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A dual-inexact fuzzy stochastic model for water resources management and non-point source pollution mitigation under multiple uncertainties

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Abstract

In this research, a dual-inexact fuzzy stochastic programming (DIFSP) method was developed for supporting the planning of water and farmland use management system considering the non-point source pollution mitigation under uncertainty. The random boundary interval (RBI) was incorporated into DIFSP through integrating fuzzy programming (FP) and chance-constrained programming (CCP) approaches within an interval linear programming (ILP) framework. The lower and upper bounds of RBI are continuous random variables, and the correlation exiting between the lower and upper bounds can be tackled in RBI through the joint probability distribution function. And thus the subjectivity of decision making is greatly reduced, enhancing the stability and robustness of obtained solutions. The proposed method was then applied to solve a water and farmland use planning model (WFUPM) with non-point source pollution. The generated results could provide decision makers with detailed water supply-demand schemes involving diversified water related activities under various system conditions. These useful solutions could allow more in-depth analyses of the trade-offs between human and environment, as well as those between system optimality and reliability. In addition, comparative analyses on the solutions obtained from ICCP (Interval chance-constraints programming) and DIFSP demonstrated the higher application of this developed approach for supporting the water and farmland use system planning.

1 Introduction

Due to population growth, ongoing urbanization, industrialization and the intensification of agriculture, water and land demands are increasing globally, while the availability and quality of water resources and farmland are decreasing and non-point source pollution sharpening. These phenomena often cause a reduction in environmental quality and endanger sustainable development (Sessa, 2007). Thus, effective water resource and farmland use planning with non-point source pollution mitigation is necessary for ensuring economic and environmental welfares of regional population (Ray et al., 2012; Mehta et al., 2013).

Previously, a plenty of modeling technologies were applied into water resources and farmland use system planning with non-point sources pollution mitigation (Satti et al., 2004; Chen et al., 2005; Riquelme and Ramos, 2005; Victoria et al., 2005; Kondilia and Kaldellis, 2006; Gregory et al., 2006; Khare et al., 2007; Castelletti et al., 2008; Qin et al., 2011; Mahmoud et al., 2011; Zarghami and Hajykazemian, 2013; Canter et al., 2014). For example, Satti et al. (2004) used the GIS-based water resources and agricultural permitting and planning system (GWRAPPS) to simulate the effect of climate, soil, and crop parameters on crop irrigation requirements. Chen et al. (2005) established force-state-response (DSR) dynamic strategy planning procedure to assist responsible authorities in obtaining alternatives of sustainable top river basin land use management. Riquelme and Ramos (2005) built up a Geographic Information System (GIS) on vine growing for supporting decision making processes related to land and water management in Castilla-La Mancha, Spain. Victoria et al. (2005) adopted modeling tools, ISAREG model and SAGBAH model, to solve multi-scale problems with irrigation water uses and non-point source pollution in basins. Qin et al. (2011) proposed a system dynamics and water environmental model (SyDWEM) to operate the integrated socio-economic and water management system in a rapidly urbanizing catchment. Mehta et al. (2013) developed integrated water resources management (IWRM) models using the water evaluation and planning (WEAP) decision support system, for three towns in the Lake Victoria (LV) region. Zarghami and Hajykazemian (2013) proposed a new optimization algorithm by coupling the mutation process to the particle swarm optimization (PSO), which was successfully applied to an urban water resources management with non-point sources pollution problem for Tabriz, Iran.

However, effective planning for water resource and farmland use management with non-point sources pollution mitigation is actually complicated with a variety of uncertainties and dynamics. For example, intricate interactions exist between various subsystems (such as economy, eco-environment, society, administration, etc), which will

inevitably produce a variety of uncertainties. Moreover, subjective judgments obtained from experts and stakeholders also exert significant impacts on data acquisition and system reliability. These complexities lead to difficulties in solving the resulted uncertain optimization problems (Azaiez et al., 2005; Sethi et al., 2006; Tan et al., 2011; Bender and Simonovic, 2000; Guo et al., 2010; Qin et al., 2007; Lu et al., 2012; Huang et al., 2012; Zhang et al., 2009; Gu et al., 2013; Dessai and Hulme, 2007; Cai et al., 2011, 2012). Nowadays, the stochastic linear programming (SLP) and interval linear programming (ILP) have become two of the most effective optimization approaches, especially the chance-constraints programming (CCP). For instance, Azaiez et al. (2005) tackled the uncertainties in the inflows through adopting chance constraints and penalties of failure for optimal multi-period operation of a multi-reservoir system. And in 2006, Sethi et al. developed deterministic linear programming (DLP) and chance-constrained linear programming (CCLP) models to allocate available land and water resources optimally on seasonal basis. Tan et al. (2011) developed a radial interval chance-constrained programming (RICCP) approach for supporting source-oriented non-point source pollution control under uncertainty. Another useful method handling uncertainties existing in water resources and farmland use management is based on fuzzy set theory. Bender and Simonovic (2000) applied a fuzzy compromise approach into water resource systems planning of the Tisza River. Qin et al. (2007) developed an interval-fuzzy nonlinear programming (IFNP) model for water quality management under uncertainty.

In reality, high degree of uncertainty may exist among some parameters and coefficients of related water resources and farmland use management models. For example, the availabilities of various water resources are sensitive to geographical conditions and climate, technology selection and utilization efficiency, as well as water-saving consciousness, causing difficulties to related data acquisition, even the determination of interval numbers, when the lower and upper bounds are correlated. In the past decades, few works were conducted to handle this type of uncertainties (dual uncertainty) existing in the processes of water and farmland use planning, which might result in missed information and thus impractical decision support (Cao et al., 2010). Therefore, in this study, a concept of random boundary interval (RBI) will be introduced to reflect such dual uncertainty. Specifically, the lower and upper bounds of RBI are continuous random variables, and the distribution information can be incorporated into the model. And moreover, correlation existing between the lower and upper bounds can be tackled in RBI through the joint probability distribution function.

Finally, the proposed RBI theory and joint probability distribution will be integrated with ILP, CCP, and FLP technologies, leading to a dual-inexact fuzzy stochastic programming (DIFSP) method. Such an approach can tackle uncertainties expressed as interval numbers with known upper and lower bounds, fuzzy sets, as well as RBI. Due to the consideration of the intersection between lower and upper bounds, the robustness of the developed model could be enhanced. Then, this method will be applied to a water and farmland use planning model (WFUPM) with non-point sources pollution mitigation for solving practical problems. And then many useful results will be generated, covering farmland use arrangement, water allocations among various consumers, resources supplies, and water pollution control under various water supply conditions and system reliabilities. The tradeoffs between system benefit and failure risks can be balanced through the use of probability of constraints violations and satisfaction degrees. In addition, the solutions obtained from ICCP and DIFSP will be compared to demonstrate the application of this developed method for supporting the planning of water and farmland use system.

2 Methodology

2.1 The concept of RBI

In many practical problems, the lower and upper bounds of the right-hand sides can rarely be acquired as deterministic values. Instead, the obtained data can be presented as random boundary interval (RBI) whose lower and upper bounds are random variables (Cao et al., 2010). Specifically, the parameters $\tilde{B}_i^-$ and $\tilde{B}_i^+$ in the right hand side

of constraints can be formulated as follows: (u_1,v_1), (u_2,v_2), ..., (u_n,v_n) where u_1, u_2, ..., u_n and v_1, v_2, ..., v_n are the random numbers of lower and upper bounds of $\tilde{B}_i^\pm$ ($\tilde{B}_i^-$ and $\tilde{B}_i^+$). And $f(s,t)$ can be defined as the joint probability distribution function of $\left(\tilde{B}_i^-,\tilde{B}_i^+\right)$, where s is the variable referring to $\tilde{B}_i^-$, and t is the variable referring to $\tilde{B}_i^+$. Then FBI can be incorporated into the IFLP model through the introduction of λ (Cao et al., 2010):

$$\text{Max}\lambda \tag{1}$$

subject to:

$$C^\pm X^\pm \geq f^+ + (1-\lambda)(f^+ - f^-) \tag{1a}$$

$$A^\pm X^\pm \leq \tilde{B}^- + (1-\lambda)\left(\tilde{B}^+ - \tilde{B}^-\right) \tag{1b}$$

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

$$0 \leq \lambda \leq 1 \tag{1d}$$

Let $Z_i = \tilde{B}^- + (1-\lambda)(\tilde{B}^+ - \tilde{B}^-) = \lambda\tilde{B}_i^- + (1-\lambda)\tilde{B}_i^+$. Given the joint probability distribution function of $\left(\tilde{B}_i^-,\tilde{B}_i^+\right)$ is available, the distribution function of its linear combination $Z_i = \lambda\tilde{B}_i^- + (1-\lambda)\tilde{B}_i^+$ can be calculated as follows:

$$G_i(z,\lambda) = \Pr\{Z_i \leq z\} = \Pr\left\{\lambda\tilde{B}_i^- + (1-\lambda)\tilde{B}_i^+ \leq z\right\} = \iint\limits_{\lambda\tilde{B}_i^- + (1-\lambda)\tilde{B}_i^+} f(s,t)\,\mathrm{d}s\mathrm{d}t \tag{1e}$$

In this model, λ not only represents the level of satisfying the objectives and constrains, but also a linear combination parameter of the lower and upper bounds of RBIs. Then RBIs can be converted into a new random variable $\left[Z_i = \lambda\tilde{B}_i^- + (1-\lambda)\tilde{B}_i^+\right]$ in IFLP, and the distribution function $[G_i(z,\lambda)]$ of Z_i can be generated (Cao et al., 2010).

2.2 Dual inexact fuzzy stochastic programming

When a right-hand side parameter is random, the CCP method should be adopted. Since parameters in the left-hand side are intervals, an interval chance-constrained linear programming (ICCP) can be developed (Huang et al., 1992, 1995). As Z_i is a random variable with known distribution function, model (1) can be converted into (Cao et al., 2010; Cai et al., 2007, 2009a, b):

$$\text{Max}\lambda \tag{2}$$

subject to:

$$C^{\pm}X^{\pm} \geq f^{+} + (1-\lambda)(f^{+} - f^{-}) \tag{2a}$$

$$\Pr\{A^{\pm}X^{\pm} \leq Z_i\} \geq 1 - p_i, \quad i = 1,2,\ldots,m \tag{2b}$$

$$X^{\pm} \geq 0 \tag{2c}$$

$$0 \leq \lambda \leq 1 \tag{2d}$$

Model (2) can be converted into an "equivalent" deterministic version as follows:

$$\text{Max}\lambda \tag{3}$$

subject to:

$$C^{\pm}X^{\pm} \geq f^{+} + (1-\lambda)(f^{+} - f^{-}) \tag{3a}$$

$$A_i^{\pm}X^{\pm} \leq Z_i^{(p_i)}, A_i^{\pm} \in A^{\pm}, \quad i = 1,2,\ldots,m \tag{3b}$$

$$X^{\pm} \geq 0 \tag{3c}$$

$$0 \leq \lambda \leq 1 \tag{3d}$$

where $Z_i^{(p_i)} = G_i^{-1}(p_i,\lambda)$. In CCP, the random variable on the right-hand side can be handled as several deterministic numbers corresponding to different violation probabilities (p_i). However, $Z_i^{(p_i)}$ in this part is a function of λ corresponding to p_i because

the distribution function of $Z_i \left[G_i^{-1}(p_i,\lambda)\right]$ is a function of z and λ. When p_i is a constant, and then $G_i^{-1}(p_i,\lambda)$ is a function of λ(Huang et al., 1992, 1995). Thus the solution method of the developed model will be different from the conventional CCP.

If $Z_i^{(p_i)}$ is a linear function of λ, according to solution algorithm developed by Huang et al. (1992, 1995), this model can be divided into two deterministic sub-models:

$$\text{Max}\lambda \tag{4}$$

subject to:

$$\sum_{j=1}^{k} c_j^{+}x_j^{+} + \sum_{j=k+1}^{n} c_j^{+}x_j^{-} \geq f^{-} + (1-\lambda)(f^{+} - f^{-}) \tag{4a}$$

$$\sum_{j=1}^{k_1} |a_{ij}|^{-}\text{sign}(a_{ij}^{-})x_j^{+} + \sum_{j=k_1+1}^{n} |a_{ij}|^{+}\text{sign}(a_{ij}^{+})x_j^{-} \leq Z_i^{(p_i)}, \quad i = 1,2,\ldots,m \tag{4b}$$

$$x_j^{+} \geq 0, \quad j = 1,2,\ldots,k \tag{4c}$$

$$x_j^{-} \geq 0, \quad j = k+1,k+2,\ldots,n \tag{4d}$$

$$0 \leq \lambda \leq 1 \tag{4e}$$

and

$$\text{Max}\lambda \tag{5}$$

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subject to:

$$\sum_{j=1}^{k} c_j^- x_j^- + \sum_{j=k+1}^{n} c_j^- x_j^+ \geq f^- + (1-\lambda)(f^+ - f^-) \tag{5a}$$

$$\sum_{j=1}^{k_1} |a_{ij}|^+ \mathrm{sign}(a_{ij}^+) x_j^- + \sum_{j=k_1+1}^{n} |a_{ij}|^- \mathrm{sign}(a_{ij}^-) x_j^+ \leq Z_i^{(p_i)}, \quad i = 1,2,\ldots,m \tag{5b}$$

$$x_j^\pm \geq 0, \ \forall j \tag{5c}$$

$$x_j^- \leq x_{j\ \mathrm{opt}}^+, \quad j = 1,2,\ldots,k \tag{5d}$$

$$x_j^+ \geq x_{j\ \mathrm{opt}}^-, \quad j = k+1, k+2, \ldots, n \tag{5e}$$

Among these two submodels, f^+ and f^- correspond to the lower and upper bounds of the objective function values, when the objective function is to be minimized, sub-model corresponding to f^- is firstly formulated, and then the sub-model corresponding to f^+ can be obtained based on the solution of the first sub-model. Through solving these two submodels, the final interval solutions can be acquired as λ, $x_{j\ \mathrm{opt}} = \left[x_{j\ \mathrm{opt}}^-, x_{j\ \mathrm{opt}}^+\right]$, and $f_{\mathrm{opt}} = \left[f_{\mathrm{opt}}^-, f_{\mathrm{opt}}^+\right]$.

However, the two-step method encounters difficulties if $Z_i^{(p_i)}$ is not a linear function of λ. In this case, it should be converted to linear or stepwise linear functions of λ in order to use the two-step method. The particular flow of this developed optimization method is displayed in Fig. 1.

3 Application to water and farmland use management system with non-point sources pollution mitigation

3.1 Overview of water and farmland use management system with non-point sources pollution mitigation

Increasing population, diminishing supplies and variable climatic conditions can cause difficulties in balancing the conflicts between human activities and environment, which have created the need for innovative water resource supply and demand management to economically and efficiently operate a system. Furthermore, since agriculture is one of the most important water users, the farmland use arrangement can directly or indirectly influence the water resources utilization and environment. Thus, a water resources and farmland use planning model with non-point sources pollution can be useful for decision makers to plan water and farmland management strategies to cope with future system changes. However, the dynamics of the water resource and agricultural land use management system makes it critical to clarify the interactions between various components and those intimately involved in the planning process (Chung et al., 2008).

Figure 2 presents a general water and farmland use management system, including internal and external factors. Specifically, resources availability, distribution, utilization technology, policy, security and other internal factors of water and agricultural land comprise the microscopic system, directly affecting the related planning processes. Besides, the external factors, such as social, economy, natural conditions, institutions, eco-environment (i.e., non-point sources pollution), and population can exert indirect impacts on the entire system operation. Given the complexity of this system and the interactions among various components, uncertainty is a necessary consideration in the process of modeling. In addition, the uncertainties existing in this system can be also generated from the errors in data collection and parameter settings, subjective judgments of experts or stakeholders, as well as uncertainty due to the structure of adopted model (Lindenschmidt et al., 2007; Dong et al., 2013).

Therefore, several optimization technologies will be introduced to handle these uncertainties in this system. For example, interval numbers will be used to indicate the economic parameters and technologies efficiencies. And the random boundary interval (RBI) will be adapted to reflect the dual uncertainty of water resources availability, with the lower and upper bounds of RBI being continuous random variables. Then the developed dual inexact fuzzy stochastic programming (DIFSP) method will be applied into a water and farmland use planning model (WFUPM) with non-point sources pollution mitigation.

3.2 Modeling formulation

In the study case, three types of water resources (i.e., surface drainage water, groundwater, and river water) are major water supplies, meeting the regional water demands of various end-users (i.e., agriculture, industry, tourism, residents, and municipal sector). Depending upon the use pattern, surface water can be sent directly to consumers or through a water treatment plant. Pumped groundwater can be delivered directly to all users before disinfection. River water can be provided to agricultural irrigation and industry production. Water is transferred between end-users by pipes with limited capacities. In this study region, corn, potato, and rice are selected as the major crops, and metallurgical and food industries constitute local industry. Figure 3 gives an overview of the components and factors that need to be taken into account in this model (Dong et al., 2013). The study time horizon is 15 yr and is further divided into three planning periods. With the consideration of these elements, water and farmland use planning model (WFUPM) with non-point sources pollution can be formulated, with its objective to maximize the total system benefit, covering benefit for agriculture irrigation, water supply benefits for industry, tourism, residents, and minus the costs for water pumping and delivering, as well as wastewater treatment, specific as follows:

$$\mathrm{Max} f^{\pm} = f^{\pm}_{\mathrm{BC}} + f^{\pm}_{\mathrm{BI}} + f^{\pm}_{\mathrm{BT}} + f^{\pm}_{\mathrm{BT}} - f^{\pm}_{\mathrm{CW}} - f^{\pm}_{\mathrm{CE}} \tag{6}$$

1. Benefit for agriculture irrigation

$$f^{\pm}_{\mathrm{BC}} = \sum_{i=1}^{3}\sum_{t=1}^{3} (\mathrm{PC}^{\pm}_{it}\cdot Y^{\pm}_{it} - \mathrm{CC}^{\pm}_{it})A^{\pm}_{it} \tag{6a}$$

2. Water supply benefit for industry

$$f^{\pm}_{\mathrm{BI}} = \sum_{k=1}^{2}\sum_{t=1}^{3} \mathrm{QI}^{\pm}_{kt}\cdot \mathrm{ZI}^{\pm}_{kt} \tag{6b}$$

3. Water supply benefit for tourism

$$f^{\pm}_{\mathrm{BT}} = \sum_{t=1}^{3} \mathrm{QT}^{\pm}_{t}\cdot \mathrm{ZT}^{\pm}_{t} \tag{6c}$$

4. Water supply benefit for residents

$$f^{\pm}_{\mathrm{BT}} = \sum_{t=1}^{3} \mathrm{QR}^{\pm}_{t}\cdot \mathrm{ZR}^{\pm}_{t} \tag{6d}$$

5. Cost for water pumping and delivering

$$f^{\pm}_{\mathrm{CW}} = \sum_{t=1}^{3} (\mathrm{QS}^{\pm}_{t}\cdot \mathrm{WS}^{\pm}_{t} + \mathrm{QG}^{\pm}_{t}\cdot \mathrm{WG}^{\pm}_{t} + \mathrm{QR}^{\pm}_{t}\cdot \mathrm{WR}^{\pm}_{t}) \tag{6e}$$

6. Cost for wastewater treatment

$$f^{\pm}_{\mathrm{CE}} = \sum_{t=1}^{3} \left(\mathrm{QWT}^{\pm}_{t}\cdot \mathrm{DWT}^{\pm}_{t}\cdot \mathrm{ZT}^{\pm}_{t} + \mathrm{QWM}^{\pm}_{t}\cdot \mathrm{DWM}^{\pm}_{t}\cdot \mathrm{ZM}^{\pm}_{t} + \mathrm{QWR}^{\pm}_{t}\cdot \mathrm{DWM}^{\pm}_{t}\cdot \mathrm{ZR}^{\pm}_{t}\right) \tag{6f}$$

$$+ \sum_{k=1}^{2}\sum_{t=1}^{3} \left(\mathrm{QWI}^{\pm}_{kt}\cdot \mathrm{DWI}^{\pm}_{kt}\cdot \mathrm{ZI}^{\pm}_{kt}\right) \tag{6g}$$

Constraints:

1. Balance for farmland use

$$\text{MINA}_t \le \sum_{i=1}^{3} A_{it}^{\pm} \le \text{MAXA}_t, \quad \forall t \tag{6h}$$

2. Balance for water resource availability

$$\text{WS}_t^{\pm} \le \text{MS}_t^{\pm}, \quad \forall t \tag{6i}$$

$$\text{WG}_t^{\pm} \le \text{MG}_t^{\pm}, \quad \forall t \tag{6j}$$

$$\text{WR}_t^{\pm} \le \text{MR}_t^{\pm}, \quad \forall t \tag{6k}$$

$$\sum_{i=1}^{2} \text{RWC}_{it}^{\pm} \cdot A_{it}^{\pm} + \sum_{k=1}^{2} \text{ZI}_{kt}^{\pm} + \text{ZT}_t^{\pm} + \text{ZM}_t^{\pm} + \text{ZR}_t^{\pm} + \text{RWG}_t^{\pm} \cdot \text{GA}_t^{\pm} \le \text{WS}_t^{\pm} + \text{WG}_t^{\pm} + \text{WR}_t^{\pm}, \forall t \tag{6l}$$

3. Balance for water supply

$$\sum_{i=1}^{2} \text{RWC}_{it}^{\pm} \cdot A_{it}^{\pm} \ge \text{MA}_t^{\pm}, \quad \forall t \tag{6m}$$

$$\sum_{k=1}^{2} \text{ZI}_{kt}^{\pm} \ge \text{MI}_t^{\pm}, \quad \forall t \tag{6n}$$

$$\text{ZT}_t^{\pm} \ge \text{MT}_t^{\pm}, \quad \forall t \tag{6o}$$

$$\text{ZM}_t^{\pm} \ge \text{MM}_t^{\pm}, \quad \forall t \tag{6p}$$

$$\text{ZR}_t^{\pm} \ge \text{MR}_t^{\pm}, \quad \forall t \tag{6q}$$

4. Balance for wastewater treatment

$$\text{DWI}_{kt}^{\pm} \cdot \text{ZI}_{kt}^{\pm} + \text{DWT}_t^{\pm} \cdot \text{ZT}_t^{\pm} + \text{DWM}_t^{\pm} \cdot \text{ZM}_t^{\pm} + \text{DWR}_t^{\pm} \cdot \text{ZR}_t^{\pm} \le \text{TWC}_t, \forall t \tag{6r}$$

5. Environment constraints

$$\begin{aligned} &\sum_{i=1}^{3} \text{NA}_t^{\pm} \cdot A_{it}^{\pm} + \left(\sum_{k=1}^{2} \text{NI}_{kt}^{\pm} \cdot \text{ZI}_{kt}^{\pm} + \text{NT}_t^{\pm} \cdot \text{ZT}_t^{\pm} + \text{NM}_t^{\pm} \cdot \text{ZM}_t^{\pm} + \text{NR}_t^{\pm} \cdot \text{ZR}_t^{\pm} \right) \\ &\quad \left(1 - \text{NRE}_t^{\pm}\right) \le \text{TN}_t^{\pm}, \forall t \\ &\sum_{i=1}^{3} \text{PA}_t^{\pm} \cdot A_{it}^{\pm} + \left(\sum_{k=1}^{2} \text{PI}_{kt}^{\pm} \cdot \text{ZI}_{kt}^{\pm} + \text{PT}_t^{\pm} \cdot \text{ZT}_t^{\pm} + \text{PM}_t^{\pm} \cdot \text{ZM}_t^{\pm} + \text{PR}_t^{\pm} \cdot \text{ZR}_t^{\pm} \right) \\ &\quad \left(1 - \text{PRE}_t^{\pm}\right) \le \text{TP}_t^{\pm}, \forall t \end{aligned} \tag{6s}$$

where f = expected net system benefit (\$); t = time period, t = 1, 2, 3; i = type of crop, i = 1, 2, 3 (where i = 1 for corn, 2 for potato, 3 for rice); k = type of industry, k = 1, 2 (where k = 1 for metallurgical industry, 2 for food industry); $\text{PC}_{it}^{\pm}$ = price of crop i in period t (\$ kg^{-1}); $Y_{it}^{\pm}$ = yield of crop i in period t (kg km^{-2}); $\text{CC}_{it}^{\pm}$ = cost for cultivating crop i in period t (\$ km^{-2}); $\text{QI}_{kt}^{\pm}$ = unit benefit of water allocated to industry k in period t (\$ m^{-3}); $\text{QT}_t^{\pm}$ = unit benefit of water allocated to tourism in period t (\$ m^{-3}); $\text{QR}_t^{\pm}$ = unit benefit of water allocated to household in period t (\$ m^{-3}); $\text{QG}_t^{\pm}$ = cost for cultivating green field in period t (\$ km^{-2}); $\text{QS}_t^{\pm}$ = cost for pumping and delivering the surface drainage water in period t (\$ m^{-3}); $\text{QG}_t^{\pm}$ = cost for pumping and delivering the ground water in period t (\$ m^{-3}); $\text{QR}_t^{\pm}$ = cost for pumping and delivering the river water in period t (\$ m^{-3}); $\text{QWI}_{kt}^{\pm}$ = treatment cost of wastewater from industry k in period t (\$ t^{-1}); $\text{QWT}_t^{\pm}$ = treatment cost of wastewater from tourism in period t (\$ t^{-1}); $\text{QWM}_t^{\pm}$ = treatment cost of wastewater from municipal sector in period t (\$ t^{-1}); $\text{QWR}_t^{\pm}$ = treatment cost of wastewater from household in period t (\$ t^{-1}); $\text{DWI}_{kt}^{\pm}$ = unit wastewater discharge by industry k in period t (t m^{-3}); $\text{DWT}_t^{\pm}$ = unit wastewater discharge by tourism industry in period t (t m^{-3}); $\text{DWM}_t^{\pm}$ = unit wastewater discharge by municipal sector in period t (t m^{-3}); $\text{DWR}_t^{\pm}$ = unit wastewater discharge by household in period t ($\mathrm{t\,m^{-3}}$); MAXA_t = the maximum area allocated to crop i in period t ($\mathrm{km^2}$); MINA_t = the minimum area allocated to crop i in period t ($\mathrm{km^2}$); $\mathrm{MS}_t^{\pm}$ = the maximum allocated amount of surface drainage water in period t ($\mathrm{m^3}$); $\mathrm{MG}_t^{\pm}$ = the maximum allocated amount of groundwater in period t ($\mathrm{m^3}$); $\mathrm{MR}_t^{\pm}$ = the maximum allocated amount of river water in period t ($\mathrm{m^3}$); $\mathrm{RWC}_{it}^{\pm}$ = unit irrigation demand for crop i in period t ($\mathrm{m^3\,km^{-2}}$); $\mathrm{RWG}_t^{\pm}$ = unit irrigation demand for green field in period t ($\mathrm{m^3\,km^{-2}}$); $\mathrm{MA}_t^{\pm}$ = water demand of agriculture in period t ($\mathrm{m^3}$); $\mathrm{MI}_t^{\pm}$ = water demand of industry in period t ($\mathrm{m^3}$); $\mathrm{MT}_t^{\pm}$ = water demand of tourism in period t ($\mathrm{m^3}$); $\mathrm{MM}_t^{\pm}$ = water demand of municipal sector in period t ($\mathrm{m^3}$); $\mathrm{MR}_t^{\pm}$ = water demand of household in period t ($\mathrm{m^3}$); TWC_t = total wastewater treatment capacity in period t (tonne); $\mathrm{NA}_t^{\pm}$ = nitrogen percent content of the soil in period t (%); $\mathrm{PA}_t^{\pm}$ = phosphorus percent content of the soil in period t (%); $\mathrm{NI}_{kt}^{\pm}$ = unit nitrogen discharge by industry k in period t ($\mathrm{t\,m^{-3}}$); $\mathrm{PI}_{kt}^{\pm}$ = unit phosphor discharge by industry k in period t ($\mathrm{t\,m^{-3}}$); $\mathrm{NT}_t^{\pm}$ = unit nitrogen discharge by tourism in period t ($\mathrm{t\,m^{-3}}$); $\mathrm{PT}_t^{\pm}$ = unit phosphor discharge by tourism in period t ($\mathrm{t\,m^{-3}}$); $\mathrm{NM}_t^{\pm}$ = unit nitrogen discharge by municipal sector in period t ($\mathrm{t\,m^{-3}}$); $\mathrm{PM}_t^{\pm}$ = unit phosphor discharge by municipal sector in period t ($\mathrm{t\,m^{-3}}$); $\mathrm{NR}_t^{\pm}$ = unit nitrogen discharge by household in period t ($\mathrm{t\,m^{-3}}$); $\mathrm{PR}_t^{\pm}$ = unit phosphor discharge by household in period t ($\mathrm{t\,m^{-3}}$); $\mathrm{NRE}_t^{\pm}$ = nitrogen removal efficiency in period t (%); $\mathrm{PRE}_t^{\pm}$ = phosphor removal efficiency in period t (%); $\mathrm{TN}_t^{\pm}$ = the maximum allowed amount of nitrogen discharge in period t (kg); $\mathrm{TP}_t^{\pm}$ = the maximum allowed amount of phosphor discharge in period t (kg); $A_{it}^{\pm}$ = area allocated to crop i in period t ($\mathrm{km^2}$); $\mathrm{ZI}_{kt}^{\pm}$ = water allocated to industry k in period t ($\mathrm{m^3}$); $\mathrm{ZT}_t^{\pm}$ = water allocated to tourism in period t ($\mathrm{m^3}$); $\mathrm{ZM}_t^{\pm}$ = water allocated to municipal sector in period t ($\mathrm{m^3}$); $\mathrm{ZR}_t^{\pm}$ = water allocated to household in period t ($\mathrm{m^3}$); $\mathrm{WS}_t^{\pm}$ = allocated amount of surface drainage water in period t ($\mathrm{m^3}$);

$\mathrm{WG}_t^{\pm}$ = allocated amount of groundwater in period t ($\mathrm{m^3}$); $\mathrm{WR}_t^{\pm}$ = allocated amount of river water in period t ($\mathrm{m^3}$).

In order to generate optimal system solutions, several effective constraints are formulated to restrain the entire model under the purpose of maximizing system benefit. Particularly, farmland use, including the planting areas of corn, potato, and rice should be limited to available farmland resources. All kinds of water resources have their own availabilities every period due to the natural and policy limitations. Water supplies to each end-user should satisfy their operational demands. The wastewater discharged to the central treatment plant should not excess its fixed capacity. Finally, the total quantity control should be applied to the non-point sources pollutions (i.e., nitrogen and phosphorus). The benefits of water supply for end-users and costs for pumping and delivering water resources are displayed in Tables 1 and 2. In this model, the RBIs are combined with the water resources availabilities, and Table 3 presents the linearization results of surface water availability.

4 Results analysis

Through computing a developed water resources and farmland use planning model (WR-FUPM) with non-point sources pollution mitigation, a series of related schemes were generated. Particularly, they can provide useful plans of planting areas for crops, water allocations to each end-user, water resources supplies, and non-point sources pollutions control under various water supply conditions and system reliabilities. In addition, the solutions obtained from ICCP and DIFCCP were compared to demonstrate the efficiency of new developed optimization method for tackling uncertainties in water and farmland use system.

According to the climate of north China, corn, potato, and rice are chosen as the staple crops. The crop planting areas under $p_i = 0.01$ are presented in Table 4. Obviously, potato would be the major crop in this region, planting [138.31, 146.85], [131.98, 140.62], and [125.66, 132.61] km^2 in periods 1 to 3, respectively. Then corn would occupy the second position of crop planning, which would require [7.65, 9.9], [7.3, 9.48], and [6.95, 8.94] km^2 in these three periods. Finally, [7.04, 8.25], [6.72, 7.9], and [6.39, 7.45] km^2 of areas would be used to plant rice in periods 1 to 3, respectively. Mainly due to imported vegetables and food, the planting areas of these crops decrease each period.

Table 5 shows the solutions of water allocations to various end-users under p_i = 0.01, mainly including agriculture, metallurgical industry, food industry, tourism, residents, and municipal sector. Among them, residents are still the biggest consumer, utilizing [32.61, 33.69], [31.34, 32.27], and [29.93, 30.76] million m^3 in periods 1, 2, and 3, respectively. For providing vegetables and rice to local residents, [27.57, 29.56], [25.53, 27.31], and [23.77, 24.67] million m^3 of water would be allocated to agricultural production in these three periods. Municipal sector is another important water user, which would require [16.78, 19.47], [16.13, 18.64], and [15.41, 17.77] million m^3. Furthermore, local industries also need adequate water to ensure their normal operations, such as metallurgical industry consuming [14.86, 15.09], [14.29, 14.45], and [13.64, 13.77] million m^3 of water resources in periods 1 to 3, respectively. As the tourism develops, it would consume rather large a proportion of water usage, increasing from [14.26, 25.3] in period 1 to [31.95, 43.42] and [44.77, 45.48] in periods 2 and 3, which should arouse the general concern of relevant department.

Table 6 presents the solutions of water pollution control. In this study, the model mainly considers wastewater and non-point sources pollution (i.e., total nitrogen and phosphorus). Restrained by the capacities of pollutions treatment, [28.12, 29.75], [30.64, 31.29], and [28.22, 31.15] × 10^3 tonnes of wastewater would be allowed to discharge to the sewage treatment facilities in periods 1, 2, and 3. For total nitrogen, [1.27, 1.34], [1.18, 1.24], and [0.98, 1] × 10^3 tonnes would be the nitrogen allowances in these three periods. In addition, [0.49, 0.50], [0.44, 0.45], and [0.34, 0.36] × 10^3 tonnes of total phosphorus could be disposed to local treatment system. In order to protect the

water environment, the discharge quantities of water pollutants should be controlled within local capacities according to current technological development situation.

In this research, four p_i values are defined, such as 0.01, 0.05, and 0.10. Generally, higher p_i values indicate a higher probability of constraint violations, which correspondingly causes a higher system benefit and larger water resources supplies. Shown as in Table 7, the supply quantity of surface drainage water would increase from [20.73, 21.54], [21.96, 21.07], and [22.18, 21.25], to [22.24, 21.37] million m^3 in period 1 under p_i = 0.01, 0.05, 0.10, and 0.15, respectively. Moreover, river water would provide [102.79, 107.79], [108.63, 103.75], [109.07, 104.26], and [109.38, 104.61] million m^3 under these four p_i values with an increasing tendency. Meanwhile, their supplies would decrease with periods, for example, groundwater would afford [28.33, 29.14], [26.52, 27.61], and [21.91, 24.16] million m^3 under p_i = 0.01 in periods 1 to 3 with a downward trend, mainly due to natural conditions and the improvement of water utilization.

Since p_i value represents the probability of the constraint being violated, bigger p_i values mean higher probability of constraints violations, presenting higher system failure risks and leading to a decreased reliability in fulfilling the system requirements, but generating higher benefits. Conversely, smaller p_i values correspond lower system risks and lower benefits. Figure 4 shows the effects of varied p_i values on the system benefit under upper bound. Specifically, the system benefits would increase from USD [316.02, 367.71], [317.54, 370.16], and [317.71, 371.09], to [317.70, 371.74] million under p_i = 0.01, 0.05, 0.10, and 0.15, respectively.

Moreover, the satisfaction degree $\lambda^{\pm}$ presents the flexibility in the constraints and fuzziness in the objective, which indicates the decision makers' preferences regarding the tradeoffs between environment and economy, as well as system reliability and benefit. Generally, higher $\lambda^{\pm}$ level means decreased system reliability, with a higher benefit, being consistent with higher p_i value; in comparison, lower $\lambda^{\pm}$ level presents decreased system reliability with a lower system benefit, corresponding to lower p_i value. Figure 5 presents the satisfaction degrees under different p_i values under upper bound. Particularly, the satisfaction degrees would increase with p_i values, rising from [0.017, 0.829], [0.041, 0.868], and [0.043, 0.882], to [0.043, 0.892] under p_i = 0.01, 0.05, 0.10, and 0.15, respectively.

In order to further demonstrate the method DIFSP more applicable than ICCP in dealing with water resources and farmland use management problems under uncertainty, the comparable study was conducted between the generated solutions from these two optimization methods. Let the lower and upper bounds of RBIs equal their mid-values, the model would be simplified into a conversional inexact chance-constrained programming (ICCP) problem (Cao et al., 2010). The system benefits obtained through ICCP and DIFSP are presented in Table 8, which indicates that the results of DIFSP are much more robust than those of ICCP, meaning the solution width of DIFSP tighter and less uncertain. For instance, the system benefits computed from ICCP and DIFSP would be $ [314.95, 370.04] and [316.02, 367.71] million under p_i = 0.01, obviously got tightened. This comparison convincingly certifies the effectiveness of DIFSP (introducing of RBIs) in tackling with the uncertainties (dual uncertainty) existing in the water resources and farmland use management system. Obtained solutions could provide decision makers with the desired schemes under preferable system reliability and economic benefit.

5 Conclusions

In this research, a dual inexact fuzzy stochastic programming (DIFSP) method was proposed through incorporating the random boundary interval (RBI) with fuzzy programming (FP), chance-constrained programming (CCP), and interval linear programming (ILP) techniques. And then the developed method was applied to the water and farmland use planning model (WFUPM) with non-point source pollution mitigation. Overall, this study can: (1) conduct comprehensive analysis of water and farmland use management system, (2) tackle multiple uncertainties presented as interval numbers, fuzzy sets, and probability distributions, (3) tackle the correlation exiting between the lower

and upper bounds of RBI through the joint probability distribution function, enhancing the stability and robustness of obtained solutions, (4) generate effective schemes including planting area arrangement of crops, water allocations among various end-users, water resources supplies, and water pollution control plans under various water supply conditions and system reliabilities, (5) balance the tradeoffs between system benefit and failure risks through utilizing the probability of constraints violations and satisfaction degrees, and (6) compare the solutions obtained from ICCP and DIFCCP to demonstrate the application of this developed method for supporting water and farmland use system planning.

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Table 1. Benefits of water supply for end-users ($\$\,m^{-3}$).

End-user	Period		
	$t = 1$	$t = 2$	$t = 3$
Metallurgical industry	[27.57, 29.56]	[25.53, 27.31]	[23.77, 24.67]
Food industry	[14.86, 15.09]	[14.29, 14.45]	[13.64, 13.77]
Tourism	[9.11, 9.25]	[8.76, 8.86]	[8.36, 8.44]
Household	[14.26, 25.3]	[31.95, 43.42]	[44.77, 45.48]

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Table 2. Costs for pumping and delivering water resources ($\$\,m^{-3}$).

Water resource type	Period		
	$t = 1$	$t = 2$	$t = 3$
Surface drainage water Groundwater	[0.0033, 0.0034]	[0.0032, 0.0033]	[0.0031, 0.0032]
Groundwater	[0.0056, 0.0062]	[0.0054, 0.0059]	[0.0052, 0.0057]
River water	[0.0062, 0.0063]	[0.0060, 0.0061]	[0.0058, 0.0059]

Table 3. Linearization results of surface water availability.

Period	p_i value	$G_i^{-1}(p_i,\lambda)/Z_i^{(p_i)}$	$\lambda = [0, 0.10]$	$\lambda = [0.81, 0.90]$
$t = 1$	$p_i = 0.01$	$-2.23\sqrt{0.34\lambda^2 - 0.51\lambda + 0.56} + 27.85 - 1.43\lambda$	$-0.0068\lambda + 26.107$	$-0.0157\lambda + 25.291$
	$p_i = 0.05$	$-1.64\sqrt{0.34\lambda^2 - 0.51\lambda + 0.56} + 27.85 - 1.43\lambda$	$-0.0090\lambda + 26.623$	$-0.0153\lambda + 25.710$
	$p_i = 0.10$	$-1.28\sqrt{0.34\lambda^2 - 0.51\lambda + 0.56} + 27.85 - 1.43\lambda$	$-0.0102\lambda + 26.893$	$-0.0150\lambda + 25.929$
	$p_i = 0.15$	$-1.03\sqrt{0.34\lambda^2 - 0.51\lambda + 0.56} + 27.85 - 1.43\lambda$	$-0.0110\lambda + 27.080$	$-0.0149\lambda + 26.080$
$t = 2$	$p_i = 0.01$	$-2.23\sqrt{0.27\lambda^2 - 0.67\lambda + 0.94} + 26.91 - 1.76\lambda$	$-0.0098\lambda + 24.651$	$-0.0152\lambda + 23.590$
	$p_i = 0.05$	$-1.64\sqrt{0.27\lambda^2 - 0.67\lambda + 0.94} + 26.91 - 1.76\lambda$	$-0.0121\lambda + 25.320$	$-0.0153\lambda + 24.257$
	$p_i = 0.10$	$-1.28\sqrt{0.27\lambda^2 - 0.67\lambda + 0.94} + 26.91 - 1.76\lambda$	$-0.0133\lambda + 25.669$	$-0.0158\lambda + 24.530$
	$p_i = 0.15$	$-1.03\sqrt{0.27\lambda^2 - 0.67\lambda + 0.94} + 26.91 - 1.76\lambda$	$-0.0141\lambda + 25.912$	$-0.0162\lambda + 24.720$
$t = 3$	$p_i = 0.01$	$-2.23\sqrt{0.14\lambda^2 - 0.22\lambda + 0.72} + 26.32 - 1.33\lambda$	$-0.0105\lambda + 24.343$	$-0.0136\lambda + 23.402$
	$p_i = 0.05$	$-1.64\sqrt{0.14\lambda^2 - 0.22\lambda + 0.72} + 26.32 - 1.33\lambda$	$-0.0113\lambda + 24.929$	$-0.0135\lambda + 23.951$
	$p_i = 0.10$	$-1.28\sqrt{0.14\lambda^2 - 0.22\lambda + 0.72} + 26.32 - 1.33\lambda$	$-0.0117\lambda + 25.234$	$-0.0135\lambda + 24.237$
	$p_i = 0.15$	$-1.03\sqrt{0.14\lambda^2 - 0.22\lambda + 0.72} + 26.32 - 1.33\lambda$	$-0.0120\lambda + 25.446$	$-0.0134\lambda + 24.436$

Table 4. Crop planting (km^2).

End-user	Period		
	$t = 1$	$t = 2$	$t = 3$
Corn	[7.65, 9.9]	[7.3, 9.48]	[6.95, 8.94]
Potato	[138.31, 146.85]	[131.98, 140.62]	[125.66, 132.61]
Rice	[7.04, 8.25]	[6.72, 7.9]	[6.39, 7.45]

Table 5. Water allocations to end-users (million m^3).

End-user	Period		
	$t = 1$	$t = 2$	$t = 3$
Agriculture	[27.57, 29.56]	[25.53, 27.31]	[23.77, 24.67]
Metallurgical industry	[14.86, 15.09]	[14.29, 14.45]	[13.64, 13.77]
Food industry	[9.11, 9.25]	[8.76, 8.86]	[8.36, 8.44]
Tourism	[14.26, 25.3]	[31.95, 43.42]	[44.77, 45.48]
Residents	[32.61, 33.69]	[31.34, 32.27]	[29.93, 30.76]
Municipal sector	[16.78, 19.47]	[16.13, 18.64]	[15.41, 17.77]

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Table 6. Water pollution control (10^3 tonnes).

End-user	Period		
	$t = 1$	$t = 2$	$t = 3$
Wastewater	[28.12, 29.75]	[30.64, 31.29]	[28.22, 31.15]
Total nitrogen	[1.27, 1.34]	[1.18, 1.24]	[0.98, 1]
Total phosphorus	[0.49, 0.50]	[0.44, 0.45]	[0.34, 0.36]

Table 7. Water resources supplies under different p_i value (million m^3).

Water resource type	Period	p_i value			
		$p_i = 0.01$	$p_i = 0.05$	$p_i = 0.10$	$p_i = 0.15$
Surface drainage water	$t = 1$	[20.73, 21.54]	[21.96, 21.07]	[22.18, 21.25]	[22.24, 21.37]
	$t = 2$	[19.45, 20.34]	[20.89, 19.88]	[21.17, 20.1]	[21.25, 20.26]
	$t = 3$	[19.18, 20.08]	[20.57, 19.63]	[20.81, 19.86]	[20.88, 20.03]
Groundwater	$t = 1$	[28.33, 29.14]	[29.62, 28.69]	[29.88, 28.87]	[30.05, 29]
	$t = 2$	[26.52, 27.61]	[27.97, 26.77]	[28.16, 26.91]	[28.29, 27]
	$t = 3$	[21.91, 24.16]	[24.94, 22.71]	[25.34, 23.13]	[25.62, 23.42]
River water	$t = 1$	[102.79, 107.79]	[108.63, 103.75]	[109.07, 104.26]	[109.38, 104.61]
	$t = 2$	[98.26, 103.88]	[105.24, 99.14]	[105.95, 99.6]	[106.44, 99.92]
	$t = 3$	[96.37, 102.06]	[103.2, 97.15]	[103.79, 97.56]	[104.2, 97.84]

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Table 8. System benefit from ICCP and DIFCCP ($ million).

Optimization method	p_i value $p_i = 0.01$	$p_i = 0.05$	$p_i = 0.10$	$p_i = 0.15$
ICCP	[314.95, 370.04]	[314.97, 371.82]	[314.95, 372.76]	[314.94, 373.40]
DIFCCP	[316.02, 367.71]	[317.54, 370.16]	[317.71, 371.09]	[317.70, 371.74]

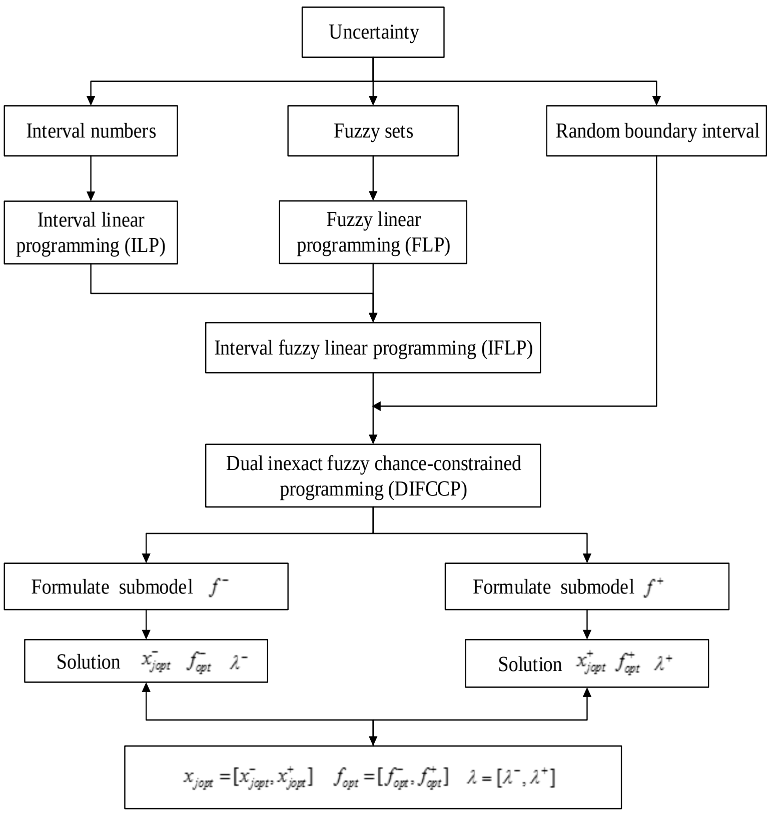

Fig. 1. Optimization method.

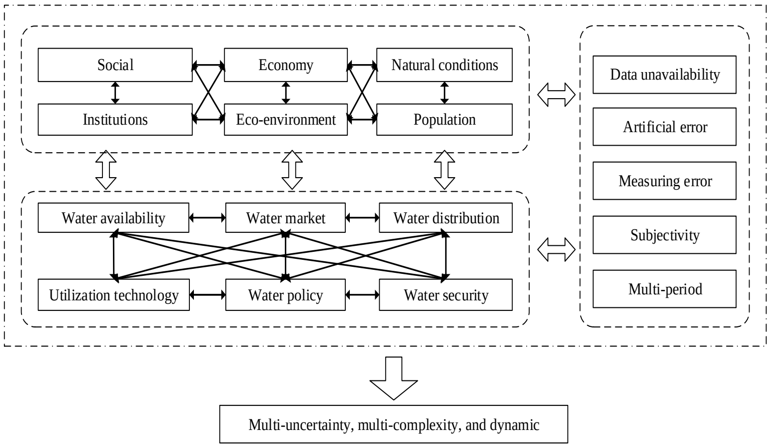

Fig. 2. Water and farmland use management system.

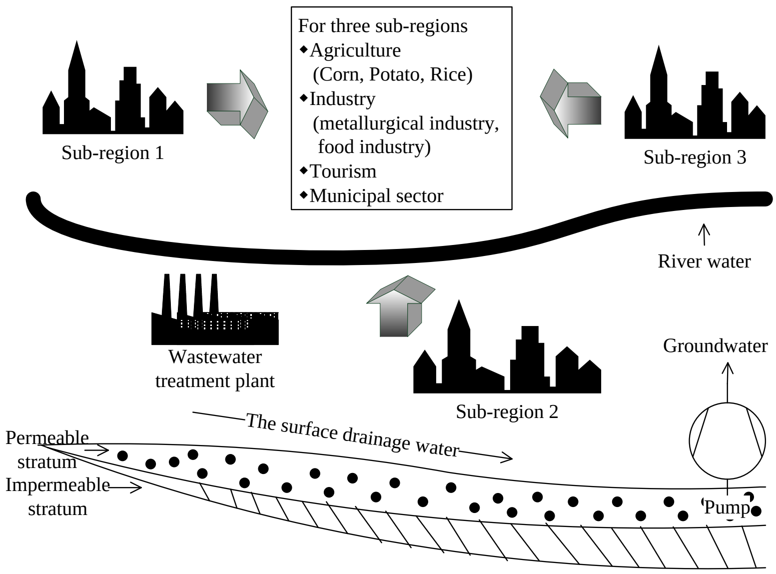

Fig. 3. The typical regional farmland use and water resources system.

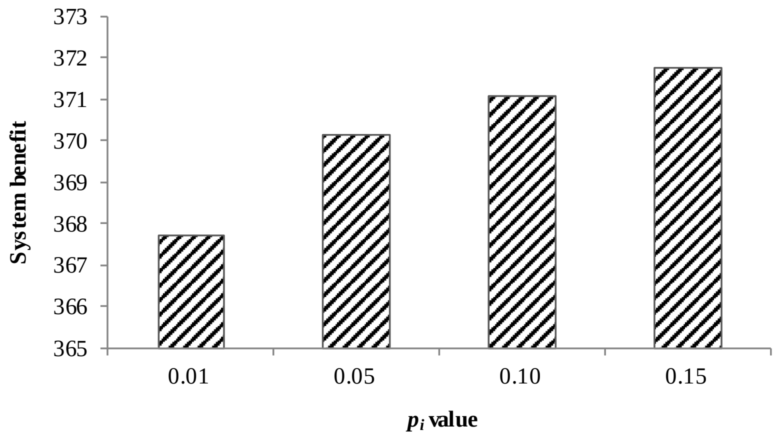

Fig. 4. System benefit under different p_i values (upper bound).

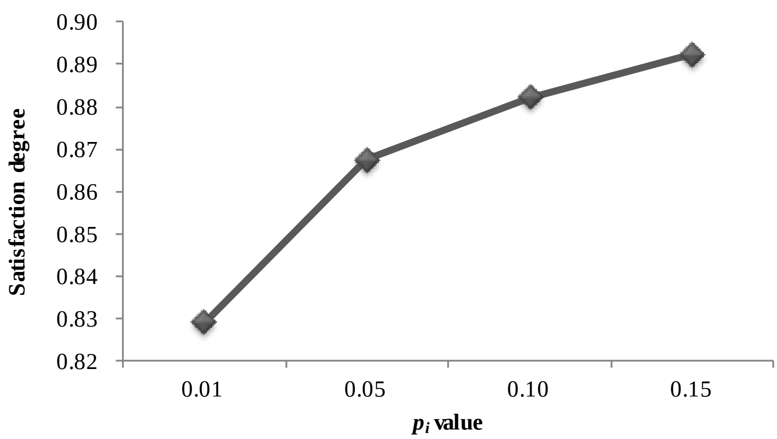

Fig. 5. Satisfaction degrees under different p_i values (upper bound).