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Identification of the optimal agricultural structure and population size in a reservoir watershed based on the water ecological carrying capacity under uncertainty

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ABSTRACT

The optimal agricultural structure and population size within typical watersheds needs to be identified based on the water ecological carrying capacity (WECC). However, real-world systems of water ecological management are complicated as multiple uncertainties exist in the system parameters, which need some effective optimization methods to deal with. This research presents an inexact simulation-based fuzzy credibility-constrained mixed-integer programming (ISFCCMIP) model. Through integrating interval linear programming, fuzzy credibility-constrained programming, mixed-integer programming, global nutrient export from watersheds, and the Kirchner–Dillon model within a general framework, the developed ISFCCMIP model can effectively deal with the multiple uncertainties in the simulation and optimization processes of water ecological management systems. The developed ISFCCMIP model is applied to a real-world case study in the Xinfengjiang Reservoir Watershed. Results show that the total population that can be carried by the watershed WECC would decrease from [204885, 412367] to [121235, 271280], when the credibility level increases from 0.55 to 0.95. On the contrary, the total agricultural benefit would increase from [3.72, 5.06] $\times 10^8$ to [3.75, 5.10] $\times 10^8$ $. The total population in the base year far exceeds the watershed WECC. Although the total agricultural benefit in the base year is between the upper and lower bounds of the optimized results, the agricultural structure is not reasonable and needs to be adjusted. Concurrently, multiple results on the optimal agricultural structure and population size are obtained under different credibility levels and in different carrying capacity scenarios. Such results can provide a series of decision alternatives for watershed policy makers to consider the tradeoff between socio-economic development and water ecological protection. The results also assist the sustainable development of the Xinfengjiang Reservoir Watershed. The proposed model is effective for the optimal management of agricultural structure and population size within a reservoir watershed based on the WECC under multiple uncertainties. It also provides a reference for other areas with similar concerns.

1. Introduction

The aquatic ecosystem plays an important role in the sustainable development of the economy, society, and environment (Englert et al., 2013; He et al., 2018; Li et al., 2016; Reckendorfer et al., 2013). However, with the rapid growth of the social economy in recent years, the aquatic ecosystem has been subjected to intensive and large-scale human activities (Shabanzadeh-Khoshrody et al., 2016). The total consumption and development intensity of water resources, as well as emission loads of water pollution, have increased, leading to a series of consequences, such as water resource shortages, environment deterioration, and ecological degradation (Jing et al., 2015; Matios and Burney, 2017; Wang et al., 2015; Xu et al., 2017). Such consequences have placed great pressure on aquatic ecosystems and seriously affected

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the sustainable utilization of their service functions (Ren et al., 2013; Zhang et al., 2017). Therefore, socio-economic activity within a watershed should simultaneously consider water quantity and quality conditions, and these considerations must be based on the water ecological carrying capacity (WECC) (Wang et al., 2014; Zhang et al., 2014). In particular, agricultural industry development and frequent human activities can lead to an increase in water consumption and release of nutrients (e.g., nitrogen and phosphorus, N and P) from watersheds to water bodies downstream, which might further result in insufficient ecological flow and water eutrophication (Rong et al., 2018; Rudnick et al., 2017; Zhang et al., 2015, 2018). It is therefore important to conduct research on the identification of the optimal agricultural structure and population size within typical watersheds based on the WECC. This will help restrain the water ecological deterioration, protect the ecosystem service function, and promote the sustainable development of the socio-economic environment. Moreover, real-world systems of water ecological management are complicated. Multiple uncertainties might exist in the system parameters, components, processes, and their interrelationships. Consequently, much information can hardly be expressed as deterministic values, leading to a number of uncertain parameters, such as discrete intervals and fuzzy sets. It is thus necessary to consider such multiple system uncertainties when investigating the management of the agricultural structure and population size based on the WECC.

Recent studies have investigated the water-related carrying capacity of typical watersheds. In particular, previous research addressed water resources and environment carrying capacities. Many assessment methods have been proposed and applied to determine the potential maximum economic growth and population size within a watershed (Ren et al., 2016; Song et al., 2011; Wang et al., 2013). As an example, system dynamics models, based on synthesis simulations of coupling effects and feedback mechanisms within the society–economy–water compound system, have been established to identify variation trends in the population, economy, water supply and demand, and pressure on the water environment (Wang et al., 2017; Yang et al., 2015; Yue et al., 2015). Concurrently, methods, such as the cloud model and integrated system dynamic and cellular automaton model, have been used in spatial variation analysis and the identification of factors affecting water resources and environment carrying capacities (Cheng et al., 2018; Reghunathan et al., 2016; Zhou et al., 2017; Zhu et al., 2010). However, existing research on the water-related carrying capacity has mainly concentrated on single components (i.e., water resources and water environment systems) in a watershed. Additionally, only the maximum economic aggregate and population scale have been investigated, while the composition of the industrial structure (e.g., the agricultural structure) has rarely been reflected. Demands on the ecological management of a watershed can no longer be fully met (Wang et al., 2014; Zhang et al., 2014). It is therefore necessary to identify the optimal agricultural structure and population size in a watershed based on the WECC, which can provide policy makers with detailed decision alternatives.

In the real-world processes of WECC assessment and optimal agricultural structure identification, systems might contain much uncertain information, which must be dealt with using advanced methods. However, existing optimization techniques under uncertainty have mainly been developed for and applied to single components of water ecosystems (e.g., water resources and environmental management systems) (Li et al., 2008b; Liao et al., 2013; Nabavi-Pelesaraei et al., 2016; Yao et al., 2015; Zeng et al., 2018). Many integrated models based on interval, fuzzy, and stochastic mathematical programming have been proposed (Dong et al., 2018; Fan et al., 2012; Li and Huang, 2009; Li et al., 2006). Concurrently, quadratic programming, risk aversion, and multi-objective programming have been introduced to the integrated interval-fuzzy-stochastic model framework to better reflect system characteristics, leading to a series of more advanced techniques. Some of these techniques (e.g., interval-parameter robust quadratic programming, inexact mixed risk-aversion two-stage stochastic programming, and inexact stochastic multiple-objective programming models) have been applied to several real-world case studies to support watershed management, such as industrial structure optimization, water resource allocation, and multiple-point-source waste reduction (Hu et al., 2013; Li et al., 2016; Li et al., 2015a; Li et al., 2008a). Moreover, a number of simulation techniques have been coupled with optimization frameworks to formulate simulation-based optimization models (Fu et al., 2017; Huang et al., 2012; Luo et al., 2006). Such models have also been proven to be effective in supporting water resource and environment management under multiple uncertainties (Cai et al., 2018; Li et al., 2018; Rong et al., 2017). Thus, system analysis using comprehensive optimization models is important to both water resource and environmental management. Water ecological management systems will also be complicated owing to the organic combination of water resources and environment. Many uncertainties, such as discrete intervals, fuzzy sets and integers, exist in system parameters, which is rarely considered in the previous researches focused on watershed management based on the WECC. Also, uncertain information regarding the simulation processes in water ecological management systems needs to be further reflected. Therefore, it is necessary to introduce some advanced methods and develop an integrated management model to address the uncertainties when investigating the optimal agricultural structure and population size in a watershed based on the WECC.

This study therefore develops an inexact simulation-based fuzzy credibility-constrained mixed-integer programming (ISFCCMIP) model for supporting identification of the optimal agricultural structure and population size in a reservoir watershed based on the WECC under uncertainty. By coupling interval linear programming (ILP), fuzzy credibility-constrained programming (FCCP), mixed-integer programming (MIP), global nutrient export from watersheds (NEWS), and the Kirchner–Dillon model within a general framework, the developed ISFCCMIP model effectively deals with multiple uncertainties in the process of water ecological management. Additionally, interval parameters are introduced to the simulation model to better reflect the real characteristics of nutrient export. The model simultaneously considers the water quantity and quality conditions and their joint effects when identifying the optimal agricultural structure and population size within a watershed. The proposed model is applied to the real-world case study of the Xinfengjiang Reservoir Watershed in South China, to reflect the optimal population size and agricultural production scales that can be supported by the watershed water ecosystem. Furthermore, multiple results under different scenarios provide several decision alternatives for policy makers to identify optimal planting areas of different crops and breeding scales of different livestock and poultry within the watershed. The model will benefit sustainable development of the Xinfengjiang Reservoir Watershed and provide a reference for other areas with similar concerns.

2. Methodology

2.1. Formulation of the ISFCCMIP model based on the WECC

The narrow definition of the WECC refers to the maximum population and economic scale that can be carried by the available water resources and the corresponding pollution-carrying capacity in the region. The agricultural structure therefore strongly affects the WECC in a watershed. In real-world agricultural management systems, there are multiple uncertainties in system parameters, components, processes, and their interrelationships. Much information (e.g., planting areas of crops, breeding scales of livestock and poultry, and allowable discharge amounts of different pollutants) can hardly be expressed as deterministic values, leading to a number of uncertain parameters, such as discrete intervals and fuzzy sets. Additionally, some parameters (e.g., the population size and livestock amount) should be integers. To effectively deal with these uncertainties, an ISFCCMIP model is proposed to support the identification of the optimal agricultural structure and population size in a reservoir watershed based on the WECC under uncertainty. In the ISFCCMIP model, the population size, planting areas of different crops, and breeding scales of livestock and poultry are set as decision variables. The objective of the model is to maximize the regional WECC, which denotes the maximum population and agricultural benefit in this study. Because the dimensionalities of the population size and agricultural benefit are different, the two parameters are divided by the values in the base year to remove the dimensionalities. The objective is subject to a series of constraints, including water quantity and quality constraints, area constraints, development level constraints, and technical constraints. Specifically, water quantity constraints are set according to the river ecological water demand. According to a relevant research, 10 percent of the average flow is the minimum instantaneous flow recommended to sustain the short-term survival habitat for most aquatic life forms; 30 percent is recommended as a base flow with which to sustain good survival conditions for most aquatic life forms and general recreation; and 60 percent provides an excellent to outstanding habitat for most aquatic life forms during their primary periods of growth and for the majority of recreational uses (Tennant, 1976). Therefore, to ensure the ecological water demand of downstream rivers, the water withdrawal amounts of economic and social activities must have an upper limit. Water quality constraints are set according to water quality requirements of the downstream functional zone. The present paper considers nutrient export loads (i.e., total nitrogen and phosphorus, TN and TP) and proposes total allowable discharge amounts of TN and TP. Area constraints are set according to regional land use planning, mainly considering the planting of crops and fruit species. Development constraints are set from the perspective of sustainable socio-economic development and the improvement of people's living standards. The agricultural benefit per capita should be no lower than that in the base year. Additionally, crop yields and livestock and poultry amounts per capita and the occupancy of grain crops per unit livestock and poultry should not be lower than those in the base year. Moreover, the decision variables of the proposed optimization model, including the total population size, planting areas of different crops, and breeding scales of livestock and poultry, should not be negative in reality. Furthermore, the population size and livestock breeding scale should be integers. Thus, an ISFCCMIP model for identifying the optimal agricultural structure and population size in a reservoir watershed based on the WECC under uncertainty can be formulated as follows:

$$\text{Max } WECC^{\pm} = POP^{\pm}/POP_{\text{b}} + AB^{\pm}/AB_{\text{b}} \tag{1a}$$

$$POP^{\pm} = \sum_{i=1}^{I} POP_i^{\pm} \tag{1b}$$

$$AB^{\pm} = \sum_{i=1}^{I}\sum_{j=1}^{J} CA_{ij}^{\pm} \cdot Yld_j^{\pm} \cdot BC_j^{\pm} + \sum_{i=1}^{I}\sum_{k=1}^{K} BL_k^{\pm} \cdot LB_{ik}^{\pm} \tag{1c}$$

subject to:

(1) Water quantity constraints

$$\text{Cr}\left\{Q^{\pm} \geq \tilde{C}_n \times Q_{\text{ave}}\right\} \geq \lambda_1 \tag{1d}$$

$$Q^{\pm} = Q_{\text{ave}} - \left(LIW^{\pm} + AGW^{\pm} + LBW^{\pm}\right)/RA_{\text{AL}}^{\pm} \tag{1e}$$

$$LIW^{\pm} = POP^{\pm} \times WCP^{\pm} \tag{1f}$$

$$AGW^{\pm} = \sum_{i=1}^{I}\sum_{j=1}^{J} CA_{ij}^{\pm} \times WCC_j^{\pm} \tag{1g}$$

$$LBW^{\pm} = \sum_{i=1}^{I}\sum_{k=1}^{K} LB_{ik}^{\pm} \times WCL_k^{\pm} \tag{1h}$$

(2) Water quality constraints:

$$\text{Cr}\left\{DN^{+} \leq \widetilde{RA}_N \cdot WEC_{TN}\right\} \geq \lambda_2 \tag{1i}$$

$$\text{Cr}\left\{DP^{+} \leq \widetilde{RA}_P \cdot WEC_{TP}\right\} \geq \lambda_3 \tag{1j}$$

(3) Area constraints:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} CA_{ij}^{\pm} \leq AC_{\text{b}},\ j = 1,\ 2,\ \ldots,\ \text{m}_1 \tag{1k}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} CA_{ij}^{\pm} \leq AF_{\text{b}},\ j = \text{m}_1+1, \text{m}_1+2, \ldots, \text{m} \tag{1l}$$

(4) Development level constraints:

$$AB^{\pm}\big/POP^{\pm} \geq AB_{\text{b}}/POP_{\text{b}} \tag{1m}$$

$$\sum_{i=1}^{I} CA_{ij}^{\pm} \cdot Yld_j^{\pm}\Big/POP^{\pm} \geq \sum_{i=1}^{I} CY_{\text{b}\ ij}\Big/POP_b,\ \ \forall j \tag{1n}$$

$$\sum_{i=1}^{I} LB_{ik}^{\pm}/POP^{\pm} \geq \sum_{i=1}^{I} LB_{\text{b}\ ik}/POP_b,\ \ \forall k \tag{1o}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J'} CA_{ij}^{\pm} \cdot Yld_j^{\pm}\Big/\sum_{i=1}^{I} LB_{ik}^{\pm} \geq \sum_{i=1}^{I}\sum_{j=1}^{J'} CY_{\text{b}\ ij}\Big/\sum_{i=1}^{I} LB_{\text{b}\ ik}^{\pm},\ \ \forall k \tag{1p}$$

(5) Technical constraints:

$$POP_i^{\pm} \in \text{N}^* \tag{1q}$$

$$LB_{ik}^{\pm} \in \text{N}^* \tag{1r}$$

$$CA_{ij}^{\pm} \geq 0 \tag{1s}$$

where $WECC^{\pm}$ is the index of the WECC; $POP^{\pm}$ is the total population; $AB^{\pm}$ is the total agricultural benefit, which includes crop production and the breeding of livestock and poultry; POP_{b} and AB_{b}

are respectively the population size and agricultural benefit in the base year; $POP_i^{\pm}$ is the population size in zone i; $CA_{ij}^{\pm}$ is the planting area of crop or fruit j in zone i (ha); $Yld_j^{\pm}$ is the yield per unit area of crop j (kg/ha); $BC_j^{\pm}$ is the unit benefit of crop j ($/kg); $BL_k^{\pm}$ is the unit benefit of livestock k ($/unit); $LB_{ik}^{\pm}$ is the number of livestock k fed in zone i; I is the number of zones; J is the number of crop types; K is the number of types of livestock and poultry; $Q^{\pm}$ is the ecological flow of the river; $\tilde{C}_n$ is the proportion of the river ecological water demand; Q_{ave} is the annual mean runoff; $LIW^{\pm}$, $AGW^{\pm}$, and $LBW^{\pm}$ are respectively the domestic, irrigation, and livestock breeding water consumptions; $RA_{AL}^{\pm}$ is the proportion of $LIW^{\pm}$, $AGW^{\pm}$, and $LBW^{\pm}$ in the total water consumption; $WCP^{\pm}$ is the water consumption per capita in the watershed; $WCC_j^{\pm}$ is the irrigation water consumption per unit area for crop j; $WCL_k^{\pm}$ is the water consumption per unit livestock and poultry; $DN^{\pm}$ and $DP^{\pm}$ are respectively TN and TP loads exported from the watershed (kg); $WEC_{TN}^{\pm}$ and $WEC_{TP}^{\pm}$ are respectively the water environmental carrying capacity of TN and TP (kg); $\widetilde{RA}_N$ and $\widetilde{RA}_P$ are proportions of dissolved pollutants; AC_b and AF_b are respectively the areas of agricultural land and orchard in the base year (ha); $CY_{b\ ij}$ is the total yield of crop j in zone i in the base year (kg); $LB_{b\ ik}$ denotes the production of each type of livestock and poultry in zone i in the base year; and J' is the numer of grain crop types. $WECC^{\pm}$, $POP^{\pm}$, $AB^{\pm}$, $POP_i^{\pm}$, $CA_{ij}^{\pm}$, $Yld_j^{\pm}$, $BC_j^{\pm}$, $BL_k^{\pm}$, $LB_{ik}^{\pm}$, $Q^{\pm}$, $LIW^{\pm}$, $AGW^{\pm}$, $LBW^{\pm}$, $RA_{AL}^{\pm}$, $WCP^{\pm}$, $WCC_j^{\pm}$, $WCL_k^{\pm}$, $DN^{\pm}$, $DP^{\pm}$, $WEC_{TN}^{\pm}$, and $WEC_{TP}^{\pm}$ are discrete intervals; $\tilde{C}_n$, $\widetilde{RA}_N$, and $\widetilde{RA}_P$ are fuzzy sets; and POP_b, AB_b, Q_{ave}, AC_b, AF_b, $CY_{b\ ij}$, and $LB_{b\ ik}$are deterministic values.

2.2. Nutrient export and allowable discharge amounts from a reservoir watershed

TN and TP loads exported from a watershed (i.e., $DN^{\pm}$ and $DP^{\pm}$ in the above-mentioned optimization model) are simulated using the global NEWS model. This model comprises independently formulated, element-form sub-models that predict steady-state annual exports of dissolved inorganic nitrogen and phosphorus (DIN and DIP), dissolved organic forms (DON, DOP, and DOC), and particulate N, P, and C forms (PN, PP, and POC). Details of the model have been published (Mayorga et al., 2010). The present paper considers dissolved nutrients and improves the model by introducing interval numbers to the model framework to better reflect the uncertain characteristics of nutrient export loads from a watershed. The improvements to the model are shown as follows.

$$Yld_F^{\pm} = FE_{riv,F}^{\pm}\cdot\left(RSpnt_F^{\pm} + RSdif_F^{\pm}\right) = \left(1 - L_F^{\pm}\right)\cdot\left(1 - D_F^{\pm}\right)\cdot\left(1 - F_{Qrem}^{\pm}\right)\cdot\left(RSpnt_F^{\pm} + RSdif_F^{\pm}\right) \quad (2a)$$

$$RSpnt_F^{\pm} = FE_{pnt,F}^{\pm}\cdot RSpnt_E^{\pm} = FE_{pnt,F}^{\pm}\cdot\left[\left(1 - hw_{frem,E}^{\pm}\right)\cdot I^{\pm}\cdot WShw_E^{\pm}\right] \quad (2b)$$

$$RSdif_F^{\pm} = RSdif_{ant,F}^{\pm} + RSdif_{nat,F}^{\pm} = \left[FE_{ws,F}^{\pm}\cdot WSdif_{ant,E}^{\pm} + Ag_{fr}^{\pm}\cdot RSdif_{ec,F}^{\pm}\right] + \left[FE_{ws,nat,F}^{\pm}\cdot WSdif_{nat,E}^{\pm} + \left(1 - Ag_{fr}^{\pm}\right)\cdot RSdif_{ec,F}^{\pm}\right] \quad (2c)$$

where F (subscript) is the nutrient form; $Yld_F^{\pm}$ is the general yield of each dissolved element form (kg·km^{-2} yr^{-1}); $RSpnt_F^{\pm}$ and $RSdif_F^{\pm}$ are respectively the export of F from the watershed to streams via point and diffuse sources; $FE_{riv,F}^{\pm}$ is the fraction of nutrient form F input to rivers that is exported at the basin mouth, corresponding to retention within the river system ($1 - FE_{riv,F}^{\pm}$); $L_F^{\pm}$ and $D_F^{\pm}$ are respectively retention fractions within reservoirs and along the river network; $F_{Qrem}^{\pm}$is the consumptive water removal fraction; $RSpnt_E^{\pm}$ is the basin area normalized point-source emission (effluent) to streams of element E; $FE_{pnt,F}^{\pm}$ is the fraction of $RSpnt_E^{\pm}$ emitted as form F; $hw_{frem,E}^{\pm}$ is the fraction of element E (i.e., N or P) in sewage influent removed via wastewater treatment; $I^{\pm}$ is the fraction of the population connected to a sewage system; $WShw_E^{\pm}$ (kg·km^{-2} yr^{-1}) denotes a gross human-waste source to the watershed; $RSdif_{ant,F}^{\pm}$ and $RSdif_{nat,F}^{\pm}$ are respectively the anthropogenic and natural nutrient inputs to the watersheds, including the net effect of land-based retention or removal (watershed sinks) of nutrients; $FE_{ws,F}^{\pm}$ is the fraction of $RSdif_E^{\pm}$ emitted as form F, where $RSdif_E^{\pm}$ is the output flux of nutrient element E (kg·km^{-2} yr^{-1}); $FE_{ws,F}^{\pm}$ is a function of the mean annual water runoff from land to streams (R_{nat}); $WSdif_{ant,E}^{\pm}$ and $WSdif_{nat,E}^{\pm}$ are explicit budgets for N and P in agricultural (anthropogenic, ant) and natural (nat) areas of the watershed; $RSdif_{ec,F}^{\pm}$ is the direct diffuse inputs to rivers; $Ag_{fr}^{\pm}$ is the fraction of the basin covered by agricultural areas; and $FE_{ws,nat,F}^{\pm} = FE_{ws,F}^{\pm}$ except for DIN. $Yld_F^{\pm}$, $FE_{riv,F}^{\pm}$, $RSpnt_F^{\pm}$, $RSdif_F^{\pm}$, $L_F^{\pm}$, $D_F^{\pm}$, $F_{Qrem}^{\pm}$, $FE_{pnt,F}^{\pm}$, $RSpnt_E^{\pm}$, $hw_{frem,E}^{\pm}$, $I^{\pm}$, $WShw_E^{\pm}$, $RSdif_{ant,F}^{\pm}$, $RSdif_{nat,F}^{\pm}$, $FE_{ws,F}^{\pm}$, $WSdif_{ant,E}^{\pm}$, $Ag_{fr}^{\pm}$, $RSdif_{ec,F}^{\pm}$, $FE_{ws,nat,F}^{\pm}$, and $WSdif_{nat,E}^{\pm}$ are interval parameters.

The total allowable amounts of nutrient exported from watersheds (i.e., WEC_{TN} and WEC_{TP}) are determined based on the water quality requirements of the downstream functional zone. In this study, an empirical method proposed by Kirchner and Dillon (1975) is used to calculate the water environmental capacity in a reservoir. Accordingly, the water environmental capacity of TN and TP in a reservoir is calculated as follows:

$$WEC = \frac{C_s \times q}{1 - R} \quad (3a)$$

$$R = 0.426 \times \exp\left(-0.271 \times \frac{q}{A_R}\right) + 0.573 \times \exp\left(-0.00949 \times \frac{q}{A_R}\right) \quad (3b)$$

where WEC is the water environmental capacity of TN and TP in a reservoir (kg/a); C_s is the water quality standard of the reservoir area (g/m^3); q is the annual outflow of the reservoir (m^3/a); A_R is the reservoir area (m^2); and R is the retention coefficient of TN and TP in the reservoir.

2.3. Solution methods

To solve the proposed simulation-based optimization model, an FCCP method is first used to deal with vagueness on the right-hand sides of constraints (1b), (1g), and (1h). A two-step solution method with the aid of an interactive algorithm is then proposed to address interval uncertainties, transforming the model into two submodels corresponding to the upper and lower bounds of the objective function (Huang et al., 1995). The interval solution is obtained by integrating the solutions of the two submodels. Details of the two solution steps are presented as follows.

The present study adopts the triangular fuzzy membership function for its computational efficiency. Assume that $\tilde{T}$ is fully determined by the triplet $(\underline{T},\ T,\ \overline{T})$ of crisp numbers with $\underline{T} < T < \overline{T}$. Let r be real numbers. According to the definition, the credibility of $r \le \tilde{T}$ and $r \ge \tilde{T}$ is expressed as follows (Li et al., 2015b; Zhang et al., 2012):

$$\mathrm{Cr}(r \le \tilde{T}) = \begin{cases} 1, & if\ r \le \underline{T} \\ \dfrac{2T - \underline{T} - r}{2(T - \underline{T})}, & if\ \underline{T} \le r \le T \\ \dfrac{r - \overline{T}}{2(T - \overline{T})}, & if\ T \le r \le \overline{T} \\ 0, & if\ r \ge \overline{T} \end{cases} \tag{4a}$$

$$\mathrm{Cr}(r \ge \tilde{T}) = \begin{cases} 1, & if\ \ge \overline{T} \\ \dfrac{r + \overline{T} - 2T}{2(\overline{T} - T)}, & if\ T \le r \le \overline{T} \\ \dfrac{r - \underline{T}}{2(T - \underline{T})}, & if\ \underline{T} \le r \le T \\ 0, & if\ r \le \underline{T}r \end{cases} \tag{4b}$$

Normally, a significant credibility level should be greater than 0.5 (Soltanian et al., 2015). Equations (1b), (1g), and (1h) can therefore be transformed into the equivalent forms as follows:

$$[C_n + (1 - 2\lambda_1)(C_n - \overline{C}_n)] \cdot \mathrm{Q_{ave}} \le \mathrm{Q}^{\pm} \tag{5a}$$

$$[RA_N + (1 - 2\lambda_2)(RA_N - \underline{RA}_N)] \cdot \mathrm{WEC_{TN}} \ge \mathrm{DN}^{\pm} \tag{5b}$$

$$[RA_P + (1 - 2\lambda_3)(RA_P - \underline{RA}_P)] \cdot \mathrm{WEC_{TP}} \ge \mathrm{DP}^{\pm} \tag{5c}$$

A two-step solution method with the aid of an interactive algorithm is then proposed to address the interval uncertainties. The method transforms the model into two submodels corresponding to the upper and lower bounds of the objective function (Huang et al., 1995). The general formula of this method is given as follows.

In the first step, the submodel corresponding to F^+ is formulated as follows (assuming that $b_i^{\pm} \ge 0$):

$$\mathrm{Max}\ F^+ = \sum_{j=1}^{k_1} c_j^+ x_j^+ + \sum_{j=k_1+1}^{n} c_j^+ x_j^- \tag{6a}$$

subject to:

$$\sum_{j=1}^{k_1} |a_{ij}|^- \mathrm{Sign}\left(a_{ij}^-\right) x_j^+ \Big/ b_i^+ + \sum_{j=k_1+1}^{n} |a_{ij}|^+ \mathrm{Sign}\left(a_{ij}^+\right) x_j^- \Big/ b_i^- \le 1 \tag{6b}$$

$x_j^{\pm} =$ interval-continuous variables, $j = 1,\ 2,\ \ldots,\ p_1,\ k_1 +\ 1,\ k_1 +\ 2,\ \ldots,\ k_1 + p_2,$

$$(p_1 \le\ k_1 \text{ and } p_2 \le k_2,\ k_1 + k_2 = n) \tag{6c}$$

$$x_j^{\pm} = \text{ interval} - \text{discrete variables},\ j = p_1 + 1,\ p_1 + 2,\ \ldots,\ k_1,\ k_1 + p_2 + 1,\ k_1 + p_2 + 2,\ \ldots,\ n \tag{6d}$$

$$x_j^{\pm} \ge 0,\ \forall j \tag{6e}$$

where $x_j^{\pm}, j = 1, 2, \ldots, p_1$ are interval-continuous variables with positive coefficients and $x_j^{\pm}, j = k_1 + 1,\ k_1 + 2,\ \ldots,\ k_1 + p_2$ are interval continuous variables with negative coefficients; $x_j^{\pm}, j = p_1 + 1,\ p_1 + 2,\ \ldots,\ k_1$ are interval-discrete variables with positive coefficients and $x_j^{\pm}, j = k_1 + p_2 + 1,\ k_1 + p_2 + 2,\ \ldots,\ n$ are interval-discrete variables with negative coefficients. $\mathrm{Sign}(a_{ij}^{\pm}) = \begin{cases} 1 & if\ a_{ij}^{\pm} \ge 0 \\ -1 & if\ a_{ij}^{\pm} \le 0 \end{cases}$. The optimal solutions $x_{j\,\mathrm{opt}}^+ (j = 1, 2, \ldots, k_1)$ and $x_{j\mathrm{opt}}^- (j = k_1 + 1,\ k_1 + 1, \ldots, n)$ are then obtained from submodel (6).

Then, on the basis of the generated upper-bound solution, another submodel corresponding to F^- is formulated as follows:

$$\mathrm{Max}\ F^- = \sum_{j=1}^{k_1} c_j^- x_j^- + \sum_{j=k_1+1}^{n} c_j^- x_j^+ \tag{7a}$$

subject to:

$$\sum_{j=1}^{k_1} |a_{ij}|^+ \mathrm{Sign}\left(a_{ij}^+\right) x_j^- \Big/ b_i^- + \sum_{j=k_1+1}^{n} |a_{ij}|^- \mathrm{Sign}\left(a_{ij}^-\right) x_j^- \Big/ b_i^+ \le 1 \tag{7b}$$

$$x_j^{\pm} = \text{interval} - \text{continuous variables},\ j = 1,\ 2,\ \ldots,\ p_1,\ k_1 + 1,\ k_1 + 2,\ \ldots,\ k_1 + p_2$$

$$(p_1 \le\ k_1 \text{ and } p_2 \le k_2 k_1 + k_2 = n) \tag{7c}$$

$$x_j^{\pm} = \text{interval} - \text{discrete variables},\ j = p_1 + 1,\ p_1 + 2,\ \ldots,\ k_1,\ k_1 + p_2 + 1,\ k_1 + p_2 + 2,\ \ldots,\ n \tag{7d}$$

$$x_j^{\pm} \ge 0,\ \forall j \tag{7e}$$

$$x_j^- \le x_{j\,\mathrm{opt}}^+,\ j = 1, 2, \ldots, k_1 \tag{7f}$$

$$x_j^+ \ge x_{j\,\mathrm{opt}}^-,\ j = k_1 + 1,\ k_1 + 1, \ldots, n \tag{7g}$$

where $x_{j\,\mathrm{opt}}^+,\ j = 1, 2, \ldots, k_1$ and $x_{j\,\mathrm{opt}}^-,\ j = k_1 + 1,\ k_1 + 1, \ldots, n$ are decision variable solutions generated from submodel (6). On the basis of the above submodel, $x_{j\mathrm{opt}}^- (j = 1, 2, \ldots, k_1)$ and $x_{j\mathrm{opt}}^+ (j = k_1 + 1,\ k_1 + 1, \ldots, n)$ are obtained.

Finally, the interval solution is obtained by integrating the solutions of the above two submodels. Fig. 1 is the schematic of the computational process of the developed ISFCCMIP model.

3. Case study

3.1. Overview of the case study area

The Xinfengjiang Reservoir (E 114°19′30″–114°45′40″, N 23°41′15″–24°7′45″) is the largest reservoir in South China and is located in the middle reach of the East River Basin (Fig. 2). The total storage capacity and annual average water inflow of the reservoir are respectively 13.9 and 6.1 billion m^3. The water area of the reservoir is 364.0 km^2 and the catchment area is approximately 5730 km^2. The area has a subtropical monsoon climate. The annual mean temperature and precipitation amount in the watershed are respectively 19.5–20.7 °C and 1562.7–2142.6 mm. The topography and landform are complex and diverse, mainly including mountains, hills, and basins. Forestland, shrubland, and farmland are the main land use types in the watershed, respectively accounting for approximately 66%, 16%, and 13% of the total area.

The river system in the Xinfengjiang Reservoir Basin is complex. The major tributaries are the Xinfeng, Lianping, Daxi, and Zhongxin Rivers. The main functions of the reservoir are supplying drinking water, power generation, flood control, irrigation, aquaculture, and transportation. As an example, the reservoir is the largest water-source reservoir in Guangdong Province. The annual water withdrawal for domestic use is approximately 1.095×10^8 m^3. The water quality and quantity of the Xinfengjiang Reservoir are critical to the securing of a water supply for more than 40 million people in the downstream watershed. Additionally, the reservoir is an important center for regulating the water quality and quantity of the East River. The reservoir is thus of great importance in maintaining the health of the aquatic ecosystem in the area. However, with the rapid development of the Guangdong–Hong Kong–Macao Greater Bay Area, especially with the transformation and advancement of industry in this area, human activities in the upstream watershed of the Xinfengjiang Reservoir have intensified. Consequently, water consumption and pollution discharge have continuously increased, greatly threatening the health of the aquatic ecosystem. For instance, with the acceleration of urbanization, there have been large changes to the structure of agricultural industry. The planting of cash crops has rapidly increased and the aquaculture industry has rapidly grown, leading to large water consumption and serious agricultural non-point-source pollution. It is thus important to investigate the optimal agricultural structure and population scale in this watershed based on the WECC. Such study will support decision making in water ecological management and facilitate sustainable development of the area.

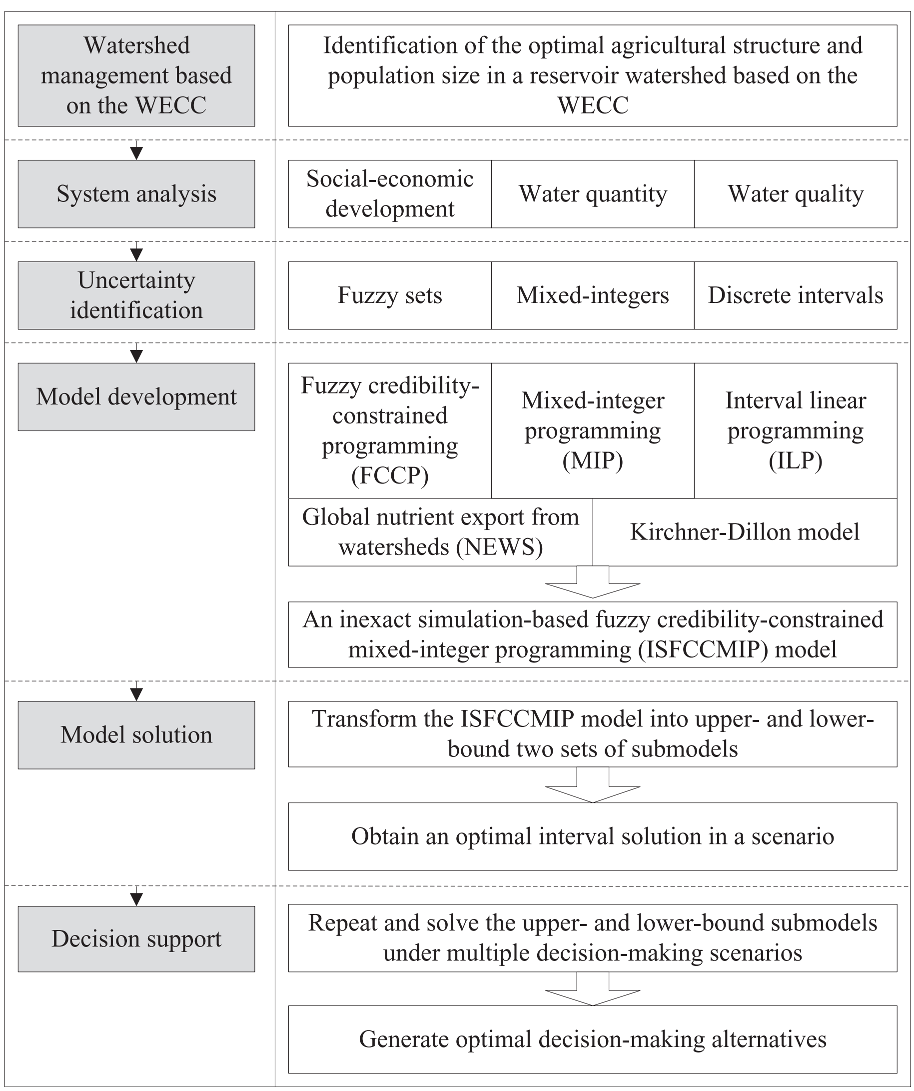

Fig. 1. Schematic of the computational process of the ISFCCMIP model.

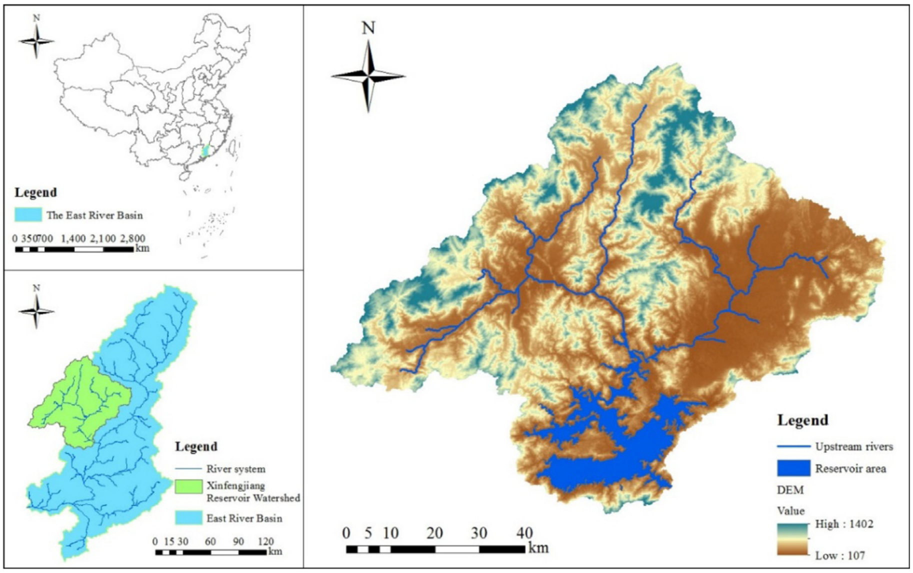

Fig. 2. Location and digital elevation model of the Xinfengjiang Reservoir Watershed.

3.2. Data collection and model implementation

Information on spatial characteristics, hydrological and meteorological conditions, pollution sources and sinks, and relevant economic data are collected and processed. The precision and sources of each type of data are given in Table 1. Table 2 lists basic information of the Xinfengjiang Reservoir Watershed. Data of crops and livestock and poultry are listed in Tables 3 and 4. The main crops in the Xinfengjiang Reservoir are rice, tubers, peanut, soybean, vegetables, and fruits while the main livestock and poultry are hogs, sow, cattle, goat, and poultry for meat and eggs. The planting areas of these crops and breeding scales of these livestock and poultry are thus set as decision variables in the proposed ISFCCMIP model. The year 2015 is selected as the base year in the model. The considered nutrient export from the watersheds include dissolved N and P. Following the proposed solution methods, vagueness on the right-hand sides of the constraint equations is handled using the FCCP method. A two-step solution method with the aid of an interactive algorithm is then adopted to transform the proposed ISFCCMIP model into two linear submodels. Finally, a program is written in Lingo to perform the model calculations.

4. Results and discussion

4.1. WECC of the Xinfengjiang Reservoir Watershed

Using the developed ISFCCMIP model, the optimal population size and agricultural benefit that can be carried in the Xinfengjiang Reservoir Watershed are obtained. Specifically, the total population that can be carried in the watershed is much smaller than that in the base year. When the credibility level is lower (i.e., $\lambda = 0.55$), the optimal population size that can be carried in the watershed would be [204,885, 412,367]. The total population in the base year (i.e., 845,441) exceeds the watershed WECC by approximately 105–310%. From the perspective of the total population, this watershed is in a state of unsustainable development. At the same time, the optimal population size in the watershed would decrease as the credibility level increases (Fig. 3). The optimal population size would decrease by more than one-third when the credibility level increases from 0.55 to 0.95. The credibility level reflects the decision-making tendency of policy makers in water ecological management. Therefore, such tendency affects the optimal population size that can be carried in the watershed. In particular, when policy makers are relatively tolerant to water ecological protection (i.e., tending to lower credibility levels), the optimal population would be greater, leading to high risks of an insufficient ecological water supply and excessive nutrient discharge. In contrast, the optimal population would be relatively lower when the policy makers are strict in terms of water ecological protection (i.e., tending to higher credibility levels). The two risks would be accordingly lower.

The optimal agricultural benefit that can be carried in the Xinfengjiang Reservoir Watershed under different credibility levels would be in the form of intervals. The total agricultural benefit in the base year is between the upper and lower bounds of the optimized results. The optimal agricultural benefit would be mainly from the breeding of livestock and poultry, which accounts for approximately 65% of the total. Conversely, the benefit of planting crops would be relatively lower. Concurrently, the credibility level would significantly affect the agricultural benefit that can be carried in the watershed. In contrast with the case of the optimal population size, the total agricultural benefit increases with the credibility level. For example, when the credibility level increases from 0.55 to 0.95, the total agricultural benefit that can be carried in the Xinfengjiang Reservoir Watershed would increase from $[3.72, 5.06] \times 10^8$ to $[3.75, 5.10] \times 10^8$ \$ (Fig. 4). Such a trend reveals that tolerant water ecological protection tendency would lead to a relatively lower agricultural benefit. Accompanying this lower benefit, there are high risks of an insufficient ecological water supply and excessive nutrient discharge. In contrast, a strict policy would result in a relatively high agricultural benefit. The main reason for this trend is that the watershed WECC is a comprehensive concept, referring to the maximum population and economic scale that can be carried by the available water resources and the corresponding pollutant carrying capacity in the region. The objective of the developed simulation-based optimization model is to maximize the sum of the total population and agricultural benefit, which are divided by values for the base year to remove dimensionalities. Because the model is subject to certain constraints, the optimal population size reduces and the total agricultural benefit increases to maximize the objective function value

Table 1
Precision and sources of input data.

Data types	Data	Date sources	Data precision
Spatial data	DEM	Geospatial Data Cloud (http://www.gscloud.cn/)	30 × 30 m
	Landuse	Global Cover 2009 landuse map (http://due.esrin.esa.int/page_globcover.php)	300 × 300 m
	Population	the National Earth System Science Data Sharing Infrastructure (http://www.geodata.cn/)	1000 × 1000 m
Meteorological and hydrological data	Precipitation	Annual Hydrological Report P. R. China (Hydrological Data of Pearl River Basin)	\
	Runoff		
Agricultural information data	Crop areas and yields	The Agricultural Statistical Yearbooks of Guangdong	\
	Fertilizer and manure		
	Livestock and poultry		
Economic data	Water consumption	Water quota standard of Guangdong (DB44/T1461-2014)	\
	economic coefficient	Information on Cost-effectiveness of Agricultural Products of China	\

Table 2
Basic information on the Xinfengjiang Reservoir Watershed.

Parameters	Value
Population in the base year (POP_b)	845441
Agricultural production in the base year (AB_b, \$)	406324053
Agricultural land area in the base year (AC_b, km^2)	747.85
Orchard area in the base year (AF_b, km^2)	129.78
Average annual flow (Q_{ave}, m^3)	50.948×10^8
Water consumption per capita (L/capita·d)	[210, 250]
Reservoir area (A_R, m^2)	3.7×10^8
Annual water runoff from land to streams (R_{nat})	0.89
Proportion of dissolved nitrogen discharge ($\widetilde{RA}_N$)	[0.70, 0.75, 0.80]
Proportion of dissolved phosphorus discharge ($\widetilde{RA}_P$)	[0.50, 0.55, 0.60]
Proportion of river ecological water demand ($\tilde{C}_n$)	[0.55, 0.60, 0.65]
Proportion of the water consumption of domestic, irrigation and livestock breeding ($RA^{\pm}_{AL}$)	[0.7, 0.75]

Table 3
Data for each crop.

Parameters	Rice	Tubers	Peanut	Soybean	Vegetables	Fruits
Water consumption (m3/ha)	[5595, 5655]	[2955, 3180]	[2835, 2895]	[1785, 2310]	[1680,2070]	[4050, 4680]
Unit benefit (BCj \$/kg)	[0.25, 0.27]	[0.34, 0.37]	[0.61, 0.69]	[0.26, 0.30]	[0.19, 0.21]	[0.25, 0.40]
Unit yield (Yld_j, kg/ha)	[5580, 5805]	[4060, 4400]	[3555, 3780]	[2550, 3000]	[14805, 16830]	[8400, 10100]
Application amount of N fertilizer (FN_j, kg/ha)	[116.55, 120.45]	[153.15, 186]	[24.45, 27.9]	[10.8, 20.25]	[46.2, 65.7]	[480, 540]
Application amount of P fertilizer (FP_j, kg/ha)	[21.75, 27.6]	[53.7, 96.9]	[29.25, 37.5]	[1.2, 4.35]	[20.1, 22.05]	[85, 115]
Application amount of Compound fertilizer (FCF_j, kg/ha)	[170.4, 194.85]	[199.5, 270.6]	[180.9, 225.75]	[33.3, 36.45]	[488.7, 576]	[861.30, 991.80]
Crop yield per capita in the base year (kg)	[224, 235]	[7, 13]	[33, 46]	[8, 11]	[178, 223]	[107, 117]

Table 4
Data for each type of livestock and poultry.

Livestock and poultry	Hogs	Sow	Cattle	Goat	poultry for meat	Poultry for eggs
Water consumption (L/capita·d)	[32,36]	[32,36]	[85,95]	[32,36]	[14,16]	[14,16]
Unit benefit (\$/unit)	[280, 295]	[775, 856]	[1470, 1625]	[136, 163]	[3.4, 4.3]	[23, 25]
Average amount per capita in the base year (Unit)	[0.133, 0.146]	[0.017, 0.025]	[0.038, 0.043]	[0.0021, 0.0035]	[1.1, 1.5]	[0.1, 0.3]
Occupancy of grain crop per unit livestock in the base year (t)	[1.76, 1.96]	[11.46, 17.19]	[6.69, 7.63]	[83.82, 139.63]	[0.18, 0.27]	[0.81, 1.83]

when the water ecological protection tendency of policy makers changes from tolerant to strict. Therefore, to enhance the WECC of the watershed, it is necessary to increase the population and reduce the agricultural benefit when the water ecological protection tendency of watershed policy makers changes from strict to tolerant. Otherwise, opposite measures should be taken to improve the WECC.

The agricultural benefits of planting crops and breeding livestock have opposite trends with a changing level of credibility. In particular, the benefit of breeding livestock and poultry would increase while that of planting crops would decrease with an intensifying credibility level. For instance, when the credibility is 0.55, the benefits of breeding livestock and poultry and planting crops would be $[2.45, 3.46] \times 10^8$ and $[1.28, 1.60] \times 10^8$ \$, respectively. As the credibility rises to 0.95, the two benefits would respectively increase and decrease by approximately 5% and 7%. Thus, although the total agricultural benefit that can be carried in the Xinfengjiang Reservoir would overall increase when the decision-making becomes strict, there are differences in the efficiency of each source of agricultural benefit in improving the WECC. When policy makers are more tolerant with water ecological protection, planting crops is more effective than breeding livestock and poultry in terms of improving the WECC of the watershed. Otherwise, effective measures are the breeding of livestock and poultry.

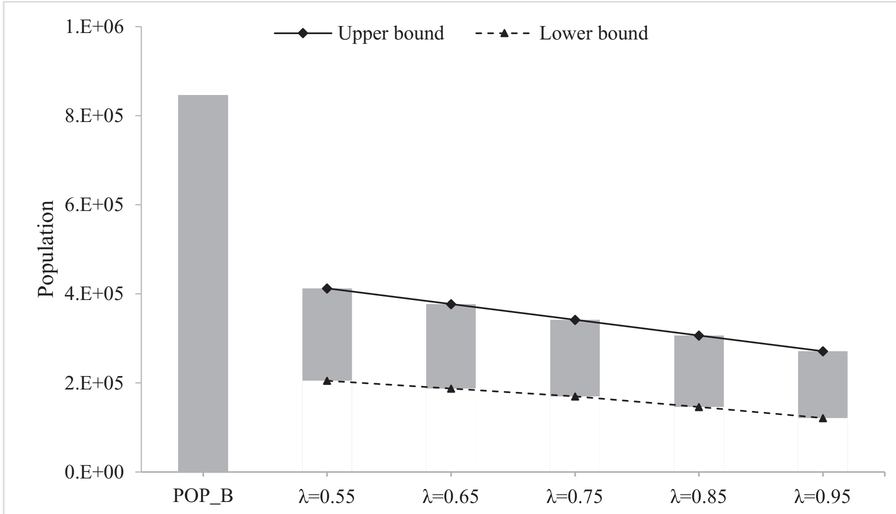

Fig. 3. Optimal population size that can be carried in the Xinfengjiang Reservoir Watershed under different credibility levels.
Note: POP_B denotes the population size in the base year.

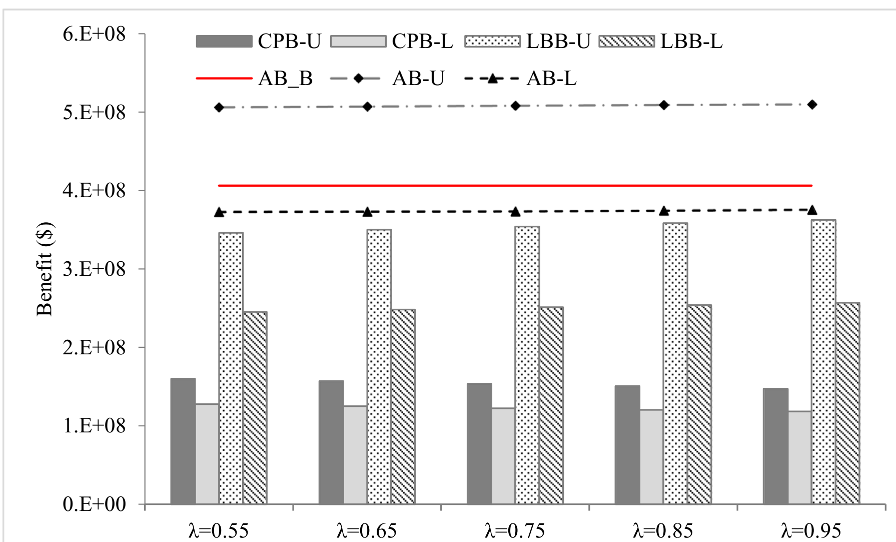

Fig. 4. Optimal agricultural benefits that can be carried in the Xinfengjiang Reservoir Watershed under different credibility levels.
Note: AB, CPB and LBB respectively represent the total agricultural benefit, agricultural benefit from planting crops, and agricultural benefit from breeding livestock and poultry; -U and -L represent the upper and lower bounds of the parameters; AB represents the agricultural benefit in the base year.

4.2. Optimal agricultural structure in the Xinfengjiang Reservoir based on the WECC

The modeling results show that the crop planting structure in the Xinfengjiang Reservoir Watershed would be adjusted to enhance the WECC. Specifically, the planting areas of rice and peanut would be greater than those in the base year while the planting areas of tubers, soybean, vegetables, and fruits would be less than those in the base year. Rice would be still the major crop in the study area after agricultural structure optimization and its proportion of planting area would be further increased, from approximately 45% in the base year to over 65%. Meanwhile, the proportion of the peanut planting area would increase from approximately 12% in the base year to more than 20%. Concurrently, the credibility level would affect the crop planting area. Specifically, the planting area of rice would increase while the planting areas of other crops would decrease with a rising credibility level. When the credibility level increases from 0.55 to 0.95, for example, the planting area of rice would increase from 51,980 to 57,801 ha while the planting areas of tubers, peanut, soybean, vegetables, and fruits would respectively drop from 656, 16688, 1100, [3991, 4361], and [2854, 4369] ha to [388, 432], 12959, 724, [1826, 2869], and [1689, 2874] ha (Table 5). Therefore, planting more rice could help improve the WECC in the watershed when the water ecological protection of watershed policy makers is relatively strict. Otherwise, planting tubers, peanut, soybean, vegetables, and fruits would be more conducive.

Similar to the planting areas of different crops, the breeding scales of livestock and poultry in the Xinfengjiang Reservoir Watershed would also change after optimization of the agricultural structure based on the WECC. In particular, the breeding scales of hogs, cattle, and poultry for meat and eggs would increase. As for

Table 5
Optimal crop planting structure under different credibility levels (Unit: ha).

	Rice	Tubers	Peanut	Soybean	Vegetables	Fruits
λ = 0.55	51980	656	16688	1100	[3991, 4361]	[2854, 4369]
λ = 0.65	53435	600	15756	1006	[3290, 3988]	[2610, 3995]
λ = 0.75	54890	544	14824	912	[2588, 3615]	[2366, 3622]
λ = 0.85	56346	[467, 488]	13891	818	[2196, 3242]	[2031, 3248]
λ = 0.95	57801	[388, 432]	12959	724	[1826, 2869]	[1689, 2874]

sows and goats, breeding quantities in the base year fall between the upper and lower bounds of the optimized interval results. At the same time, the credibility level would affect the breeding scales of livestock and poultry. The breeding quantities would overall increase with the rising credibility level. The optimal quantities of each type of livestock and poultry in the Xinfengjiang Reservoir Watershed would increase by approximately 5% when the credibility level increases from 0.55 to 0.95 (Table 6). Therefore, when the water ecological management strategy of watershed decision makers is relatively strict, it is necessary to improve the breeding scales of livestock and poultry to enhance the WECC of the watershed.

Comparing the agricultural benefit and structure in the base year with those obtained from the model, although the total agricultural benefit is between the upper and lower bounds of the optimized results, the sources of this benefit are different. The agricultural structure in the Xinfengjiang Reservoir Watershed needs to be adjusted to improve the WECC of the watershed. Adjustment strategies include increasing the planting areas of rice and peanuts and the breeding scales of each type of livestock and poultry. Compared with the previous research on the WECC (Wang et al., 2014; Zhang et al., 2014), the developed ISFCCMIP model has the advantages of providing the decision makers with some detailed management schemes for agricultural production in the watershed. However, the evaluation index system of the WECC in the model is relatively simpler.

4.3. Identification of critical water quality parameters affecting the WECC

The effect of each water quality constraint on the watershed WECC is analyzed. Results show that the optimal population size that can be carried in the watershed would decrease with a rising credibility level of the TN discharge constraint. Conversely, the optimal agricultural benefit would have an increase trend. Thus, no matter the decision tendency of TP discharge, the decision tendency of TN discharge would affect the WECC in the Xinfengjiang Reservoir. The effect of the TP discharge constraint would be much more complicated. As an example, when the credibility level of the TN discharge constraint is equal to 0.55, the upper bound of the optimal population size would be first steady and then increase with the rising credibility level of the TP discharge constraint. Concurrently, the lower bound would first decrease and then increase. As for the optimal agricultural benefit, the upper bound would be first steady and then decrease as the credibility level rises, while the lower bound would show a decreasing trend (Figs. 5 and 6). The main reason for these trends is that the major restriction factor of the system would change from TN to TP in the process of increasing credibility level of the TP discharge constraint. When the credibility level of the TN discharge constraint is equal to 0.95, the effect of the TP constraint is not important. Both the optimal population size and agricultural benefit would have an overall steady trend with an increasing credibility level of the TP discharge constraint (Figs. 5 and 6). Such variation characteristics reveal that, when the decision tendency of TN discharge is relatively strict, the main factor limiting water

Table 6
Optimal breeding scale of each type of livestock and poultry under different credibility levels.

	Hogs	Sow	Cattle	Goat	Poultry_M	Poultry_E
λ = 0.55	[440535, 512950]	[20642, 32374]	[46506, 55457]	[2541, 4426]	[9593882, 15046530]	[193902, 458036]
λ = 0.65	[445920, 519025]	[20894, 32757]	[47074, 56114]	[2572, 4478]	[9711160, 15224720]	[196273, 463462]
λ = 0.75	[451307, 525101]	[21147, 33141]	[47643, 56771]	[2603, 4531]	[9828463, 15402960]	[198644, 468888]
λ = 0.85	[456590, 531181]	[21394, 33525]	[48201, 57428]	[2633, 4583]	[9943534, 15581310]	[200969, 474315]
λ = 0.95	[461865, 537259]	[21641, 33908]	[48757, 58085]	[2664, 4636]	[10058400, 15759590]	[203291, 479744]

Note: Poultry_M and Poultry_E respectively represent poultry for meat and eggs.

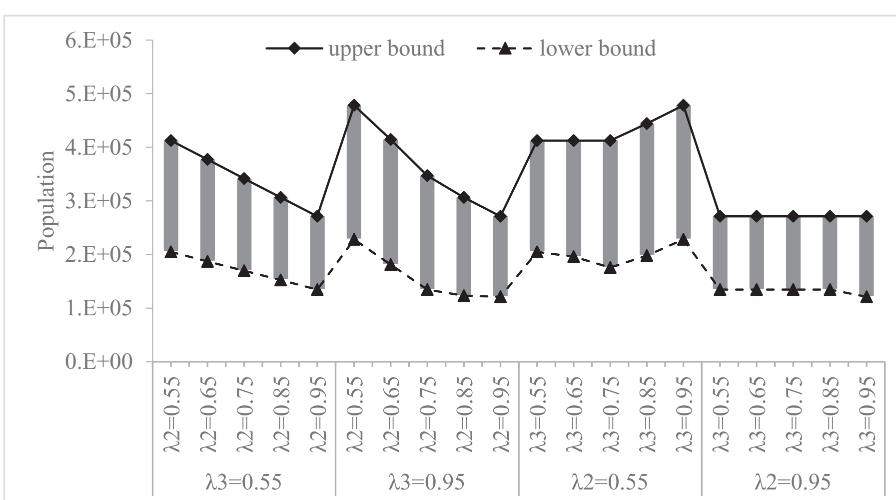

Fig. 5. Variation trends of the optimal population size for different credibility levels of TN and TP constraints.

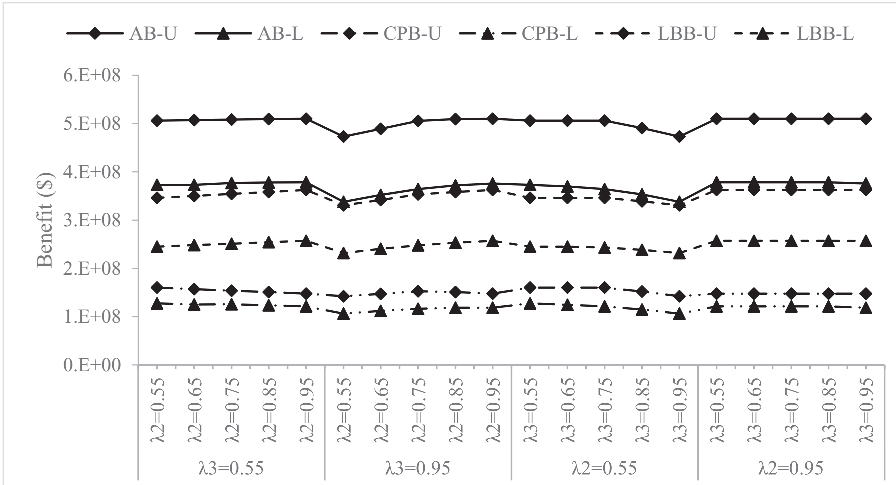

Fig. 6. Variation trends of the agricultural benefit for different credibility levels of TN and TP constraints.

Table 7
Optimal population size, agricultural benefit, and structure in different carrying capacity scenarios.

Index	Water resources carrying capacity	Water environmental carrying capacity
Total population	[484786, 975714]	[169846, 341844]
Total agricultural benefit	$[3.80, 5.20] \times 10^8$	$[3.73, 5.08] \times 10^8$
Benefit of crop planting	$[1.51, 1.97] \times 10^8$	$[1.22, 1.54] \times 10^8$
Benefit of livestock and poultry breeding	$[2.29, 3.23] \times 10^8$	$[2.51, 3.54] \times 10^8$
Planting areas of each crop (ha)		
Rice	51793	54890
Tubers	1552	544
Peanut	8518	14824
Soybean	2602	912
Vegetable	10319	[2588, 3615]
Fruits	12978	[2366, 3622]
Breeding scale of each livestock and poultry		
Hogs	$[4.12, 4.80] \times 10^5$	$[4.51, 5.25] \times 10^5$
Sow	$[1.93, 2.96] \times 10^4$	$[2.11, 3.31] \times 10^4$
Cattle	$[4.35, 5.19] \times 10^4$	$[4.76, 5.68] \times 10^4$
Goat	2.05×10^3	$[2.60, 4.53] \times 10^3$
Poultry-M	$[0.90, 1.41] \times 10^7$	$[0.98, 1.54] \times 10^7$
Poultry-E	$[1.82, 4.18] \times 10^5$	$[1.99, 4.69] \times 10^5$

Note: Results for water environmental carrying capacity scenarios were obtained at a moderate credibility level (i.e., $\lambda_2 = \lambda_3 = 0.75$).

ecological management in the Xinfengjiang Reservoir watershed would be TN. The TP discharge constraint would not affect the model results. The effect of variation in the TN discharge constraint on the WECC of the watershed would be thus much larger than the effect of variation in the TP discharge constraint. The decision tendency of TN discharge of the watershed policy makers would have a greater effect on the optimal population size and agricultural benefit of the watershed.

4.4. Optimal agricultural structure and population size in different carrying capacity scenarios

Differences in the optimal agricultural structure and population size in the Xinfengjiang Reservoir Watershed are also analyzed in terms of water resource, environmental, and ecological carrying capacity scenarios. Water resource and environmental carrying capacities represent the largest population and economic scale that the local water resources and environment can support in a specific region during a period of time (Song et al., 2011; Zhou et al., 2017). Results show that the optimal population size and agricultural benefit in the water resource carrying capacity scenario would be greater than those in water environmental and ecological scenarios. However, there would be no difference between the scenarios of water environmental and ecological carrying capacities (Table 7). The Xinfengjiang Reservoir Watershed has a subtropical monsoon climate. Annual precipitation is high (i.e., 1562.7–2142.6 mm), leading to a relatively abundant water resource. The water resource carrying capacity in this area is thus high. Concurrently, the total water supply only accounts for a small proportion of the total available water resource (e.g., approximately 23% in the base year). The flow of water thus well satisfies the ecological water demand of the rivers. Consequently, the water quantity constraint does not limit the model results in the study area. The water environmental and ecological carrying capacities would be thus equal in the Xinfengjiang Reservoir Watershed.

The benefit of planting crops would be much higher in the scenario of the water resource carrying capacity than in water environmental and ecological scenarios, while the benefit of breeding livestock and poultry would be much lower. A comparison of the agricultural patterns in the three scenarios shows that the planting areas of rice and peanut in the scenario of the water resource carrying capacity would be smaller than those in water environmental and ecological scenarios, while the planting areas of tubers, soybean, vegetables, and fruits would be much larger.

Additionally, the breeding scales of each type of livestock and poultry would be much smaller in the scenario of the water resource carrying capacity. Thus, planting rice and peanut and breeding livestock and poultry would be much more effective in improving the water environmental and ecological carrying capacities. Analysis of the optimal agricultural structure and population size in different carrying capacity scenarios reveals that nutrient discharge constraints would sharply reduce the total population and the planting areas of tubers, soybean, vegetables, and fruits. The water ecological management in the Xinfengjiang Reservoir Watershed should focus on reducing point-source pollution from domestic wastewater and non-point-source pollution from the planting of tubers, soybean, vegetables, and fruits.

The development of carrying capacity theory has passed through three main stages, from the resource carrying capacity to the environmental carrying capacity and to the ecological carrying capacity. There have been some attempts to develop optimization methods for water resources and environmental management. For example, based on the analysis of wetland water resources system, some measures, such as implementing water saving policies and increasing pollution control investment, were proposed to guarantee the sustainable utilization of water resources and social economy development in Beijing city (Wang et al., 2017). An inexact stochastic multiple objective programming was applied to analyze the optimization of industrial structure based on water environmental carrying capacity in Huai River Basin within Shandong Province (Li et al., 2016). Similar to the relevant research on the water resource and environment carrying capacities, system analysis has great potential to remarkably improve the water ecological management. This research is an attempt to develop a new model for identifying the optimal agricultural structure and population size in a watershed based on the WECC. Through coupling a number of tools and techniques, the relevant components of a water ecological management system and their interactions can be identified. The developed ISFCCMIP model can generate multiple decision alternatives and provide desired policy suggestions for the decision makers within a reservoir watershed.

5. Conclusions

With the rapid growth of the social economy in recent years, the aquatic ecosystem has been subjected to intensive and large-scale human activities that greatly threaten the ecological health of regional water bodies. It is necessary to simultaneously consider water quantity and quality conditions when identifying the optimal agricultural structure and population size that can be carried in a watershed under multiple uncertainties. The present paper developed an ISFCCMIP model by integrating the ILP, FCCP, MIP, global NEWS, and Kirchner−Dillon model into a general framework. The proposed model effectively deals with multiple uncertainties in the process of water ecological management and reflects uncertain characteristics of nutrient export. The ISFCCMIP model was applied to a real-world case study of the Xinfengjiang Reservoir Watershed to support the identification of the optimal agricultural structure and population size based on the WECC under uncertainty. Results show that the Xinfengjiang Reservoir Watershed is in a state of unsustainable development from the perspective of the WECC. The total population in the base year far exceeds the watershed WECC. Although the total agricultural benefit in the base year is between the upper and lower bounds of optimized results, the agricultural structure is not reasonable and needs to be adjusted. Meanwhile, the decision-making tendency of watershed policy makers in terms of TN discharge would have lager influence on the optimal population size, and agricultural benefit and structure of the watershed, compared with TP discharge. The WECC of the studied watershed is much smaller than the water resource carrying capacity. Additionally, there would be no difference between the water ecological and environmental carrying capacities. Such results are helpful in terms of providing multiple decision alternatives to support the sustainable development of the study area. The proposed model is effective for WECC assessment and agricultural structure optimization in a reservoir watershed under interval and fuzzy uncertainties. However, the ISFCCMIP model still has limitations in reflecting the effect of the spatial distribution of agricultural areas and land management. Furthermore, stochastic uncertainties are beyond the coverage of the model. The model might thus be improved in the future by coupling distributed simulation models and stochastic parameter programming methods to better describe the pollution generation process and system uncertain characteristics. Also, development and application of the model should be extended to the optimization of industrial structure to support integrated watershed management based on the WECC.

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