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Research article

Water quality constrained adjustment planning for regional breeding management with nonlinear programming model under uncertainty in Wenchang City, China

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A B S T R A C T

Basin water pollution caused by livestock, poultry and fish breeding is still a serious problem for remote villages, however, reliable regional breeding management programming have the potentials to improve pollution status. This paper focuses on the optimal model design and water quality analysis of the livestock, poultry and fish breeding system for Wenchang City, China. Methods of multi-objective programming (MOP), interval parameter programming (IPP), fuzzy-stochastic parameter programming (FSPP), and chance constrained programming (CCP) were incorporated into the developed model to tackle multi uncertainties described by interval values, probability distributions, fuzzy membership function. Based on the estimation of local breeding potential and current situation of surface water section, a multi-objective mixed fuzzy-stochastic nonlinear programming optimization model is presented with one-dimensional water quality model. In order to evaluate the environmental carrying capacity of livestock, poultry and fishery manure, predict its development trend and investigate the implementation effect of different emission reduction policies, this paper designs quantization system of the urban water environmental carrying capacity for the model. The results indicated that the water environment pollutant absorption capacity and carrying capacity of Wenchang city have approached the limit especially the towns in the northeast of City which limited the overall development space of the City. The modeling results are valuable for supporting the adjustment of the existing livestock, poultry and fish breeding schemes within a complicated system benefit and surface water quality situation under uncertainty.

1. Introduction

Water is critical for human survival, social development, and ecological environmental security. With the continuous increase of water demand, water resource shortage has become a key factor restricting social and economic development, and it is urgent to improve status of water environment and ensure water quality safety in river basin. Therefore, state control and provincial control water quality monitoring section was planned and designed to ensure the safety of surface water quality by ecological and environmental protection department. Corresponding water quality categories and surface water control units were introduced to assist basin

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water quality improvement accordingly ([1]; Zhang et al., 2019; [2,3]). On the other hand, with the continuous improvement of social and economic development, China's livestock, poultry, and fish breeding has been rapidly developed, and the manure discharge problem brought have also been produced, resulting in increasingly apparent environmental pressure especially water environment. As an important part of China's agricultural industry, livestock, poultry, and fish breeding industry is currently facing the dual challenges of stable production capacity and environmental protection constraints especially water environment. In the context of the continuous adjustment of livestock, poultry, and fish breeding farming patterns, it is necessary to pay attention to the risk of local regional water environment overload caused by livestock, poultry, and fish breeding in China. Wenchang City as a typical city where local regional water environment problems are caused by livestock, poultry, and fish breeding need optimization and overall re-layout of aquaculture management in urgent in China (see Fig. 1).

Due to the characteristics of livestock manure and urine, natural consumption is still a relatively economic and feasible mean of livestock pollutants treatment so under the current economic and feasible technical conditions. However, the unit drainage basin of breeding manure consumption capacity is limited in a certain period. The development of regional livestock and poultry industry should conform to the water environmental bearing capacity of the region, and its breeding density should not exceed the maximum carrying capacity of water resources in the region. Therefore, the effective livestock, poultry, and fish breeding planning and management are needed under water environmental quality constraints for different scales imminently. At present, the relevant theoretical and practical achievements of the carrying capacity of water quality have been developed for a long time, and have also made due contributions to guiding the formulation of environmental policies [4–6]. For example, Dong et al [7] proposed estimation and Analysis of water environment capacity approach and applied to Huaxi Watershed in Guizhou Province. Chakravarty and Gupta [8] applied water quality index and multivariate statistical analysis to a hilly river of south Assam, north east India. Ma et al [9] assessed coastal water quality in main aquaculture areas of Dalian, China by using Application of modified water quality index (WQI). Yang et al. [10] developed a hybrid model with attention mechanism for water quality prediction. Wu et al. [11] advanced a water quality prediction model based on multi-task deep learning in the Yellow River, China. Yunjeong et al. [12] proposed deep learning methods for predicting tap-water quality time series in South Korea. Ozgur et al. [13] developed hybrid neuro-fuzzy model for water quality prediction of the Yamuna River in India. The carrying capacity of water quality research direction today mainly focuses on the updating of technology and methods. The main application is also water quality prediction research. There are few cross-cutting studies with carrying capacity of water quality and planning research, especially for livestock, poultry and fish breeding system management planning which is an effective tool to solve the problems concerned in this study. It is precisely the water quality related planning research that is real need for regional breeding system management. Therefore, such cross-cutting study is urgent needed.

Moreover, in a regional livestock, poultry and fish breeding system, there are complicated with various uncertain factors associated with economic and demographic parameters (e.g., the uncertain breeding demands, fluctuating price of livestock, poultry and fishery products, breeding cost, market requirement). Such uncertainties would affect the related exercises for generating desired

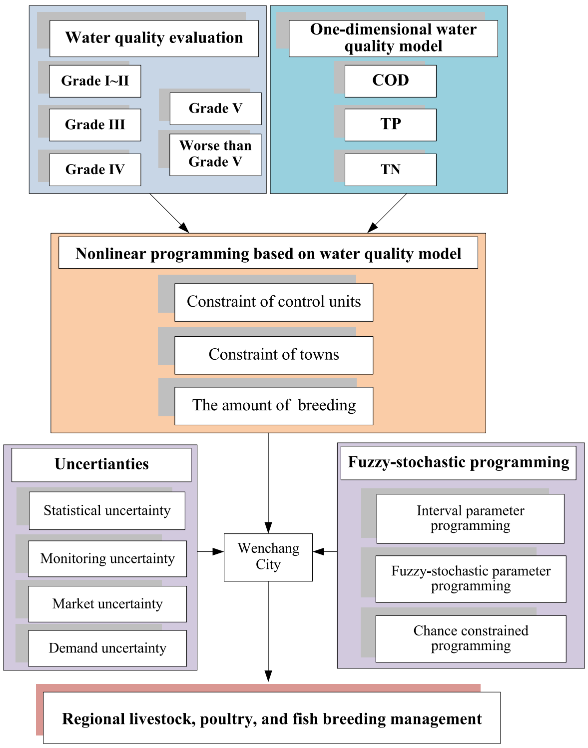

Fig. 1. The flowchart of the MFSNP-WQM model.

management schemes. Therefore, effective livestock, poultry and fish breeding systems planning with water environment constraint is desired under various uncertainties. As a result, a number of systems uncertainty optimization methods that could were employed for assisting development of regional systems management plans such as regional water resources management. For example, Zarghami et al [14] advanced the tool of nonlinear interval parameter programming for addressing uncertainty in water allocation using. Liu et al [15] established an interval-parameter fuzzy robust nonlinear programming model for water quality management. Zhang and Li [16] developed an interval quadratic programming water quality management model and studied its solution algorithms. Birhanu et al. [17] advanced optimizing method by using chance constraint nonlinear programming for Koga irrigation dam in Ethiopia. Among these uncertainty optimization techniques [18,19], interval-parameter programming (IPP), fuzzy stochastic parameters programming (FSPP) and chance constrained programming (CCP) could deal with uncertainties expressed as probability distributions, discrete intervals, and degree of fuzzy membership, and received extensive attentions over the past years [20]. Although these uncertainty optimization techniques had been applied in many real-world applications, few references were in the planning and management of livestock, poultry, and fish breeding.

Based on the considerations: i) the development of a livestock, poultry, and fish breeding management planning model to address interactions among breeding products supply, demand activities, discharge mitigation, and water quality assurance is desired under various uncertainties; ii) MOP IPP, FSPP, and CCP are effective for problems where an analysis of predefined policies for water environment scenarios is desired, and dealing with the uncertainties as probability distributions, discrete intervals, and degree of fuzzy membership; iii) one-dimensional water quality model is effective to analyze the multi-water-quality assessment indicators (COD, TP, TN) for helping regional water quality standard; the objective of this study is to develop a multi-objective mixed fuzzy-stochastic nonlinear programming model for supporting regional livestock, poultry, and fish breeding management planning based on water quality model in Wenchang City, China. The cross-research form and model composition of this study are novel in related fields. The combination of multi-objective livestock management planning, nesting of water quality model and application of uncertainty method can provide a new perspective and inspiration for cross-disciplinary researches in related fields. The developed nonlinear programming model has many advantages in regional livestock, poultry, and fish breeding management planning. For example, multi-objective optimization help meet the multiple needs of management planning which includes cost, environment, and regional conditions. Multiple uncertainty optimization has great advantages for regional data analysis which have great complexity and uncertainty. Water quality indicators are embedded in the model as modules to treatment the water quality constraint. The modeling results will help generate multiple management strategies under water quality planning policies and water environmental requirements, and are valuable in generating cost-effective breeding system management schemes, scale control and spatial layout for supporting decision makers of each town in Wenchang City.

2. Methodology

In this study, the multi-objective mixed fuzzy-stochastic nonlinear programming based on water quality model (MFSNP-WQM) for livestock, poultry, and fish breeding management planning was established.

2.1. Water quality evaluation method

Evaluation basis of surface water quality is “Methods for The Assessment of Surface Water Environmental Quality (Trial)” (Environmental Affairs Office [2011] 22 [21]), “Environmental Quality Standards for Surface Water” (GB 3838-2002) of “National Standard of the People’s Republic of China”. The water quality was evaluated according to the annual average water quality. The rate of annual water quality reaching the standard is the proportion of the monitoring frequency of water quality reaching the standard in the total annual monitoring frequency. Table B1 shows the qualitative evaluation of water quality in each monitoring section. Table B2 shows qualitative evaluation of water quality of rivers and basins (water systems).

2.2. One-dimensional water quality model

The maximum allowable amount of pollution in the water area per unit time under the premise of the given water area and hydrological conditions, the prescribed discharge mode and water quality objectives is called the water environmental capacity. The pollution carrying capacity calculation adopts the one-dimensional water quality model of “Rules for calculation of pollution carrying capacity of water” (GB/T 25173-2010) according to the “Technical Outline of the Pollution Carrying Capacity Verification and Phased Total Discharge Control Plan for the National Important River and Lake Water Functional Areas” and “Review of the pollution Carrying Capacity and Phased Total Discharge Control Plan for the Important River and Lake Functional Areas in Hainan Province”. The content of prediction analysis is based on impact type, prediction factor, forecast scenario, forecast range, surface water category, selected prediction model type, and determined evaluation requirements. The water pollution impact construction projects mainly include: a) the concentration and change of water quality prediction factors of each concerned section (control section, water intake section, pollution source discharge accounting section, etc.); b) the concentration of pollutants which reaching the water environment protection target. The one-dimensional water quality comprehensive degradation model:

$$M = (C_S - C_X)(Q - Q_P) \tag{1}$$

$$C_X = C_0 \exp\left(-\kappa \frac{x}{86400u}\right) \tag{2}$$

where, M:Water carrying capacity (g/s), C_X:The contaminant concentration after traveling x distance (mg/L), Q: The design flow of river reach in control unit (m^3/s), Q_P: The amount of wastewater entering the river (m^3/s), C_0: The background concentration of section in control units (mg/L), u: The average velocity of the river section under the design of the comprehensive degradation coefficient (m/s), x: The longitudinal distance of control unit along the section of the river (m), κ: The daily comprehensive degradation coefficient (1/d).

According to research report of "Policy of Ecological Protection Red Line - environmental quality bottom line, resource utilization line and ecological environment access list" for regional spatial ecological environment evaluation of Wenchang City ("III Line and I List" of Wenchang City), the degradation coefficient is shown in Table 1. The nesting of one-dimensional water quality models in the developed nonlinear programming model can help to analyze the impact of different water quality requirements for different regions in regional livestock, poultry, and fish breeding management planning (see Table 2).

2.3. Fuzzy-stochastic programming

2.3.1. Interval parameter programming

In many real-world problems, uncertainties may be expressed as interval variables because of the limitations of survey data. In general, the basic linear programming model has the form:

$$\max f = CX \tag{3}$$

Subject to

$$AX \le B \tag{4}$$

$$X \ge 0 \tag{5}$$

where f is the model objective function, X is General decision matrix (variables), A, B and C are coefficient matrices (Parameters). In model research, coefficient data may not necessarily be definitive data due to information loss and other reasons, so the planning results of deterministic models will face the risk of declining the reference value of the results, and even the situation of invalid results. Therefore, uncertainty optimization methods will be used to avoid the risks in this situation.

In uncertainty programming, the model can introduce the interval parameter programming method when the information of the uncertain parameters is not enough to establish the probability distribution and the identifiability cannot reach the situation of constructing fuzzy membership degree. The interval programming method can characterize the special uncertainties in the system, and can directly deal with the uncertainty variables characterized as interval numbers in the model.

2.3.2. Fuzzy-stochastic parameter programming (FSPP)

The inherent fuzzy-stochastic uncertainty existing in real livestock, poultry and fish breeding management are difficult to evaluate. In the livestock, poultry and fish breeding supply and demand system, demand is a parameter that is extremely difficult to estimate. In this study, demand is defined as a fuzzy-random parameter: (D^L, ρ, D^U), i.e. $\rho \sim N(\mu_0, \sigma_0^2)$. The influencing aspects for demand include population, geography, economic situation, and relevant policy of Wenchang City. The decisions on demand exhibit fluctuations because of uncertainty of judgment, insufficient information, and the dynamic environment of a complicated huge urban status of city. Therefore, demand would be vaguely defined with relevant reports giving a range wherein the most possible value is regarded as a random variable. Moreover, the most possible value of the demand approximately follows a normal distribution. The fuzzy random parameter can be denoted as $\widetilde{\widetilde{DM}}_t = (D_t^L, \rho_t(\omega), D_t^U)$. $\rho_t(\omega)$ is supposed to approximately follow a normal distribution $N_t(\mu_t, \sigma_t^2)$ with a probability density function $\varphi_{\rho_t}(x)$.Suppose that σ is a given probability level of stochastic parameter ($\sigma \in [0, \sup \varphi_{\rho_t}(x)]$). r is a given possibility level for the fuzzy parameter ($r \in [r_i, 1]$).

2.3.3. Interval parameter planning based on fuzzy stochastic parameters

The interval planning based on fuzzy stochastic parameters model form can be expressed as:

$$\max f^{\pm} = C^{\pm}X \tag{6}$$

Subject to:

$$A_i^{\pm}X \le B_i^{\pm}, i = 1, 2, ..., t \tag{7}$$

Table 1
The degradation coefficient from"III Line and I List".

	COD	TN	TP
Degradation coefficient	0.22/d	0.28/d	0.15/d

Table 2
Water quality status and objectives of Wenchang City.

Control unit	Basin	Water quality monitoring point	Water quality (2021)	Water quality targets	
				2025	2035
Puqian River- Puqian Town	**Puqian River**	**Jiagang village entrance in Puqian town**	**worse than V**	**V**	**IV**
Mulan River- Puqian Town	**Mulan River**	**Qinglong Village in Puqian town**	**V**	**V**	**IV**
Zhuxi River- Jinshan Town	**Zhuxi River**	**Zhuxi River estuary**	**worse than V**	**V**	**IV**
Zhuxi River-Fengpo Town		**/**	**worse than V**	**V**	**IV**
Wengtian Town-Dalangang River	**Dalangang River**	**Tiantou Village Highway Bridge in Wengtian Town**	**V**	**IV**	**IV**
Hei Stream- Baoluo Town-Gongpo Town	**Hei Stream**	**/**	**worse than V**	**IV**	**IV**
Wenjiao River- Donglu Town	**Wenjiao River**	**Tanniu Road Bridge**	**III**	**III**	**III**
Wenjiao River-Tanniu Town		**Tanniu Road Bridge**	**III**	**III**	**III**
Wenjiao River- Dongge Town		**/**	**IV**	**IV**	**III**
Wenjiao River-Wenjiao Town		**Poliu Sluice**	**IV**	**IV**	**III**
Beishui Stream- Changsa Town	**Beishui Stream**	**/**	**worse than V**	**IV**	**IV**
Baoling River-Beishui Stream	**Baoling River-Beishui Stream**	**Baoling Sluice of Baoling Village in Longlou Town**	**worse than V**	**IV**	**IV**
Wenchang River- Tanniu Town	**Wenchang River**	**/**	**III**	**III**	**III**
Wenchang River-Wencheng Town		**Xiayuan Sluice**	**III**	**III**	**III**
Nanyang River–Wencheng Town		**/**	**III**	**III**	**III**
Beishan Stream–Wencheng Town	**Beishan Stream**	**Beishan Village**	**III**	**III**	**III**
Wuqian Stream–Wencheng Town	**Wuqian Stream**	**Renmin Bridge Shuya New District**	**IV**	**III**	**III**
Wenqing River–Wencheng Town	**Wenqing River**	**Tangfu Village**	**worse than V**	**III**	**III**
Shentian Reservoir-Wencheng Town	**Shentian Reservoir**	**Shentian Reservoir outlet**	**III**	**III**	**III**
Chizhi Reservoir-Penglai Town	**Chizhi Reservoir**	**Chizhi Reservoir outlet**	**II**	**II**	**II**
Shibi River-Penglai Town	**Shibi River**	**Shibi Reservoir outlet**	**III**	**IV**	**III**
Shibi River-Chongxing Town		**/**	**III**	**IV**	**III**
Shibi River- Huiwen Town		**Shibi River estuary**	**III**	**IV**	**III**
Zhuhucun River-Zhongxing Town	**Zhuhucun River**	**Huiwen Town**	**V**	**IV**	**IV**
Shalao River- Chongxing Town	**Shalao River**	**Shuixi Reservoir outlet**	**III**	**IV**	**IV**

$$A_i^{\pm}X \leq \tilde{\tilde{B}}_i^{\pm}, i = t+1, t+2, ..., I \tag{8}$$

$$x_j^{\pm} \geq 0, x_j^{\pm} \in X^{\pm}, j = 1, 2, ..., n \tag{9}$$

where, $A^{\pm} \in \{R^{\pm}\}^{m \times n}$, $\tilde{\tilde{B}}^{\pm} \in \{\tilde{\tilde{B}}^{\pm}\}^{m \times 1}$, $C^{\pm} \in \{R^{\pm}\}^{1 \times n}$, $X^{\pm} \in R^{\pm}$, $R^{\pm}$ are interval number matrixes

2.3.4. Chance constrained programming (CCP)

CCP can describe the risk problem of whether the constraint is satisfied in the planning under certain conditions, to effectively reflect the default risk of the research system under uncertain conditions. In general, programming model can be expressed as

$$\max f = C(t)X \tag{10}$$

Subject to:

$$A(t)X \leq B(t) \tag{11}$$

$$X \geq 0 \tag{12}$$

where, *X* is decision variable, *A(t)*, *B(t)*, and *C(t)* is a probability matrix of probability space *T*. The CCP can be introduced to transform the model into an uncertainty optimization model. The level of breach is introduced as $p_i \geq [0\ ,\ 1]$. The probability of the constraint condition is not lower than a certain level($1-pi$). Constraints can be expressed as:

$$Pr[A_i(t)X \leq B_i(t)] \geq 1 - p_i, A_i(t) \in A(t), i = 1, 2, ..., m \tag{13}$$

Then, the model can be further transformed as:

$$A_i(t)X \leq B_i(t)^{(p_i)}, A_i(t) \in A(t), i = 1, 2, ..., m \tag{14}$$

Due to the uncertainty characteristics of data, CCP can be coupled with interval parameters in the programming model.

3. Case study

3.1. Overview of the study area

Wenchang City (19°21'∼20°1′N, 110°28'∼111°03′E), located in the northeast of Hainan Province, China, is one of the key livestock, poultry, and fish breeding cities of the province. The coastline is 289.82 km long, and the sea area is 5245.50 km^2. The whole plane outline is half-moon shape, facing the sea in the east, south and north. It covers a land area of 2459.18 km^2, and governs seventeen towns. The research areais the whole area of Wenchang City, including 17 towns, from north to south, from east to west are Puqian Town, Jinshan Town, Fengpo Town, Wengtian Town, Baoluo Town, Gongpo Town, Donglu Town, Changsa Town, Tanniu Town, Wenjiao Town, Dongge Town, Longlou Town, Wencheng Town, Dongjiao Town, Penglai Town, Huiwen Town and Chongxing Town, successively.

The total water resources of Wenchang City are 1.903×10^9 m^3, of which the annual average runoff is 1.831×10^9 m^3, the non-repeatable amount of groundwater and surface water is 72×10^6 m^3, the water production coefficient is 46.9 %, and the water production modulus is $807 \times 10^3 m^3/(a \cdot km^2)$. The theoretical reserves of groundwater are 1.233×10^9 m^3, and the groundwater runoff supply is 260×10^6 m^3. The total water output is 2.842×10^9 m^3, and the annual exploitable capacity is 88×106 m^3 (excluding underground runoff water). Five rivers with a drainage area of more than 100 square kilometers flow through Wenchang, including Wenjiaohe, Zhuxi, Wenchang, Shibi and Beishui, with an annual water collection of 3.944×10^9 m^3, an average annual surface runoff of 1.869×10^9 m^3, and an average runoff modulus of 26 s/L per square kilometer. There are 36 large and small harbors.

There are 273 rivers flowing through Wenchang City, with a total length of 1694.74 km. Among them, there are 9 rivers with a drainage area of more than 100 km^2: Wenjiao River, Zhuxi River, Tayang River, Wenchangjiang River, Shibi River, Hei Stream Beishui River, Beishanxi River and Yongfeng River. Coastal rivers show storm flow by rainfall replenishment affected and the difference between flood and dry in summer and winter. In terms of water quality, historical monitoring data shows Zhuxi River is classified as Class V and inferior Class V in all the year round, mainly for total phosphorus (TP) exceeding the standard. Therefore, it is necessary to further strengthen the water quality control. Since 2021, the water quality of Zhuxi River estuary has repeatedly appeared inferior Class V. The Ministry of Ecology and Environment of China has repeatedly warned this condition, and has organized the Ecological Environment Supervision Administration of the Pearl River Basin to conduct an independent investigation to eliminate inferior Class V as soon as possible.

3.2. Water environmental capacity assessment

3.2.1. Water environment control unit division

Wenchang City has been divided into 26 water environment control units (Offshore islands are far from land and have no surface water, so they are directly used as a separate control unit) in Research report of "Policy of ecological protection red line, environmental quality bottom line, resource utilization line and ecological environment access list" for regional spatial ecological environment evaluation of Wenchang City ("III Line and I List"). The scheme of water environment control unit division was designed on the basis of the determined catchment units, the coverage area of the existing control monitoring sections(e.g., national control, provincial control and municipal control monitoring sections), and the vector data of the township administrative boundary of Wenchang City. The river basins involved included Wenjiao River, Zhuxi River, Baoling River (Beishui River), Wenchang River, Shibi River, Hei River, Beishan River, Nga Qian River, Dalangang River, Mulan River, Wenqing River, Zhuhu Village River, Laonhe River and Pu Qian River in the scheme.

3.2.2. Water environment quality status and objectives

Water quality objectives of each water environment control unit in Wenchang city has been formulated in research report of "III Line and I List" based on the water quality status and target of the existing monitoring section according to the principle of "only better, not worse".

3.3. Data collection and scenarios definition

The planning horizon is 15 years (2021–2035) which is divided into three periods with each representing a 5-year span. Over the planning horizon, Livestock, poultry and fish breeding system is available to meet production and living needs of the city and its towns. Reports of regional spatial ecological environment evaluation and "III Line and I List" in Wenchang City was provided by local agencies for regional water quality improvement studies. The hydrological regime of a river mainly includes water body form, runoff conditions, hydraulic conditions, erosion, deposition changes, water surface area, water volume, water temperature, runoff process, water level, depth, velocity, surface width were provided by the water department. Distribution of sewage outlets of each river and water system were obtained from field surveys and statistical reports. State control, provincial control, municipal control units monitoring section distribution and list of sewage treatment plants that have been built and put into use, under construction, and proposed construction in Wenchang City were obtained the local Department of Ecology and Environment. The data of sewage treatment plants included construction scale and treatment capacity, geographical location and distribution, coverage area of sewage treatment, implementation standards, sewage capacity, actual daily treatment capacity (import flow, export flow) influent quality and effluent quality. The related water quality and hydrological data of Wenchang City were obtained through analyses for a number of representative reports such as water quality monitoring and improvement report of Baoling River - Wenjiao River - Zhuxi River for Wenchang City within 100 days in

2021, water environmental quality monitoring report of Wenchang City urban inland river (lake) in 2021, surface water quality monitoring report of Wenchang City in 2014–2021, water quality monitoring report of Wenchang City key tributary examination section. The number of livestock farms (communities) and breeding households, the number of livestock and poultry stocks and their location, scale, spatial distribution, and other basic conditions, as well as the status quo of sewage discharge of each farm/household in Wenchang City were obtained from the local Agriculture Department. Field research and multi-departmental research support ensure the data quality of this study.

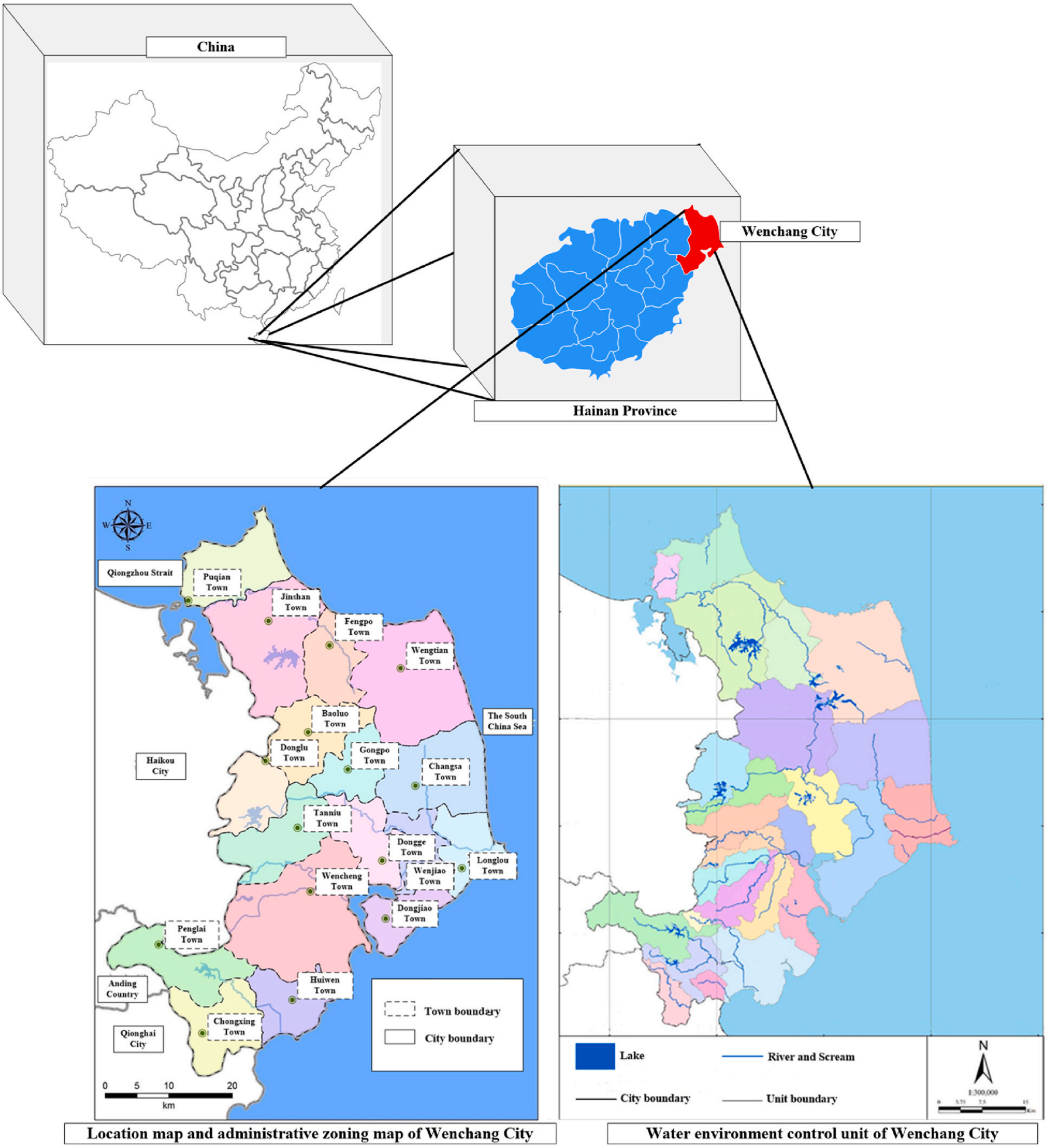

Fig. 2. Location map and Water environment control unit of Wenchang City.

3.4. Model formulation

This study focuses on livestock, poultry, and fish breeding management to reduce the discharge for improve Wenchang City's watershed water quality. In a long run perspective, the future breeding demand during the planning horizon can be modeled as a multi-uncertain parameter associated with probability distribution and degree of membership for its uncertainty features, and the breeding plan would be of complex features, such as population, geography, economic situation, and relevant policy. Thus, the developed multi-objective mixed fuzzy-stochastic nonlinear programming (MFSNP) can be considered suitable for studying the livestock, poultry, and fish breeding management and environmental water quality management issues. In addition, one-dimensional water quality model was introduced and embedded into the model for water quality and pollutant concentration calculation to ensure that the relevant calculation scheme is consistent with "Technical Guidelines for Environmental Impact Assessment - Surface Water Environment". The multi-objective function would be to maximum the expected benefit, minimize the expected pollution discharge of livestock, poultry, and fish breeding for all applicable decisions. The water quality capacity constraints are formulated to secure ecological environmental security for watersheds and towns in city. The pollutant concentration constraints are formulated to secure watershed section up to standard for satisfying targets of control units and towns. Three types of water pollutant (COD, TP, and TN) will be considered to measure the degree of water pollution which is also the most important pollutant type for surface water quality judgment.

The demand constraints are generated for each town to ensure that the people's living and markets of livestock, poultry, and fishery products. The unit of measurement for result is represented by pig equivalent which can be transfer to other species by using conversion coefficient. The conversion coefficient of pig equivalent to other breeds of livestock, poultry and fish is based on "Pollutant discharge standards for livestock and poultry farming" (GB 18596-2001). The discharge constraints set up limitations for control units and towns under the different discharge reduction options are based on "III Line and I List", "One river, one policy" and Urban Planning. Therefore, the MFSNP-WQM for livestock, poultry, and fish breeding management planning can be formulated as follows:

(1) Benefits for livestock, poultry, and fish breeding

$$Max \quad f^{\pm} = \sum_{t=1}^{T} \sum_{i=1}^{I} BS_{i,t}^{\pm} \mathrm{PC}_{i,k}^{\pm} \delta_{i,k} \mathrm{CO}_{k}^{\pm} \tag{15}$$

(2) Pollutant discharge

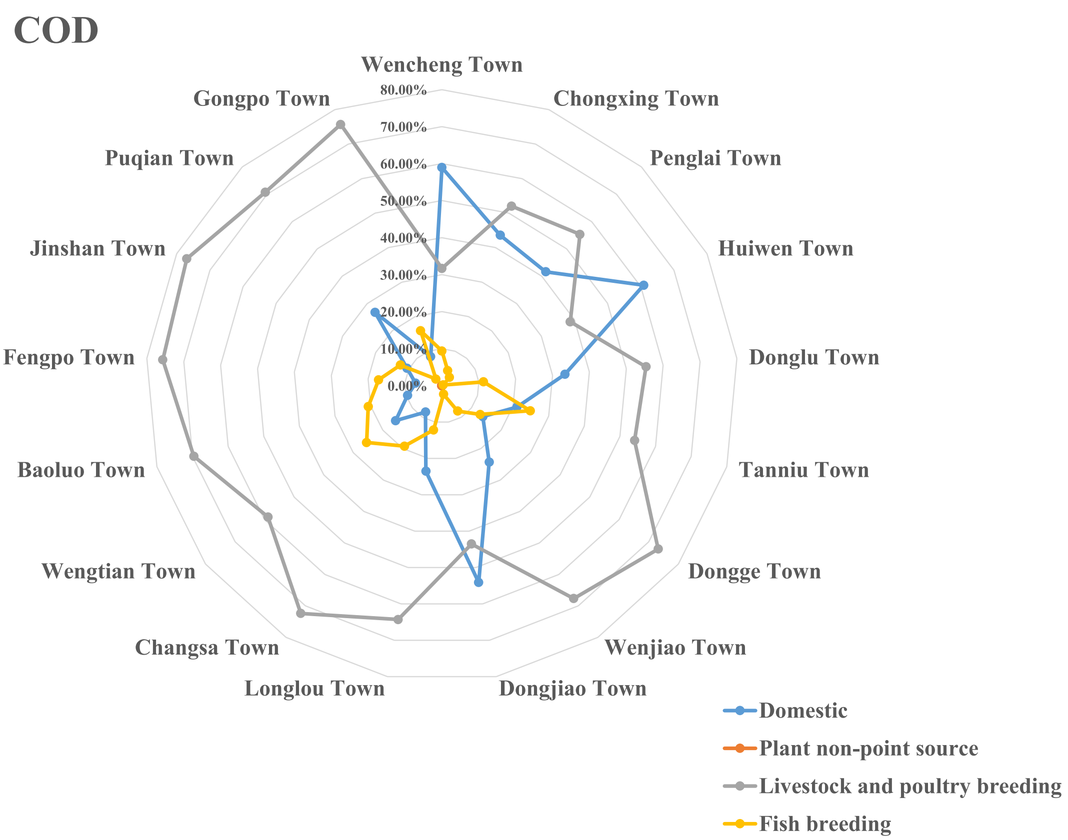

Fig. 3. Discharge source structure of COD in each town of Wenchang City.

$$Min \quad g^{\pm}_{COD} = \sum_{t=1}^{T} \sum_{i=1}^{I} BS^{\pm}_{i,t} \rho_{COD} \tag{16}$$

$$Min \quad g^{\pm}_{TN} = \sum_{t=1}^{T} \sum_{i=1}^{I} BS^{\pm}_{i,t} \rho_{TN} \tag{17}$$

$$Min \quad g^{\pm}_{TP} = \sum_{t=1}^{T} \sum_{i=1}^{I} BS^{\pm}_{i,t} \rho_{TP} \tag{18}$$

Subject to:

(1) Constraints for water quality capacity of control units

$$BS^{\pm}_{i,t} \rho_{\mathrm{COD}} \leq \mathrm{PCOD}^{\pm}_{i,t} \tag{19}$$

$$BS^{\pm}_{i,t} \rho_{\mathrm{TN}} \leq \mathrm{PTN}^{\pm}_{i,t} \tag{20}$$

$$BS^{\pm}_{i,t} \rho_{\mathrm{TP}} \leq \mathrm{PTP}^{\pm}_{i,t} \tag{21}$$

$$\mathrm{PCOD}^{\pm}_{i,t} = \left(\mathrm{CS}_{i,t,\mathrm{COD}} - \mathrm{CX}_{i,t,\mathrm{COD}}\right)\left(\mathrm{Q}^{\pm}_{i,t} + \mathrm{QP}^{\pm}_{i,t}\right) \tag{22}$$

$$\mathrm{PTN}^{\pm}_{i,t} = \left(\mathrm{CS}_{i,t,\mathrm{TN}} - \mathrm{CX}_{i,t,\mathrm{TN}}\right)\left(\mathrm{Q}^{\pm}_{i,t} + \mathrm{QP}^{\pm}_{i,t}\right) \tag{23}$$

$$\mathrm{PTP}^{\pm}_{i,t} = \left(\mathrm{CS}_{i,t,\mathrm{TP}} - \mathrm{CX}_{i,t,\mathrm{TP}}\right)\left(\mathrm{Q}^{\pm}_{i,t} + \mathrm{QP}^{\pm}_{i,t}\right) \tag{24}$$

(2) Constraints for pollutant concentration limits of control units

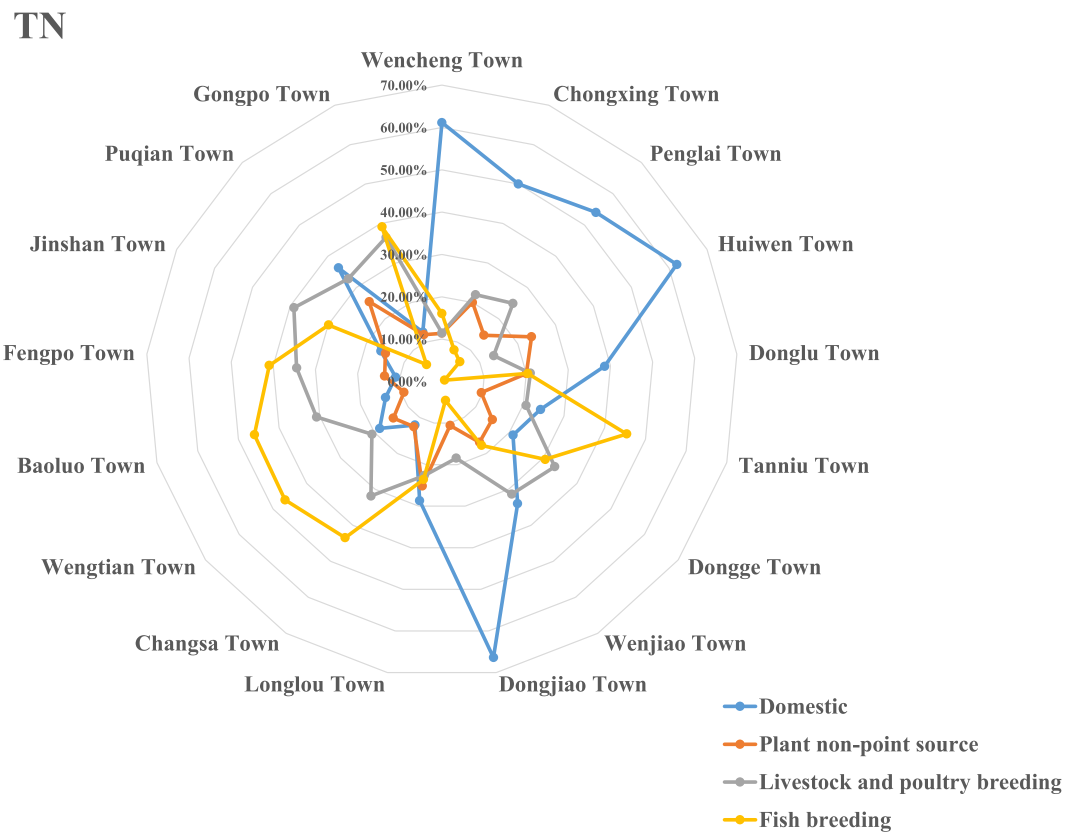

Fig. 4. Discharge source structure of TN in each town of Wenchang City.

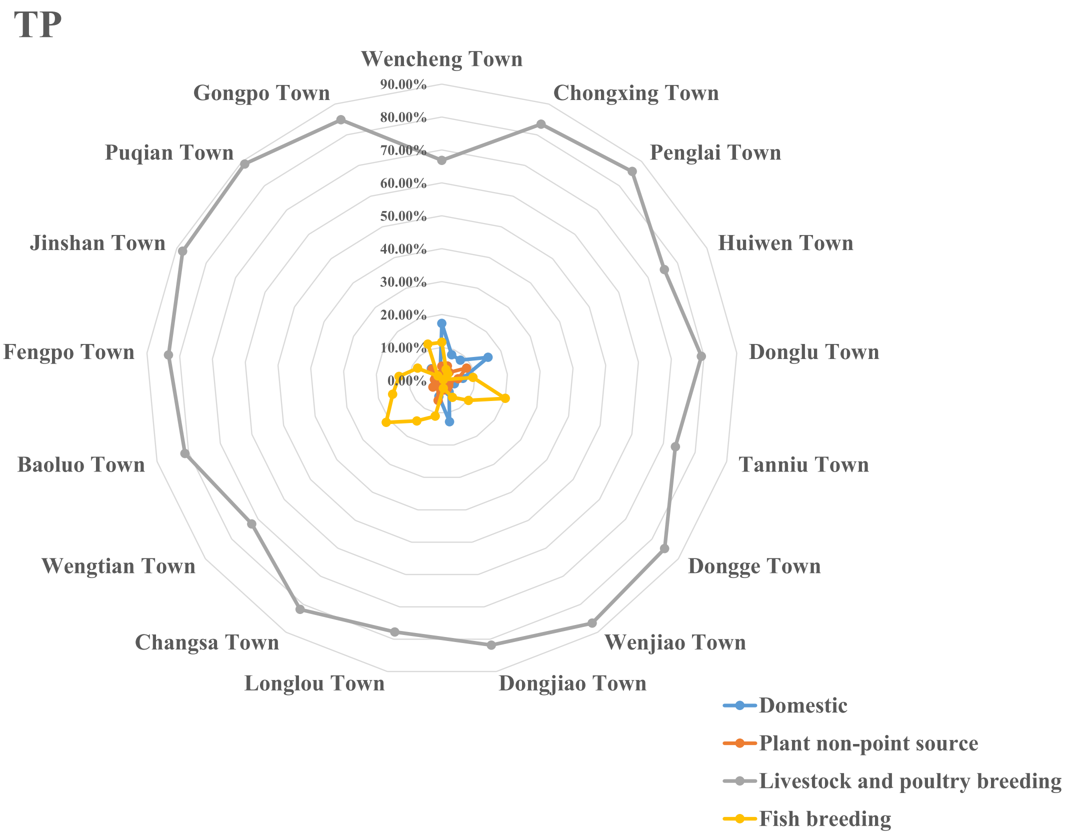

Fig. 5. Discharge source structure of TP in each town of Wenchang City.

$$\frac{BS^{\pm}_{i,t}\varphi_{\mathrm{COD}} + \mathrm{CB}^{\pm}_{i,t,\mathrm{COD}}\mathrm{Q}^{\pm}_{i,t}}{\mathrm{Q}^{\pm}_{i,t} + \mathrm{QP}^{\pm}_{i,t}} \exp\left(- k_{\mathrm{COD}}\frac{x_i}{86400u_i}\right) \le \mathrm{CS}_{i,t,\mathrm{COD}} \tag{25}$$

$$\frac{BS^{\pm}_{i,t}\varphi_{\mathrm{TN}} + \mathrm{CB}_{i,t,\mathrm{TN}}\mathrm{Q}^{\pm}_{i,t}}{\mathrm{Q}^{\pm}_{i,t} + \mathrm{QP}^{\pm}_{i,t}} \exp\left(- k_{\mathrm{TN}}\frac{x_i}{86400u_i}\right) \le \mathrm{CS}_{i,t,\mathrm{TN}} \tag{26}$$

$$\frac{BS^{\pm}_{i,t}\varphi_{\mathrm{TP}} + \mathrm{CB}_{i,t,\mathrm{TP}}\mathrm{Q}^{\pm}_{i,t}}{\mathrm{Q}^{\pm}_{i,t} + \mathrm{QP}^{\pm}_{i,t}} \exp\left(- k_{\mathrm{TP}}\frac{x_i}{86400u_i}\right) \le \mathrm{CS}_{i,t,\mathrm{TP}} \tag{27}$$

(3) Constraints for breeding quantity and demand balance

$$\sum_{i=1}^{I_c} BS^{\pm}_{i,t} \ge \widetilde{\mathrm{DM}}^{\pm}_{c,t} \tag{28}$$

(4) Constraints for water quality capacity of towns

$$\Pr\left\{ \sum_{i}^{I_c} BS^{\pm}_{i,t}\rho_{\mathrm{COD}} \le \mathrm{PMC}^{\pm}_{c,i,t} \right\} \ge 1 - q_C \tag{29}$$

$$\Pr\left\{ \sum_{i}^{I_c} BS^{\pm}_{i,t}\rho_{\mathrm{TN}} \le \mathrm{PMTN}^{\pm}_{c,i,t} \right\} \ge 1 - q_{TN} \tag{30}$$

$$\Pr\left\{ \sum_{i}^{I_c} BS^{\pm}_{i,t}\rho_{\mathrm{TP}} \le \mathrm{PMTP}^{\pm}_{c,i,t} \right\} \ge 1 - q_{TP} \tag{31}$$

$$\frac{BS_{i,t}^{\pm}\varphi_{\mathrm{COD}}+\mathrm{CB}_{i,t,\mathrm{COD}}\mathrm{Q}_{i,t}^{\pm}}{\mathrm{Q}_{i,t}^{\pm}+\mathrm{QP}_{i,t}^{\pm}}\exp\left(-k_{\mathrm{COD}}\frac{xc_i}{86400u_i}\right)\leq\mathrm{CSC}_{i,t,\mathrm{COD}} \tag{32}$$

$$\frac{BS_{i,t}^{\pm}\varphi_{\mathrm{TN}}+\mathrm{CB}_{i,t,\mathrm{TN}}\mathrm{Q}_{i,t}^{\pm}}{\mathrm{Q}_{i,t}^{\pm}+\mathrm{QP}_{i,t}^{\pm}}\exp\left(-k_{\mathrm{TN}}\frac{xc_i}{86400u_i}\right)\leq\mathrm{CSC}_{i,t,\mathrm{TN}} \tag{33}$$

$$\frac{BS_{i,t}^{\pm}\varphi_{\mathrm{TP}}+\mathrm{CB}_{i,t,\mathrm{TP}}\mathrm{Q}_{i,t}^{\pm}}{\mathrm{Q}_{i,t}^{\pm}+\mathrm{QP}_{i,t}^{\pm}}\exp\left(-k_{\mathrm{TP}}\frac{xc_i}{86400u_i}\right)\leq\mathrm{CSC}_{i,t,\mathrm{TP}} \tag{34}$$

4. Results analysis and discussion

The developed model was encoded and solved based on Lingo 18.0 software package. A large amount of uncertainty in the data and the balance of multiple objectives are exist in the case study. The incorporating of MOP IPP, FSPP, and CCP are effective for handle the trade-off between system and dealing with the uncertainties as probability distributions, discrete intervals, and degree of fuzzy membership (see Fig. 2).

4.1. Discharge source structure and water environment capacity

Figs. 3–5 presents the discharge source structure of COD, TN, TP in each town of Wenchang City. For example, Wencheng Town, which belongs to Wenchang City, Hainan Province, located in the middle of Wenchang City, bordering Tanniu Town to the north, Dongge Town to the east, Huiwen Town to the south, Penglai Town to the west, and the sea to the southeast, is the most important population gathering city. The permanent resident population is about 156,000, accounting for more than 50 % of the city's population. The domestic sewage enters the surface water without treatment make domestic sewage the main contributor of COD in Wencheng Town. The secondary contributor of COD is sewage discharge from livestock breeding, and the COD contribution rate of its sewage and domestic sewage exceeds 85 % of total COD of Wencheng Town. The sewage of residents and livestock and poultry breeding is borne by Wenchang River and Beishan River, and the sewage of fish breeding is borne by Wenqing River, Wuqian River, Gangwei Ditch and Hengshan River among the rivers flow through Wencheng Town. Livestock and poultry breeding discharge is the

Table 3
List of serial number reference for control units and towns.

Town	Town number	Control unit	Unit number
Wencheng Town	1	Wenchang River-Wencheng Town	1
		Nanyang River–Wencheng Town	2
		Beishan Stream–Wencheng Town	3
		Wuqian Stream–Wencheng Town	4
		Wenqing River–Wencheng Town	5
		Shentian Reservoir-Wencheng Town	6
Chongxing Town	2	Shibi River-Chongxing Town	7
		Zhuhu village river-Zhongxing Town	8
		Shalao River- Chongxing Town	9
Penglai Town	3	Chizhi Reservoir-Penglai Town	10
		Shibi River-Penglai Town	11
Huiwen Town	4	Shibi River-Penglai Town	12
Donglu Town	5	Wenjiao River- Donglu Town	13
Tanniu Town	6	Wenjiao River-Tanniu Town	14
		Wenchang River- Tanniu Town	15
Dongge Town	7	Wenjiao River- Dongge Town	16
Wenjiao Town-Dongjiao Town	8	Wenjiao River-Wenjiao Town	17
Longlou Town	9	Baoling River-Beishui Stream	18
Changsa Town	10	Beishui Stream- Changsa Town	19
Wengtian Town	11	Dalangang River-Wengtian Town	20
Baoluo Town-Gongpo Town	12	Hei Stream- Baoluo Town-Gongpo Town	21
Fengpo Town	13	Zhuxi River-Fengpo Town	22
Jinshan Town	14	Zhuxi River- Jinshan Town	23
Puqian Town	15	Puqian River- Puqian Town	24
		Mulan River- Puqian Town	25

Table 4
Water environment capacity in control unit in 2025 (t).

Town	Control unit	Dry season			Wet season		
		COD_{Cr}	NH_3–N	TP	COD_{Cr}	NH_3–N	TP
Wencheng Town	**1**	**−83.66**	**8.19**	**0.00**	**147.05**	**70.42**	**−1.47**
	2	**137.89**	**27.90**	**−0.34**	**1546.48**	**241.08**	**−27.81**
	3	**96.14**	**7.89**	**0.16**	**0.05**	**8.19**	**−0.19**
	4	**185.63**	**37.09**	**−1.39**	**1.21**	**108.98**	**−6.95**
	5	**−132.38**	**−0.13**	**−1.46**	**−132.07**	**8.63**	**−1.99**
	6	**18.33**	**8.96**	**0.00**	**27.48**	**9.01**	**0.00**
Chongxing Town	**7**	**42.90**	**3.73**	**−0.18**	**278.23**	**29.01**	**1.59**
	8	**−41.56**	**9.84**	**−6.43**	**−41.56**	**9.84**	**−6.43**
	9	**102.67**	**9.80**	**−0.60**	**102.67**	**9.80**	**−0.60**
Penglai Town	**10**	**27.62**	**3.86**	**−0.35**	**27.62**	**3.86**	**−0.35**
	11	**42.90**	**3.71**	**0.18**	**278.23**	**29.01**	**1.59**
Huiwen Town	**12**	**27.76**	**−44.14**	**−0.68**	**238.51**	**25.03**	**0.99**
Donglu Town	**13**	**−48.57**	**2.68**	**−1.05**	**133.84**	**19.17**	**−0.67**
Tanniu Town	**14**	**−64.78**	**7.71**	**−1.13**	**0.12**	**15.16**	**−1.78**
	15	**−132.38**	**−0.13**	**−1.46**	**−132.07**	**8.63**	**−1.99**
Dongge Town	**16**	**24.37**	**8.43**	**0.00**	**−66.69**	**30.32**	**0.00**
Wenjiao Town-Dongjiao Town	**17**	**−72.86**	**11.83**	**−0.22**	**67.04**	**32.99**	**−0.09**
Longlou Town	**18**	**104.17**	**4.74**	**−0.88**	**−130.14**	**−4.37**	**−0.65**
Changsa Town	**19**	**−72.01**	**0.40**	**−3.20**	**204.69**	**5.26**	**−0.09**
Wengtian Town	**20**	**−219.37**	**4.07**	**−1.06**	**−181.54**	**5.39**	**−3.25**
Baoluo Town-Gongpo Town	**21**	**−246.80**	**−0.51**	**−5.28**	**25.60**	**3.75**	**−7.41**
Fengpo Town	**22**	**−87.82**	**70.91**	**0.88**	**−1928.18**	**399.61**	**−49.65**
Jinshan Town	**23**	**−529.20**	**67.91**	**−30.46**	**2.89**	**540.85**	**−63.45**
Puqian Town	**24**	**4.42**	**0.71**	**0.06**	**34.60**	**8.70**	**−3.66**
	25	**0.78**	**0.74**	**−0.37**	**0.07**	**11.74**	**−5.52**

main contributor to COD and TP in Chongxing Town, while domestic sewage and aquaculture are the secondary contributors to COD. The main sewage of non-point sources of resident living and farming is borne by the Shalao River and Tayang River. The sewage of livestock and poultry breeding and aquaculture shall be borne by Shibi River and Sanhe River.

Tables 4 and 5 presents the water environment capacity in control unit of each town in 2025 and 2035 (see Table 3). For instance, the residual water environmental capacity of 6 control units in Wencheng Town is calculated under the constraint of surface water environmental quality objectives in different periods. Water environment capacity of NH_3–N is 8.19 tons in Control Unit 1 Wencheng Town in 2025. It indicated that NH_3–N discharge should under 8.19 tons in Control Unit 1 Wencheng Town in 2025 to reach water quality target.

4.2. Variable increment

Fig. 6 and Table 6 presents the variable increment of livestock, poultry, and fish breeding for each town in Wenchang City. For example, although there is still space for breeding in Wencheng town, the Wenchang River and Wenqing River sections inside the town have exceeded the standard. The breeding scale of Jinshan town which is in the northeast of the city has seriously exceeded the breeding restrictions. The management of livestock and poultry aquaculture discharge and controlling the breeding scale should be key water environmental protection tasks. The results indicated specific suggestions on the increase and decrease of livestock, poultry and fish in Wenchang City and each town in different period. In terms of details, the variable increment of livestock, poultry and fish breeding are based on the breeding scale of Wenchang City in 2021. For instance, the variable increment of livestock, poultry, and fish breeding in 2025 is the maximum value that can be increased and the minimum value that must be reduced under the breeding scale in 2021 under surface water control targets for 2025.

According to the calculation results of Table 6, some towns located in the southwest of Wenchang city such as Wencheng Town, Dongjiao Town, Huiwen Town and Chongxing Town have a large population and are the main sources of domestic sewage. For example, the Wenchang River control unit (Unit 1) and Wenqing River control unit (Unit 5) in Wencheng Town are the main pollutant discharge reduction control areas and the control of livestock, poultry and fish breeding discharge should be strengthened or the scale of aquaculture should be downscaled. Wencheng Town still has about 32,863 pig equivalents for livestock, poultry and fish breeding space on the basis of the livestock, poultry and fish breeding scale in 2021, but not all rivers in the town have surplus breeding space around the town, such as Wenchang River and Wenqing River in the town have exceeded the carrying capacity of the control unit. The result suggested that the breeding quantity in Wenchang River and Wenqing River reaches in Wencheng Town should be reduced by at least 12,387 pig equivalents in 2025 and 19,601 pig equivalents in 2035 based on the breeding quantity in 2021. In addition, the breeding scale should not increase from 2021 to 2035 to keep reaching the surface water quality standards in these two reaches in Wencheng Town. Other reaches can increase the breeding amount appropriately, but it should be controlled within the corresponding equivalent of Table 6, such as the Beishan Stream section of Wencheng Town has about 14,235 pig equivalents increasable breeding amount. According to the calculation results of Table 6, the control unit of Zhuhucun River - Chongxing Town (unit 8) is the key discharge reduction control area, and the control of livestock, poultry and fish breeding discharge should be strengthened or the scale of aquaculture should be downscaled. Chongxing Town still has about 15,401 pig equivalents for livestock, poultry, and fish breeding space based on the livestock, poultry and fish breeding scale in 2021, but not all rivers in the town have surplus breeding space around the town, such as Zhuhucun River in the town have exceeded the carrying capacity of the control unit. The result suggested that the breeding quantity in Zhuhucun River reach in Chongxing Town should be reduced by at least 6153 pig equivalents in 2025 based on the breeding amount in 2021. Other reaches can increase the breeding capacity appropriately, it should be controlled within the corresponding equivalent of Table 6, such as the Shibi River section of Chongxing Town has about 6351 pig equivalents increasable breeding capacity in 2025. Huiwen Town has about 4111 pig equivalents for livestock, poultry, and fish breeding space based on the livestock, poultry, and fish breeding scale in 2021. However, due to the upgrading of the surface water quality control target of control Unit (unit 12) in 2035, the increased breeding capacity will be reduced about 375 pig equivalents.

On the other hand, the breeding pressure is mainly concentrated in the northeast of Wenchang City. For instance, result suggested that Jingshan Town should reduce at least 78,356 pig equivalents in 2025 under the breeding scale in 2021. Moreover, Jingshan Town should reduce at least 143,727 pig equivalents in 2035 under the breeding scale in 2021. Result suggested that Jingshan Town should reduce at least 78,356 pig equivalents in 2025 under the breeding scale in 2021. Moreover, Jingshan Town should reduce at least 143,727 pig equivalents in 2035 under the breeding scale in 2021.

From the perspective of the total amount of livestock and poultry farming, Wenchang City has no surplus in the whole area, and it needs to be cleared at the present stage. Moreover, the units and towns which exceeded the warning in Wenchang City were mainly distributed in the northeast. In order to meet the requirements of surface water quality management objectives in the target year, the study proposed that the livestock and poultry aquaculture in Wenchang should move to the south to release the water environmental pressure.

Table 5
Water environment capacity in control unit in 2035 (t).

Town	Unit number	Dry season			Wet season		
		COD_{Cr}	NH_3–N	TP	COD_{Cr}	NH_3–N	TP
Wencheng Town	**1**	**−83.66**	**8.19**	**0.00**	**147.05**	**70.42**	**−1.47**
	2	**137.89**	**27.90**	**−0.34**	**1546.48**	**241.08**	**−27.81**
	3	**96.14**	**7.89**	**0.16**	**0.05**	**8.19**	**−0.19**
	4	**185.63**	**37.09**	**−1.39**	**1.21**	**108.98**	**−6.95**
	5	**−132.38**	**−0.13**	**−1.46**	**−132.07**	**8.63**	**−1.99**
	6	**18.33**	**8.96**	**0.00**	**27.48**	**9.01**	**0.00**
Chongxing Town	**7**	**17.67**	**2.47**	**−0.30**	**79.55**	**19.07**	**0.60**
	8	**−41.56**	**9.84**	**−6.43**	**−41.56**	**9.84**	**−6.43**
	9	**102.67**	**9.80**	**−0.60**	**102.67**	**9.80**	**−0.60**
Penglai Town	**10**	**27.62**	**3.86**	**−0.35**	**27.62**	**3.86**	**−0.35**
	11	**17.67**	**2.45**	**0.05**	**79.55**	**19.07**	**0.60**
Huiwen Town	**12**	**2.54**	**−45.40**	**−0.81**	**39.83**	**15.10**	**0.00**
Donglu Town	**13**	**−246.80**	**−0.51**	**−5.28**	**25.60**	**3.75**	**−7.41**
Tanniu Town	**14**	**−64.78**	**7.71**	**−1.13**	**0.12**	**15.16**	**−1.78**
	15	**−132.38**	**−0.13**	**−1.46**	**−132.07**	**8.63**	**−1.99**
Dongge Town	**16**	**−56.68**	**4.38**	**−0.41**	**−289.61**	**19.17**	**−1.11**
Wenjiao Town-Dongjiao Town	**17**	**−153.91**	**7.78**	**−0.62**	**−155.89**	**21.85**	**−1.20**
Longlou Town	**18**	**104.17**	**4.74**	**−0.88**	**−130.14**	**−4.37**	**−0.65**
Changsa Town	**19**	**−72.01**	**0.40**	**−3.20**	**204.69**	**5.26**	**−0.09**
Wengtian Town	**20**	**−219.37**	**4.07**	**−1.06**	**−181.54**	**5.39**	**−3.25**
Baoluo Town-Gongpo Town	**21**	**−246.80**	**−0.51**	**−5.28**	**25.60**	**3.75**	**−7.41**
Fengpo Town	**22**	**−529.32**	**48.83**	**−3.53**	**−4687.58**	**261.64**	**−77.24**
Jinshan Town	**23**	**−970.71**	**45.83**	**−34.87**	**−2756.51**	**402.88**	**−91.04**
Puqian Town	**24**	**0.00**	**0.49**	**0.02**	**−34.47**	**5.25**	**−4.35**
	25	**−3.64**	**0.52**	**−0.41**	**−68.99**	**8.29**	**−6.21**

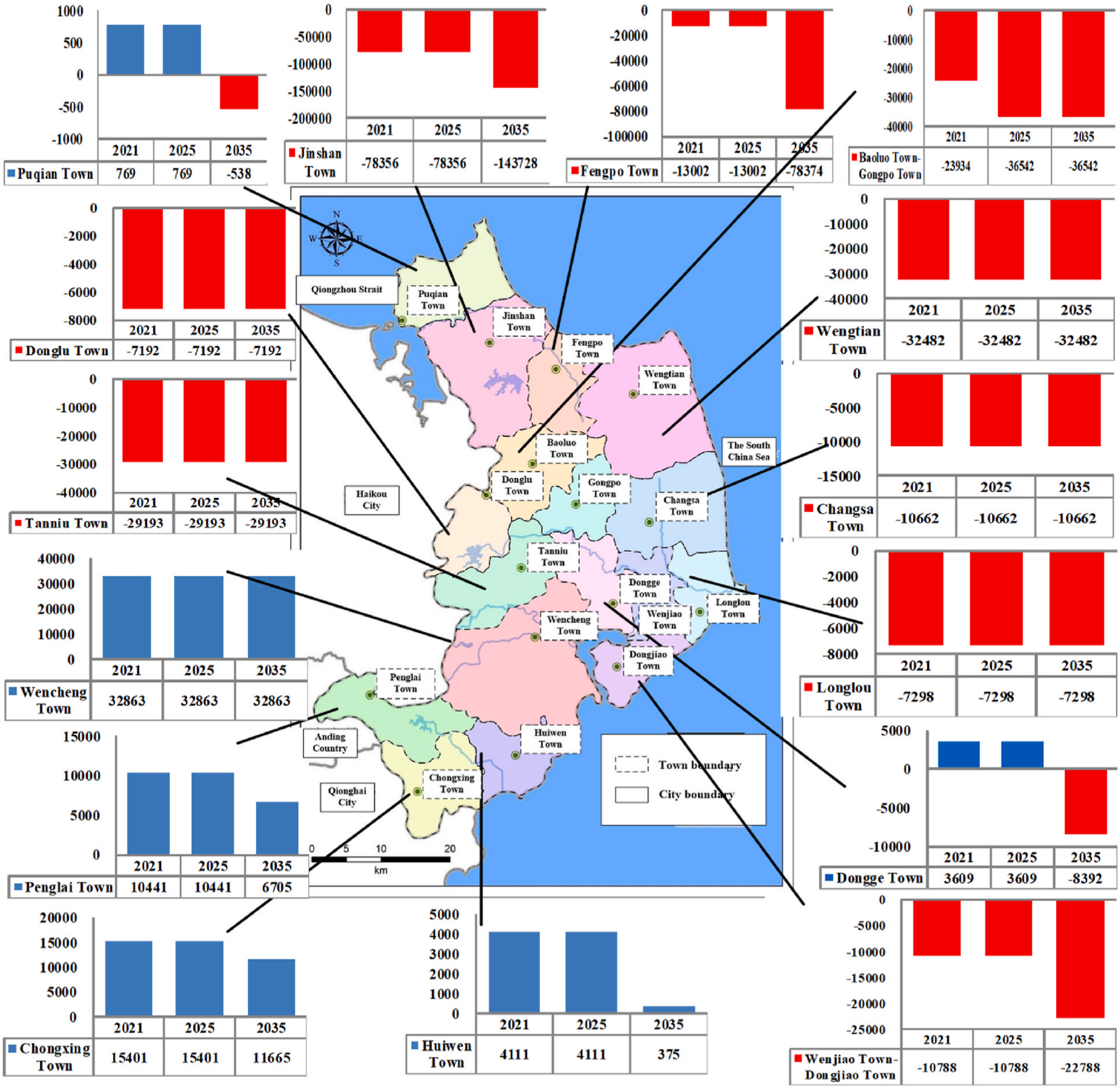

Fig. 6. Surplus breeding space of livestock, poultry and fish breeding for each town in Wenchang City under water quality goal (X-axis: year, Y-axis: pig equivalents).

4.3. Sensitivity analysis

In this sub-section, parameters such as discharge reduction rate and supporting measures were chosen to conduct the sensitivity analysis to explore the influence of their values' change on Wenchang's the total amount in 2025.

Discharge reduction rate and supporting measures is one of the most important factors that could affect the total amount. Wenchang City's amount of livestock, poultry and fish breeding is about 1,756,600 pig equivalents in 2020. If the city does not increase discharge reduction measures such as conversion of distributed breeding to concentrated breeding, sewage treatment, and fecal recycling, the total amount of livestock, poultry and fish farming will need to be removed by 158,320 pig equivalents in 2025 and 325,577 pig equivalents in 2035 based on the breeding scale in 2021. To reflect how discharge reduction measures such as conversion of distributed breeding to concentrated breeding, sewage treatment, and fecal recycling target effect on the breeding strategies, six scenarios are designed. The scenarios will be design based on the increase the discharge reduction rate as 0 %, 10 %, 25 %, 30 %, 50 %, 75 %, and 100 % based on pollutant emissions in 2021. Scenario of 0 % implied that Wenchang City will does not increase the measures of livestock, poultry, and fish breeding from 2021. Scenario of 100 % implied that Wenchang City will increase the measures of

Table 6
Surplus breeding space of Wenchang City under water quality goal.

Town	Unit number	2025 (pig equivalents)	2035 (pig equivalents)	Water quality targets	
				2025	2035
Wencheng Town	**1**	**−12386.72**	**−12386.72**	**III**	**III**
	2	**20417.18**	**20417.18**	**III**	**III**
	3	**14234.73**	**14234.73**	**III**	**III**
	4	**27484.66**	**27484.66**	**III**	**III**
	5	**−19601.09**	**−19601.09**	**III**	**III**
	6	**2714.62**	**2714.62**	**III**	**III**
		32863.38	**32863.38**		
Chongxing Town	**7**	**6351.62**	**2616.12**	**IV**	**III**
	8	**−6153.15**	**−6153.15**	**IV**	**IV**
	9	**15202.53**	**15202.53**	**IV**	**IV**
		15400.99	**11665.49**		
Penglai Town	**10**	**4089.22**	**4089.22**	**II**	**II**
	11	**6351.62**	**2616.12**	**IV**	**III**
		10440.83	**6705.33**		
Huiwen Town	**12**	**4110.91**	**375.41**	**IV**	**III**
		4110.91	**375.41**		
Donglu Town	**13**	**−7192.00**	**−7192.00**	**III**	**III**
		−7192.00	**−7192.00**		
Tanniu Town	**14**	**−9591.43**	**−9591.43**	**III**	**III**
	15	**−19601.09**	**−19601.09**	**III**	**III**
		−29192.52	**−29192.52**		
Dongge Town	**16**	**3608.57**	**−8391.71**	**IV**	**III**
		3608.57	**−8391.71**		
Wenjiao Town-Dongjiao Town	**17**	**−10788.00**	**−22788.28**	**IV**	**III**
		−10788.00	**−22788.28**		
Longlou Town	**18**	**−7297.56**	**−7297.56**	**IV**	**IV**
		−7297.56	**−7297.56**		
Changsa Town	**19**	**−10662.07**	**−10662.07**	**IV**	**IV**
		−10662.07	**−10662.07**		
Wengtian Town	**20**	**−32481.51**	**−32481.51**	**IV**	**IV**
		−32481.51	**−32481.51**		
Baoluo Town-Gongpo Town	**21**	**−36541.70**	**−36541.70**	**IV**	**IV**
		−36541.70	**−36541.70**		
Fengpo Town	**22**	**−13002.34**	**−78373.54**	**V**	**IV**
		−13002.34	**−78373.54**		
Jinshan Town	**23**	**−78356.42**	**−143727.62**	**V**	**IV**
		−78356.42	**−143727.62**		
Puqian Town	**24**	**654.23**	**0.51**	**V**	**IV**
	25	**115.05**	**−538.66**	**V**	**IV**
		769.28	**−538.14**		
Wenchagn City		**−158320**	**−325577**		

Table 7
The optimized result under multiple scenarios (Unit: pig equivalents).

Discharge reduction rate	Scenarios for new added breeding quantity			
	S1		S2	
	2025	2030	2025	2030
0 %	−15.832	−32.5577	−15.832	−32.5577
10 %	1.734	−14.9917	1.9267	−16.6574
25 %	28.083	11.3573	37.444	15.1431
50 %	71.998	55.2723	143.996	110.5446
75 %	115.913	99.1873	463.652	396.7492
100 %	159.828	143.1023	/	/

livestock, poultry and fish breeding to reach zero discharge. In addition, we further set two scenarios which are no supporting measures (S1) and providing supporting measures (S2) for new added breeding quantity, respectively.

Therefore, and the breeding amount can be increased indefinitely if the new breeding amount can also ensure zero discharge under the scenario 100 % (this cross scenario does not count). Table 7 shows the optimized result of the new livestock, poultry, and fish breeding amount under multiple scenarios of different supporting measures.

5. Conclusions and policy implications

In this study, the multi-objective mixed fuzzy-stochastic nonlinear programming based on water quality model (MFSNP-WQM) for livestock, poultry, and fish breeding management planning was developed for planning and management of regional livestock, poultry, and fish breeding. Methods of interval parameter programming (IPP), stochastic Fuzzy-stochastic parameter programming (FSPP), and Chance constrained programming (CCP) were incorporated into the developed model to tackle uncertainties described by interval values, probability distributions, fuzzy membership function. Multi-water-quality assessment indicators (COD, TP, TN) was considered to construct model for supporting livestock, poultry, and fish breeding management to help solve the substandard surface water quality of control section of Wenchang City for a long time. According to the result, the water environment pollutant absorption capacity and carrying capacity of Wenchang city have approached the limit which limited the overall development space of livestock, poultry, and fish breeding in Wenchang City. Wenchang City's amount of livestock, poultry and fish breeding is about 1,756,600 pig equivalents in 2020. If the city does not increase discharge reduction measures such as conversion of distributed breeding to concentrated breeding, sewage treatment, and fecal recycling, the total amount of livestock, poultry and fish farming will need to be removed by 158,320 pig equivalents in 2025 and 325,577 pig equivalents in 2035 based on the breeding scale in 2021. The results indicated that livestock and poultry breeding is the main contribution source of COD, fish breeding is the main contribution source of COD and TP from the perspective of the contribution rate of pollution sources. Some towns located in the southwest of Wenchang city such as Wencheng Town, Dongjiao Town, Huiwen Town and Chongxing Town have a large population and are the main sources of domestic sewage. Some pollutant structure and spatial layout of the southwest towns need to be regulated, but the surface water environmental quality is relatively good and the pollution in the southwest of the city is lighter than that in the northeast. The sewage discharge of livestock, poultry, fish breeding in Puqian Town, Jinshan Town, Fengpo Town, Wengtian Town, Baoluo Town, Changsa Town and Gongpo town which located in the northeast of the city is the main contribution source of COD and TP discharge for Wenchang city. Moreover, livestock, poultry, and fish breeding of the Zhuxi River basin where Jinshan Town is located are densely distributed, and the sewage discharge of fish breeding is one of the main reasons for the water quality exceeding the standard in the above areas and downstream monitoring sections. Therefore, the towns in the northeast of Wenchang City need to optimize the spatial layout of livestock, poultry, and fish breeding for promoting the continuous improvement of surface water quality. Through the analysis of this study, it can be seen that "III Line and I List", "One river, one policy" and Urban Planning which are policy and planning as the basis of this study should be reformulate based on new data and the new "Five-year plan of China".

Wenchang City has no variable increments in the whole city by judging from the total amount of livestock, poultry, and fish breeding. Moreover, a phased clearance of livestock, poultry, and fish breeding will be required. The proposed model could help various local farmers and governments to identify low-cost path planning of pollution reduction under water quality goals. However, there are still a number of limitations of this study. Firstly, only water quality was considered in this study. In order to obtain detailed comprehensive livestock, poultry, and fish breeding may be taken soil environmental quality into account in the developed model. The boundary limitations of the model have too complex uncertainty parameters and would bring analytic burden for domain researchers in various industries. Therefore, the parameters need to be integrated and more field testing should be carried out. In addition, the model and its calculation are significant complexity and would bring computational burden for domain managers in various industries. Therefore, the model volume needs to be simplified and optimization analysis method still has space to improve.

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CRediT authorship contribution statement

Shen Wang: Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Xuesong Xie:** Visualization, Software, Data curation. **Jing Wu:** Software, Data curation. **Siyi Wang:** Visualization. **Lianhong Lv:** Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Solving Method

A. Fuzzy-stochastic programming

A.1 Interval parameter programming

In many real-world problems, uncertainties may be expressed as interval variables because of the limitations of survey data. In general, the basic linear programming model has the form:

$$\max f = CX \tag{A1}$$

Subject to

$$AX \leq B \tag{A2}$$

$$X \geq 0 \tag{A3}$$

where f is the model objective function, X is General decision matrix (variables), A, B and C are coefficient matrices (Parameters). In model research, coefficient data may not necessarily be definitive data due to information loss and other reasons, so the planning results of deterministic models will face the risk of declining the reference value of the results, and even the situation of invalid results. Therefore, uncertainty optimization methods will be used to avoid the risks in this situation.

In uncertainty programming, the model can introduce the interval parameter programming method when the information of the uncertain parameters is not enough to establish the probability distribution and the identifiability cannot reach the situation of constructing fuzzy membership degree. The interval programming method can characterize the special uncertainties in the system, and can directly deal with the uncertainty variables characterized as interval numbers in the model. The common interval parameters, the interval parameter operation method and the interval parameter planning model can be expressed as:

(1) Interval parameters

$x^{\pm} = [x^{-}, x^{+}] = \{x | x^{-} \leq x \leq x^{+}, x \in R\}$ is interval parameter, x^{-}, x^{+} are lower bound and upper bound of $x^{\pm}$, respectively.

$$\text{if } x^{+} \geq 0, x^{-} \geq 0, x^{\pm} \geq 0 \tag{A4}$$

$$\text{if } x^{+} \leq 0, x^{-} \leq 0, x^{\pm} \leq 0 \tag{A5}$$

(2) The interval parameter operation method

The calculation between $x^{\pm} = [x^{-}, x^{+}]$ and $y^{\pm} = [y^{-}, y^{+}]$ is as follows:

$$x^{\pm} + y^{\pm} = [x^{-} + y^{-}, x^{+} + y^{+}] \tag{A6}$$

$$x^{\pm} - y^{\pm} = [x^{-} - y^{+}, x^{+} - y^{-}] \tag{A7}$$

$$rx^{\pm} = \begin{cases} [rx^{-}, rx^{+}], r \geq 0 \\ [rx^{+}, rx^{-}], r < 0 \end{cases} \tag{A8}$$

$$x^{\pm} \times y^{\pm} = [\min(x \times y), \max(x \times y)] \tag{A9}$$

$$x^{\pm} \div y^{\pm} = [\min(x \div y), \max(x \div y)] \tag{A10}$$

Length of interval parameter $len(x^{\pm}) = x^{+} - x^{-}$, its parameter vector and matrix can be expressed as:

$$X^{\pm} = \{x_i^{\pm} = [x^{-}, x^{+}] | \forall i\}, X^{\pm} \in \{R^{\pm}\}^{1 \times n}; \tag{A11}$$

$$X^{\pm} = \left\{x_{i,j}^{\pm} = \left[x_{i,j}^{-}, x_{i,j}^{+}\right] | \forall i, j\right\}, X^{\pm} \in \{R^{\pm}\}^{m \times n} \tag{A12}$$

where $R^{\pm}$ is the interval number set:

$$\text{If } x_{i,j}^{\pm} \geq 0, \forall i, j, X^{\pm} \in \{R^{\pm}\}^{m \times n}, (m \geq 1), X^{\pm} \geq 0; \tag{A13}$$

$$\text{If } x_{i,j}^{\pm} \leq 0, \forall i, j, X^{\pm} \in \{R^{\pm}\}^{m \times n}, (m \geq 1), X^{\pm} \leq 0。 \tag{A14}$$

(3) Interval programming model

Hypothesis can be expressed as:

$$A^{\pm} = \left\{ a_{i,j}^{\pm} = \left[a_{i,j}^{-}, a_{i,j}^{+} \right] | \forall i, j \right\}, A^{\pm} \in \{R^{\pm}\}^{m \times n}; \tag{A15}$$

$$B^{\pm} = \left\{ b_{i,j}^{\pm} = \left[b_{i,j}^{-}, b_{i,j}^{+} \right] | \forall i, j \right\}, B^{\pm} \in \{R^{\pm}\}^{m \times n}; \tag{A16}$$

$$C^{\pm} = \left\{ c_{i,j}^{\pm} = \left[c_{i,j}^{-}, c_{i,j}^{+} \right] | \forall i, j \right\}, C^{\pm} \in \{R^{\pm}\}^{m \times n}; \tag{A17}$$

$$X^{\pm} \in \{R^{\pm}\}^{n \times 1} \tag{A18}$$

The model form can be expressed as:

$$\max f^{\pm} = C^{\pm} X \tag{A19}$$

Subject to:

$$A^{\pm} X \leq B^{\pm} \tag{A20}$$

$$x_j^{\pm} \geq 0, x_j^{\pm} \in X^{\pm}, j = 1, 2, ..., n \tag{A21}$$

where $A^{\pm} \in \{R^{\pm}\}^{m \times n}$, $B^{\pm} \in \{R^{\pm}\}^{m \times 1}$, $C^{\pm} \in \{R^{\pm}\}^{1 \times n}$, $X^{\pm} \in R^{\pm}$, $R^{\pm}$ are interval number matrixes.

A.2 Fuzzy-stochastic parameter programming (FSPP)

The inherent fuzzy-stochastic uncertainty existing in real livestock, poultry and fish breeding management are difficult to evaluate. In the livestock, poultry and fish breeding supply and demand system, demand is a parameter that is extremely difficult to estimate. In this study, demand is defined as a fuzzy-random parameter: $\left(D^L, \rho, D^U\right)$, i.e. $\rho \sim N\left(\mu_0, \sigma_0^2\right)$. The influencing aspects for demand include population, geography, economic situation, and relevant policy of Wenchang City. The decisions on demand exhibit fluctuations because of uncertainty of judgment, insufficient information, and the dynamic environment of a complicated huge urban status of city. Therefore, demand would be vaguely defined with relevant reports giving a range wherein the most possible value is regarded as a random variable. Moreover, the most possible value of the demand approximately follows a normal distribution. The fuzzy random parameter can be denoted as $\widetilde{\widetilde{DM}}_t = \left(D_t^L, \rho_t(\omega), D_t^U\right)$. $\rho_t(\omega)$ is supposed to approximately follow a normal distribution $N_t\left(\mu_t, \sigma_t^2\right)$ with a probability density function $\varphi_{\rho_t}(x)$.Suppose that σ is a given probability level of stochastic parameter ($\sigma \in [0, \sup \varphi_{\rho_t}(x)]$). r is a given possibility level for the fuzzy parameter ($r \in [r_i, 1]$). A fuzzy-stochastic parameter can be processed as follows

(1) Estimate the parameters: D_t^L, D_t^U, μ_t, σ_t^2;
(2) σ and r are determined by using a group-based decision-making approach;

$$r = \left(D_t^U - D_t^L\right) / \left(D_t^U - D_t^L + \rho_{t\sigma}^U - \rho_{t\sigma}^L\right) \tag{A22}$$

(3) Let $\rho_{t\sigma}$ be the $\sigma - cut$ of $\rho_t(\omega)$, $\rho_{t\sigma} = \left[\rho_{t\sigma}^L, \rho_{t\sigma}^U\right] = \{x \in R | \varphi_{t\rho}(x) \geq \sigma\}$,where

$$\rho_{t\sigma}^L = \inf\{x \in R | \varphi_{t\rho}(x) \geq \sigma\} = \inf \varphi_{t\rho}^{-1}(\sigma) = \mu_t - \sqrt{-2\sigma_t^2 \ln\left(\sqrt{2\pi}\, \sigma_t \sigma\right)} \tag{A23}$$

$$\rho_{t\sigma}^U = \sup\{x \in R | \varphi_{t\rho}(x) \geq \sigma\} = \sup \varphi_{t\rho}^{-1}(\sigma) = \mu_t + \sqrt{-2\sigma_t^2 \ln\left(\sqrt{2\pi}\, \sigma_t \sigma\right)} \tag{A24}$$

(4) The parameter $\widetilde{\widetilde{DM}}_t = \left(D_t^L, \rho_t(\omega), D_t^U\right)$ can be converted into a trapezoidal fuzzy number $\widetilde{\omega}_{\widetilde{DM}_t(r,\sigma)} = \left(D_t^L, d_t^L, d_t^U, D_t^U\right)$:

$$d_t^U = D_t^L + r\left(\rho_{t\sigma}^U - D_t^L\right) = D_t^L + r\left(\mu_t + \sqrt{-2\sigma_t^2 \ln\left(\sqrt{2\pi}\, \sigma_t \sigma\right)} - D_t^L\right) \tag{A25}$$

$$d_t^L = D_t^U - r\left(D_t^U - \rho_{t\sigma}^L\right) = D_t^U - r\left(D_t^U - \mu_t + \sqrt{-2\sigma_t^2 \ln\left(\sqrt{2\pi}\, \sigma_t \sigma\right)}\right) \tag{A26}$$

Thus, $\widetilde{\widetilde{DM}}_t = \left(D_t^L, \rho_t(\omega), D_t^U\right)$ can be specified by $\widetilde{\omega}_{\widetilde{DM}_t(r,\sigma)} = \left(D_t^L, d_t^L, d_t^U, D_t^U\right)$ with the membership function as follows:

$$\widetilde{\omega}_{\overline{\widetilde{DM}}_t(r,\sigma)} = \begin{cases} 0 \quad x < D_t^L, x > D_t^U \\ \dfrac{x - D_t^L}{d_t^L - D_t^L} \quad D_t^L \le x < d_t^L \\ 1 \quad d_t^L \le x < d_t^U \\ \dfrac{D_t^U - x}{D_t^U - d_t^U} \quad d_t^L < x \le D_t^U \end{cases} \tag{A27}$$

A.3 Interval parameter planning based on fuzzy stochastic parameters

The interval planning based on fuzzy stochastic parameters model form can be expressed as:

$$\max f^{\pm} = C^{\pm}X \tag{A28}$$

Subject to:

$$A_i^{\pm}X \le B_i^{\pm}, i = 1, 2, ..., t \tag{A29}$$

$$A_i^{\pm}X \le \widetilde{\overline{B}}_i^{\pm}, i = t+1, t+2, ..., I \tag{A30}$$

$$x_j^{\pm} \ge 0, x_j^{\pm} \in X^{\pm}, j = 1, 2, ..., n \tag{A31}$$

where, $A^{\pm} \in \{R^{\pm}\}^{m\times n}$, $\widetilde{\overline{B}}^{\pm} \in \{\widetilde{\overline{B}}^{\pm}\}^{m\times 1}$, $C^{\pm} \in \{R^{\pm}\}^{1\times n}$, $X^{\pm} \in R^{\pm}$, $R^{\pm}$ are interval number matrixes

Decompose the model into lower bound sub-model f^- and upper bound sub-model f^+, lower bound sub-model f^- can be solved first when the target of the model is to maximize system benefits:

$$\max f^- = \sum_{j=1}^{k} c_j^- x_j^- + \sum_{j=k+1}^{n} c_j^- x_j^+ \tag{A32}$$

Subject to:

$$\sum_{j=1}^{k} |a_{i,j}|^- sign\left(a_{i,j}^-\right)x_j^+ + \sum_{j=k+1}^{n} |a_{i,j}|^+ sign\left(a_{i,j}^+\right)x_j^- \le b_i^+, i = 1, 2, ..., t \tag{A33}$$

$$\sum_{j=1}^{k} |a_{i,j}|^- sign\left(a_{i,j}^-\right)x_j^+ + \sum_{j=k+1}^{n} |a_{i,j}|^+ sign\left(a_{i,j}^+\right)x_j^- \le \widetilde{\omega}^{+}_{\overline{B}_M(r,\sigma)}, i = t+1, t+2, ..., I \tag{A34}$$

$$x_j^- \ge 0, j = 1, 2, ..., k \tag{A35}$$

$$x_j^+ \ge 0, j = k+1, k+2, ..., n \tag{A36}$$

where k is nonnegative, $c_j^{\pm} \ge 0, j = 1,2,...,k$; $c_j^{\pm} < 0, j = k+1, k+2,...,n$. *sign* is sign function,if $a_{i,j} > 0$, *sign* is"+"; if $a_{i,j} < 0$, *sign* is "-"; if $a_{i,j} > 0$, *sign* is "+1"; if $a_{i,j} < 0$, *sign* is "-1". $x_{jopt}^-(j = 1, 2, ..., k)$, $x_{jopt}^+(j = k+1, k+2, ..., n)$ are optimal solutions of above sub-model. Then, upper bound sub-model f^+ can be expressed as:

$$\max f^- = \sum_{j=1}^{k} c_j^+ x_j^+ + \sum_{j=k+1}^{n} c_j^+ x_j^- \tag{A37}$$

Subject to:

$$\sum_{j=1}^{k} |a_{i,j}|^+ sign\left(a_{i,j}^+\right)x_j^- + \sum_{j=k+1}^{n} |a_{i,j}|^- sign\left(a_{i,j}^-\right)x_j^+ \le b_i^-, i = 1, 2, ..., t \tag{A38}$$

$$\sum_{j=1}^{k} |a_{i,j}|^+ sign\left(a_{i,j}^+\right)x_j^- + \sum_{j=k+1}^{n} |a_{i,j}|^- sign\left(a_{i,j}^-\right)x_j^+ \le \widetilde{\omega}^{-}_{\overline{B}_M(r,\sigma)}, i = t+1, t+2, ..., I \tag{A39}$$

$$x_j^+ \ge x_{jopt}^-, j = 1, 2, ..., k \tag{A40}$$

$$0 \le x_i^+ \le x_{jopt}^+, i = k+1, k+2, ..., n \tag{A41}$$

$x_{jopt}^{+}(j=1,2,...,k), x_{jopt}^{-}(j=k+1,k+2,...,n)$ are optimal solutions of above sub-model. Optimal solutions of f^- and f^+ will be combined as solutions of the interval planning model based on fuzzy stochastic parameters:

$$x_{jopt}^{\pm} = \left[x_{jopt}^{-}, x_{jopt}^{+}\right], \forall j \tag{A42}$$

$$f^{\pm} = \left[f_{\mathrm{opt}}^{-}, f_{\mathrm{opt}}^{+}\right] \tag{A43}$$

A.4 Chance constrained programming (CCP)

CCP can describe the risk problem of whether the constraint is satisfied in the planning under certain conditions, to effectively reflect the default risk of the research system under uncertain conditions. In general, programming model can be expressed as

$$\max f = C(t)X \tag{A44}$$

Subject to:

$$A(t)X \leq B(t) \tag{A45}$$

$$X \geq 0 \tag{A46}$$

where,X is decision variable, $A(t)$, $B(t)$, and $C(t)$ is a probability matrix of probability space T. The CCP can be introduced to transform the model into an uncertainty optimization model. The level of breach is introduced as $p_i \geq [0 \ , \ 1]$. The probability of the constraint condition is not lower than a certain level $(1- pi)$. Constraints can be expressed as:

$$Pr[A_i(t)X \leq B_i(t)] \geq 1 - p_i, A_i(t) \in A(t), i = 1,2,...,m \tag{A47}$$

Then, the model can be further transformed as:

$$A_i(t)X \leq B_i(t)^{(p_i)}, A_i(t) \in A(t), i = 1,2,...,m \tag{A48}$$

Due to the uncertainty characteristics of data, CCP can be coupled with interval parameters in the programming model. Its basic form can be expressed as follows:

$$\max f^{\pm} = C^{\pm}X^{\pm} \tag{A49}$$

Subject to:

$$Pr[A_i(t)X^{\pm} \leq B_i(t)] \geq 1 - p_i, A_i(t) \in A(t), i = 1,2,...,m \tag{A50}$$

$$x_j^{\pm} \geq 0, x_j^{\pm} \in X^{\pm}, j = 1,2,...,n \tag{A51}$$

According to further transformation, the model can be expressed as:

$$\max f^{\pm} = C^{\pm}X^{\pm} \tag{A52}$$

Subject to:

$$A_i(t)X^{\pm} \leq B_i(t)^{(p_i)}, A_i(t) \in A(t), i = 1,2,...,m \tag{A53}$$

$$x_j^{\pm} \geq 0, x_j^{\pm} \in X^{\pm}, j = 1,2,...,n \tag{A54}$$

Appendix B. Table. Qualitative evaluation

Table B1
Qualitative evaluation of water quality in each monitoring section (mg/L)

Classification	Grade I ~ II	Grade III	Grade IV	Grade V	Worse than Grade V
Water quality	**Excellent**	**Good**	**Slight pollution**	**Middle level pollution**	**Heavy pollution**
COD	**15**	**15**	**20**	**30**	**40**
NH_3–N	**0.015**	**0.5**	**1**	**1.5**	**2**
TP	**0.01**	**0.025**	**0.05**	**0.1**	**0.2**

Table B2
Qualitative evaluation of water quality of rivers and basins (water systems)

Classification proportion	Water quality
Proportion of Grade I ∼ III ≥ 90 %	**Excellent**
75 % ≤ Proportion of Grade I ∼ III < 90 %	**Good**
Proportion of Grade I ∼ III < 75 %, and Proportion of worse than Grade V < 20 %	**Slight pollution**
Proportion of Grade I ∼ III < 75 %, and 20 % ≤ Proportion of worse than Grade V < 40 %	**Middle level pollution**
Proportion of Grade I ∼ III < 60 %, and Proportion of worse than Grade V ≥ 40 %	**Heavy pollution**

Appendix C. Differences and relationship between cities

Wencheng Town is located in the middle of Wenchang City, bordering Tanniu Town to the north, Dongge Town to the east, Huiwen Town to the south, Penglai Town to the west, and the sea to the southeast. Wenchang River, Beishan River, Wenqing River, Nga Qian River, Gangwei Ditch, and Hengshan River flow through Wencheng Town. Zhongxing Town is located in the southernmost part of Wenchang City, adjacent to Huiwen Town in the east, Changpo Town and Yantang Town in Qionghai City in the south and west, and Penglai Town in the north. The Shalaonriver, Tayang River, Shibi River, and Sanheshui River flow through Chongxing town. Penglai Town is located in the southwest of Wenchang City, bordering Wencheng Town in the east and Huiwen Town and Chongxing Town in the south. Shibi River, Yongfeng water, Hengshan River, and Sanhe River flow through Penglai Town. Huiwen Town is located in the southeast of Wenchang City, east of the South China Sea, west of Chongxing town, north of Wencheng town bordering. Shibi River and Hengshan River flow through Huiwen Town. Donglu Tow, is located in the northwest of Wenchang City, east of Baoluo Town, south of Tanniu Town, west and north of Haikou City, of Haikou City. Wenjiao River, ancient city river flow through Donglu town. Tanniu Town is located in the middle of Wenchang City, bordering Gongpo Town and Dongge Town in the east, Wencheng Town in the south, Donglu Town in the west, and Baoluo Town in the north. Wenjiao River, Wenchangjiang River, and Gucheng River flow through Tanniu town. Dongge Town is located in the east of Wenchang City, east of Wenjiao Town, west of Wencheng Town, north of Gongpo town. The Wenjiao River and its tributary Hei stream flow through Dongge town. Wenjiao Town is located in the east of Wenchang City, east of Longlou Town, south of Dongjiao Town, west of Dongge Town, nort of Changsa Town. Wenjiao River and Beishui River flow through Wenjiao Town. Dongjiao Tow is located in the southeast coast of Wenchang City, south of the South China Sea, north of Bamwan, east of Wenjiao Town and Longlou Town. Longlou Town is located in the east of Wenchang City, facing the sea in the east, south and north, connected with Wenjiao Town in the west, north of Changsha Town, and southwestvof Dongjiao Town. Beishui Stream and Baoling River flow through Longlou Town. Changsa Town is located in the east coast of Wenchang City, east of the South China Sea, west of Gongpo Town, south of Wenjiao Town and Longlou town. Beishui Stream, Wenjiao River and its tributaries Hei Stream and flow through Changsa Town. Wengtian Town is located in the northeast of Wenchang City, south of Changsa Town, west of Fengpo Town and Baoluo town. Zhuxi River, Dalangang River, Wenjiao River and its tributaries Hei Stream flow through Wengtian Town. Baoluo Tow is located in the north of Wenchang City, east of Gongpo Tow, south of Tanniu Town, west of Donglu Town, north of Jinshan Tow, Fengpo Town and Wengtian Town. Nanyang River, Baimang Stream, Wenjiao River and its tributaries, Hei Stream flow through Baoluo Town. Fengpo Town is located in the north of Wenchang City, east of the sea, south of Wengtian Town, north of Jinshan town, west of Baoluo town. Jinshan Town is located in the northeast of Wenchang City, adjacent to Fengpo Town in the east, south of Baoluo Townand north of Puqian Town. Zhuxi River, Baimang River, and Paiggang Stream flow through Jinshan Town. Puqian Town is located in the north of Wenchang City. Zhuxi River flows through Puqian town. Gongpo Town, located in the northeast of Wenchang City, connected to Changsa Town in the east, south of Dongge Tow, north of Wengtian Tow, and west of Boruo Town. Wenjiao River and its tributary Hei Stream flow through Gongpo Town.

Each town has a complex pollutant discharge structure. For example, Wencheng Town, which belongs to Wenchang City, Hainan Province, located in the middle of Wenchang City, bordering Tanniu Town to the north, Dongge Town to the east, Huiwen Town to the south, Penglai Town to the west, and the sea to the southeast, is the most important population gathering city. The permanent resident population is about 156,000, accounting for more than 50 % of the city's population. The domestic sewage enters the surface water without treatment make domestic sewage the main contributor of COD in Wencheng Town. The secondary contributor of COD is sewage discharge from livestock breeding, and the COD contribution rate of its sewage and domestic sewage exceeds 85 % of total COD of Wencheng Town. The sewage of residents and livestock and poultry breeding is borne by Wenchang River and Beishan River, and the sewage of fish breeding is borne by Wenqing River, Wuqian River, Gangwei Ditch and Hengshan River among the rivers flow through Wencheng Town.

Table C1
Discharge source structure of COD Wencheng Town

Town	COD			
	Domestic	Plant non-point source	Livestock and poultry breeding	Fish breeding
Wencheng Town	**58.96 %**	**0.00 %**	**31.68 %**	**9.36 %**
Chongxing Town	**43.61 %**	**0.00 %**	**52.04 %**	**4.35 %**
Penglai Town	**41.63 %**	**0.00 %**	**55.33 %**	**3.04 %**

(continued on next page)

Table C1 (*continued*)

Town	COD			
	Domestic	Plant non-point source	Livestock and poultry breeding	Fish breeding
Huiwen Town	**60.87 %**	**0.00 %**	**38.71 %**	**0.42 %**
Donglu Town	**33.37 %**	**0.00 %**	**55.35 %**	**11.28 %**
Tanniu Town	**21.08 %**	**0.00 %**	**54.11 %**	**24.81 %**
Dongge Town	**13.85 %**	**0.00 %**	**73.22 %**	**12.93 %**
Wenjiao Town	**24.28 %**	**0.00 %**	**67.64 %**	**8.08 %**
Dongjiao Town	**54.10 %**	**0.00 %**	**43.53 %**	**2.37 %**
Longlou Town	**23.53 %**	**0.00 %**	**64.30 %**	**12.17 %**
Changsa Town	**8.38 %**	**0.00 %**	**72.40 %**	**19.23 %**
Wengtian Town	**15.67 %**	**0.00 %**	**58.86 %**	**25.47 %**
Baoluo Town	**9.65 %**	**0.00 %**	**69.66 %**	**20.69 %**
Fengpo Town	**7.14 %**	**0.00 %**	**75.69 %**	**17.17 %**
Jinshan Town	**10.51 %**	**0.00 %**	**76.98 %**	**12.52 %**
Puqian Town	**26.82 %**	**0.00 %**	**70.76 %**	**2.42 %**
Gongpo Town	**8.39 %**	**0.00 %**	**75.69 %**	**15.92 %**

Table C2
Discharge source structure of TN Wencheng Town

Town	TN			
	Domestic	Plant non-point source	Livestock and poultry breeding	Fish breeding
Wencheng Town	**61.15 %**	**11.37 %**	**11.43 %**	**16.04 %**
Chongxing Town	**50.04 %**	**20.01 %**	**21.97 %**	**7.98 %**
Penglai Town	**54.03 %**	**14.75 %**	**24.93 %**	**6.28 %**
Huiwen Town	**62.00 %**	**23.65 %**	**13.66 %**	**0.69 %**
Donglu Town	**38.60 %**	**20.04 %**	**20.98 %**	**20.37 %**
Tanniu Town	**24.23 %**	**9.68 %**	**20.69 %**	**45.39 %**
Dongge Town	**21.07 %**	**14.93 %**	**33.42 %**	**30.57 %**
Wenjiao Town	**33.96 %**	**16.92 %**	**31.35 %**	**17.77 %**
Dongjiao Town	**66.38 %**	**10.59 %**	**18.46 %**	**4.58 %**
Longlou Town	**28.66 %**	**25.13 %**	**22.63 %**	**23.58 %**
Changsa Town	**12.12 %**	**12.60 %**	**31.84 %**	**43.44 %**
Wengtian Town	**18.44 %**	**14.38 %**	**20.72 %**	**46.46 %**
Baoluo Town	**13.83 %**	**9.33 %**	**30.78 %**	**46.06 %**
Fengpo Town	**10.98 %**	**13.59 %**	**34.47 %**	**40.97 %**
Jinshan Town	**16.12 %**	**14.89 %**	**39.07 %**	**29.92 %**
Puqian Town	**36.30 %**	**25.50 %**	**32.81 %**	**5.39 %**
Gongpo Town	**12.48 %**	**11.84 %**	**36.51 %**	**39.18 %**

Table C3
Discharge source structure of TP Wencheng Town

Town	TP			
	Domestic	Plant non-point source	Livestock and poultry breeding	Fish breeding
Wencheng Town	**17.30 %**	**4.31 %**	**66.83 %**	**11.56 %**
Chongxing Town	**8.30 %**	**4.68 %**	**83.46 %**	**3.56 %**
Penglai Town	**8.30 %**	**3.23 %**	**85.84 %**	**2.62 %**
Huiwen Town	**15.69 %**	**8.36 %**	**75.49 %**	**0.46 %**
Donglu Town	**6.40 %**	**4.91 %**	**79.19 %**	**9.50 %**
Tanniu Town	**3.95 %**	**2.25 %**	**73.76 %**	**20.05 %**
Dongge Town	**2.46 %**	**2.60 %**	**84.81 %**	**10.13 %**
Wenjiao Town	**4.17 %**	**3.03 %**	**86.74 %**	**6.06 %**
Dongjiao Town	**12.78 %**	**2.96 %**	**81.82 %**	**2.44 %**
Longlou Town	**4.95 %**	**6.20 %**	**77.77 %**	**11.07 %**
Changsa Town	**1.44 %**	**2.21 %**	**81.84 %**	**14.51 %**
Wengtian Town	**2.96 %**	**3.45 %**	**72.38 %**	**21.21 %**
Baoluo Town	**1.65 %**	**1.66 %**	**81.14 %**	**15.56 %**
Fengpo Town	**1.23 %**	**2.28 %**	**83.42 %**	**13.07 %**
Jinshan Town	**1.58 %**	**2.16 %**	**87.98 %**	**8.27 %**
Puqian Town	**4.76 %**	**4.51 %**	**88.93 %**	**1.81 %**
Gongpo Town	**1.48 %**	**1.87 %**	**84.87 %**	**11.78 %**

Wenchang's main breeding breeds are pigs, beef cattle (according to Wenchang Statistical Yearbook, Wenchang has no dairy cattle), sheep, Wenchang chickens (belonging to broilers), ducks, geese. According to the data, it can be calculated that in the past two years, the pigs raised by large-scale livestock and poultry in Wenchang City accounted for 75.69 % of the city's total, and the pigs raised by livestock and poultry farmers accounted for 24.31 % of the total. In Wenchang City, the chickens raised by large-scale livestock and poultry accounted for 93.13 % of the city's total, and the chickens raised by livestock and poultry farmers accounted for 6.87 % of the total.

Table C4
Types and cultured quantity of livestock activities in 2020

	Types and cultured quantity						
	cow	sheep	pig	poultry (10^4)	chicken (10^4)	duck (10^4)	goose (10^4)
Wencheng Town	**3430**	**13300**	**31065**	**226**	**219**	**6**	**1**
Chongxing Town	**166**	**6667**	**17189**	**247**	**243**	**4**	**0**
Penglai Town	**1172**	**30266**	**13698**	**39**	**39**	**0**	**0**
Huiwen Town	**1063**	**3484**	**11146**	**30**	**28**	**2**	**0**
Donglu Town	**2081**	**2608**	**18000**	**103**	**85**	**18**	**0**
Tanniu Town	**3086**	**3997**	**25884**	**386**	**385**	**1**	**0**
Dongge Town	**8246**	**3909**	**31119**	**140**	**131**	**9**	**0**
Wenjiao Town	**3838**	**1907**	**33893**	**59**	**56**	**3**	**0**
Dongjiao Town	**1804**	**519**	**22921**	**78**	**72**	**5**	**1**
Longlou Town	**5699**	**3433**	**10173**	**24**	**21**	**2**	**1**
Changsa Town	**9032**	**7996**	**33075**	**333**	**297**	**33**	**3**
Wengtian Town	**8822**	**10296**	**34626**	**88**	**84**	**4**	/
Baoluo Town	**6052**	**4279**	**26643**	**342**	**315**	**27**	**0**
Fengpo Town	**8405**	**3148**	**20895**	**394**	**308**	**85**	**1**
Jinshan Town	**11868**	**10445**	**123205**	**1745**	**1578**	**149**	**18**
Puqian Town	**5672**	**8709**	**45752**	**352**	**343**	**8**	**1**
Gongpo Town	**5632**	**3495**	**16771**	**448**	**420**	**28**	**0**
Wenchang City	**86068**	**118458**	**516055**	**5034**	**4624**	**384**	**26**

Appendix D. Table. List of sets, parameters, and decision variables

Table D
List of sets, parameters, and decision variables of the model

Sets	Definition
t	The planning period
i	The control unit (Unit numbers and units correspond to Table 4)
k	The species of livestock, poultry, and fish breeding ($k = 1, \ldots, 7$ for pig, beef cattle, sheep, chicken, duck, goose, and tilapia)
c	The towns (Town numbers and towns correspond to Table 4)
Parameters	**Definition**
$PC^{\pm}_{i,k}$	The proportion for different species of livestock, poultry, and fish breeding
$\delta_{i,k}$	The species conversion coefficient (%)
$CO^{\pm}_{k}$	The income per unit of breeding volume (10,000 yuan/ton of pigs)
ρ_{COD}	The COD annual discharge coefficient of breeding (mg/a)
ρ_{TN}	The TN annual discharge coefficient of breeding (mg/a)
ρ_{TP}	The TP annual discharge coefficient of breeding (mg/a)
$PCOD^{\pm}_{i,t}$	The COD contaminant capacity of control units (g/a)
$PTN^{\pm}_{i,t}$	The TN contaminant capacity of control units (g/a)
$PTP^{\pm}_{i,t}$	The TP contaminant capacity of control units (g/a)
$CS_{i,t,COD}$	The COD water quality target concentration value of control units (mg/L)
$CS_{i,t,TN}$	The TN water quality target concentration value of control units (mg/L)
$CS_{i,t,TP}$	The TP water quality target concentration value of control units (mg/L)
$CX_{i,t,COD}$	The COD contaminant concentration after traveling x distance (mg/L)
$CX_{i,t,TN}$	The TN contaminant concentration after traveling x distance (mg/L)
$CX_{i,t,TP}$	The TP contaminant concentration after traveling x distance (mg/L)
$Q^{\pm}_{i,t}$	The design flow of river reach in control unit (m^3/s)
$QP^{\pm}_{i,t}$	The amount of wastewater entering the river (m^3/s)
φ_{COD}	The COD discharge coefficient (mg/s)
φ_{TN}	The TN discharge coefficient (mg/s)
φ_{TP}	The TP discharge coefficient (mg/s)
$CB^{\pm}_{i,t,COD}$	The COD background concentration of section in control units (mg/L)
$CB_{i,t,TN}$	The TN background concentration of section in control units (mg/L)
$CB_{i,t,TP}$	The TP background concentration of section in control units (mg/L)
x_i	The longitudinal distance of control unit along the section of the river (m)
k_{COD}	The COD daily comprehensive degradation coefficient (1/d)
k_{TN}	The TN daily comprehensive degradation coefficient (1/d)
k_{TP}	The TP daily comprehensive degradation coefficient (1/d)
u_i	The average velocity of the river section under the design of the comprehensive degradation coefficient (m/s)
$CS_{i,t,COD}$	The COD target water concentration of control units (mg/L)

(*continued on next page*)

Table D (*continued*)

Sets	Definition
$CS_{i,t,TN}$	The TN target water concentration of control units (mg/L)
$CS_{i,t,TN}$	The TP target water concentration of control units (mg/L)
$DM_{c,t}^{\pm}$	Demand for livestock, poultry and fish breeding (pig equivalent, tons of pigs)
$PMC_{c,i,t}^{\pm}$	The COD annual assimilative capacity limits for towns (g/a)
$PMTN_{c,i,t}^{\pm}$	The TN annual assimilative capacity limits for towns (g/a)
$PMTP_{c,i,t}^{\pm}$	The TP annual assimilative capacity limits for towns (g/a)
xc_i	The longitudinal distance of the town along the section of the river (m)
$CSC_{i,t,COD}$	The COD target water concentration of towns (mg/L)
$CSC_{i,t,TN}$	The TN target water concentration of towns (mg/L)
$CSC_{i,t,TP}$	The TP target water concentration of towns (mg/L)
Variables	**Definition**
$BS_{i,t}^{\pm}$	The amount of livestock, poultry and fish breeding (pig equivalent, tons of pigs)

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