that under PM because the decision making under NM is based on a risk-averse attitude. Besides, results indicate that the effects of three-factor interactions are insignificant and can be neglected. For example, the interaction of C, A, and F would own 1.3% on f_{ave} under PM; the interaction of C, A, and D would have 0.8% under NM. More attention should be paid to the significance of individual factors and two-factor interactions to advance the model's performance.

Figure 8 provides the interactions plot matrix for A, C, D, and F under PM and NM. The intersection lines present an interactive effect between factors on f_{ave}. In Fig. 5a, the three lines of F would rise as D varies across its three levels, while the line denoting the low level (−1) of D increases faster than the other two. It is revealed that, when benefit from chemical plant (D) is low, the variation of benefit of water supply (F) would lead to relatively significant variation of f_{ave}; f_{ave} would respectively be 1283.4×10^6, 1311.7×10^6, and 1319.4×10^6 RMB¥ under the three levels of factor F. According to Eq. (20), the interactive effect between factors D and F would contribute nearly 12.7% of f_{ave}. In Fig. 5b, the effect of F would depend on A under NM. The interaction of A and F has an obvious effect on f_{ave} compared with the other factors. F would have a low effect when A is at the high level; moreover, it would have a relatively high effect when A remains at the low level. f_{ave} would respectively be 977.5×10^6, 985.1×10^6, and 994.3×10^6 RMB¥ under the three levels of F. The interactive effect between factors A and F would contribute nearly 15.8% of f_{ave}. It is indicated that a higher benefit of water supply would lead to increased system benefit when the risk level of violating water quality is low. Generally, the trade-off between production scales and pollutant discharges of chemical plants would be a challenge for the

Fig. 8 Interaction plots for the average system benefit under: **a** PM; **b** NM (10^6 RMB¥)



decision makers. For example, decision makers can adopt the improved wastewater treatment technologies such as tertiary wastewater treatment and depth processing technologies to further improve pollutant removal efficiency.

Discussion

The first attempt to employ the MRPP method to support water quality management of a watershed system demonstrates its applicability. Generally, the MRPP method has advantages in the following: (i) it is superior to the conventional optimization techniques for handling fuzzy-boundary intervals, probability distributions and interval numbers; (ii) it is effective in quantifying the effect of individual factors and their interactions on modeling outputs; (iii) it can investigate the nonlinear relationship between uncertainty parameters and modeling outputs. Especially, compared with the traditional global sensitivity analysis methods, the MRPP can obtain the importance of uncertain parameters and analyzing their interactions without simulation method (e.g., Monte Carlo method).

However, the MRPP method still has space for further improvement. Firstly, it is solved for probability distributions (associated with the pollutant discharge allowances) that the decision maker believes in the probability range of interest. The solutions with respect to the randomness may be questioned. Monte Carlo filtering and Bayesian estimation may be alternatives to deal with such a problem, which can catch the randomness of pollutant discharge allowances. Secondly, the MRPP is very complex to calculate when a large number of factors and levels are taken into account (due to the increased number of experimental runs). In addition, water quality trading is a promising policy alternative for pollution control, which is a market-based strategy and can provide cost-effective and flexible environmental compliance in a basin. It allows one source to meet its regulatory obligations by using pollutant reductions created by another source that possesses lower pollution control costs on a basin basis; such trading could effectively capitalize on economies of scale and the control cost differentials among multiple sources. The MRPP can be improved through incorporating more water quality trading programs into its framework to cost-effectively control water pollution.

Conclusions

In this study, a MRPP method has been developed for supporting water quality management under multiple uncertainties, through introducing MTD into RIPP framework. Then, the MRPP method has been employed to plan water quality management in the Xiangxihe watershed. Solutions with probability of satisfying objective function (θ) and probability of violating environmental requirements (q_i) concerning industrial and agricultural activities have been generated. Some findings can be discovered on the basis of the optimization results: (1) a higher θ level and/or a higher q_i level correspond to a lower possibility/necessity degree (i.e., a higher system benefit) and an increased risk of violating system feasibility; (2) possibility degree would be lower than necessity degree under a given probability level due to different risk attitudes of decision makers; (3) XL and BSH are the main economic contributors to industrial activities; (4) areas of potato and wheat would occupy [77.8, 80.6]% of the total farmland in dry season, and [74.4, 76.4]% of the tillable land in wet season would be planted with vegetables; (5) [61.6, 85.6]% of BOD and [61.6, 85.6]% of TP are from chemical plants, and crop farming discharge the most of TN ([74.8, 86.5]% of TN).

Six parameters including q_i (A), θ (B), benefit from phosphorus mining company (C), benefit from chemical plant (D), benefit from agricultural product (E), and benefit of water supply (F) are selected to investigate impact factors and their interactions. The individual and interactive effects are calculated based on the Eq. (20) (which is formulated according to the Yates' order table). Results disclose that (1) the effects of the six factors on the system benefit are positive; (2) D has the most significant effect, averagely contributing 53.8% and 28.3% on the system benefit under PM and NM, respectively; (3) the interaction between D and F has statistically significant effect on the system benefit under PM (the interactive effect between factors D and F would contribute nearly 12.7% of f_{ave}); (4) the interactive effect between A and F is important under NM (The interactive effect between factors A and F would contribute nearly 15.8% of f_{ave}). Decision makers can enhance the performance of the model through adjusting the benefit from chemical plant as well as balancing the interactions between benefits of water supply and chemical plant. Although benefit of chemical plant plays a significant role, chemical plants are the major contributors to BOD and TP discharges. The trade-off between production scales and pollutant discharges of chemical plants would be a challenge for the decision makers.

Acknowledgements This research was supported by the National Key Research Development Program of China (2016YFC0502803 and 2016YFA0601502), and the 111 Project (B14008). The authors are grateful to the editors and the anonymous reviewers for their insightful comments and suggestions.

Appendix A: Solution method

A robust two-step method is proposed to convert model (10) into two submodels that correspond to lower and upper bounds of the objective function value. Since the objective is to maximize the system benefit, the submodel corresponding to the upper bound of the objective function value (h^+) should be first formulated. Submodel (2) corresponding to h^- is then formulated. In the first step, a set of submodels corresponding to h^+ can be reformulated as:

$$\text{Max } h^+ \tag{22}$$

subject to:

$$\frac{\sum_{j=1}^{k_1}\left(\lambda_j^+-\mu_j^+\right)x_j^+ + \sum_{j=k_1+1}^{n}\left(\lambda_j^+-\mu_j^+\right)x_j^- - \Phi^{-1}(1-\theta)\sqrt{\sum_{j=1}^{k_1}\left(\sigma_j^+x_j^+\right)^2 + \sum_{j=k_1+1}^{n}\left(\sigma_j^+x_j^-\right)^2} + z_0^+}{\sum_{j=1}^{k_1}\lambda_j^+x_j^+ + \sum_{j=1}^{n}\lambda_j^+x_j^- - z_1^+ + z_0^+} \ge h_+ \tag{23}$$

$$\sum_{j=1}^{j_1}|a_{ij}|^-\text{Sign}\left(a_{ij}^-\right)x_j^+ + \sum_{j=k_1+1}^{n}|a_{ij}|^+\text{Sign}\left(a_{ij}^+\right)x_j^- \le b_i(\omega)^{q_i},\quad i = 1,2,\ldots,m \tag{24}$$

$$x_j^+ \ge 0,\quad j = 1,2,\ldots,k_1 \tag{25}$$

$$x_j^- \ge 0,\quad j = k_1+1, k_1+2,\ldots,n \tag{26}$$

where x_j^+ (j = 1, 2, ..., k_1) are upper bounds of the decision variables ($x_j^\pm$) with positive coefficients in the objective function, and x_j^- (j = k_1 + 1, k_1 + 2, ..., n) are lower bounds with negative coefficients. Submodels corresponding to h^- can be formulated as:

$$\text{Max } h^- \tag{27}$$

subject to:

$$\frac{\sum_{j=1}^{k_1}\left(\lambda_j^--\mu_j^-\right)x_j^- + \sum_{j=k_1+1}^{n}\left(\lambda_j^--\mu_j^-\right)x_j^+ - \Phi^{-1}(1-\theta)\sqrt{\sum_{j=1}^{k_1}\left(\sigma_j^-x_j^-\right)^2 + \sum_{j=k_1+1}^{n}\left(\sigma_j^-x_j^+\right)^2} + z_0^-}{\sum_{j=1}^{k_1}\lambda_j^-x_j^- + \sum_{j=1}^{n}\lambda_j^-x_j^+ - z_1^- + z_0^-} \ge h^- \tag{28}$$

$$\sum_{j=1}^{j_1}|a_{rj}|^+\text{Sign}\left(a_{rj}^+\right)x_j^- + \sum_{j=k_1+1}^{n}|a_{rj}|^-\text{Sign}\left(a_{rj}^-\right)x_j^+ \le b_i(\omega)^{q_i},\quad i = 1,2,\ldots,m \tag{29}$$

$$0 \le x_j^- \le x_{j\ opt}^+,\quad j = 1,2,\ldots,k_1 \tag{30}$$

$$x_j^+ \ge x_{j\ opt}^-,\quad j = k_1+1, k_2+1,\ldots,n \tag{31}$$

where $x_{j\ opt}^+$ (j = 1, 2, ..., k_1) and $x_{j\ opt}^-$ (j = k_1 + 1, k_1 + 2, ..., n) are solutions corresponding to h^-. The model can be similarly solved when NM is adopted.

Appendix B: Nomenclatures and the RIPP model under NM

I	chemical plant, 1 = Gufu (GF), 2 = Baishahe (BSH), 3 = Pingyikou (PYK), 4 = Liucaopo (LCP), 5 = Xiangjinlianying (XJLY)
J	agricultural zone, and j = *1*, *2*, *3*, *4*
K	main crop, 1 = citrus, 2 = tea, 3 = wheat, 4 = potato, 5 = rapeseed, 6 = alpine rice, 7 = second rice, 8 = maize, 9 = vegetables
P	phosphorus mining company; 1 = Xinglong (XL), 2 = Xinghe (XH), 3 = Xingchang (XC), 4 = Geping (GP), 5 = Jiangjiawan (JJW), 6 = Shenjiashan (SJS)
r	livestock, 1 = pig, 2 = ox, 3 = sheep, 4 = domestic fowls
s	town, 1 = Gufu, 2 = Nanyang, 3 = Gaoyang, 4 = Xiakou
t	planning time period, 1 = dry season, 2 = wet season
$\lambda_{it}^\pm, \mu_{it}^\pm, \sigma_{it}^\pm$	mean value, expected value, and standard deviation of benefit from chemical plant (RMB¥/t)
$PLC_{it}^\pm$	production level of chemical plant (t)
$\lambda_{pt}^\pm, \mu_{pt}^\pm, \sigma_{pt}^\pm$	mean value, expected value, and standard deviation of benefit for phosphate ore (RMB¥/t)
$PLM_{pt}^\pm$	production level of phosphorus mining company p during period t (t)
$\lambda_{st}^\pm, \mu_{st}^\pm, \sigma_{st}^\pm$	mean value, expected value, and standard deviation of benefit from water supply (RMB¥/m^3)
$QW_{st}^\pm$	quantity of water supply (m^3)
$CY_{jkt}^\pm$	yield of crop (t/ha);
$\lambda_{jkt}^\pm, \mu_{jkt}^\pm, \sigma_{jkt}^\pm$	mean value, expected value, and standard deviation of benefit for agricultural product (RMB¥/t)

$PA^{\pm}_{jkt}$ planning area of crop k in agricultural zone j during period t (ha)
$\lambda^{\pm}_{r}$,$\mu^{\pm}_{r}$,$\sigma^{\pm}_{r}$ mean value, expected value, and standard deviation of benefit from livestock (RMB¥/unit)
$NL^{\pm}_{r}$ number of livestock r in the study area (unit)
$\lambda'^{\pm}_{it}$,$\mu'^{\pm}_{it}$,$\sigma'^{\pm}_{it}$ mean value, expected value, and standard deviation of wastewater treatment cost of chemical plant (RMB¥/t)
$\lambda'^{\pm}_{st}$,$\mu'^{\pm}_{st}$,$\sigma'^{\pm}_{st}$ mean value, expected value, and standard deviation of wastewater treatment cost at town (RMB¥/m^3)
$\lambda^{\pm}_{jt}$,$\mu^{\pm}_{jt}$,$\sigma^{\pm}_{jt}$ mean value, expected value, and standard deviation of cost for manure disposal (RMB¥/t)
$\lambda'^{\pm}_{jt}$,$\mu'^{\pm}_{jt}$,$\sigma'^{\pm}_{jt}$ mean value, expected value, and standard deviation of cost for purchasing fertilizer (RMB¥/t)
$z^{\pm}_{0}$ minimum total net benefit that decision makers want to obtain (RMB¥)
$z^{\pm}_{1}$ maximum total net benefit that decision makers want to obtain (RMB¥)
$AM^{\pm}_{jkt}$ amount of manure applied to agricultural zone (t)
$AF^{\pm}_{jkt}$ amount of fertilizer applied to agricultural zone (t)
$TPC^{\pm}_{st}$ capacity of wastewater treatment capacity (WTPs) (m^3)
$TPD^{\pm}_{it}$ capacity of wastewater treatment capacity (chemical plants) (m^3)
$IC^{\pm}_{it}$ BOD concentration of raw wastewater from chemical plant (kg/m^3)
$\eta^{\pm}_{BOD,it}$ BOD treatment efficiency in chemical plant (%)
$ABC^{\pm}_{it}$ allowable BOD discharge for chemical plant (kg)
$BM^{\pm}_{st}$ BOD concentration of municipal wastewater at town (kg/m^3)
$\eta'^{\pm}_{BOD,st}$ BOD treatment efficiency of WTPs at town (%)
$ABW^{q_i}_{st}$ allowable BOD discharge for WTPs at town (kg)
$AML^{\pm}_{rt}$ amount of manure generated by livestock [t/ unit]
$AMH^{\pm}_{t}$ amount of manure generated by humans [t/ unit]
$RP^{\pm}_{t}$ total rural population in the study area during period t (unit)
$MS^{\pm}_{t}$ manure loss rate in period t (%)
$\varepsilon^{\pm}_{NM}$ nitrogen content of manure (%)
$ACW^{\pm}_{t}$ wastewater generation of per capita water consumption during period t (m^3/ unit)
$DNR^{\pm}_{t}$ dissolved nitrogen concentration of rural wastewater during period t (t/m^3)
$ANL^{q_i}_{t}$ maximum allowable nitrogen loss from rural life section in period t (t)
$NS^{\pm}_{jk}$ nitrogen content of soil in agricultural zone (%)
$SL^{\pm}_{jkt}$ average soil loss from agricultural zone (t/ha)
$RF^{\pm}_{jkt}$ runoff from agricultural zone (mm)
$DN^{\pm}_{jkt}$ dissolved nitrogen concentration in runoff from agricultural zone (mg/L)
$MNL^{\pm}_{jt}$ maximum allowable nitrogen loss in agricultural zone j during period t (t/ha)
$TA^{\pm}_{jt}$ tillable area of agricultural zone (ha)
$PCR^{\pm}_{it}$ phosphorus concentration of raw wastewater from chemical plant (kg/m^3)
$\eta^{\pm}_{TP,it}$ phosphorus treatment efficiency in chemical plant (%)
$ASC^{\pm}_{it}$ amount of slag discharged by chemical plant (kg/t)
$SLR^{\pm}_{it}$ slag loss rate due to rain wash in chemical plant (%)
$PSC^{\pm}_{it}$ phosphorus content in slag generated by chemical plant (%)
$APC^{q_i}_{it}$ allowable phosphorus discharge for chemical plant (kg)
$\varepsilon^{\pm}_{PM}$ phosphorus content of manure (%)
$DPR^{\pm}_{t}$ dissolved phosphorus concentration of rural wastewater (t/m^3)
$APL^{\pm}_{t}$ maximum allowable phosphorus loss from rural life during period t (t)
$PCM^{\pm}_{st}$ phosphorus concentration of municipal wastewater at town (kg/m^3)
$\eta^{\pm}_{TP,st}$ phosphorus treatment efficiency of WTP at town (%)
$APW^{\pm}_{st}$ allowable phosphorus discharge for WTP at town (kg)
$WPM^{\pm}_{pt}$ wastewater generation from phosphorus mining company (m^3/t)
$MWC^{\pm}_{pt}$ phosphorus concentration of wastewater from mining company (kg/ m^3)
$\eta^{\pm}_{TP,pt}$ phosphorus treatment efficiency in mining company (%)
$ASM^{\pm}_{pt}$ amount of slag discharged by mining company (kg/t)
$PCS^{\pm}_{pt}$ phosphorus content in generated slag (%)
$SLW^{\pm}_{pt}$ slag loss rate due to rain wash (%)
$APM^{q_i}_{pt}$ allowable phosphorus discharge for mining company (kg)
$PS^{\pm}_{jk}$ phosphorus content of soil in agricultural zone (%)
$SL^{\pm}_{jkt}$ average soil loss from agricultural zone (t/ha)
$DP^{\pm}_{jkt}$ dissolved phosphorus concentration in runoff from agricultural zone (mg/L)
$MPL^{\pm}_{jt}$ maximum allowable phosphorus loss in agricultural zone (t/ha)
$MSL^{\pm}_{jt}$ maximum allowable soil loss agricultural zone (t/ha)
$NVF^{\pm}_{t}$ nitrogen volatilization/denitrification rate of fertilizer (%)

$NVM_t^{\pm}$ nitrogen volatilization/denitrification rate of manure (%)
$\varepsilon_{NF}^{\pm}$ nitrogen content of fertilizer (%)
$\varepsilon_{PF}^{\pm}$ phosphorus content of fertilizer (%)
$\varepsilon_{NM}^{\pm}$ nitrogen content of manure (%)
$\varepsilon_{PM}^{\pm}$ phosphorus content of manure (%)
$NR_{jkt}^{\pm}$ nitrogen requirement of agricultural zone (t/ha)
$PR_{jkt}^{\pm}$ phosphorus requirement of crop k in agricultural zone (t/ha)
$TAH_{jt}^{\pm}$ dry farmland of agricultural zone (ha)
$TAS_{jt}^{\pm}$ paddy farmland of agricultural zone (ha)
$MFP_t^{\pm}$ the government requirement for minimum area of farmland (ha);
$PLC_{it,\min}^{\pm}$ minimum production level of chemical plant (t/day)
$PLC_{it,\max}^{\pm}$ maximum production level of chemical plant (t/day)
$NL_{r,\min}^{\pm}$ minimum number of livestock (unit)
$NL_{r,\max}^{\pm}$ maximum number of livestock (unit)
$QW_{st,\min}^{\pm}$ minimum quantity of water supply to town (m^3/day)
$QW_{st,\max}^{\pm}$ maximum quantity of water supply to town (m^3/day)
$PLM_{pt,\min}^{\pm}$ minimum production level of phosphorus mining company (t/day)
$PLM_{pt,\max}^{\pm}$ maximum production level of phosphorus mining company (t/day)

The RIPP model under NM for supporting support water quality management in the Xiangxihe watershed can be represented as follows:

$$\text{Max } h^{\pm} \tag{32}$$

subject to:

(1) Risk inference of decision maker:

$$\frac{\begin{array}{l}\left\{\sum_{i=1}^{5}\sum_{t=1}^{2}\left[\mu_{it}^{\prime\pm}-\mu_{it}^{\pm}\right]PLC_{it}^{\pm}-\sum_{p=1}^{6}\sum_{t=1}^{2}\mu_{pt}^{\pm}PLM_{pt}^{\pm}+\sum_{s=1}^{4}\sum_{t=1}^{2}\left[\mu_{st}^{\prime\pm}-\mu_{st}^{\pm}\right]QW_{st}^{\pm}-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\mu_{jkt}^{\pm}CY_{jkt}^{\pm}PA_{jkt}^{\pm}\right.\\ \left.+\sum_{r=1}^{4}\mu_{r}^{\pm}NL_{r}^{\pm}+\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\mu_{jt}^{\pm}AM_{jkt}^{\pm}+\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\mu_{jt}^{\prime\pm}AF_{jkt}^{\pm}\right\}\\ -\Phi^{-1}(1-\theta)\sqrt{\begin{array}{l}\sum_{i=1}^{5}\sum_{t=1}^{2}\left[\left(\sigma_{it}^{\pm}PLC_{it}^{\pm}\right)^{2}-\left(\sigma_{it}^{\prime\pm}PLC_{it}^{\pm}\right)^{2}\right]+\sum_{p=1}^{6}\sum_{t=1}^{2}\left(\sigma_{pt}^{\pm}PLM_{pt}^{\pm}\right)^{2}\\+\sum_{s=1}^{4}\sum_{t=1}^{2}\left[\left(\sigma_{st}^{\pm}QW_{st}^{\pm}\right)^{2}-\left(\sigma_{st}^{\prime\pm}QW_{st}^{\pm}\right)^{2}\right]+\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\left(\sigma_{jkt}^{\pm}CY_{jkt}^{\pm}PA_{jkt}^{\pm}\right)^{2}+z_0^{\pm}\\+\sum_{r=1}^{4}\left(\sigma_{r}^{\pm}NL_{r}^{\pm}\right)^{2}-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\left(\sigma_{jt}^{\pm}AM_{jkt}^{\pm}\right)^{2}-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\left(\sigma_{jt}^{\prime\pm}AF_{jkt}^{\pm}\right)^{2}\end{array}}\end{array}}{\begin{array}{l}\sum_{i=1}^{5}\sum_{t=1}^{2}\left(\gamma_{it}^{\pm}-\gamma_{it}^{\prime\pm}\right)PLC_{it}^{\pm}+\sum_{p=1}^{6}\sum_{t=1}^{2}\gamma_{pt}^{\pm}PLM_{pt}^{\pm}+\sum_{s=1}^{4}\sum_{t=1}^{2}\left(\gamma_{st}^{\pm}-\gamma_{st}^{\prime\pm}\right)QW_{st}^{\pm}+\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\gamma_{jkt}^{\pm}CY_{jkt}^{\pm}PA_{jkt}^{\pm}\\+\sum_{r=1}^{4}\gamma_{r}^{\pm}NL_{r}^{\pm}-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\gamma_{jt}^{\pm}AM_{jkt}^{\pm}-\sum_{j=1}^{4}\sum_{k=1}^{9}\sum_{t=1}^{2}\gamma_{jt}^{\prime\pm}AF_{jkt}^{\pm}-z_1^{\pm}+z_0^{\pm}\end{array}}\geq h^{\pm} \tag{33}$$

(2) Constraints of water supply:

$$QW_{st}^{\pm}\cdot GT_{st}^{\pm}\leq TPC_{st}^{\pm},\quad \forall s,t \tag{34}$$

$$QW_{st}^{\pm}\cdot GT_{st}^{\pm}\cdot BM_{st}^{\pm}\cdot\left(1-\eta_{BOD,st}^{\pm}\right)\leq ABW_{st}^{q_i},\quad \forall s,t \tag{35}$$

$$QW_{st}^{\pm}\cdot GT_{st}^{\pm}\cdot PCM_{st}^{\pm}\left(1-\eta_{TP,st}^{\pm}\right)\leq APW_{st}^{\pm},\forall s,\quad t \tag{36}$$

$$QW_{st,\min}\leq QW_{st}^{\pm}\leq QW_{st,\max},\quad \forall s,t \tag{37}$$

(3) Constraints of chemical plant production:

$$PLC_{it}^{\pm}\cdot WC_{it}^{\pm}\leq TPD_{it}^{\pm},\quad \forall i,t \tag{38}$$

$$PLC_{it}^{\pm}\cdot WC_{it}^{\pm}\cdot IC_{it}^{\pm}\cdot\left(1-\eta_{BOD,it}^{\pm}\right)\leq ABC_{it}^{\pm},\quad \forall i,t \tag{39}$$

$$PLC_{it}^{\pm}\cdot\left[WC_{it}^{\pm}\cdot PCR_{it}^{\pm}\left(1-\eta_{TP,it}^{\pm}\right)+ASC_{it}^{\pm}\cdot SLR_{it}^{\pm}\cdot PSC_{it}^{\pm}\right]\leq APC_{it}^{q_i},\quad \forall i,t \tag{40}$$

$$PLC_{it,\min}\leq PLC_{it}^{\pm}\leq PLC_{it,\max},\quad \forall i,t \tag{41}$$

(4) Constraints of phosphorus mining company production:

$$PLM_{pt}^{\pm}\cdot\left[WPM_{pt}^{\pm}\cdot MWC_{pt}^{\pm}\left(1-\eta_{TP,pt}^{\pm}\right)+ASM_{pt}^{\pm}\cdot PCS_{pt}^{\pm}\cdot SLW_{pt}^{\pm}\right]\leq APM_{pt}^{q_i},\ \forall p,t \tag{42}$$

$$PLM_{pt,\min}\leq PLM_{pt}^{\pm}\leq PLM_{pt,\max},\ \forall p,t \tag{43}$$

(5) Constraints of crop farming:

$$\sum_{k=1}^{9}\left(NS_{jk}^{\pm}\cdot SL_{jkt}^{\pm}+RF_{jkt}^{\pm}\cdot DN_{jkt}^{\pm}\cdot 10^{-5}\right)\cdot PA_{jkt}^{\pm}\leq MNL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\ \forall j,t \tag{44}$$

$$\sum_{k=1}^{9}\left(PS_{jk}^{\pm}\cdot SL_{jkt}^{\pm}+DP_{jkt}^{\pm}\cdot RF_{jkt}^{\pm}\cdot 10^{-5}\right)PA_{jkt}^{\pm}\leq MPL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\forall j,t \tag{55}$$

$$\sum_{k=1}^{9}SL_{jkt}^{\pm}\cdot PAQ_{jkt}^{\pm}\leq MSL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\forall j,t \tag{56}$$

$$\left(1-NVF_t^{\pm}\right)\cdot\varepsilon_{NF}^{\pm}\cdot AF_{jkt}^{\pm}+\left(1-NVM_t^{\pm}\right)\cdot\varepsilon_{NM}^{\pm}\cdot AM_{jkt}^{\pm}\geq NR_{jkt}^{\pm}\cdot PA_{jkt}^{\pm},\ \forall j,k,t \tag{57}$$

$$\varepsilon_{PF}^{\pm}\cdot AF_{jkt}^{\pm}+\varepsilon_{PM}^{\pm}\cdot AM_{jkt}^{\pm}\geq PR_{jkt}^{\pm}\cdot PA_{jkt}^{\pm},\ \forall j,k,t \tag{58}$$

$$\sum_{k=1}^{9}\left(\varepsilon_{NF}^{\pm}\cdot AF_{jkt}^{\pm}+\varepsilon_{NM}^{\pm}\cdot AM_{jkt}^{\pm}-NR_{jkt}^{\pm}\cdot PA_{jkt}^{\pm}\right)\leq MNL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\ \forall j,t \tag{59}$$

$$\sum_{k=1}^{9}\left(\varepsilon_{PF}^{\pm}\cdot AF_{jkt}^{\pm}+\varepsilon_{PM}^{\pm}\cdot AM_{jkt}^{\pm}-PR_{jkt}^{\pm}\cdot PA_{jkt}^{\pm}\right)\leq MPL_{jt}^{\pm}\cdot TA_{jt}^{\pm},\ \forall j,t \tag{60}$$

$$\sum_{j=1}^{4}\sum_{k=1}^{6}PA_{jkt}^{\pm}\geq MFP_t^{\pm},\ t=1 \tag{61}$$

$$\sum_{j=1}^{4}\sum_{k=1}^{2}PA_{jkt}^{\pm}+\sum_{j=1}^{4}\sum_{k=8}^{9}PA_{jkt}^{\pm}\geq MFP_t^{\pm},\ t=2 \tag{62}$$

$$PA_{jkt}^{\pm}\leq TAS_{jt}^{\pm},\ k=6,t=1 \tag{63}$$

$$\sum_{k=1}^{5}PA_{jkt}^{\pm}\leq TAH_{jt}^{\pm},\ t=1 \tag{64}$$

$$PA_{jkt}^{\pm}\leq TAS_{jt}^{\pm},\ k=7,t=2 \tag{65}$$

$$\sum_{k=1}^{2}PA_{jkt}^{\pm}+\sum_{k=8}^{9}PA_{jkt}^{\pm}\leq TAH_{jt}^{\pm},\ t=2 \tag{66}$$

$$TAS_{jt}^{\pm}+TAH_{jt}^{\pm}=TA_{jt}^{\pm},\ \forall j,t \tag{67}$$

(6) Constraints of livestock husbandry:

$$\left(\sum_{r=1}^{4}AML_{rt}^{\pm}\cdot NL_r^{\pm}+AMH_t^{\pm}\cdot RP_t^{\pm}-\sum_{j=1}^{4}\sum_{k=1}^{9}AM_{jkt}^{\pm}\right)\cdot MS_t^{\pm}\cdot\varepsilon_{NM}^{\pm}+RP_t^{\pm}\cdot ACW_t^{\pm}\cdot DNR_t^{\pm}\leq ANL_t^{q_i},\ \forall t \tag{68}$$

$$\sum_{r=1}^{4}AML_{rt}^{\pm}\cdot NL_r^{\pm}+AMH_t^{\pm}\cdot RP_t^{\pm}\geq\sum_{j=1}^{4}\sum_{k=1}^{9}AM_{jkt}^{\pm},\ \forall t \tag{69}$$

$$NL_{r,\min}\leq NL_r^{\pm}\leq NL_{r,\max},\ \forall r \tag{70}$$

(7) Non-negative constraints:

$$PLC_{it}^{\pm},\ PA_{jkt}^{\pm},\ NL_r^{\pm},\ QW_{st}^{\pm},\ PLM_{pt}^{\pm},\ AM_{jkt}^{\pm},\ AF_{jkt}^{\pm}\geq 0 \tag{71}$$

Solutions for the MRPP model under a given risk level can be obtained through integration of solutions of the lower and upper submodels. A set of interval solutions associated with possiblistic and probabilistic information for the objective and decision variables can be obtained by solving the submodels under the other risk levels.

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