Multi-Watershed Nonpoint Source Pollution Management Through Coupling Bayesian-Based Simulation And Mechanism-Based Effluent Trading Optimization

Xiaomei Xu
Qingdao University
Xueting Zeng
Capital University of Economics and Business
Yongping Li
Beijing Normal University
Chunrong Wang
Qingdao University
Lei Yu
Zhengzhou University
Guohe Huang
University of Regina
Junlong Zhang (zhangjunlong@126.com)
Qingdao University
Juan Feng
Qingdao University
Xinyu Han
Qingdao University

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Multi-watershed nonpoint source pollution management through coupling Bayesian-based simulation and mechanism-based effluent trading optimization

Xiaomei Xu[1], Xueting Zeng[3], Yongping Li[4], Chunrong Wang[1], Lei Yu[5], Guohe Huang[6], Junlong Zhang[1,2*], Juan Feng[1*], Xinyu Han[1].

[1] College of Environmental Science and Engineering, Qingdao University, Qingdao, Shandong 266071, China

[2] Shandong Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Shandong University, Jinan 250100, China

[3] Research Scientist, School of Labor Economics, Capital University of Economics and Business, Beijing, 100070, China

[4] Research Scientist, School of Environment, Beijing Normal University, Beijing 100875, China

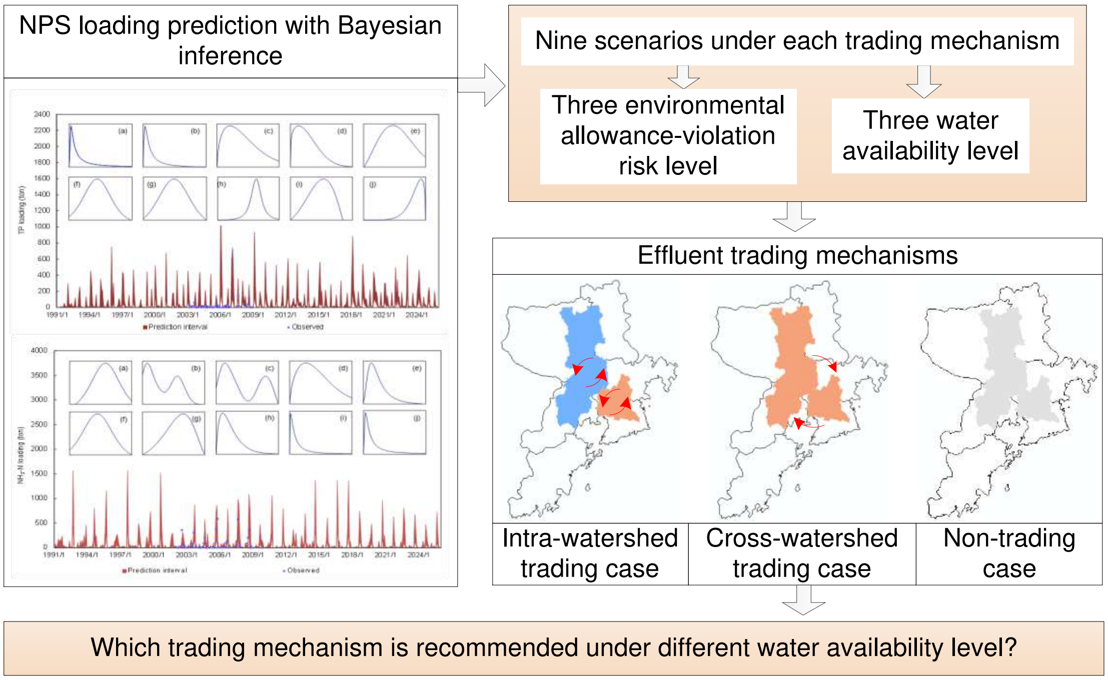
[5] School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China

[6] Professor and Canada Research Chair, Environmental Systems Engineering Program, Faculty of Engineering and Applied Science, University of Regina, Regina, Sask. S4S 0A2, Canada

*Correspondence: Dr. J. L. Zhang
School of Environment Science and Engineering
Qingdao University
Qingdao, 266071
China

Tel.: +86 15865547092
E-mail: zhangjunlongabc@126.com

Graphical Abstract



Highlights

► Bayesian inference provides random NPS loading prediction for optimization process.

► The effects of allowance-violation risk and water availability level are analyzed.

► Non-trading case generates highest benefits under low water availability level.

► Cross-watershed trading performs best at medium and high water availability level.

► The trading scale under cross-watershed trading would be highest.

Abstract

Multiple rivers flowing into the same bay can be correlated in water quality management and together determine the environmental status of the bay. Nonpoint source pollution management for multi-watershed aiming to alleviate environmental contamination can be under additional challenges and yield considerable economic and environmental benefits. In this study, a Bayesian simulation-based multi-watershed effluent trading designing model (BS-METM) is established for multi-watershed nonpoint source pollution management through incorporating techniques of water quality simulation, uncertainty analysis with Bayesian inference, optimal design for effluent trading, as well as mechanism analysis. BS-METM is capable of reflecting parameter uncertainties in nutrient simulation, disclosing the detailed optimal trading schemes under the impact of uncertainties and vital factors, and identifying optimal effluent trading mechanisms through revealing interaction among trading processes of multiple watersheds. BS-METM is applied to a real case of adjacent coastal watersheds (i.e. Daguhe and Moshuihe watersheds), which are identified as major sources of total phosphorus and ammonia nitrogen loadings to Jiaozhou Bay, China. Effluent trading optimization under multiple mechanisms, including intra-watershed trading, cross-watershed trading and non-trading, are conducted. The optimized industry scales and trading processes are obtained. The effects of vital factors on the trading process (i.e. environmental allowance-violation risk level and water availability level) are investigated. The interactions between water availability level and trading mechanism are also analyzed. It is proved that non-trading mechanism would be recommended under low water availability level and cross-watershed trading mechanism would be recommended under medium and high water availability level. The results provide a solid scientific basis for nonpoint source

pollution management as well as effective sustainable development for multi-watershed region.

Keywords: Bayesian inference; Constraint-violation risk; Multi-watershed management; Nonpoint source; Trading mechanism

1. Introduction

The prevalence of nonpoint source (NPS) pollution, such as pollution generated by agricultural activities, has dramatically accelerated water quality deterioration (Zhang et al., 2009). Multiple rivers flowing into the same bay can be correlated in water quality management and together determine the environmental status of the bay. NPS management for multi-watershed aiming to alleviate environmental contamination can be under additional challenges and yield considerable economic and environmental benefits (Sith et al., 2019; Alnahit et al., 2020).

Effluent trading program provides flexibility of discharge permits to nonpoint and point sources and achieves optimal configuration for discharge permits, which can be a promising water quality management measure for pollution control across watersheds (Zeng et al., 2016). A number of literatures have been dedicated to designing trading system and recognizing optimal environmental and political factors (Clark et al., 2008; Nguyen et al., 2013; Chen et al., 2016; Zolfagharipoor and Ahmadi, 2017). For example, Hung and Shaw (2005) designed a trading-ratio system (TRS) for discharge permits in controlling water pollution, utilizing the unidirectional flow property of water; the TRS can meet the predetermined environmental quality standards within minimum aggregate abatement costs. Zhang et al. (2019) developed a Bayesian risk-induced interval stochastic modeling framework to disclose the interactions of trading ratio and treatment rate on effluent trading under system risk. Corrales et al. (2017) applied an integrated hydrology-economic modeling framework for assessing the effectiveness of effluent trading across two watersheds in Lake Okeechobee; the two-watershed phosphorus credit trading effort achieved a lower cost compared with command-and-control methods. Cross watershed

trading has the potential to facilitate the water quality management system by enabling permit transaction among pollution sources with surplus discharge permits in multiple watersheds. The multi-watershed trading policy has a favorable role in promoting the development of green economy under certain conditions (Wang and Pang, 2019). Nevertheless, there have been few studies assessing factors on success of multi-watershed effluent trading programs as well as identifying optimal trading mechanisms.

In practical effluent trading, the trading planning can be affected due to various uncertainties. They are derived from variability in nutrient loadings and fluctuation in economic coefficients. Many stochastic mathematical programming methods have been extensively studied for supporting optimization modeling in water quality management under uncertainty (Li and Huang, 2006; Maeda et al., 2009; Xu and Qin, 2010; Miao et al., 2014; Liu et al., 2016; Pastori et al., 2017). Among them, two-stage stochastic programming (TSP) can tackle decision-making problems related to randomness, which can utilize probability event of environmental penalties in the second-stage to rectify initial (first-stage) decision (Zeng et al., 2015; Rong et al., 2017; Chen et al., 2019; Wang, 2020). Chance constrained programming (CCP) is a programming method in addressing random variables' uncertainties on the right-hand side of the optimal models; it is capable of obtaining trading decision making through providing the trade-off analysis between system benefits and risk at different risk levels (Zhang et al., 2019). On the other hand, optimal design of trading planning can also be restricted by errors in hydrology/water quality simulation associated with a variety of complicated physical processes and spatiotemporal heterogeneity (Alam and Dutta, 2012; Shang et al., 2012; Shen et al., 2015; Shrestha and Wang, 2020). The errors in watershed process simulation lead to the research of Markov chain Monte Carlo

(MCMC) sampling method (Laloy et al., 2013; Rajabi et al., 2015; Vrugt and Beven, 2018; Wu et al., 2020). For example, Zhai et al. (2020a) quantified the parameter uncertainties of the dynamic constitutive model accurately by using Bayesian theory with Differential Evolution Adaptive Metropolis algorithm (DREAM). MCMC provides an efficient way to draw samples of parameter values from complex, high-dimensional statistical distributions in a Bayesian framework. Thus an integration model framework with Bayesian inference based simulation efforts and optimization approaches is desired to be developed for improving the accuracy in nutrient fate modeling as well as to accounting for uncertainties in water quality management problems.

Therefore, this study aims to propose a Bayesian simulation-based multi-watershed effluent trading designing model (BS-METM) for multi-watershed water quality management. BS-METM combines uncertainty analysis of SWAT model with MCMC, constraint-violation risk-based two-stage stochastic programming (CRTSP) and mechanism analysis into a general framework. According to the water quality protocols based on SWAT model, Bayesian estimation (DREAM algorithm) is used to analyze the parameters' posterior distributions and the nutrient loadings' simulated uncertainty ranges for agriculture. The uncertainty ranges can provide random inputs of NPS loading in order to gain optimal effluent trading schemes. CRTSP couples TSP, CCP and interval parameter linear programming (ILP) optimization approaches, which is capable of disclosing optimal industry scales and trading process as well as identifying the best trading mechanism. The mechanism analysis can compare the trading schemes under intra-watershed trading, cross-watershed trading and non-trading cases based on the performance of net system benefits, excess nutrient emissions, trading amount of pollution permits and eliminated permits from trading market. The BS-METM will be applied in a real case of water

quality management for two agricultural watersheds, Daguhe and Moshuihe watersheds, close to Jiaozhou Bay, China. The modeling framework will (i) disclose the detailed optimized effluent trading planning between every pair of pollutant sources under multiple uncertainties and system risks; (ii) reveal the effects of vital factors on the trading process (i.e. environmental allowance-violation risk level and water availability level); (iii) analyze effluent trading under different trading mechanisms and select the best mechanism to make policy suggestions.

2. Methodology

2.1 DREAM algorithm within Bayesian inference

Dream is a multi-chain and self-adaptive differential evolutionary probability sampling method based on Bayesian theory (Vrugt JA, 2016). It generally does not depend on the prior distribution determined artificially. In addition, the offset abnormal chains can be removed (Zhai et al., 2020a). DREAM procedure steps are as follows (Vrugt JA, 2009; Sheng et al., 2019):

1) Each Markov chain's initial value is derived from determined the parametric prior distribution, denoted as ϕ^i $(i = 1, 2, ..., N)$.
2) The initial value's likelihood of each chain can be calculated:

$$\pi\left(\phi^i\right) = f\left(\phi^i \mid \delta\right) \tag{1}$$

3) Candidate samples are generated by mutation operation. In addition, perform candidate samples are cross-operated according to the crossover probability $CR \in [0,\ 1]$, namely the

crossover probability. The likelihood and receptance rate of the newly gained candidate sample $Z_{j,t+1}$ are computed. If the receptance rate $\alpha\left(\phi_{j,t}, Z_{j,t+1}\right) > U$ (sampling from uniform distribution $U(0,\ 1)$), otherwise refuse. The Inter-Quartile-Range (IQR) method can remove the useless chain.

4) Exit conditions on account of convergent judgment are calculated. If the convergence criterion is reached, the calculation will end. Or else, step (3) will always be repeated to develop the Markov chain. When the scale down factor of each parameter in DREAM algorithm: $R_{stat} < 1.2$, the posterior distribution of the parameter is stably converged. The formula for R_{stat} is:

$$R_{stat} = \sqrt{\left(1 - \frac{1}{J}\right) + \frac{N+1}{NW}\frac{B}{J}} \tag{2}$$

where, J is the sample number of each chain, N is the number of Markov chains, B/J is the variance of the mean value of J Markov chains. W is the mean value of the variance of J Markov chains. DREAM algorithm is used for uncertainty analysis for parameters in SWAT model. Nutrient (e.g. NH_3-N and TP) migration eqautions etc. based on SWAT are shown in Appendix A.

2.2 Interval two-stage stochastic programming with constraint-violation risk

In a decision problem with risk or penalty, two-stage stochastic programming method will be provided to deal with stochastic uncertainty of parameters (Li et al., 2008). The basic idea is the

concept of recourse, which is to take up remedial measures, reduce the environment penalties or curtail activity plans after the occurrence of a random event. In this problem, a first-stage decision of production targets are formulated before the random nutrient emission is achieved (Li and Huang, 2008). For example, the decision variables of the first stage can be the scales of livestock and poultry industry and fishery, production level of companies as well as targeted area of agriculture. In order to minimize the possible penalties owing to the infeasibility of the first-stage decision after a random event has occurred, the recourse action to correct the benefits of the first stage through the second-stage penalties would be taken. For example, the second-stage variables can be the excess annual NH_3-N and TP loadings from the nonpoint sources. Although the stochastic uncertainty of nutrient loadings emission would be effectively reflected with the two-stage stochastic programming model, the uncertainties of other parameters couldn't be addressed with it. For example, the parameters on economy, energy and protein may not be used as definite values. So, interval parameters are introduced on the basis of TSP framework to reflect the uncertainty of this kind of parameters, transmitting the uncertain information in economic, energy and protein parameters to the optimization process, which forms an interval two-stage stochastic programming (ITSP) model (Huang, 2000; Zhang, 2019):

$$Max\, f^{\pm} = \sum_{j=1}^{n_1} c_j^{\pm} x_j^{\pm} - \sum_{j=1}^{n_2} \sum_{h=1}^{v} p_h d_j^{\pm} y_{jh}^{\pm} \tag{3a}$$

Subject to:

$$\sum_{j=1}^{n_1} a_{rj}^{\pm} x_j^{\pm} \le b_r^{\pm}, r = 1, 2, ..., m_1 \tag{3b}$$

$$\sum_{j=1}^{n_1} a_{tj}^{\pm} x_j^{\pm} + \sum_{j=1}^{n_2} a'^{\pm}_{tj}\, y_{jh}^{\pm} \ge w_t^{\pm}, t = 1, 2, ... m_2 \tag{3c}$$

$$x_j^{\pm} \geq 0, j = 1, 2, \ldots n_1 \quad (3d)$$

$$y_{jh}^{\pm} \geq 0, j = 1, 2, \ldots n_2; h = 1, 2, \ldots v \quad (3e)$$

where superscripts "$-$" and "$+$" represent the lower and upper bounds of an interval parameter or variable, respectively; j denotes the pollution sources; t and r are marks of constraints; h represents the probability level; $f^{\pm}$, $c_j^{\pm}$, $d_j^{\pm}$, $a_{rj}^{\pm}$, $a_{tj}^{\pm}$, $a'^{\pm}_{tj}$, $b_r^{\pm}$, $x_j^{\pm}$, $y_{jh}^{\pm}$ and $w_t^{\pm}$ are interval coefficients/objectives that are presented as interval numbers. For example, letting b_r^{-} and b_r^{+} be lower and upper bounds of interval number $b_r^{\pm}$, meanwhile, $b_r^{\pm} = \left[b_r^{-}, b_r^{+}\right]$.

However, the right-hand side parameters (e.g. environmental capacity of NH_3-N in Daguhe watershed) involve randomness originating from spatiotemporal heterogeneity in practical effluent trading. The above problem cannot be addressed with the interval two-stage stochastic programming model. While, Chance-constrained programming (CCP) is introduced to deal with the random uncertainties and analyze constraint-violation risk effectively (Zhu et al., 2012; Piao et al., 2014), as follows:

$$Max\, f = C(t)X \quad (4a)$$

Subject to:

$$\Pr\left[\{t \mid A_u(t)X \geq b_u(t)\}\right] \geq \alpha_u \quad (4b)$$

$$A_u(t) \in A(t), b_u(t) \in B(t), \quad u = 1, 2, \ldots\ldots, U \quad (4c)$$

$$X \geq 0 \quad (4d)$$

$$\alpha_u \in [0,1] \tag{4e}$$

where X denotes a vector of decision variables; $A(t)$, $B(t)$, and $C(t)$ are sets with random elements defined on a probability space T, $t \in T$; model (4b) consists of a prescribed level of probability $\alpha_u \in [0,1]$ for each constraint u and imposes a condition that the constraint is satisfied with at least a probability of $1-\alpha_u$ (Xie et al., 2011). When $A(t)$ are deterministic and $b_u(t)$ are stochastic, constraint (4b) becomes linear:

$$A_u X \geq b_u(t)^{1-\alpha_u} \tag{5}$$

Equation (5) is equivalent to equation (4b), given the cumulative distribution function of b_u and the probability of violating constraint u. Accordingly, CCP and ITSP can be integrated to deal with multiple uncertainties existing in the objective function and constraints, which leads to a two-stage stochastic programming with constraint-violation risk (TSPCR) model as follows:

$$Max\, f^{\pm} = \sum_{j=1}^{n_1} c_j^{\pm} x_j^{\pm} - \sum_{j=1}^{n_2} \sum_{h=1}^{v} p_h d_j^{\pm} y_{jh}^{\pm} \tag{6a}$$

Subject to:

$$\sum_{j=1}^{n_1} a_{rj}^{\pm} x_j^{\pm} \leq b_r^{\pm}, r = 1,2,...,m_1 \tag{6b}$$

$$\sum_{j=1}^{n_1} a_{tj}^{\pm} x_j^{\pm} + \sum_{j=1}^{n_2} a'^{\pm}_{tj} y_{jh}^{\pm} \geq \left(w_t^{\pm}\right)^{1\text{-}\alpha_u}, t = 1,2,...m_2 \tag{6c}$$

$$x_j^{\pm} \geq 0, j = 1,2,...n_1 \tag{6d}$$

$$y_{jh}^{\pm} \geq 0, j = 1,2,...n_2; h = 1,2,...v \quad (6e)$$

In above model, $\left(w_t^{\pm}\right)^{1-\alpha_u}$ is the stochastic coefficient under period t and under constraint-violation probability α_u. Model (6) can be transformed into two sub-models which correspond to lower and upper bounds of the target function values (Huang et al., 2000). Then the interval solutions can be gained by solving two sub-models in sequence.

3. Case Study

3.1 Study area

Daguhe watershed is the largest river of all the rivers flowing into Jiaozhou Bay, with a length of more than 140 km. And the total area is 4631 km^2, which is located between latitudes of 36°10'N-37°12'N and longtitudes of 120°03'E-120°25'E in the northwestern part of Qingdao, China (Chen et al., 2010). It flows through Laixi, Pingdu, Jiaozhou and Jimo cities, accounting for 45% of the total area of Qingdao. The region has an average annual precipitation of 707.4 mm and an average annual temperature of 10-11℃ with a warm temperate coastal humid monsoon climate in North China. Brown soil, tidal soil and sandy ginger and black soil are the main soil types within the watershed (Liao et al, 2010; Sun et al, 2016). Moshuihe watershed has a length of 21.3 km and a total area of 276.1 km^2 with an average annual precipitation of 680 mm (Qiao et al., 2012). Moshuihe watershed flows through Jimo city into Jiaozhou Bay, which includes four main tributaries including Liucun River, Longquan River, Tuqiaotou River and Xifengliu River.

The main agricultural crops for the two watersheds are wheat, corn and peanut, chinese cabbage, celery, carrot, potato, apple, pear, peach and grape and the main livestocks are chicken, pig, cattle and cow.

On one hand, Daguhe and Moshuihe watersheds are agricultural watersheds. To meet the increasing food demand, long-term utilization of fertilizers and manures make agricultural nitrogen and phosphorus pollution be in a high status. Intensive livestock and poultry industry and fishery can also be factors that trigger NPS pollution, which can be regarded as a major threat to water quality of the two watersheds and Jiaozhou Bay. NH_3-N and TP are two main contaminants for the watersheds. The amount of TP flowing into Jiaozhou Bay through Daguhe watershed accounts for 55.34% of total TP loading to the Bay. The amount of NH_3-N accounts for 24.18% of total NH_3-N loading to Jiaozhou Bay (Li et al., 2009). On the other hand, Daguhe watershed and Moshuihe watershed are two adjacent rivers flowing into Jiaozhou Bay and correlated in water quality management. They together determine the environmental status of Jiaozhou Bay. Thus, it is desired that an effective system analysis method be advanced to accomplish a sound decision scheme for multi-watershed NPS pollution control. Figure 1 shows the general framework of the advocated BS-METM. The system incorporates uncertainty analysis of SWAT model with MCMC, constraint-violation risk-based two-stage stochastic programming (CRTSP) and mechanism analysis. Each part has a distinctive contribution as shown in introduction to improve the capability of the model in dealing with complexities in effluent trading planning.

Place Figure 1 here

3.2 Modeling formulation

The ecological environment of Daguhe and Moshuihe watersheds is extremely vulnerable because of the excessive nutrient emission. The improper allocation of discharge permits strategy may lead to the inefficiency of environmental management even lead to the issue of hot spots. Instead, effluent trading would contribute to allocate discharge permits with optimal economic benefits or enhanced environmental benefits. In addition, those with pollution sources that are not easy to mitigate or who choose to heighten production can purchase the unused permits deriving from the others within the trading system, without paying huge environmental penalties. TP and NH_3-N are selected as water quality indicators.

As shown in Figure 2, firstly, six reaches have been demarcated in the two watersheds for avoiding the issue of hot spots in trading, including 4 reaches in Daguhe watershed and 2 reaches in Moshuihe watershed (Xu, 2004; Ning et al., 2017). Secondly, there are 18 major pollution sources in the two watersheds, including 10 nonpoint sources in Daguhe watershed (i.e. four agricultural zones, three livestock and poultry industry zones and three fishery zones) as well as one agricultural zone in Moshuihe watershed. Besides, seven companies in Moshuihe watershed are also considered. The planning period in this study is one year (2021), and the discharge permit trading of three levels of water availability (high level (w = 1), low level (w = 2) and medium level (w = 3)) is respectively planned. In study area, TP and NH_3-N discharge permits would be allocated to 18 pollution sources in two watersheds, which include multiple human

activities (i.e. agriculture, livestock and poultry industry, fishery and company). The initial allocation is based on the proportion of their own ecological, economic benefits and pollutant emissions. BS-METM can be formulated under three trading mechanism cases. Under Case 1, the discharge permits are forced to be traded only within the pollution sources from the same watershed. Under Case 2, cross-watershed effluent trading is allowed, which means that the pollution sources in Daguhe watershed can be traded with those in Moshuihe watershed. Under Case 3, cross-watershed environmental constraints are allowed but all pollution sources are not traded for discharge permits. The models of effluent trading under Case 1 and 3 are provided in Compressed File. The model of effluent trading scheme under Case 2 can be formulated as follows:

Place Figure 2 here

$$
\begin{aligned}
Max f = & \sum_{i=1}^{5}\sum_{j=1}^{11}\sum_{w=1}^{3} AB_{j}^{\pm}\cdot(X_{ij}^{-}+\Delta X_{ij}\cdot o_{ijw}) + \sum_{n=1}^{3}\sum_{r=1}^{4}\sum_{w=1}^{3} W_{r}^{\pm}\cdot(N_{nr}^{-}+\Delta N_{nr}\cdot r_{nrw}) \\
& + \sum_{p=1}^{3}\sum_{w=1}^{3} SB_{p}^{\pm}\cdot(Z_{p}^{-}+\Delta Z_{p}\cdot s_{pw}) + \sum_{m=1}^{7}\sum_{w=1}^{3} CB_{m}^{\pm}\cdot(Y_{m}^{-}+\Delta Y_{m}\cdot e_{mw}) \\
& - \sum_{i=1}^{5}\sum_{k=1}^{3}\sum_{w=1}^{3} h_{k}\cdot EDPA_{ikw}^{\pm}\cdot PF^{\pm} - \sum_{n=1}^{3}\sum_{w=1}^{3} EDPR_{nw}^{\pm}\cdot PF^{\pm} \\
& - \sum_{p=1}^{3}\sum_{w=1}^{3} EDPP_{pw}^{\pm}\cdot PF^{\pm} - \sum_{m=1}^{7}\sum_{w=1}^{3} EDPC_{mw}^{\pm}\cdot PF^{\pm} \\
& - \sum_{i=1}^{5}\sum_{s=1}^{3}\sum_{w=1}^{3} k_{s}\cdot EDNA_{isw}^{\pm}\cdot NF^{\pm} - \sum_{n=1}^{3}\sum_{w=1}^{3} EDNR_{nw}^{\pm}\cdot NF^{\pm} \\
& - \sum_{p=1}^{3}\sum_{w=1}^{3} EDNP_{pw}^{\pm}\cdot NF^{\pm} - \sum_{m=1}^{7}\sum_{w=1}^{3} EDNC_{mw}^{\pm}\cdot NF^{\pm}
\end{aligned}
\tag{7a}
$$

The objective is to maximize the ultimate net system benefit, which is calculated with the total environmental penalty and the total initial net system benefit which removes the cost. The ultimate system net benefit considers the total initial net system benefits and the total environmental penalties of agriculture, livestock and poultry industry, fishery and company. The constraints to be complied with can be divided into the following groups:

1. Constraints for TP permit reallocation

$$\sum_{j=1}^{11}(X_{ij}^{-}+\Delta X_{ij}\cdot o_{ijw})\cdot CWPA_{k}^{\pm}-EDPA_{ikw}^{\pm}\leq ACEP_{iw} \quad (7b)$$

$$\sum_{r=1}^{4}(N_{nr}^{-}+\Delta N_{nr}\cdot r_{nrw})\cdot CWPR_{r}^{\pm}-EDPR_{nw}^{\pm}\leq LCEP_{nw} \quad (7c)$$

$$(Z_{p}^{-}+\Delta Z_{p}\cdot s_{pw})\cdot DWP^{\pm}\cdot CWPP^{\pm}-EDPP_{pw}^{\pm}\leq SCEP_{pw} \quad (7d)$$

$$(Y_{m}^{-}+\Delta Y_{m}\cdot e_{mw})\cdot DWM_{m}^{\pm}\cdot CWPM_{m}^{\pm}-EDPC_{mw}^{\pm}\leq CCEP_{mw} \quad (7e)$$

2. Constraints for NH_3-N permit reallocation

$$\sum_{j=1}^{11}(X_{ij}^{-}+\Delta X_{ij}\cdot o_{ijw})\cdot CWNA_{s}^{\pm}-EDNA_{isw}^{\pm}\leq ACEN_{iw} \quad (7f)$$

$$\sum_{r=1}^{4}(N_{nr}^{-}+\Delta N_{nr}\cdot r_{nrw})\cdot CWNR_{r}^{\pm}-EDNR_{nw}^{\pm}\leq LCEN_{nw} \quad (7g)$$

$$(Z_{p}^{-}+\Delta Z_{p}\cdot s_{pw})\cdot DWP^{\pm}\cdot CWNP^{\pm}-EDNP_{pw}^{\pm}\leq SCEN_{pw} \quad (7h)$$

$$(Y_{m}^{-}+\Delta Y_{m}\cdot e_{mw})\cdot DWM_{m}^{\pm}\cdot CWNM_{m}^{\pm}-EDNC_{mw}^{\pm}\leq CCEN_{mw} \quad (7i)$$

Constraints (7j)-(7m) and (7n)-(7q) represent the trading process. The discharge permits are traded among 18 sources of pollution, including cross-watershed agricultural zones, livestock and poultry industry zones, fishery zones and companies. In addition, the reallocated TP and NH_3-N discharge permits for each pollution source in Daguhe and Moshuihe watersheds are equal to that the initial discharge permits plus the purchasing permits, and minus the selling permits.

3. Constraints for TP trading rules

$$\sum_{i'=1}^{5} TP_{ii'w} + \sum_{n=1}^{3} TPs_{inw} + \sum_{p=1}^{3} TPs_{ipw} + \sum_{m=1}^{7} TPs_{imw} \le TPI_{iw} + \sum_{i'=1}^{5} TP_{i'iw} / tp_{i'i} + \sum_{m=1}^{7} TPb_{miw} / tp_{mi} + \sum_{n=1}^{3} TPb_{niw} / tp_{ni} + \sum_{p=1}^{3} TPb_{piw} / tp_{pi} \quad (7j)$$

$$\sum_{n'=1}^{3} TP_{nn'w} + \sum_{i=1}^{5} TPs_{niw} + \sum_{p=1}^{3} TPs_{npw} + \sum_{m=1}^{7} TPs_{nmw} \le TPN_{nw} + \sum_{n'=1}^{3} TP_{n'nw} / tp_{n'n} + \sum_{i=1}^{5} TPb_{inw} / tp_{in} + \sum_{p=1}^{3} TPb_{pnw} / tp_{pn} + \sum_{m=1}^{7} TPb_{mnw} / tp_{mn} \quad (7k)$$

$$\sum_{p'=1}^{3} TP_{pp'w} + \sum_{i=1}^{5} TPs_{piw} + \sum_{n=1}^{3} TPs_{pnw} + \sum_{m=1}^{7} TPs_{pmw} \le TPP_{pw} + \sum_{p'=1}^{3} TP_{p'pw} / tp_{p'p} + \sum_{n=1}^{3} TPb_{npw} / tp_{np} + \sum_{i=1}^{5} TPb_{ipw} / tp_{ip} + \sum_{m=1}^{7} TPb_{mpw} / tp_{mp} \quad (7l)$$

$$\sum_{m'=1}^{7} TP_{mm'w} + \sum_{i=1}^{5} TPs_{miw} + \sum_{n=1}^{3} TPs_{mnw} + \sum_{p=1}^{3} TPs_{mpw} \le TPM_{mw} + \sum_{m'=1}^{7} TP_{m'mw} / tp_{m'm} + \sum_{i=1}^{5} TPb_{imw} / tp_{im} + \sum_{n=1}^{3} TPb_{nmw} / tp_{nm} + \sum_{p=1}^{3} TPb_{pmw} / tp_{pm} \quad (7m)$$

4. Constraints for NH_3-N trading rules

$$\sum_{i'=1}^{5} TN_{ii'w} + \sum_{n=1}^{3} TNs_{inw} + \sum_{p=1}^{3} TNs_{ipw} + \sum_{m=1}^{7} TNs_{imw} \le TNI_{iw} + \sum_{i'=1}^{5} TN_{i'iw} / tn_{i'i} + \sum_{m=1}^{7} TNb_{miw} / tn_{mi} + \sum_{n=1}^{3} TNb_{niw} / tn_{ni} + \sum_{p=1}^{3} TNb_{piw} / tn_{pi} \quad (7n)$$

$$\sum_{n'=1}^{3} TN_{nn'w} + \sum_{i=1}^{5} TNs_{niw} + \sum_{p=1}^{3} TNs_{npw} + \sum_{m=1}^{7} TNs_{nmw} \le TNN_{nw} + \sum_{n'=1}^{3} TN_{n'nw} / tn_{n'n} + \sum_{i=1}^{5} TNb_{inw} / tn_{in} + \sum_{p=1}^{3} TNb_{pnw} / tn_{pn} + \sum_{m=1}^{7} TNb_{mnw} / tn_{mn} \quad (7o)$$

$$\sum_{p'=1}^{3} TN_{pp'w} + \sum_{i=1}^{5} TNs_{piw} + \sum_{n=1}^{3} TNs_{pnw} + \sum_{m=1}^{7} TNs_{pmw} \le TNP_{pw} + \sum_{p'=1}^{3} TN_{p'pw} / tn_{p'p} + \sum_{n=1}^{3} TNb_{npw} / tn_{np} + \sum_{i=1}^{5} TNb_{ipw} / tn_{ip} + \sum_{m=1}^{7} TNb_{mpw} / tn_{mp} \quad (7p)$$

$$\sum_{m'=1}^{7} TN_{mm'w} + \sum_{i=1}^{5} TNs_{miw} + \sum_{n=1}^{3} TNs_{mnw} + \sum_{p=1}^{3} TNs_{mpw} \le TNM_{mw} + \sum_{m'=1}^{7} TN_{m'mw} / tn_{m'm} + \sum_{i=1}^{5} TNb_{imw} / tn_{im} + \sum_{n=1}^{3} TNb_{nmw} / tn_{nm} + \sum_{p=1}^{3} TNb_{pmw} / tn_{pm} \quad (7q)$$

Constraints (7j)-(7m) and (7n)-(7q) can contribute to ensure that the selling TP and NH_3-N discharge permits from pollution sources should be larger than the initial permits they possess, respectively.

5. Constraints for TP environmental limit

$$ACEP_{iw} \le TPA_{iw}, \quad LCEP_{nw} \le TPL_{nw} \quad (7r)$$

$$SCEP_{pw} \le TPS_{pw}, \quad CCEP_{mw} \le TPC_{mw} \quad (7s)$$

$$ACEP_{iw} + LCEP_{nw} + SCEP_{pw} \le TPGF_{qw} \quad \forall i = n = p, i = 1, 2, 3, q \ne 4 \quad (7t)$$

$$ACEP_{iw} \le TPGF_{qw} \quad i=4, q=4 \tag{7u}$$

$$ACEP_{5w} + CCEP_{3w} + CCEP_{4w} + CCEP_{5w} + CCEP_{6w} \le TPWF_{1w} \tag{7v}$$

$$CCEP_{1w} + CCEP_{2w} + CCEP_{7w} \le TPWF_{2w} \tag{7ai}$$

$$\sum_{i=1}^{4} ACEP_{iw} + \sum_{n=1}^{3} LCEP_{nw} + \sum_{p=1}^{3} SCEP_{pw} \le TPG_{w}^{1-p_h} \tag{7w}$$

$$ACEP_{iw} + \sum_{m=1}^{7} CCEP_{mw} \le TPW_{w} \quad i=5 \tag{7x}$$

$$\sum_{i=1}^{5} ACEP_{iw} + \sum_{n=1}^{3} LCEP_{nw} + \sum_{p=1}^{3} SCEP_{pw} + \sum_{m=1}^{7} MCEP_{mw} \le TPT_{w} \tag{7y}$$

6. Constraints for NH_3-N environmental limit

$$ACEN_{iw} \le TNA_{iw}, \quad LCEN_{nw} \le TNL_{nw} \tag{7z}$$

$$SCEN_{pw} \le TNS_{pw}, \quad CCEN_{mw} \le TNC_{mw} \tag{7aa}$$

$$ACEN_{iw} + LCEN_{nw} + SCEN_{pw} \le TNGF_{qw} \quad \forall i=n=p, i=1,2,3, q \ne 4 \tag{7ab}$$

$$ACEN_{iw} \le TNGF_{qw} \quad i=4, q=4 \tag{7ac}$$

$$ACEN_{5w} + CCEN_{3w} + CCEN_{4w} + CCEN_{5w} + CCEN_{6w} \le TNWF_{1w} \tag{7ad}$$

$$CCEN_{1w} + CCEN_{2w} + CCEN_{7w} \le TNWF_{2w} \tag{7ae}$$

$$\sum_{i=1}^{4} ACEN_{iw} + \sum_{n=1}^{3} LCEN_{nw} + \sum_{p=1}^{3} SCEN_{pw} \le TNG_{w}^{1\text{-}p_h} \tag{7af}$$

$$ACEN_{iw} + \sum_{m=1}^{7} CCEN_{mw} \le TNMM_{w} \quad i=5 \tag{7ag}$$

$$\sum_{i=1}^{5} ACEN_{iw} + \sum_{n=1}^{3} LCEN_{nw} + \sum_{p=1}^{3} SCEN_{pw} + \sum_{m=1}^{7} CCEN_{mw} \le TNT_{w} \qquad (7ah)$$

The environmental restrictions for TP and NH_3-N are set for the four industries, the four reaches in Daguhe watershed, the two reaches in Moshuihe watershed, the whole Daguhe watershed, the whole Moshuihe watershed and the cross watersheds in constraints (7r)-(7y) and (7z)-(7ah).

7. Energy and protein requirements constraints for cross-watersheds

$$\begin{aligned}&\sum_{i=1}^{5}\sum_{j=1}^{11} AP_{ij}^{\pm} \cdot (X_{ij}^{-} + \Delta X_{ij} \cdot o_{ijw}) \cdot PE_{j} - \sum_{n=1}^{3}\sum_{r=1}^{4} LE_{r} \cdot (N_{nr}^{-} + \Delta N_{nr} \cdot r_{nrw}) \\ &- DP \cdot NE - MP \cdot NE \ge 0\end{aligned} \qquad (7ai)$$

$$\begin{aligned}&\sum_{i=1}^{5}\sum_{j=1}^{11} AP_{ij}^{\pm} \cdot (X_{ij}^{-} + \Delta X_{ij} \cdot o_{ijw}) \cdot CE_{j} - \sum_{n=1}^{3}\sum_{r=1}^{4} LP_{r} \cdot (N_{nr}^{-} + \Delta N_{nr} \cdot r_{nrw}) \\ &- DP \cdot NP - MP \cdot NP \ge 0\end{aligned} \qquad (7aj)$$

Constraint (7ai) and (7aj) represent that the energy and digestible protein content in cross-watersheds crops should be larger than the demands of humans and livestocks, respectively.

8. Technical and non-negativity constraints

$$0 \le o_{ijw} \le 1, 0 \le r_{nrw} \le 1, 0 \le s_{pw} \le 1, 0 \le e_{mw} \le 1 \qquad (7ak)$$

Besides, the technology and non-negative constraints comprise other decision variables in the model, including the excess TP and NH_3-N emission of each pollution source and the trading amount between two sources. In addition, the excess TP and NH_3-N emission of each pollution

source are lower than the total TP and NH_3-N emission from the source, respectively; the sources' reallocated TP and NH_3-N emission permits should be higher than the minimum reallocated emission permits, which are set as 25% of the initial emission permits in this study; the TP and NH_3-N emission permits sold from source A to source B should be equal to the emission permits purchased from source A by source B, such as $TPb_{niw}=TPs_{niw}$, and the TP and NH_3-N trading amount should be lower than the initial pollutant discharge permit of the source. Nomenclature of the model is as shown in Appendix B.

3.3 Data collection

In this study, a range of general meteorological data associated with model inputs are demanded for watershed hydrological simulation, including maximum and minimum temperature and daily rainfall data during the period of 1991–2018 (China Meteorological Data Service Center: CMDC). Using digital elevation model (DEM), the physical characteristics, flow direction and hydrological network of rivers are calculated. DEM data set is gained from the Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn), with a resolution of 90 m. The 2000, 2010 and 2018 land use datasets were provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The 1:1 million soil map was collected from Soil and Terrain (SOTER) database (Zhang and Zhao, 2008). The relevant uncertain data of each pollution source, represented by interval values due to the uncertainty of the obtained information were derived from historical records (e.g. Qingdao statistical yearbook) and by field survey. The

discharge permits initially allocated to each industry are based on nutrient loadings, net economic benefits and net ecological benefits. The analytic hierarchy process (AHP) was used to determine three factors concerning weights.

4. Results and Discussion

4.1 Prediction of nutrient loadings with SWAT

In this study, parameters' uncertainties in modeling the fate of TP and NH_3-N from nonpoint sources were assessed; the associated nutrient loadings with random characteristics were predicted. The results would be used as the random inputs of optimization process to gain the sound effluent trading schemes. Twenty most sensitive parameters for TP and NH_3-N in modeling nutrient loadings were identified with LH-OAT (Latin Hypercube One-factor-at-a-time) technique as shown in Table 1. The parameter uncertainties for the sensitive parameters and the related nutrient fate simulation were addressed by using MCMC method with DREAM (Differential Evolution Adaptive Metropoils) algorithm. Parameters were estimated with eight Markov chains comprising 20,000 iterations for each parameter, and the first 10% of which would be removed as burn in period. Their prior densities were designed to be uniform within their limits as shown in Table 1.

Place Table 1 here

The marginal posterior probability density distributions for the parameters of TP and NH_3-N are highlighted as shown in Figures 3 and 4. The prediction intervals of TP and NH_3-N loadings are acquired by running SWAT model for years 1991-2025 (Figures 3 and 4). The parameter uncertainties are analyzed based on the observed data for TP and NH_3-N loadings, which are highlighted with blue circles. The results depict that 31.3% and 51.3% of the observed TP and NH_3-N loadings are captured by the uncertain range, respectively. The simulated lower and upper time series of TP and NH_3-N loading are statistically analyzed in order to obtain random inputs for the effluent trading planning. Figure 5 shows the cumulative probability distribution function (CDFs) under the three generation levels and lower- and upper-bound TP loading. The best cumulative probability distributions for the upper- and lower-bound time series of TP loading at any emission level are Rician and Rayleigh distributions, respectively. Figure 6 displays the cumulative probability distribution function (CDFs) under the three generation levels of lower- and upper-bound NH_3-N loading. The best cumulative probability distributions for the upper- and lower-bound time series of NH_3-N loading at any emission level are Weibull and Gamma distributions, respectively. Table 2 shows loading distributions and the associated probabilities for TP and NH_3-N, respectively.

Place Table 2 and Figures 3 to 6 here

4.2 Optimal trading scheme

In this study, totally 9 scenarios based on each trading mechanism are examined considering

three levels of water availability (w) and three environmental allowance-violation risk levels (p). The trading ratio is introduced to ensure that the water quality between the trading sources is equivalent. It is determined according to the hazard degree of pollutants produced by each industry, the location of pollution sources and the water quality standard of the discharged watershed.

In tables 3 to 6, the results are provided in forms of "selling amount/purchasing amount". The selling and purchasing amount would be different because of trading ratio. Tables 3 and 4 show the detailed optimal trading schemes for TP and NH_3-N permits when $p = 0.01$ under Case 1 and $w = 1$. Under Case 1, transactions are implemented across different reaches within same watershed. For example, Jiaozhou agricultural zone would purchase 79.7 ton of NH_3-N permits from Laixi livestock and poultry industry zone (selling amount of 154.6 ton) ($w = 1$) under Case 1 as shown in Table 4. 74.9 ton of NH_3-N permits would be eliminated in this trading section because of trading ratio. Tables 5 and 6 illustrate the detailed optimal trading schemes for TP and NH_3-N permits when p takes 0.01 under Case 2 and $w = 1$. The transactions are implemented across different reaches and watersheds to satisfy the discharge allowance for all the sections. For example, Moshuihe Jimo agricultural zone would sell 134.08 ton of NH_3-N permits to Pingdu livestock and poultry industry zone (purchasing amount of 134.08 ton) ($w = 1$) under Case 2 (Table 6). The detailed trading processes under $p = 0.01$ in medium level of water availability are shown in Compressed File, Table S1-S4.

Place Tables 3 to 6 here

The excess total TP and NH_3-N emissions from agricultural zones, total TP and NH_3-N emissions, system net benefits and total trading amounts are investigated under the three environmental allowance-violation risks (p). Table 7 shows the total excess TP and NH_3-N emissions from agriculture at different p. The results indicate that generally the total excess TP and NH_3-N emissions from agriculture would be decreased as p is increased except for the scenarios under no excess TP and NH_3-N. Table 8 shows the total excess TP and NH_3-N emissions at different p. From the results, the total excess TP and NH_3-N emissions would also be decreased as p is increased accordingly. For example, under Case 1 and $w = 2$, the total excess TP emissions would be decreased from 521.48 ton to 520.30 ton as p is raised from 0.01 to 0.1.Figure 7 shows the net system benefits at different p. The results illustrate that net system benefits would be increased as p is improved due to the decreased total excess TP and NH_3-N emissions. For example, under Case 1 and $w = 2$, the net system benefits would be RMB¥ 17947.415×10^6 ($p = 0.01$) and RMB¥ 17947.578 ×10^6 ($p = 0.1$). Figure 8 shows the total TP and NH_3-N trading amounts at different p. The results indicate that TP and NH_3-N trading amounts under $p = 0.01$ are higher than those under $p = 0.1$ because the decreased total excess pollution emissions would decrease the desire for TP and NH_3-N permits trading program. Above results imply that the total excess TP and NH_3-N emissions from agricultural zones would be decreased when p is raised. Then the total excess TP and NH_3-N emissions would be decreased, leading to the increased net system benefits and decreased total trading amounts.

Place Tables 7, 8 and Figures 7, 8 here

The total trading amounts, excess total TP and NH_3-N emissions and system net benefits are investigated under three levels for water availability (*w*). From the results in Figure 8, when the level of water availability varies from low to high, the total TP and NH_3-N trading amounts would increase. For example, under Case 2 and when *p* takes 0.01, the NH_3-N trading amounts would be 54.87 ton and 1139.11 ton when $w = 2$ and $w = 1$, respectively. This is mainly because the existence of demand and more supply for TP and NH_3-N permits when the level of water availability is high. The demand represents the existence of excess pollution emissions from many pollution sources which need to require more pollution permits. The supply represents that the total surplus TP and NH_3-N permits would be increased by 0.76 ton and 1287.49 ton before trading when the level of water availability rises from low to high. This implies that the effluent trading would be promoted in high level of water availability. The total excess TP and NH_3-N emissions would be decreased when the level of water availability is raised due to the increased total trading amounts (Table 8). For example, when $p = 0.01$ under Case 2, the total excess NH_3-N emissions would be decreased from 1195.66 ton to 614.11 ton. What's more, the net system benefits would be increased accordingly (Figure 7). For example, when $p = 0.01$ under Case 2, the net system benefits are RMB¥ 17970.639 $\times 10^6$ and RMB¥ 17947.415 $\times 10^6$ under $w = 1$ and $w = 2$. Above the results indicate that the total trading amounts would be increased when the level of water availability is raised. After that, the total excess TP and NH_3-N emissions would be decreased and net system benefits would be increased.

4.3 Interactive effects between the water availability level and trading mechanism

Firstly, from the results in Table 8, the total excess TP and NH_3-N emissions under Cases 1 and 2 would be lower than those under Case 3 when $w = 1$. For example, when $p = 0.1$ and $w = 1$, the total excess TP emissions under Cases 1, 2 and 3 are 238.63 ton, 231.96 ton and 240.82 ton. Figure 9 depicts the amounts of the eliminated TP and NH_3-N permits from trading market under three levels for water availability as well as Cases 1 and 2. The eliminated TP and NH_3-N permits imply the reduced emission permits under Cases 1 or 2 over Case 3. From the results, there are some eliminated TP and NH_3-N permits under Cases 1 and 2 when $w = 1$. This leads to strict environmental allowances under Cases 1 and 2. In addition, from the results of Figure 7, the net system benefits under Cases 1 and 2 would be higher than those under Case 3 when $w = 1$. For example, when $p = 0.1$ and $w = 1$, the net system benefits are RMB¥ 17970.439×10^6 (Case 1), 17970.639×10^6 (Case 2), 17970.028×10^6 (Case 3). Based on the above results, trading cases perform better than non-trading case in high level of water availability. This is mainly because the trading cases can achieve the optimal configuration for pollution permits. Secondly, the total excess TP and NH_3-N emissions under Cases 1 and 2 would be higher than those under Case 3 when $w = 2$ (Table 8). For example, when $p = 0.1$ and $w = 2$, the total excess TP emissions under Cases 1, 2 and 3 are 520.30 ton, 520.30 ton and 519.05 ton. In addition, the increased amounts of total excess TP and NH_3-N emissions under Case 1 and 2 compared with Case 3 are similar to the eliminated permits under Case 1 and 2. Furthermore, the net system benefits under Cases 1 and 2 would be lower than those under Case 3 when $w = 2$ (Figure 7). For example, when $p = 0.1$ and $w = 2$, the net system benefits are RMB¥ 17947.578×10^6 (Case 1), 17947.578×10^6 (Case 2), 17947.768×10^6 (Case 3). The above results imply that the system in low level of water availability is suitable for non-trading mechanism. This is mainly because there is almost no surplus pollution discharge permits for all pollution sources in low level of water availability.

Thirdly, the total excess TP emissions under Cases 1 and 2 would be higher than those under Case 3 when $w = 3$ (Table 8). But total excess NH_3-N emissions under Cases 1 and 2 would be lower than those under Case 3. For example, when $p = 0.1$ and $w = 3$, the total excess TP (NH_3-N) emissions under Cases 1, 2 and 3 are 380.95 ton (732.82 ton), 372.88 ton (732.82 ton) and 370.46 ton (750.31 ton). In addition, from the results in Figure 9, there are some eliminated TP and NH_3-N permits under Cases 1 and 2 when $w = 3$. This leads to strict environmental allowances under Cases 1 and 2. Furthermore, the results indicate that the net system benefits under Cases 1 and 2 would be higher than those under Case 3 when $w = 3$ (Figure 7). For example, when $p = 0.1$ and $w = 3$, the net system benefits are RMB¥ 17963.202×10^6 (Case 1), 17963.444×10^6 (Case 2), 17963.080×10^6 (Case 3). The above results indicate that trading cases perform better than non-trading case in medium level of water availability. This is mainly because trading cases can achieve the optimal configuration for pollution permits.

Place Figure 9 here

From the results in Table 8, the total excess TP emissions under Case 1 would be increased by [6.67, 11.2] ton compared with Case 2 when $w = 1$. This is mainly because certain surplus pollution permits would be traded between pollution sources under cross-watershed trading case, but they cannot be traded under intra-watershed trading. The results illustrate that the eliminated TP permits under Case 1 would almost be equivalent to those under Case 2 when $w = 1$ (Figure 9). The above results imply that the TP trading under Case 2 can better achieve pollution permits' optimal configuration than Case 1. In addition, the total excess NH_3-N emissions would be same

under Cases 1 and 2 when $w = 1$ (Table 8). However, the eliminated NH_3-N permits under Case 1 would be increased by [234.39, 292.02] ton compared with Case 2 (Figure 9). This results in the stricter environmental allowance for NH_3-N under Case 1. This is mainly because the total agricultural NH_3-N reallocation emission permits under case 1 would be higher than Case 2 when the total agricultural excess NH_3-N emissions are all 0 ton with the same total agricultural NH_3-N emissions under Cases 1 and 2. This leads to [321.22, 335.76] ton of surplus NH_3-N permits under Case 2. Therefore, the above results imply that NH_3-N trading under intra-watershed trading case performs better than cross-watershed trading case. From the results in Figure 7, the net system benefits under Case 2 would be higher than those under Case 1 when $w = 1$. For example, when $p = 0.01$ and $w = 1$, the net system benefits under Cases 1 and 2 would be RMB¥ 17970.303×10^6 and RMB¥ 17970.639×10^6. All the above results imply that cross-watershed trading case would be better than intra-watershed trading case due to the increased net system benefits. But the environmental allowance for NH_3-N is stricter under intra-watershed trading case than cross-watershed trading case. From the results in Table 8, the total excess TP emissions under Case 1 would be increased by [2.65, 8.06] ton compared with Case 2 when $w = 3$. This is mainly because the certain surplus pollution permits would be traded between pollution sources under cross-watershed trading case, but they cannot be traded under intra-watershed trading. In addition, the results illustrate that the eliminated TP permits under Case 1 would almost be equivalent to those under Case 2 when $w = 3$ (Figure 9). The above results imply the TP trading under Case 2 that can better obtain the optimal configuration for pollution permits. In addition, the total excess NH_3-N emissions would be equivalent under Cases 1 and 2 when $w = 3$ (Table 8). And the eliminated NH_3-N permits under Case 1 would be

decreased by [4.43, 7.73] ton compared with Case 2 when w = 3 (Figure 9). This leads to the stricter environmental allowance for NH_3-N under Case 2. The above results imply that the optimal configuration for pollution permit of the trading for NH_3-N under cross-watershed trading case is better than intra-watershed trading case in medium level of water availability. The net system benefits under Case 2 would be higher than those under Case 1 when w = 3. For example, when p = 0.01 and w = 3, the net system benefits would be RMB¥ 17963.282×10^6 (Case 1)and RMB¥ 17963.595×10^6 (Case 2). All the above results imply that the trading under cross-watershed trading case would be better in optimal configuration for pollution permit due to the increased net system benefits. Meanwhile, the environmental allowance for TP and NH_3-N is stricter under cross-watershed trading case than intra-watershed trading case.

Figure 10 shows the TP and NH_3-N detailed trading processes for agriculture, livestock and poultry industry, fishery and company under Cases 1 and 2. From the results, Firstly, under Case 1, the main selling (purchasing) industries for TP permits are agriculture (fishery), livestock and poultry industry (agriculture) and livestock and poultry industry (agriculture) under the three w, respectively. And the main selling (purchasing) industries for NH_3-N permits are agriculture (livestock and poultry industry), livestock and poultry industry (agriculture) and agriculture (livestock and poultry industry) for the three w. For example, under p = 0.01 and when w = 1, the TP (NH_3-N) trading amounts for agriculture, livestock and poultry industry, fishery and company would be 27.83 ton (392.17 ton), 7.44 ton (-75.53 ton), -2.76 ton (-34.47 ton) and 0.25 ton (1.29 ton) under Case 1. Secondly, agriculture (livestock and poultry industry) is the main selling

(purchasing) industry for TP and NH_3-N permits in the trade under Case 2 for the three *w*, except for NH_3-N permits when $w = 1$.

Place Figure 10 here

From the results in Figure 8, the total TP and NH_3-N trading amounts under Case 2 would generally be higher than those under Case 1, except for NH_3-N trading amount when $w = 1$. For example, when *p* takes 0.01 and $w = 2$, the total TP and NH_3-N trading amounts would be 8.97 ton and 36.06 ton under Case 1; the total TP and NH_3-N trading amounts would be 21.29 ton and 54.87 ton under Case 2. This is mainly because when cross-watershed effluent trading (Case 2) is allowed, the permits in pollution sources from Daguhe watershed can be sold to other sources from Moshuihe watershed. This implies that cross-watershed effluent trading can motivate the market's vitality.

5. Conclusions

In this study, a Bayesian simulation-based multi-watershed effluent trading designing model (BS-METM) has been proposed to support multi-watershed nonpoint source pollution management. BS-METM combines Bayesian estimation with DREAM, nutrient fate modeling by using SWAT, optimal design for effluent trading and mechanism analysis within a framework. BS-METM has several advantages in: (i) estimating the uncertainties of parameters in modeling fate of nutrients from nonpoint sources through Bayesian inference; (ii) disclosing the detailed

optimal effluent trading schemes considering multiple uncertainties as well as system risk; (iii) revealing the influences of vital factors on the trading process (i.e. environmental allowance-violation risk level and water availability level); (iv) identifying optimal effluent trading mechanism through revealing interaction among trading processes of multiple watersheds.

BS-METM has been applied to multi-watershed effluent trading design for two agricultural watersheds, i.e., Daguhe and Moshuihe watersheds, China, where TP and NH_3-N are selected as water quality indicators. The optimized industry scales and trading processes are obtained. The effects of important factors on the trading process (i.e. environmental allowance-violation risk level and water availability level) are investigated. The interactions between water availability level and trading mechanism are also analyzed. Several results are revealed: (i) the increased level of environment allowance leads to the decreased total excess TP and NH_3-N emissions and trading amounts as well as the increased net system benefits; the net system benefits would be increased by RMB¥ $[0, 227] \times 10^3$ with environmental allowance-violation risk level; (ii) the total trading amounts should be enlarged under high water availability level because of the existence of demand and more supply for TP and NH_3-N permits; high water availability level also corresponds to high net system benefits; (iii) the total TP and NH_3-N trading amounts under cross-watershed trading would be generally higher than those under intra-watershed trading; this implies that cross-watershed effluent trading can motivate the trading market's vitality; (iv) the trading cases would be recommended due to the optimal configuration for pollution permit in medium and high levels of water availability; and the net system benefits under trading cases

would increase by RMB¥ [47, 611]$\times 10^3$ compared with non-trading case; but non-trading case would be recommended in low water availability level because there is almost no surplus pollution discharge permits in the region; (v) in medium and high water availability level, cross-watershed trading case would be recommended compared with intra-watershed trading case, with increased net system benefits of RMB¥ [200, 336]$\times 10^3$ and [80, 242]$\times 10^3$ for the two levels; strict environmental management of NH_3-N should be strengthened due to less eliminated discharge permits under cross-watershed trading.

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Appendix A

The assessment of SWAT model parameters contains uncertainties originating from errors and spatiotemporal heterogeneity, which may encounter difficulties in accurately depicting nutrient fate with an unrealistic estimation of parameter uncertainty. MCMC will provide a valid way that would account for parameter uncertainty in a Bayesian inference. The Bayesian theorem can be showed as follows (Zhang et al., 2019):

$$f_{post}(\theta|y_{obs}) = \frac{f_{pri}(\theta)\cdot f_M(y_{obs}|\theta)}{\int f_{pri}(\theta)\cdot f_M(y_{obs}|\theta)d\theta} \quad \text{(A1)}$$

where $f_{post}(\theta|y_{obs})$ represents the posterior distribution of parameter set θ that is dated from the prior distribution $f_{pri}(\theta)$ conditioned on observed data y_{obs}; $f_M(y_{obs}|\theta)$ is the likelihood function. In the study, the simulation errors are assumed to be independent and identically normally distributed, which determines the construction of the likelihood function and is the basis of the entire Bayesian calibration process. The likelihood function is (Raje and Krishnan, 2012):

$$f_M(y_{obs}|\theta_M) = \prod_t \frac{1}{\sqrt{2\Pi}\sigma_e}\exp\left[-\frac{(y_t - y_{obs,t})^2}{2\sigma_e^{\,2}}\right] \quad \text{(A2)}$$

where y_t is the simulated nutrient loading with SWAT at time step t; $y_{obs,t}$ is the observed data at time step t; $\sigma_e^{\,2}$ is the variance of the simulation errors.

Phosphorous (P) and Nitrogen (N) are transported by attaching to eroded soil or being dissolved

in surface runoff, which is simulated based on spatial information on climate, topography, soil properties, land use and management practices. The process simulation of nitrogen (N) in soil can be divided into two main parts, including nitrate transport and organic nitrogen N loss. Nitrate is transported by dissolving in surface runoff, lateral flow, or percolation. The nitrate concentration in mobile water can be calculated by the following equation:

$$w_{3surf} = Q_{surf} + Q_{lat,ly} + w_{perc,ly} \tag{A9}$$

$$NO_{3surf} = \frac{\beta_{NO_3} Q_{surf} NO_{3_{ly}} \left\{1 - \exp\left[-w_{mobile} / \left(1-\theta_e\right) SAT_{ly}\right]\right\}}{w_{mobile}} \tag{A10}$$

where NO_{3surf} is the nitrate removed in surface runoff (kg/ha); β_{NO_3} represents the nitrate percolation coefficient; $NO_{3_{ly}}$ is the amount of nitrate in the soil layer (kg/ha); w_{mobile} represents the amount of mobile water in the layer (mm H_2O); θ_e is the fraction of porosity from which anions are excluded; SAT_{ly} is the water content of the soil layer; $Q_{lat,ly}$ represents the water discharged from the layer by lat-eral flow (mm H_2O); and $w_{perc,ly}$ denotes the amount of water percolating to the underlying soil layer (mm H_2O). The organic N runoff loss based on the organic N concentration in the top soil layer and the sediment yield can be calculated by using the following equation:

$$orgN_{surf} = \frac{0.001 conc_{orgN} \varepsilon_{sedN} sed}{area_{hru}} \tag{A11}$$

where $orgN_{surf}$ is the amount of organic N transported to the chief channel in surface runoff

(kg/ha); $conc_{orgN}$ denotes the organic N concentration in the top 10 mm (g/kg); $area_{hru}$ is the HRU area (ha); and ε_{sedN} represents the N enrichment ratio. SWAT simulates the dynamics of three forms of phosphorous (P), including organic P which exists in humus, insoluble mineral P and soluble P. The amount of organic P transported with sediment to the stream is simulated with a loading function as depicted in organic N as follows:

$$orgP_{surf} = 0.001 conc_{orgP} \varepsilon_{sedP} sed \big/ area_{hru} \qquad \text{(A12)}$$

where $orgP_{surf}$ is the amount of organic P transported to the main channel in surface runoff (kg/ha); $conc_{orgP}$ denotes the organic P concentration in the top 10 mm (g/kg); and ε_{sedP} represents the P enrichment ratio. Because of the low mobility of soluble P, SWAT only considers the loss of the soluble P with surface runoff based on labile P concentration in the top soil layer. The migration of soluble P in surface runoff is:

$$P_{surf} = \frac{10 P_{soluble,surf} Q_{surf}}{\rho_b k_{d,surf}} \qquad \text{(A13)}$$

where P_{surf} represents the amount of soluble P lost in surface runoff (kg/ha); $P_{soluble,surf}$ is the amount of soluble P in the top 10 mm (kg/ha); ρ_b denotes the bulk density of the top 10 mm (Mg/m^3); and $k_{d,surf}$ the P soil partitioning coefficient (m^3 /Mg).

Appendix B

i	Agricultural zone, $i=1, 2, 3, 4, 5$; $i=1$ for Laixi zone, $i=2$ for Pingdu zone, $i=3$ for Jiaozhou zone, $i=4$ for Daguhe Jimo zone, $i=5$ for Moshuihe Jimo zone.
j	Species of crops, $j=1, 2, 3, 4, \ldots, 11$; $j=1$ for wheat, $j=2$ for corn, $j=3$ for peanut, $j=4$ for chinese cabbage, $j=5$ for celery, $j=6$ for carrot, $j=7$ for potato, $j=8$ for apple, $j=9$ for pear, $j=10$ for peach, $j=11$ for grape.
n	Livestock and poultry industry zone, $n=1, 2, 3$; $n=1$ for Laixi zone, $n=2$ for Pingdu zone, $n=3$ for Jiaozhou zone.
r	Species of livestocks, $r=1, 2, 3, 4$; $r=1$ for chicken, $r=2$ for pig, $r=3$ for cattle, $r=4$ for cow.
p	Fishery zone, $p=1, 2, 3$; $p=1$ for Laixi zone, $p=2$ for Pingdu zone, $p=3$ for Jiaozhou zone
m	company, $m=1, 2, 3, 4, 5, 6, 7$; $m=1$ for Qingdao Zhengyuan Iron and Steel Co., Ltd $m=2$ for Qingdao Tongyuanchang Steel Co., Ltd $m=3$ for Qingdao Hehe Chemical Co., Ltd $m=4$ for Qingdao Zeyukaisheng Machinery Manufacturing Co., Ltd $m=5$ for Qingdao Huataida Machinery Manufacturing Co., Ltd $m=6$ for Qingdao Jingrui Machinery Manufacturing Co., Ltd $m=7$ for Qingdao Jinguangxin Textile Co., Ltd
i'	Other agricultural zone except zone i
n'	Other livestock and poultry industry zone except zone n
r'	Other species of livestocks except r

p'	Other fishery zone except zone p
m'	Other company except company m
w	The level of water availability, $w = 1, 2, 3$; $w = 1$ for high level, $w = 2$ for low level, $w = 3$ for medium level.
q	Reaches in Daguhe watershed, $q = 1, 2, 3, 4$; $q = 1$ for Laixi reach, $q = 2$ for Pingdu reach, $q = 3$ for Jiaozhou reach, $q = 4$ for Jimo reach.
o	Reaches in Moshuihe watershed, $o = 1, 2$
k	TP-generation level of agriculture
s	NH_3-N-generation level of agriculture
h	A prescribed level of probability for each constraint
$AB_j^{\pm}$	Net benefit of crop j (RMB¥/ha)
$AP_{ij}^{\pm}$	Production level of crop j in agricultural zone i (kg/ha)
$X_{ij}^{-}, \Delta X_{ij}$	Lower bound and range of area target for crop j in zone i (ha)
o_{ijw}, r_{nrw}, s_{pw}, e_{mw}	Decision variables which are used for identifying the optimized targets of cropped area, the scale of livestock and poultry industry, the scale of fishery and the production level of company
$SB_p^{\pm}$	Net benefit of zone p (RMB¥/ha)
$Z_p^{-}, \Delta Z_p$	Lower bound and range of the scale of fishery zone p
$CB_m^{\pm}$	Net benefit of per unit product of company m (RMB¥)
$Y_m^{-}, \Delta Y_m$	Lower bound and range of the production level of company m
h_k	Probability of TP generation rate in agriculture
k_s	Probability of NH_3-N generation rate in agriculture
PF	Penalties per ton excess TP effluents exceeding to discharge permits from pollution source (RMB¥/ton)
NF	Penalties per ton excess NH_3-N effluents exceeding

	to discharge permits from pollution source (RMB¥/ton)
$EDPA_{ikw}^{\pm}$, $EDPR_{nw}^{\pm}$, $EDPP_{pw}^{\pm}$, $EDPC_{mw}^{\pm}$	Excess annual TP loading for agricultural zone i, livestock and poultry industry zone n, fishery zone p and company m (ton)
$EDNA_{isw}^{\pm}$, $EDNR_{nw}^{\pm}$, $EDNP_{pw}^{\pm}$, $EDNC_{mw}^{\pm}$	Excess annual NH_3-N loading for agricultural zone i, livestock and poultry industry zone n, fishery zone p and company m (ton)
$DWP^{\pm}$, $DWM_{m}^{\pm}$	Effluent generation rate of fishery zone and company m (m^3/ha; m^3/ton, item)
$CWPA_{k}^{\pm}$, $CWPR_{r}^{\pm}$, $CWPP^{\pm}$, $CWPM_{m}^{\pm}$	TP generation rate of agricultural zone i, livestock r, fishery zone p and company m (ton/ha; ton/item; ton/m^3; ton/m^3)
$CWNA_{s}^{\pm}$, $CWNR_{r}^{\pm}$, $CWNP^{\pm}$, $CWNM_{m}^{\pm}$	NH_3-N generation rate of agricultural zone i, livestock r, fishery zone p and company m (ton/ha; ton/item; ton/m^3; ton/m^3)
TPI_{iw}, TPN_{nw}, TPP_{pw}, TPM_{mw}	TP discharge permit allocated to agricultural zone i, livestock and poultry industry n, fishery zone p and company m in level w, respectively (ton)
TNI_{iw}, TNN_{nw}, TNP_{pw}, TNM_{mw}	NH_3-N discharge permit allocated to agricultural zone i, livestock and poultry industry n, fishery zone p and company m in level w, respectively (ton)
$ACEP_{iw}$, $LCEP_{nw}$, $SCEP_{pw}$, $CCEP_{mw}$	TP discharge permit that agricultural i, livestock and poultry industry zone n, fishery zone p and company m possess after trading program in level w (ton)
$ACEN_{iw}$, $LCEN_{nw}$, $SCEN_{pw}$, $CCEN_{mw}$	NH_3-N discharge permit that agricultural i, livestock and poultry industry zone n, fishery zone p and company m possess after trading program in level w (ton)
$TP_{i'iw}$, TPs_{niw}, TPs_{piw}, TPs_{miw}	TP discharge permit sold to agricultural zone i from agricultural zone i', livestock and poultry

industry zone n, fishery zone p and company m, respectively (ton)

$TP_{n'nw}$, TPs_{inw}, TPs_{pnw}, TPs_{mnw} — TP discharge permit sold to livestock and poultry industry zone n from livestock and poultry industry zone n', agricultural zone i, fishery zone p and company m, respectively (ton)

$TP_{p'pw}$, TPs_{ipw}, TPs_{npw}, TPs_{mpw} — TP discharge permit sold to fishery zone p from fishery zone p', agricultural zone i, livestock and poultry industry zone n and company m, respectively (ton)

$TP_{m'mw}$, TPs_{imw}, TPs_{nmw}, TPs_{pmw} — TP discharge permit sold to company m from company m', agricultural zone i, livestock and poultry industry zone n and fishery zone p, respectively (ton)

TPb_{niw}, TPb_{piw}, TPb_{miw} — TP discharge permit in agricultural zone i purchased from livestock and poultry industry zone n, fishery zone p and company m, respectively (ton)

TPb_{inw}, TPb_{pnw}, TPb_{mnw} — TP discharge permit in livestock and poultry industry zone n purchased from agricultural zone i, fishery zone p and company m, respectively (ton)

TPb_{ipw}, TPb_{npw}, TPb_{mpw} — TP discharge permit in fishery zone p purchased from agricultural zone i, livestock and poultry industry zone n and company m, respectively (ton)

TPb_{imw}, TPb_{nmw}, TPb_{pmw} — TP discharge permit in company m purchased from agricultural zone i, livestock and poultry industry zone n and fishery zone p, respectively (ton)

$TP_{ii'w}$, $TP_{nn'w}$, $TP_{pp'w}$, $TP_{mm'w}$ — TP discharge permit agricultural zone i sold to i', livestock and poultry industry zone n sold to n', fishery zone p sold to p' and company m sold to m',respectively (ton)

$TN_{i'iw}$, TNs_{niw}, TNs_{piw}, TNs_{miw}	NH_3-N discharge permit sold to agricultural zone i from agricultural zone i', livestock and poultry industry zone n, fishery zone p and company m, respectively (ton)
$TN_{n'nw}$, TNs_{inw}, TNs_{pnw}, TNs_{mnw}	NH_3-N discharge permit sold to livestock and poultry industry zone n from livestock and poultry industry zone n', agricultural zone i, fishery zone p and company m, respectively (ton)
$TN_{p'pw}$, TNs_{ipw}, TNs_{npw}, TNs_{mpw}	NH_3-N discharge permit sold to fishery zone p from fishery zone p', agricultural zone i, livestock and poultry industry zone n and company m, respectively (ton)
$TN_{m'mw}$, TNs_{imw}, TNs_{nmw}, TNs_{pmw}	NH_3-N discharge permit sold to company m from company m', agricultural zone i, livestock and poultry industry zone n and fishery zone p, respectively (ton)
TNb_{niw}, TNb_{piw}, TNb_{miw}	NH_3-N discharge permit in agricultural zone i purchased from livestock and poultry industry zone n, fishery zone p and company m, respectively (ton)
TNb_{inw}, TNb_{pnw}, TNb_{mnw}	NH_3-N discharge permit in livestock and poultry industry zone n purchased from agricultural zone i, fishery zone p and company m, respectively (ton)
TNb_{ipw}, TNb_{npw}, TNb_{mpw}	NH_3-N discharge permit in fishery zone p purchased from agricultural zone i, livestock and poultry industry zone n and company m, respectively (ton)
TNb_{imw}, TNb_{nmw}, TNb_{pmw}	NH_3-N discharge permit in company m purchased from agricultural zone i, livestock and poultry industry zone n and fishery zone p, respectively (ton)
$TN_{ii'w}$, $TN_{nn'w}$, $TN_{pp'w}$, $TN_{mm'w}$	NH_3-N discharge permit agricultural zone i sold

	to i', livestock and poultry industry zone n sold to n', fishery zone p sold to p' and company m sold to m',respectively (ton)
$tp_{i'i}$, tp_{ni}, tp_{pi}, tp_{mi}	TP trading ratio of transaction from agricultural zone i', livestock and poultry industry zone n, fishery zone p and company m to agricultural zone i, respectively
$tp_{n'n}$, tp_{in}, tp_{pn}, tp_{mn}	TP trading ratio of transaction from livestock and poultry industry zone n', agricultural zone i, fishery zone p and company m to livestock and poultry industry zone n, respectively
$tp_{p'p}$, tp_{ip}, tp_{np}, tp_{mp}	TP trading ratio of transaction from fishery zone p', agricultural zone i, livestock and poultry industry zone n and company m to fishery zone p, respectively
$tp_{m'm}$, tp_{im}, tp_{nm}, tp_{pm}	TP trading ratio of transaction from company m', agricultural zone i, livestock and poultry industry zone n and fishery zone p to company m, respectively
$tp_{ii'}$, $tp_{nn'}$, $tp_{pp'}$, $tp_{mm'}$	TP trading ratio of transaction from agricultural zone i to i', from livestock and poultry industry zone n to n', from fishery zone p to p' and from company m to m', respectively
$tn_{i'i}$, tn_{ni}, tn_{pi}, tn_{mi}	NH_3-N trading ratio of transaction from agricultural zone i', livestock and poultry industry zone n, fishery zone p and company m to agricultural zone i, respectively
$tn_{n'n}$, tn_{in}, tn_{pn}, tn_{mn}	NH_3-N trading ratio of transaction from livestock and poultry industry zone n', agricultural zone i, fishery zone p and company m to livestock and poultry industry zone n, respectively
$tn_{p'p}$, tn_{ip}, tn_{np}, tn_{mp}	NH_3-N trading ratio of transaction from fishery zone p', agricultural zone i, livestock and poultry industry zone n and company m to

	fishery zone p, respectively
$tn_{m'm}$, tn_{im}, tn_{nm}, tn_{pm}	NH_3-N trading ratio of transaction from company m', agricultural zone i, livestock and poultry industry zone n and fishery zone p to company m, respectively
$tn_{ii'}$, $tn_{nn'}$, $tn_{pp'}$, $tn_{mm'}$	NH_3-N trading ratio of transaction from agricultural zone i to i', from livestock and poultry industry zone n to n', from fishery zone p to p' and from company m to m', respectively
p_h	Constraint-violation probability
PE_r	The quantity of energy in per kg of crop j (kcal/kg)
LE_r	The quantity of required energy in per livestock r (kcal/one)
DP	Total population in Daguhe watershed
MP	Total population in Moshuihe watershed
NE	The quantity of required energy for per person from the crop in each year (kcal/one/a)
CE_j	The quantity of digestible protein in per kg of crop j (g/kg)
LP_r	The quantity of required digestible protein for per livestock r in each year (g/one/a)
NP	The quantity of required digestible protein for per person (g/one/a)
TPA_{iw}, TPL_{nw}, TPS_{pw}, TPC_{mw}	Allowance of TP emission for agricultural zones, livestock and poultry industry zones, fishery zones and companies within the two watersheds in level w (ton)
TNA_{iw}, TNL_{nw}, TNS_{pw}, TNC_{mw}	Allowance of NH_3-N emission for agricultural zones, livestock and poultry industry zones, fishery zones and companies within the two watersheds in level w (ton)
TPG_w	Allowance of TP emission in Daguhe watershed in

	level *w* (ton)
TNG_w	Allowance of NH_3-N emission in Daguhe watershed in level *w* (ton)
$TPGF_{qw}$	Allowance of TP emission in reach q, Daguhe watershed in level *w* (ton)
$TNGF_{qw}$	Allowance of NH_3-N emission in reach q, Daguhe watershed in level *w* (ton)
TPW_w	Allowance of TP emission in Moshuihe watershed in level *w* (ton)
TNW_w	Allowance of NH_3-N emission in Moshuihe watershed in level *w* (ton)
$TPWF_{ow}$	Allowance of TP emission in reach o, Moshuihe watershed in level *w* (ton)
$TNWF_{ow}$	Allowance of NH_3-N emission in reach o, Moshuihe watershed in level *w* (ton)
TPT_w	Allowance of TP emission in both watersheds in level *w* (ton)
TNT_w	Allowance of NH_3-N emission in both watersheds in level *w* (ton)

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List of Table Captions

Table 1 Sensitive parameters of SWAT model for TP and NH_3-N

	Parameter	Description	Limit value range		Units
			Min	Max	
TP	CH_N（2）	Manning's "n" value for the main channel	0	0.3	
	ALPHA_BF	Baseflow recession factor	0.001	0.056	
	USLE_P	USLE equation support practice factor	0	1	
	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur	0	500	mm
	CH_K2	Effective hydraulic conductivity in main channel alluvium	0	500	mm/hr
	GW_REVAP	Groundwater revap coefficient	0.02	0.2	
	LAT_TTIME	Lateral flow travel time	0	180	
	GWSOLP	Concentration of soluble phosphorus in groundwater contribution to streamflow from subbasin	0	1000	mg P/l
	SOL_AWC	Available water capacity of the soil layer	0	1	mm/mm soil
	CN2	SCS runoff curve number for moisture condition II	35	98	
NH_3-N	CN2	SCS runoff curve number for moisture condition II	35	98	
	SOL_AWC	Available water capacity of the soil layer	0	1	mm/mm soil
	SURLAG	Surface runoff lag coefficient	0.05	24	
	SHALLST_N	Concentration of nitrate in groundwater contribution to streamflow from subbasin	0	1000	mg N/l
	GWQMN	Treshold depth of water in the shallow aquifer required for return flow to occur	0	5000	mm
	BC2	Rate constant for biological oxidation of NO2 to NO3 in the reach at 20 ℃.	0.2	2	1/day
	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur	0	500	mm
	CH_K2	Effective hydraulic conductivity in main channel alluvium	0	500	mm/hr
	HRU_SLP	Average slope steepness	0	0.6	
	N_UPDIS	Nitrogen uptake distribution parameter	0	100	

Table 2 TP and NH_3-N loading distribution and the associated probabilities (unit ton)

TP loading level	Low (k = 1)	Medium (k = 2)	High (k = 3)
Probability	0.42	0.46	0.12
Lower-bound loading	109.4	313.4	570.2
Probability	0.42	0.46	0.12
Upper-bound loading	419.9	1083.0	1751.4
NH_3-N loading level	Low (s = 1)	Medium (s = 2)	High (s = 3)
Probability	0.36	0.53	0.11
Lower-bound loading	112.3	342.8	662.7
Probability	0.36	0.53	0.11
Upper-bound loading	638.5	1598.8	2457.0

Table 3 The detailed trading process for TP under Case 1 when p = 0.01 and w = 1

Seller/purchaser	i = 1	i = 2	i = 3	i = 4	i = 5	n = 1	n = 2	n = 3	p = 1
i = 1	0/0	0/0	0/0	35.43/14.82	0/0	0/0	0/0	1.32/1.08	0/0
i = 2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 3	0/0	0/0	0/0	25.39/19.68	0/0	0/0	0/0	0/0	0/0
i = 4	0/0	3.32/3.32	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 5	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1.18/1.13
n = 2	0/0	0/0	19.05/18.45	0/0	0/0	0/0	0/0	0/0	0/0
n = 3	0/0	0/0	0/0	0/0	0/0	0/0	3.42/2.63	0/0	0/0
p = 1	0/0	0/0	0/0	0/0	0/0	3.44/3.44	0/0	0/0	0/0
p = 2	3.34/3.34	7.89/6.16	0/0	7.89/5.48	0/0	0/0	0/0	0/0	0/0
p = 3	0/0	0.52/0.31	0/0	0	0/0	0/0	4.47/3.6	0/0	0/0
m = 1	/	/	/	/	0/0	/	/	/	/
m = 2	/	/	/	/	0.2/0.2	/	/	/	/
m = 3	/	/	/	/	0/0	/	/	/	/
m = 4	/	/	/	/	0.01/0	/	/	/	/
m = 5	/	/	/	/	0/0	/	/	/	/
m = 6	/	/	/	/	0/0	/	/	/	/
m = 7	/	/	/	/	0.82/0.82	/	/	/	/

Seller/purchaser	p = 2	p = 3	m = 1	m = 2	m = 3	m = 4	m = 5	m = 6	m = 7
i = 1	0/0	0/0	/	/	/	/	/	/	/
i = 2	0/0	0/0	/	/	/	/	/	/	/
i = 3	0/0	0/0	/	/	/	/	/	/	/
i = 4	34.70/34.70	0/0	/	/	/	/	/	/	/
i = 5	0/0	0/0	0/0	0/0	0/0	0/0	0.08/0.03	0/0	0/0
n = 1	0/0	2.2/1.28	/	/	/	/	/	/	/
n = 2	0/0	0/0	/	/	/	/	/	/	/
n = 3	0/0	0/0	/	/	/	/	/	/	/
p = 1	0/0	0/0	/	/	/	/	/	/	/
p = 2	0/0	0/0	/	/	/	/	/	/	/
p = 3	0/0	0/0	/	/	/	/	/	/	/
m = 1	/	/	0/0	0.2/0.2	0/0	0/0	0.02/0.01	0/0	0/0
m = 2	/	/	0/0	0/0	0/0	0.01/0.01	0.02/0.01	0/0	0.38/0.38
m = 3	/	/	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 4	/	/	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 5	/	/	0/0	0.15/0.15	0/0	0/0	0/0	0/0	0/0
m = 6	/	/	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 7	/	/	0.13/0.13	0/0	0/0	0/0	0.02/0.01	0/0	0/0

Table 4 The detailed trading process for NH_3-N under Case 1 when p = 0.01 and w = 1

Seller/purchaser	i = 1	i = 2	i = 3	i = 4	i = 5	n = 1	n = 2	n = 3	p = 1
i = 1	0/0	440.76/209.89	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 2	0/0	0/0	0/0	177.16/168.72	0/0	228/228	0/0	0/0	0/0
i = 3	0/0	0/0	0/0	177.16/125.64	0/0	0/0	0/0	0/0	45.07/45.07
i = 4	0/0	0/0	0/0	0/0	0/0	177.16/177.16	49.15/49.15	0/0	0/0
i = 5	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 1	0/0	154.6/54.82	154.6/79.7	32.28/11.17	0/0	0/0	120.04/57.16	0/0	0/0
n = 2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 3	8.40/8.40	0/0	21.83/16.29	0/0	0/0	0/0	0/0	0/0	0/0
p = 1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	39.43/18.78
p = 2	0/0	39.43/30.8	0/0	10.43/7.73	0/0	39.43/39.43	0/0	39.43/39.43	0/0
p = 3	34.12/34.12	34.12/18.95	34.12/26.66	34.12/19.06	0/0	34.12/34.12	0/0	0/0	0/0
m = 1	/	/	/	/	2.3/2.3	/	/	/	/
m = 2	/	/	/	/	3.46/3.46	/	/	/	/
m = 3	/	/	/	/	0.01/0.01	/	/	/	/
m = 4	/	/	/	/	0.14/0.14	/	/	/	/
m = 5	/	/	/	/	0.36/0.36	/	/	/	/
m = 6	/	/	/	/	0.06/0.06	/	/	/	/
m = 7	/	/	/	/	29.1/29.1	/	/	/	/
Seller/purchaser	p = 2	p = 3	m = 1	m = 2	m = 3	m = 4	m = 5	m = 6	m = 7
i = 1	0/0	0/0	/	/	/	/	/	/	/
i = 2	0/0	0/0	/	/	/	/	/	/	/
i = 3	0/0	0/0	/	/	/	/	/	/	/
i = 4	0/0	174.39/174.39	/	/	/	/	/	/	/
i = 5	0/0	0/0	42.67/34.14	0/0	0/0	0/0	0/0	0/0	0/0
n = 1	0/0	0/0	/	/	/	/	/	/	/
n = 2	120.04/114.33	0/0	/	/	/	/	/	/	/
n = 3	0/0	0/0	/	/	/	/	/	/	/
p = 1	0/0	0/0	/	/	/	/	/	/	/
p = 2	0/0	0/0	/	/	/	/	/	/	/
p = 3	0/0	0/0	/	/	/	/	/	/	/
m = 1	/	/	0/0	3.46/3.46	0.01/0.01	0.14/0.14	0.36/0.18	0/0	29.1/29.1
m = 2	/	/	0/0	0/0	0.01/0.01	0/0	0.36/0.18	0.06/0.06	0/0
m = 3	/	/	0/0	0/0	0/0	0/0	0/0	0/0	0.02/0.02
m = 4	/	/	0/0	0/0	0.01/0.01	0/0	0/0	0.06/0.06	0/0
m = 5	/	/	0/0	0/0	0/0	0.08/0.08	0/0	0/0	0.07/0.07
m = 6	/	/	0/0	0/0	0.01/0.01	0/0	0/0	0/0	0.05/0.05
m = 7	/	/	0/0	0.81/0.81	0/0	0/0	0.36/0.18	0/0	0/0

Table 5 The detailed trading process for TP under Case 2 when p = 0.01 and w = 1

Seller/purchaser	i = 1	i = 2	i = 3	i = 4	i = 5	n = 1	n = 2	n = 3	p = 1
i = 1	0/0	0/0	0/0	0/0	0.41/0.31	0/0	0/0	0/0	4.56/4.56
i = 2	0/0	0/0	4.12/4.12	0/0	0/0	0/0	0/0	0/0	0/0
i = 3	0/0	0/0	0/0	0/0	23.73/23.73	0/0	0/0	0/0	0/0
i = 4	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 5	0/0	0/0	0/0	0.88/0.88	0/0	0/0	0/0	0/0	0/0
n = 1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 3	0/0	0/0	2.36/1.76	0/0	0/0	0/0	0/0	0/0	0/0
p = 1	0/0	0/0	0/0	0/0	0/0	3.44/3.44	0/0	0/0	0/0
p = 2	0/0	7.89/6.16	7.89/7.89	0/0	0/0	0/0	2.67/2.67	0/0	0/0
p = 3	0/0	0/0	2.2/1.72	0/0	0/0	0/0	0/0	0/0	0/0
m = 1	0/0	0.13/0.13	0.13/0.13	0.13/0.13	0.13/0.13	0/0	0/0	0/0	0/0
m = 2	0/0	0.2/0.2	0.2/0.2	0.2/0.2	0.2/0.2	0/0	0/0	0/0	0/0
m = 3	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 4	0/0	0.01/0.01	0.01/0.01	0.01/0.01	0.01/0.01	0/0	0/0	0.01/0.01	0/0
m = 5	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 6	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 7	0/0	0.97/0.97	0.97/0.97	0.97/0.97	0.97/0.97	0/0	0/0	0/0	0/0

Seller/purchaser	p = 2	p = 3	m = 1	m = 2	m = 3	m = 4	m = 5	m = 6	m = 7
i = 1	0/0	0/0	0/0	0/0	0/0	0.03/0.03	0/0	0/0	0/0
i = 2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 3	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 4	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 5	26.66/26.66	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 3	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
p = 1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
p = 2	0/0	2.62/2.62	0/0	0.08/0.08	0/0	0/0	0.01/0.01	0/0	4.64/4.64
p = 3	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 1	0/0	0.13/0.13	0/0	0/0	0/0	0/0	0/0	0/0	0.13/0.13
m = 2	0/0	0.2/0.2	0.20/0.20	0/0	0/0	0/0	0/0	0.02/0.02	0/0
m = 3	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 4	0/0	0.01/0.01	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 5	0/0	0/0	0/0	0.02/0.02	0/0	0/0	0/0	0/0	0/0
m = 6	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 7	0/0	0/0	0.51/0.51	0.97/0.97	0/0	0/0	0/0	0/0	0/0

Table 6 The detailed trading process for NH_3-N under Case 2 when p = 0.01 and w = 1

Seller/purchaser	i = 1	i = 2	i = 3	i = 4	i = 5	n = 1	n = 2	n = 3	p = 1
i = 1	0/0	296.19/141.04	119.99/82.18	0/0	0/0	0/0	0/0	0/0	0/0
i = 2	307.09/307.09	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 3	0/0	0/0	0/0	0/0	381.4/381.4	0/0	0/0	0/0	0/0
i = 4	0/0	0/0	0/0	0/0	13.44/13.44	0/0	0.73/0.73	25.31/25.31	0/0
i = 5	134.08/134.08	0/0	0/0	0/0	0/0	0/0	134.08/134.08	134.08/134.08	0/0
n = 1	0/0	0/0	0/0	0/0	0/0	0/0	74.1/35.29	0/0	0/0
n = 2	0/0	94.07/70.2	0/0	0/0	0/0	0/0	0/0	0/0	120.04/120.04
n = 3	82.77/82.77	0/0	82.77/61.77	82.77/44.03	0/0	0/0	0/0	0/0	0/0
p = 1	0/0	0/0	0/0	0/0	0/0	50.78/50.78	50.78/25.39	7.68/5.56	0/0
p = 2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	39.43/39.43
p = 3	0/0	0/0	0/0	0/0	0/0	0/0	0/0	34.12/34.12	0/0
m = 1	2.30/2.30	2.30/1.90	2.30/2.30	2.30/1.90	2.30/2.30	2.30/2.30	2.30/1.79	2.30/2.30	2.30/2.30
m = 2	3.46/3.46	3.46/2.88	0/0	3.46/2.88	3.46/3.46	3.46/3.46	3.46/2.68	3.46/3.46	3.46/3.46
m = 3	0.01/0.01	0.01/0.01	0.01/0.01	0.01/0.01	0.01/0.01	0.01/0.01	0.01/0.01	0.01/0.01	0.01/0.01
m = 4	0.14/0.11	0/0	0/0	0.14/0.11	0/0	0/0	0.14/0.11	0/0	0/0
m = 5	0.36/0.36	0.36/0.36	0.36/0.36	0.36/0.36	0.36/0.36	0.36/0.36	0.36/0.36	0.36/0.36	0.36/0.36
m = 6	0.06/0.06	0/0	0/0	0/0	0.06/0.06	0/0	0/0	0/0	0.06/0.06
m = 7	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

Seller/purchaser	p = 2	p = 3	m = 1	m = 2	m = 3	m = 4	m = 5	m = 6	m = 7
i = 1	0/0	0/0	0/0	59.56/35.88	0/0	0/0	0/0	0/0	0/0
i = 2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 3	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 4	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
i = 5	14.96/14.96	65.84/65.84	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
n = 3	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
p = 1	50.78/24.18	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
p = 2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
p = 3	0/0	0/0	34.12/30.74	0/0	0/0	0/0	0/0	0/0	0/0
m = 1	2.30/1.71	2.30/2.30	0/0	2.30/2.30	0/0	0.53/0.53	0/0	0/0	2.30/2.30
m = 2	3.46/2.56	3.46/2.56	0/0	0/0	0/0	0/0	0/0	0.24/0.24	3.46/3.46
m = 3	0.01/0.01	0.01/0.01	0.01/0.01	0.01/0.01	0/0	0.01/0.01	0/0	0.01/0.01	0.01/0.01
m = 4	0/0	0/0	0/0	0.14/0.14	0/0	0/0	0/0	0.14/0.14	0/0
m = 5	0.36/0.36	0.36/0.36	0/0	0/0	0/0	0/0	0/0	0/0	0/0
m = 6	0.06/0.05	0.06/0.06	0/0	0/0	0/0	0.06/0.06	0/0	0/0	0.06/0.06
m = 7	0/0	0/0	0/0	0/0	0.13\0.13	0/0	7.77/3.98	0/0	0/0

Table 7 Total excess TP and NH_3-N emissions in agriculture under three cases (ton)

	Case	Probability	$w = 1$	$w = 2$	$w = 3$
TP	Case 1	$p = 0.01$	0	183.54	60.78
		$p = 0.1$	0	183.34	60.78
	Case 2	$p = 0.01$	0	188.49	84.14
		$p = 0.1$	0	187.80	73.81
	Case 3	$p = 0.01$	0	185.35	69.87
		$p = 0.1$	0	185.35	69.87
NH_3-N	Case 1	$p = 0.01$	0	253.83	0
		$p = 0.1$	0	249.27	0
	Case 2	$p = 0.01$	0	273.34	0
		$p = 0.1$	0	268.24	0
	Case 3	$p = 0.01$	0	259.57	0
		$p = 0.1$	0	259.57	0

Table 8 Total excess TP and NH_3-N emissions under three cases (ton)

	Case	Probability	$w = 1$	$w = 2$	$w = 3$
		$p = 0.01$	243.16	521.48	383.11
	Case 1	$p = 0.05$	238.63	520.62	383.46
		$p = 0.1$	238.63	520.30	380.95
		$p = 0.01$	231.96	521.48	380.46
TP	Case 2	$p = 0.05$	231.96	520.62	375.40
		$p = 0.1$	231.96	520.30	372.88
		$p = 0.01$			
	Case 3	$p = 0.05$	240.82	519.05	370.46
		$p = 0.1$			
		$p = 0.01$	614.11	1195.66	732.82
	Case 1	$p = 0.05$	614.11	1192.36	732.82
		$p = 0.1$	614.11	1190.56	732.82
		$p = 0.01$	614.11	1195.66	732.82
NH_3-N	Case 2	$p = 0.05$	614.11	1192.36	732.82
		$p = 0.1$	614.11	1190.56	732.82
		$p = 0.01$			
	Case 3	$p = 0.05$	627.93	1184.46	750.31
		$p = 0.1$			

List of Figure Captions

fishery and company [(a) TP, $p = 0.01$; (b) TP, $p = 0.05$; (c) TP, $p = 0.1$; (d) NH_3-N, $p = 0.01$; (e) NH_3-N, $p = 0.05$; (f) NH_3-N, $p = 0.1$]

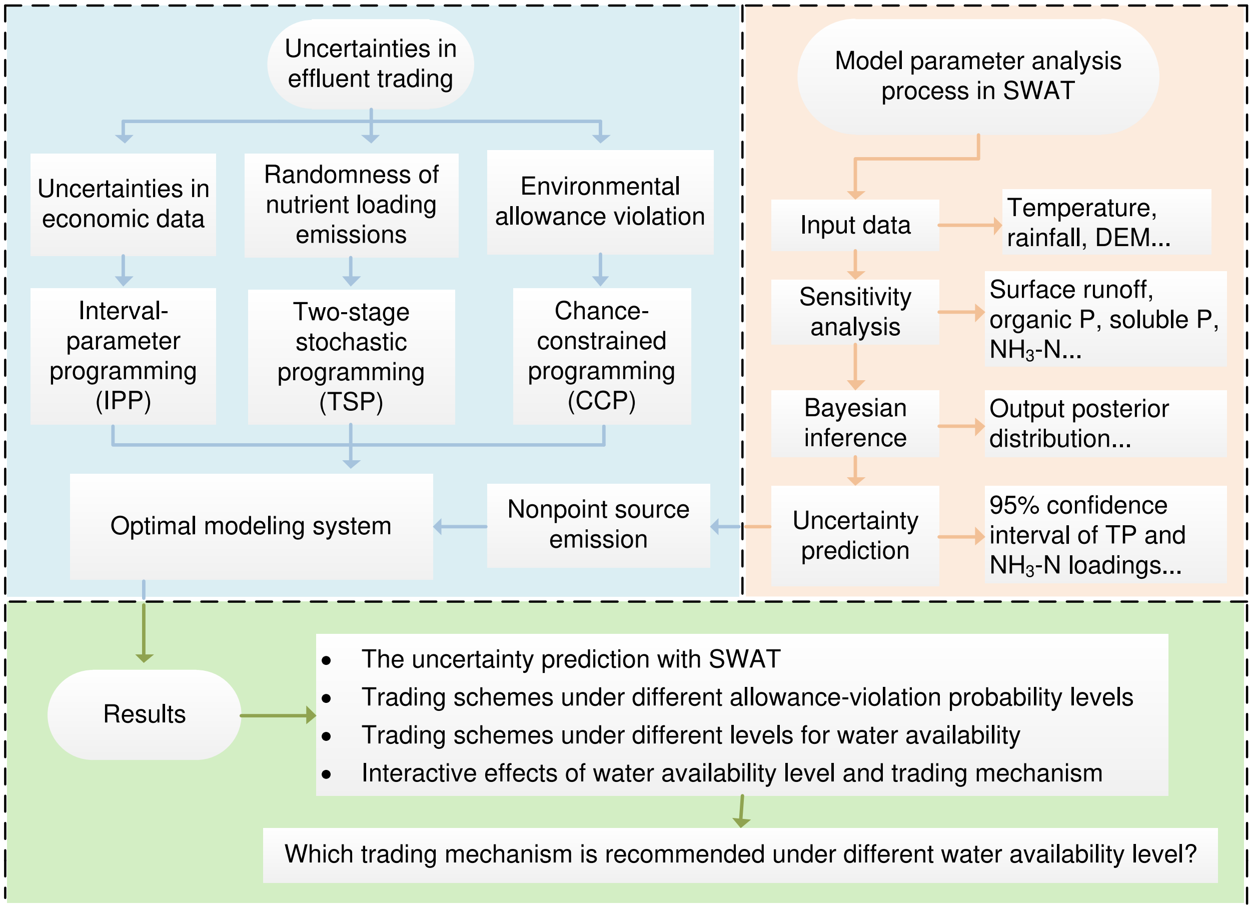

Figure 1 Framework of a Bayesian simulation-based multi-watershed effluent trading designing model (BS-METM)

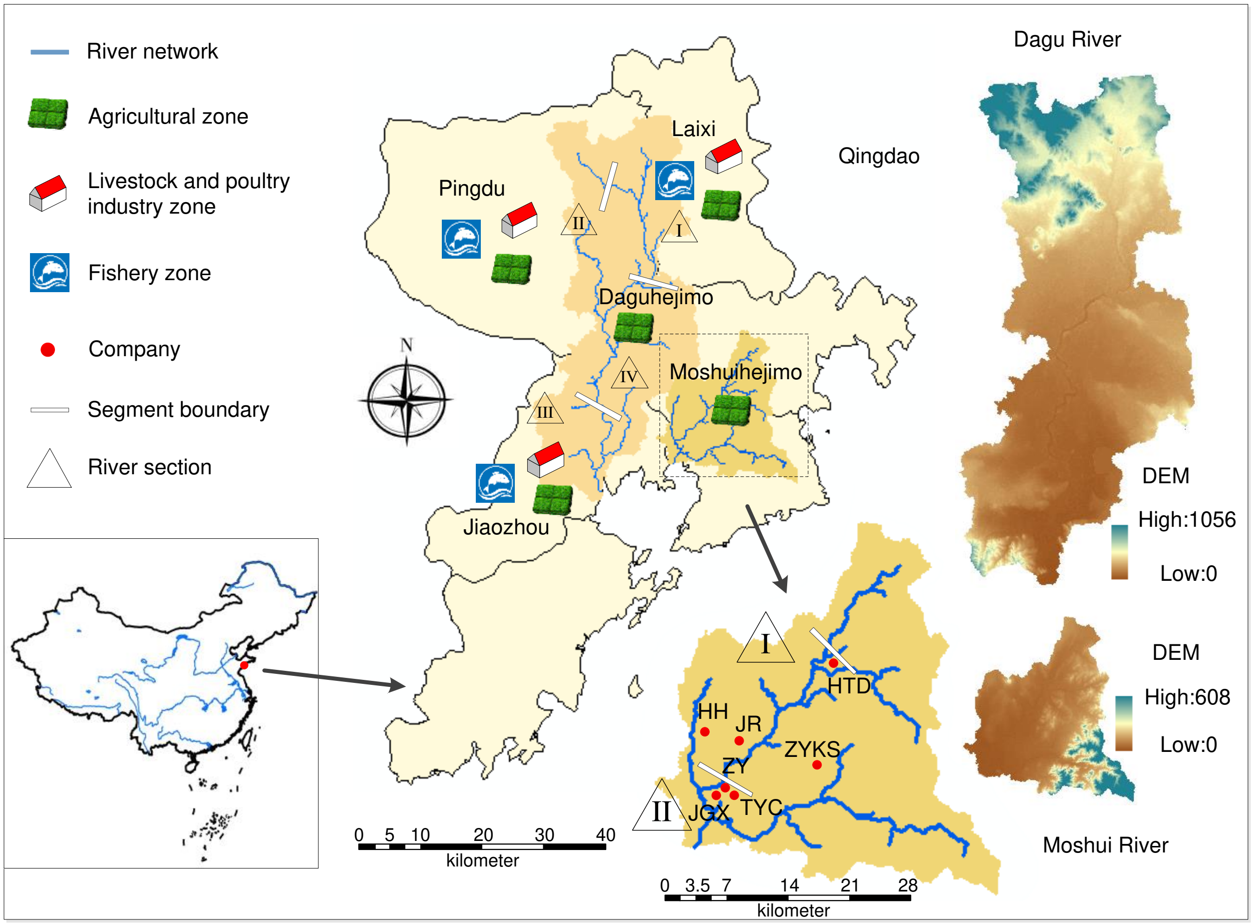

Figure 2 Location and pollution sources of Daguhe and Moshuihe watersheds

Footnote: ZY, TYC, HH, ZYKS, HTD, JR and JGX represent Qingdao Zhengyuan Iron and Steel Co., Ltd, Qingdao Tongyuanchang Steel Co., Ltd, Qingdao Hehe Chemical Co., Ltd, Qingdao Zeyukaisheng Machinery Manufacturing Co., Ltd, Qingdao Huataida Machinery Manufacturing Co., Ltd, Qingdao Jingrui Machinery Manufacturing Co., Ltd and Qingdao Jinguangxin Textile Co., Ltd. Respectively.

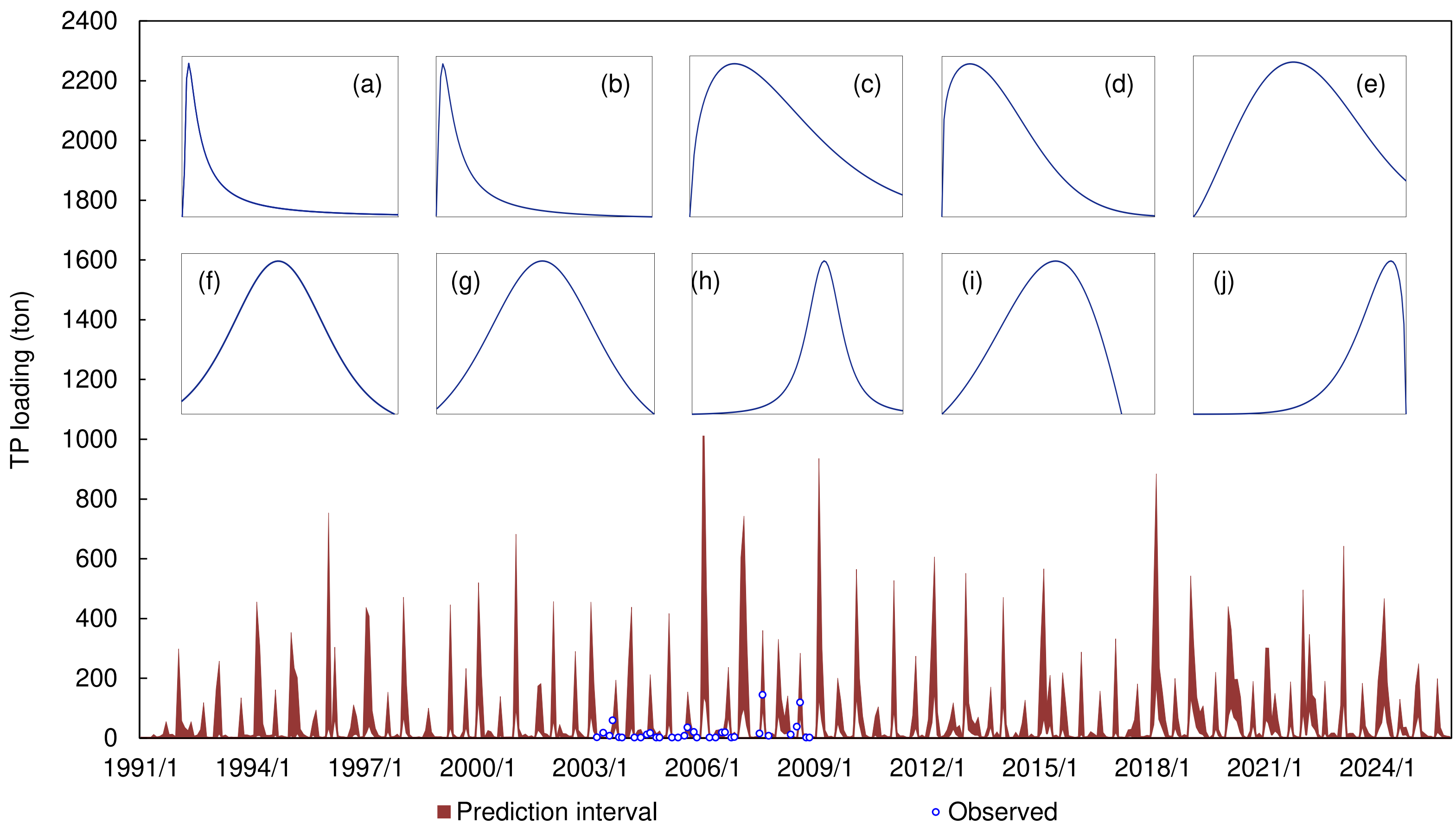

Figure 3 The prediction intervals of TP loading

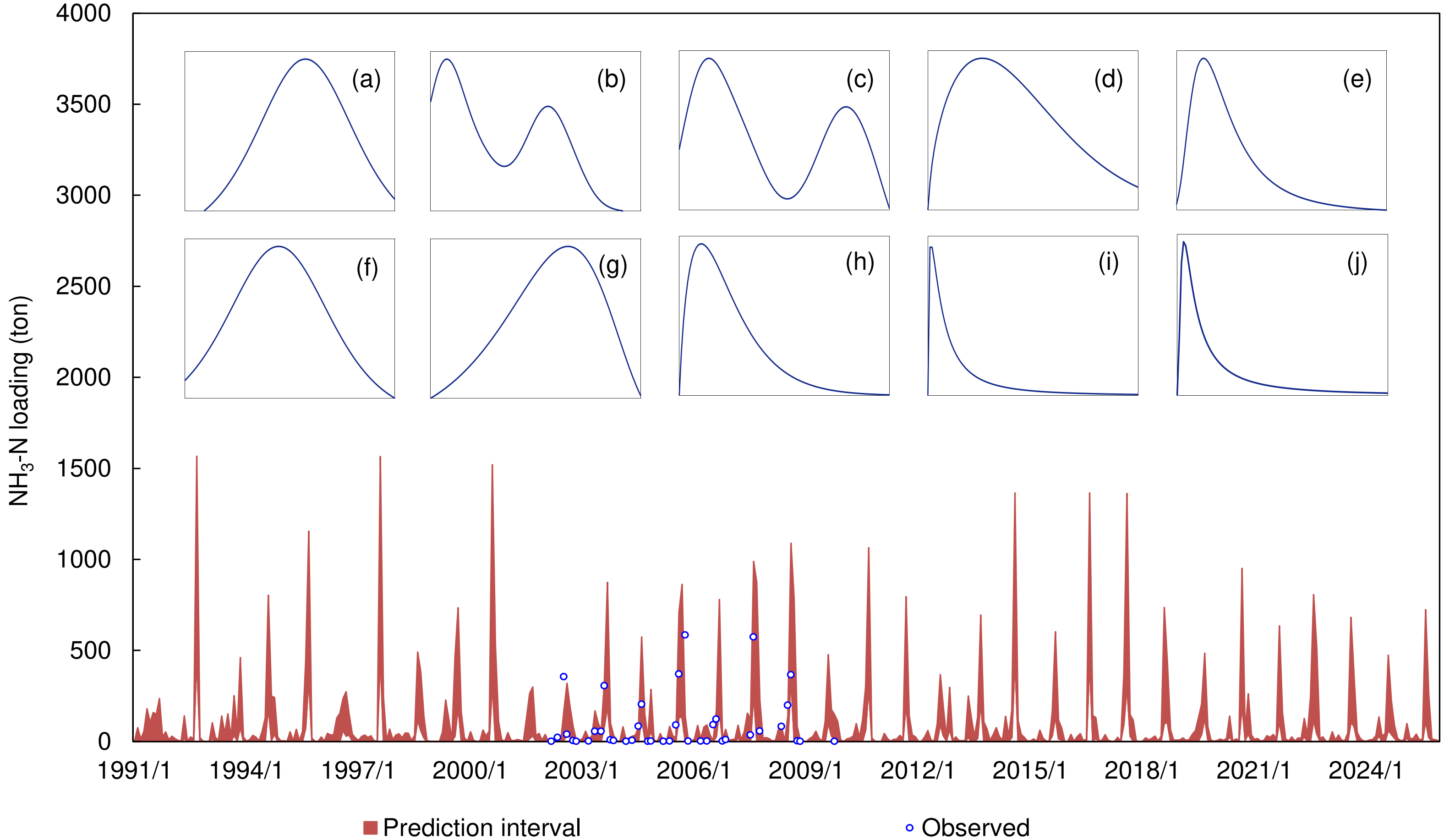

Figure 4 The prediction intervals of NH_3-N loading

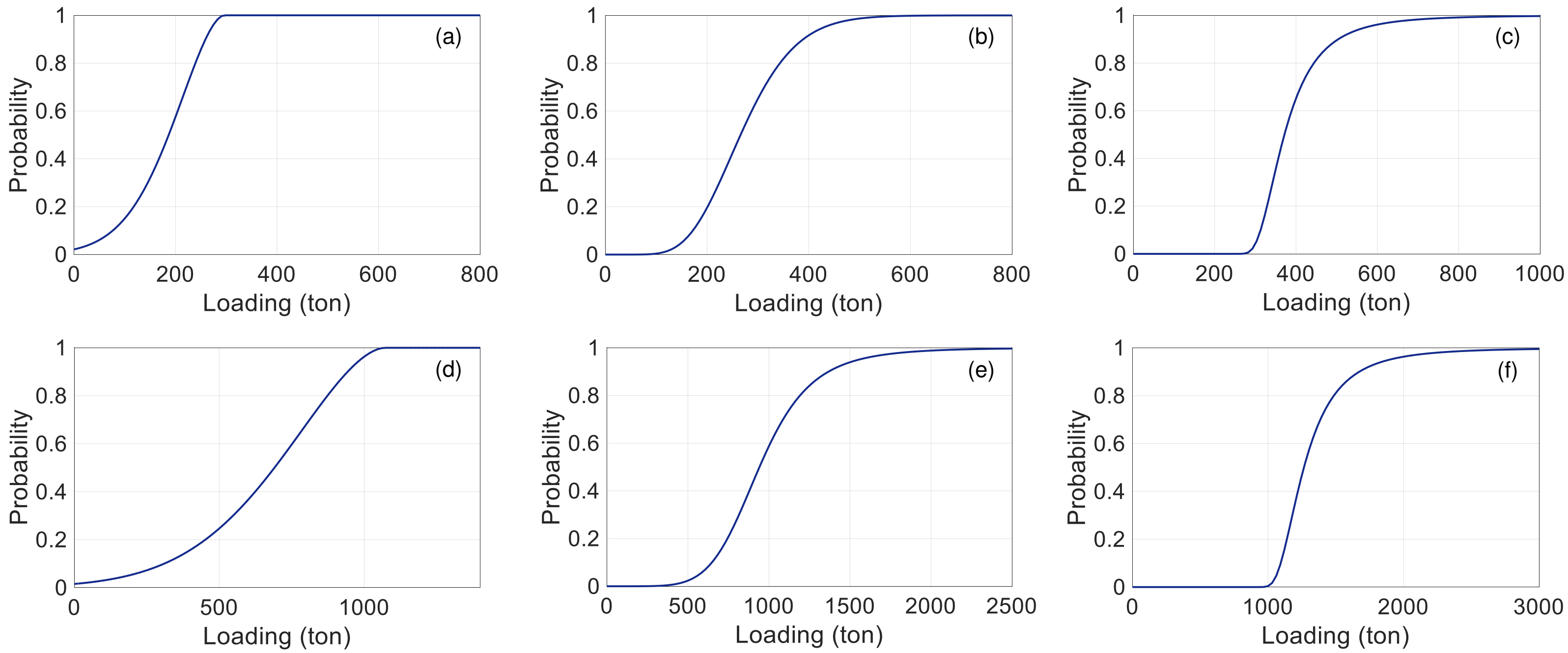

Figure 5 Cumulated distribution functions of TP loadings [(a) low TP loading level for lower bound, (b) medium TP loading level for lower bound, (c) high TP loading level for lower bound, (d) low TP loading level for upper bound, (e) medium TP loading level for upper bound, (f) high TP loading level for upper bound]

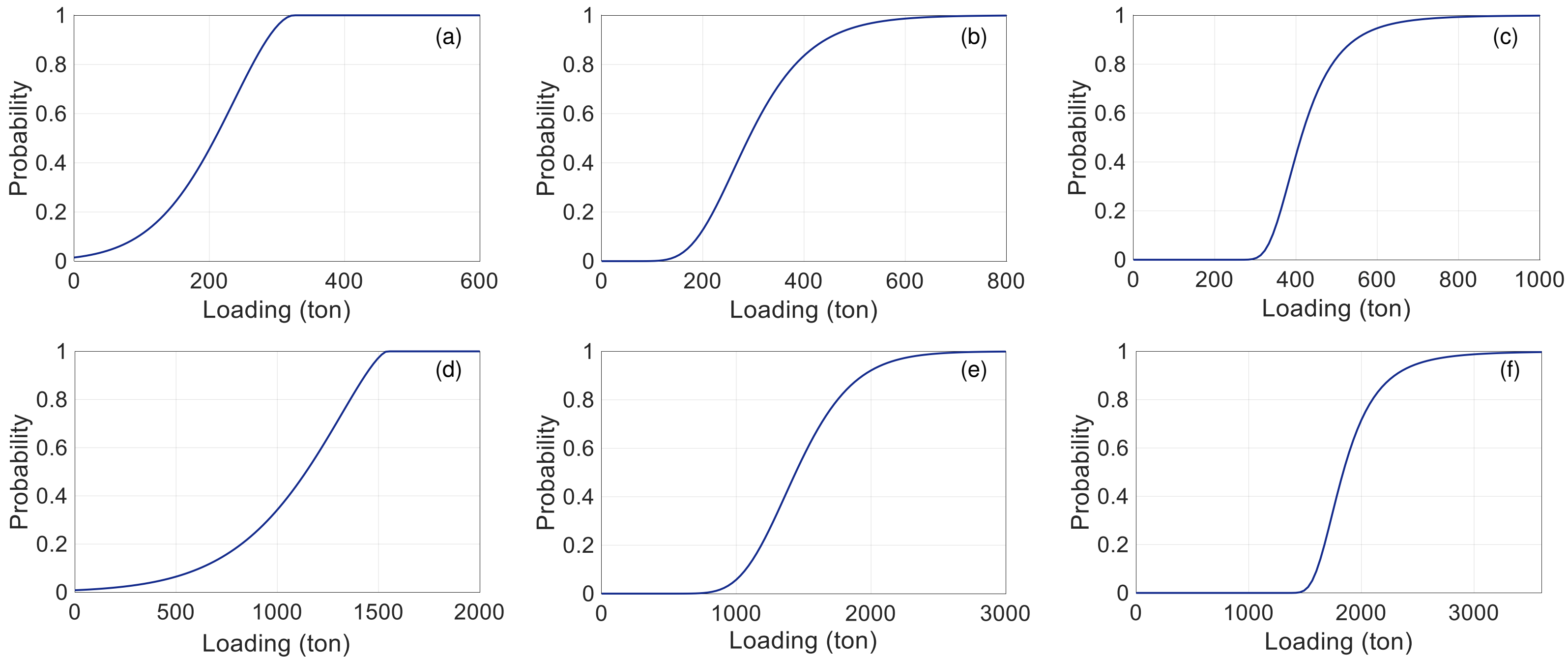

Figure 6 Cumulated distribution functions of NH_3-N loadings [(a) low NH_3-N loading level for lower bound, (b) medium NH_3-N loading level for lower bound, (c) high NH_3-N loading level for lower bound, (d) low NH_3-N loading level for upper bound, (e) medium NH_3-N loading level for upper bound, (f) high NH_3-N loading level for upper bound]

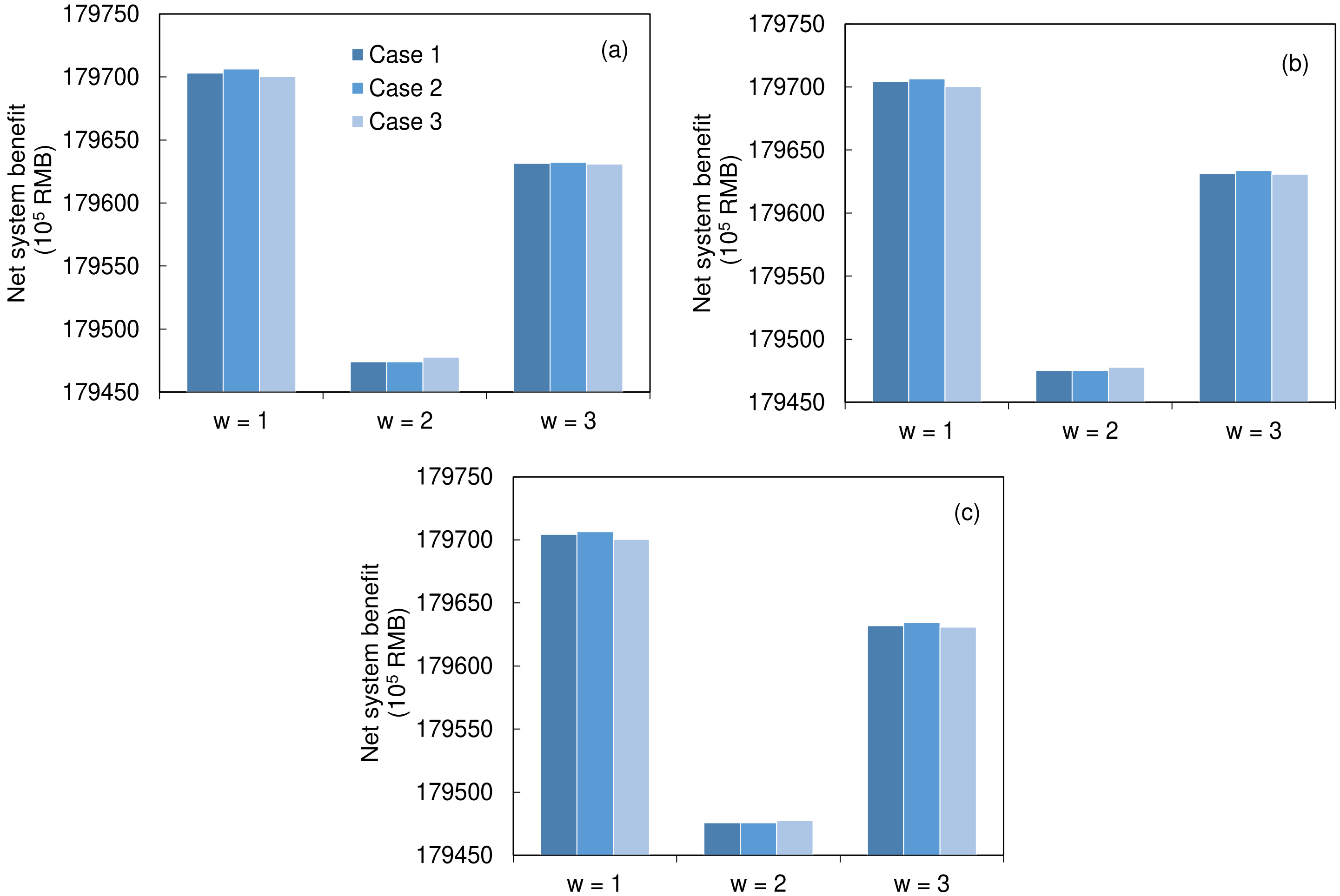

Figure 7 Net system benefits under intra-watershed trading, cross-watershed trading and non-trading cases [(a) $p = 0.01$, (b) $p = 0.05$, (c) $p = 0.1$]

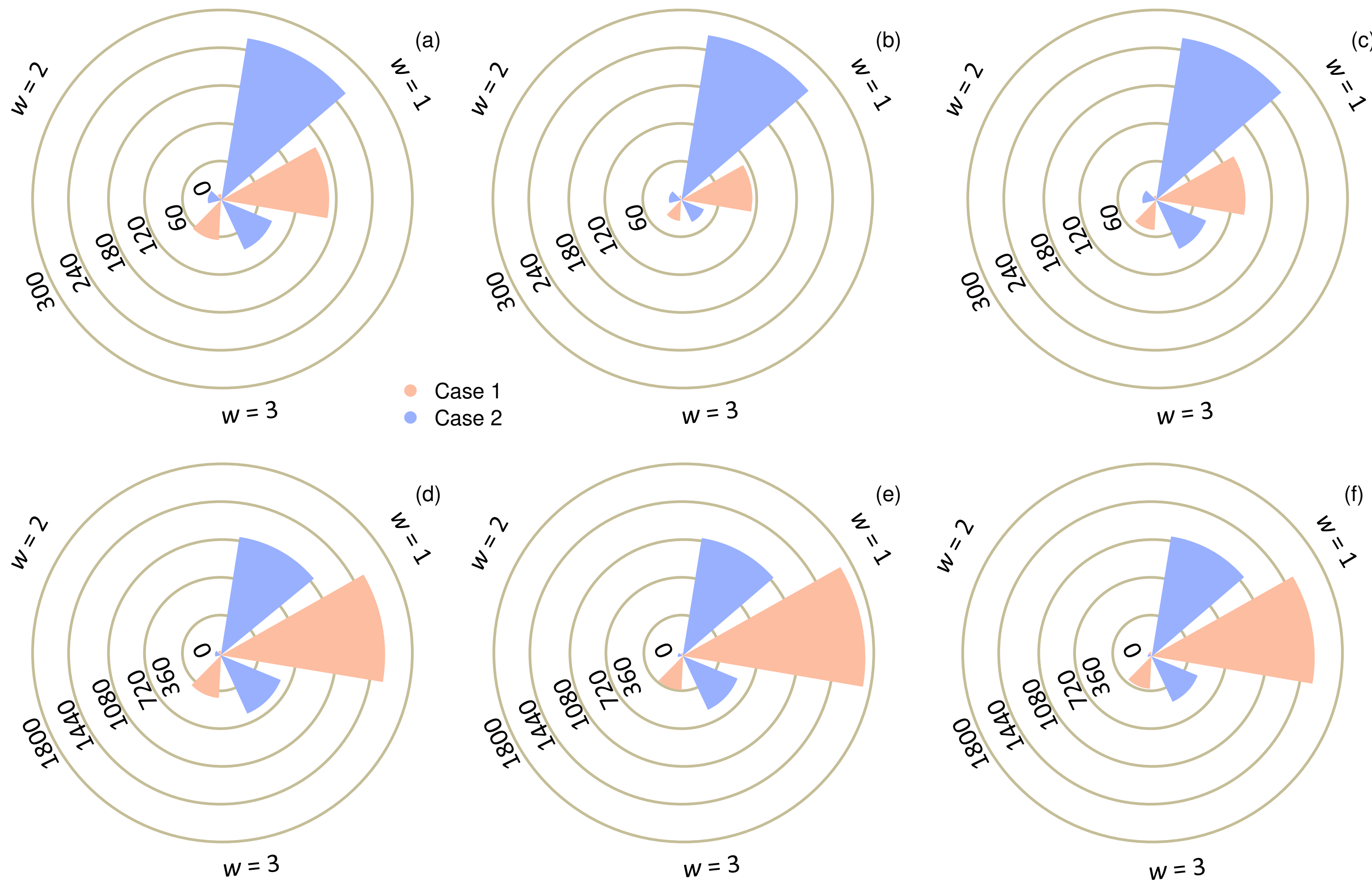

Figure 8 The total trading amounts under Cases 1 and 2 [(a) TP, $p = 0.01$; (b) TP, $p = 0.05$, (c) TP, $p = 0.1$; (d) NH_3-N, $p = 0.01$; (e) NH_3-N, $p = 0.05$, (f) NH_3-N, $p = 0.1$]

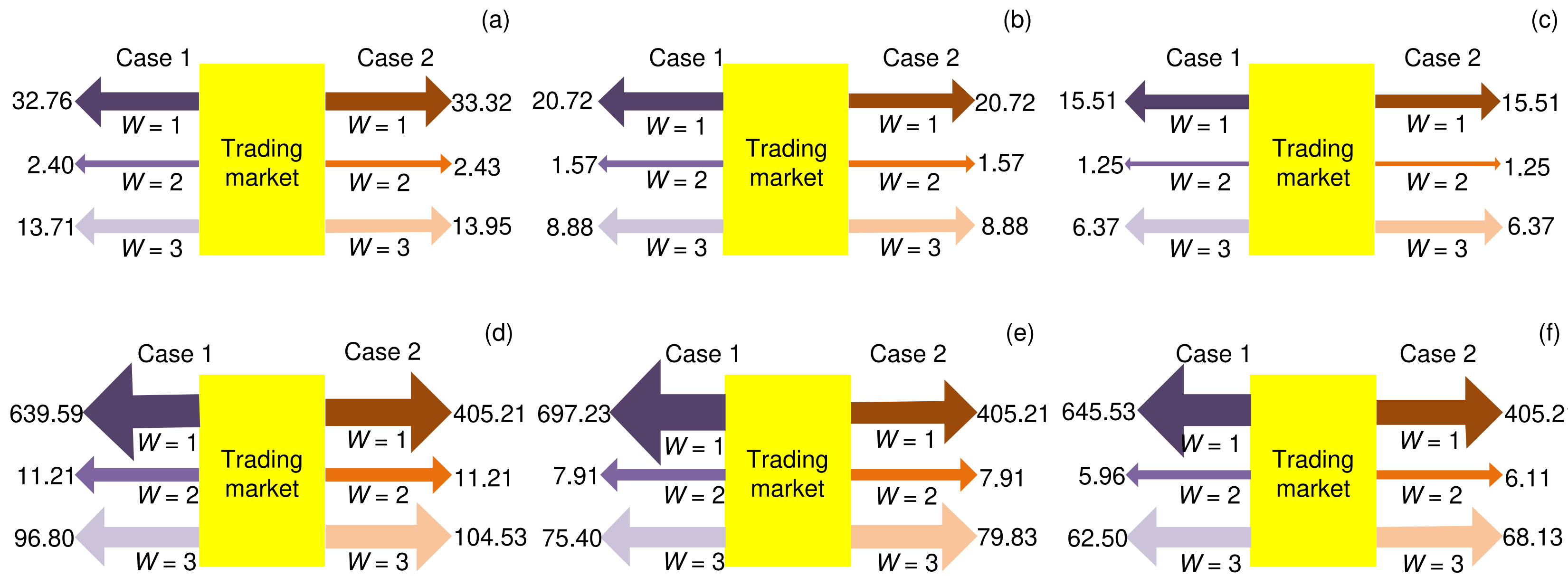

Figure 9 The eliminated trading amounts of tradings under Cases 1 and 2 for TP and NH_3-N [(a) TP, $p = 0.01$; (b) TP, $p = 0.05$; (c) TP, $p = 0.1$; (d) NH_3-N, $p = 0.01$; (e) NH_3-N, $p = 0.05$; (f) NH_3-N, $p = 0.1$]

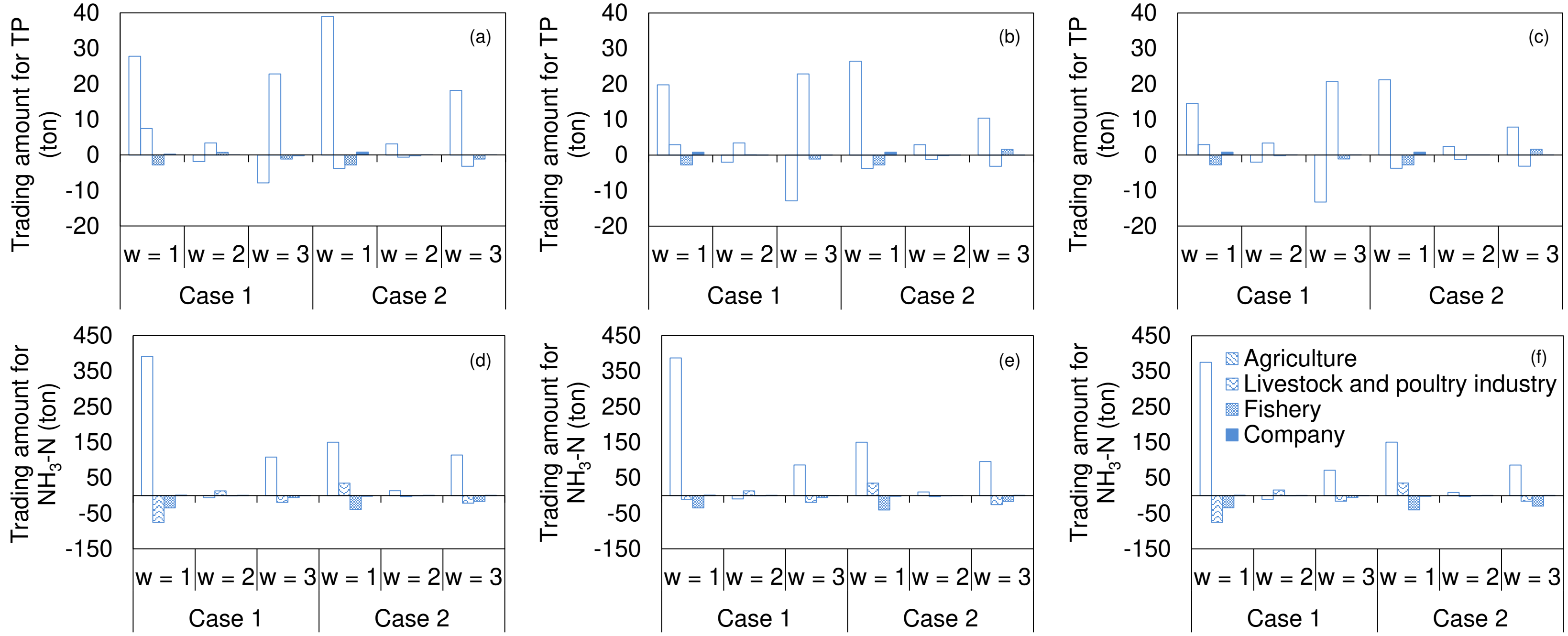

Figure 10 TP and NH_3-N detailed trading process for agriculture, livestock and poultry industry, fishery and company [(a) TP, $p = 0.01$; (b) TP, $p = 0.05$; (c) TP, $p = 0.1$; (d) NH_3-N, $p = 0.01$; (e) NH_3-N, $p = 0.05$; (f) NH_3-N, $p = 0.1$]

Conflicts of interest/Competing intrersts

☐ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Code availability   **Not applicable**

Figures

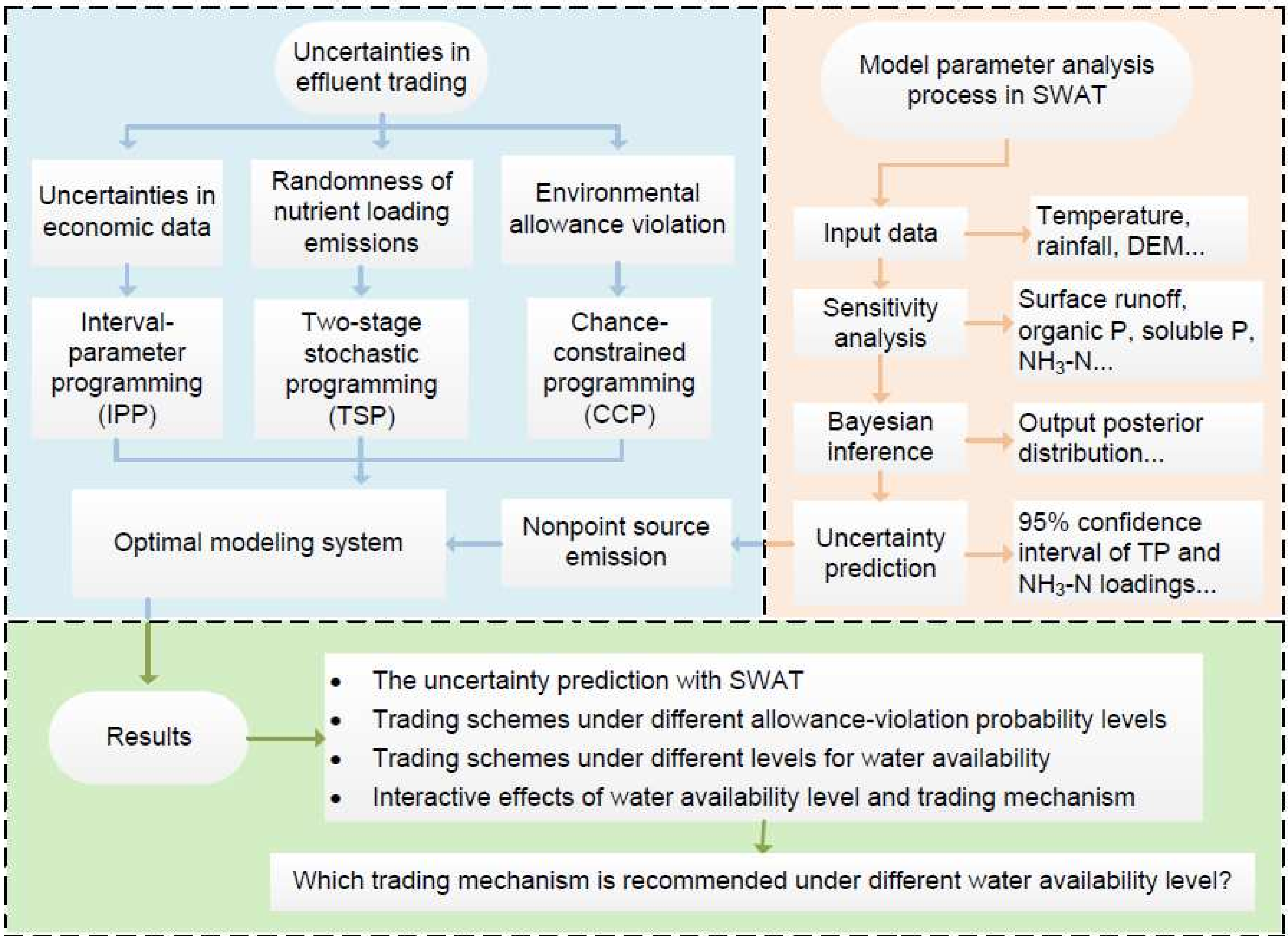


Figure 1

Framework of a Bayesian simulation-based multi-watershed effluent trading designing model (BS-METM)

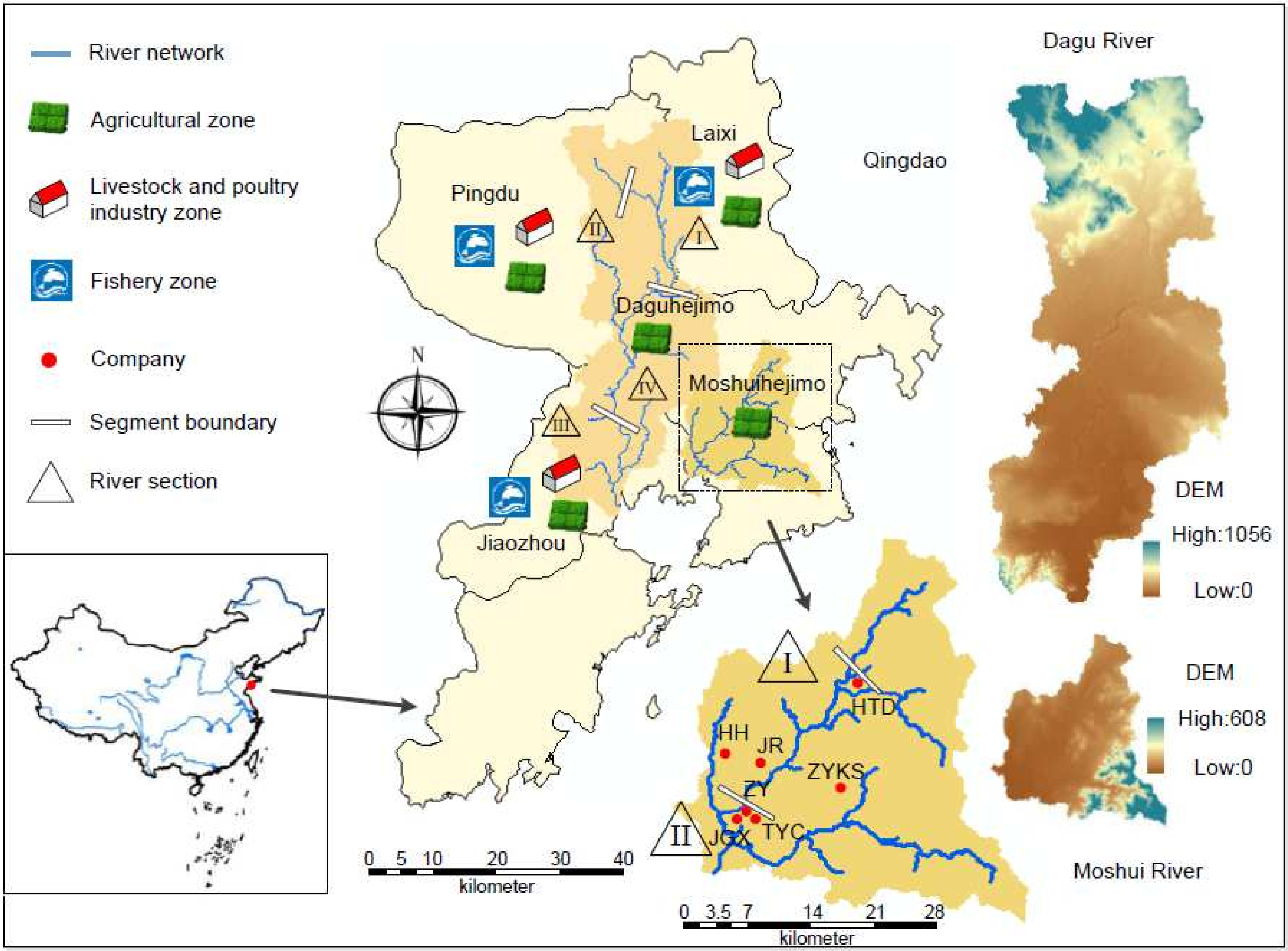


Figure 2

Location and pollution sources of Daguhe and Moshuihe watersheds Footnote: ZY, TYC, HH, ZYKS, HTD, JR and JGX represent Qingdao Zhengyuan Iron and Steel Co., Ltd, Qingdao Tongyuanchang Steel Co., Ltd, Qingdao Hehe Chemical Co., Ltd, Qingdao Zeyukaisheng Machinery Manufacturing Co., Ltd, Qingdao Huataida Machinery Manufacturing Co., Ltd, Qingdao Jingrui Machinery Manufacturing Co., Ltd and Qingdao Jinguangxin Textile Co., Ltd. Respectively. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

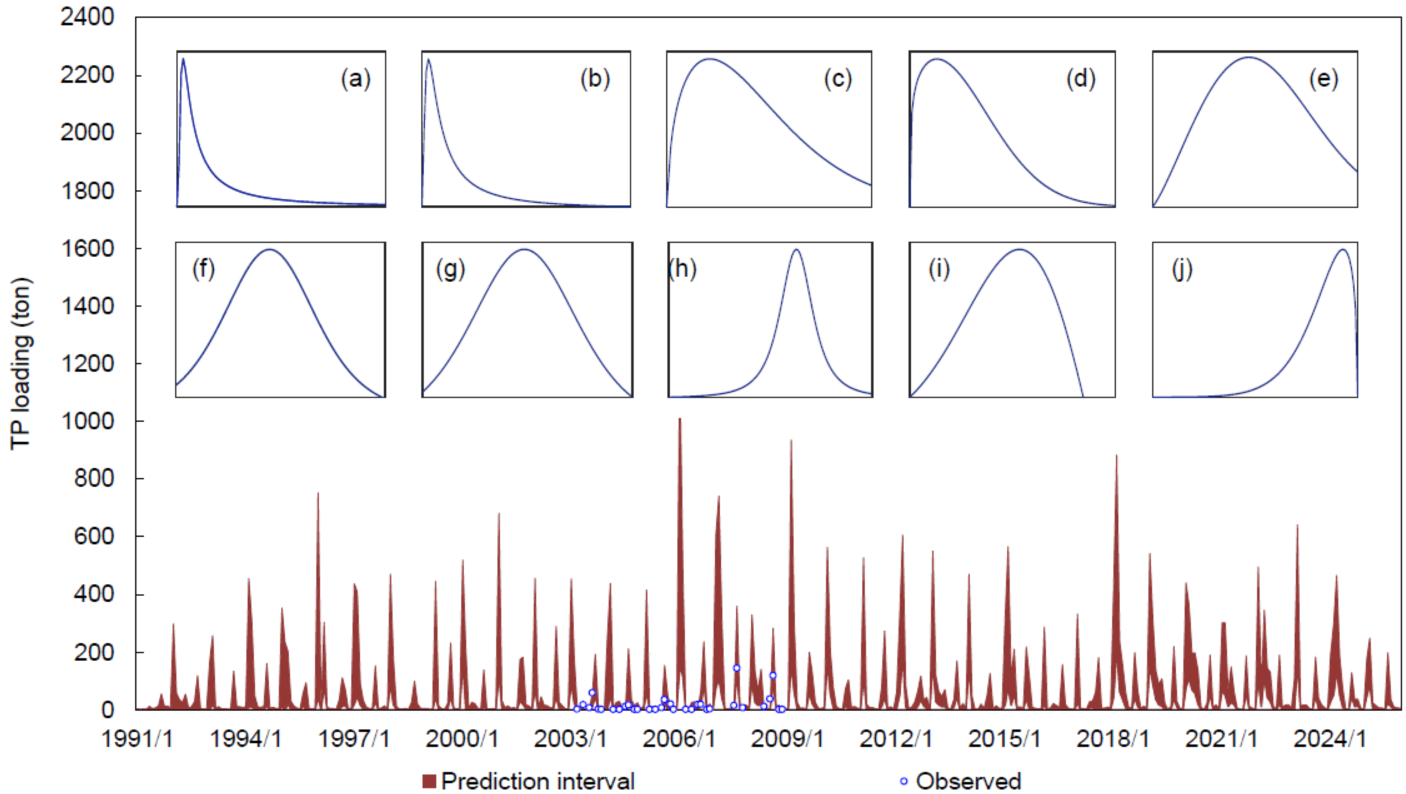


Figure 3

The prediction intervals of TP loading

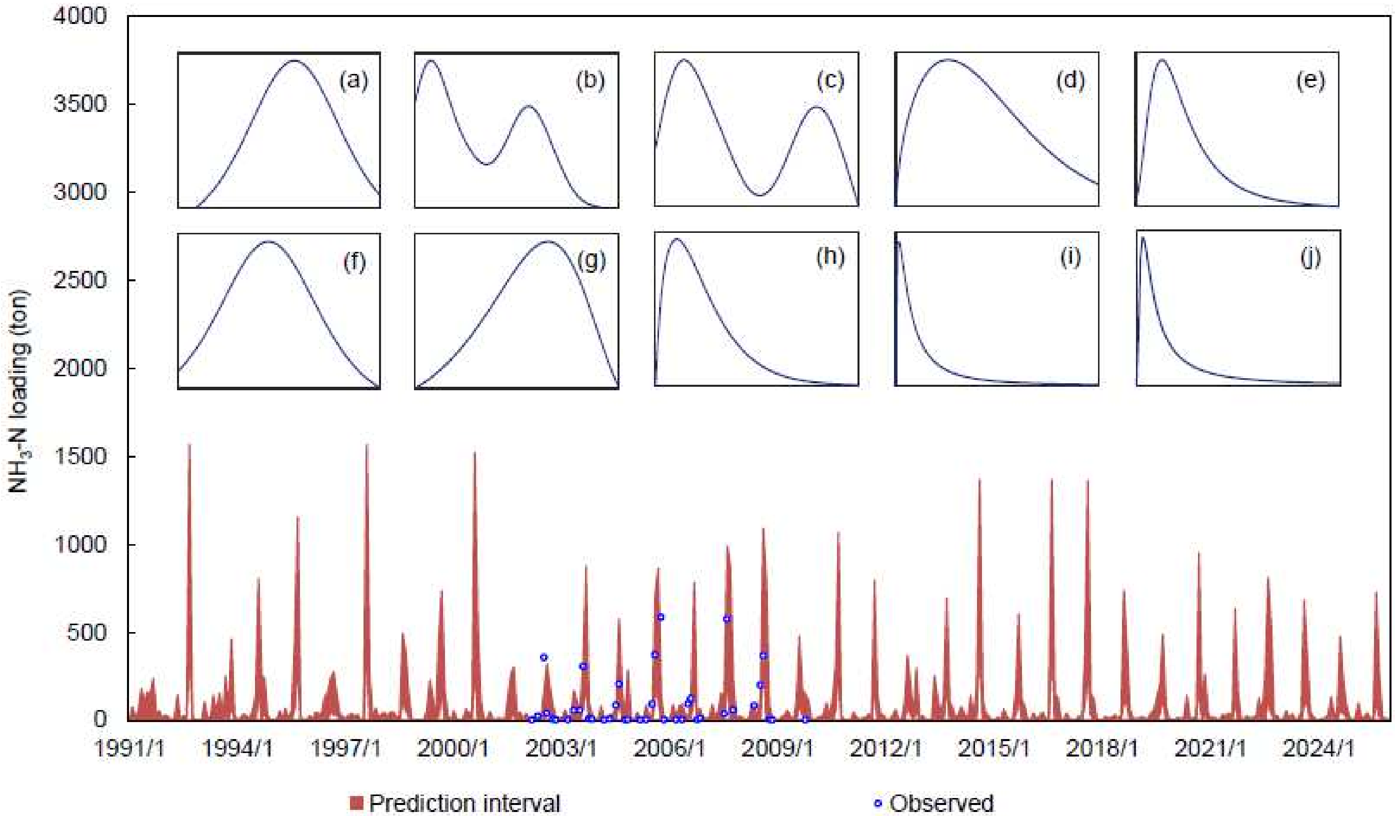


Figure 4

The prediction intervals of NH3-N loading

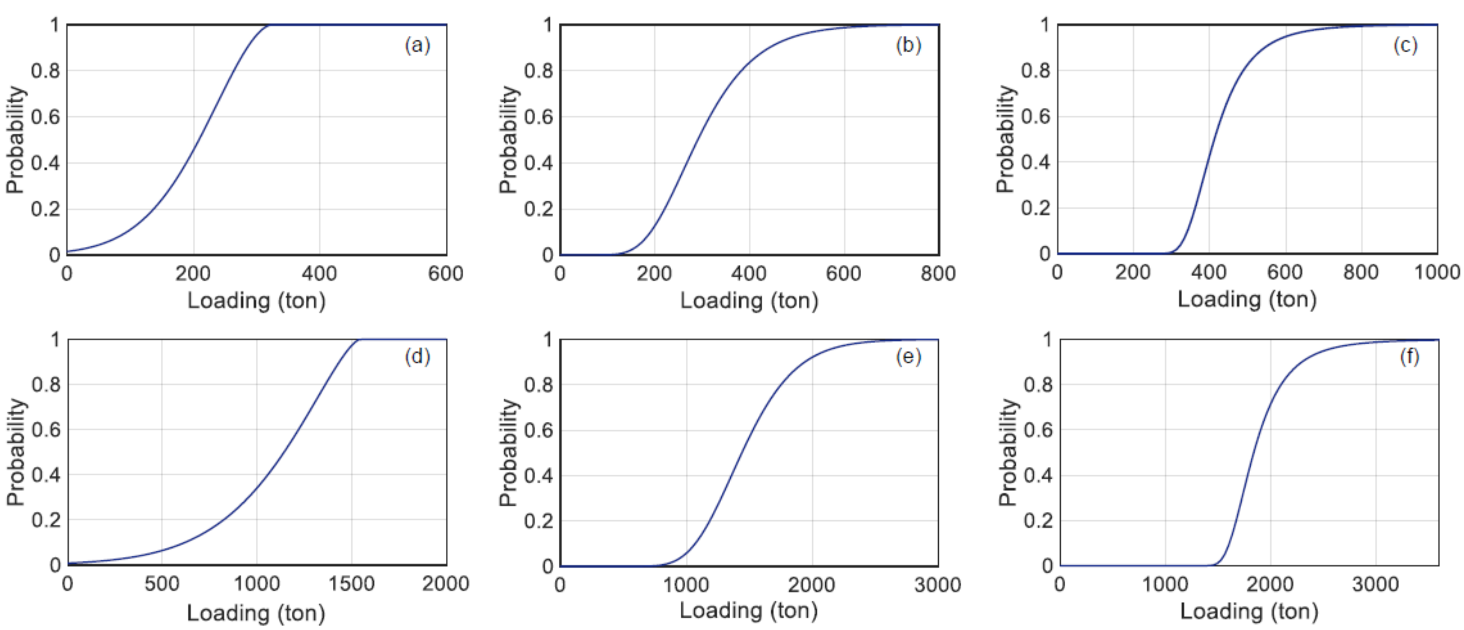
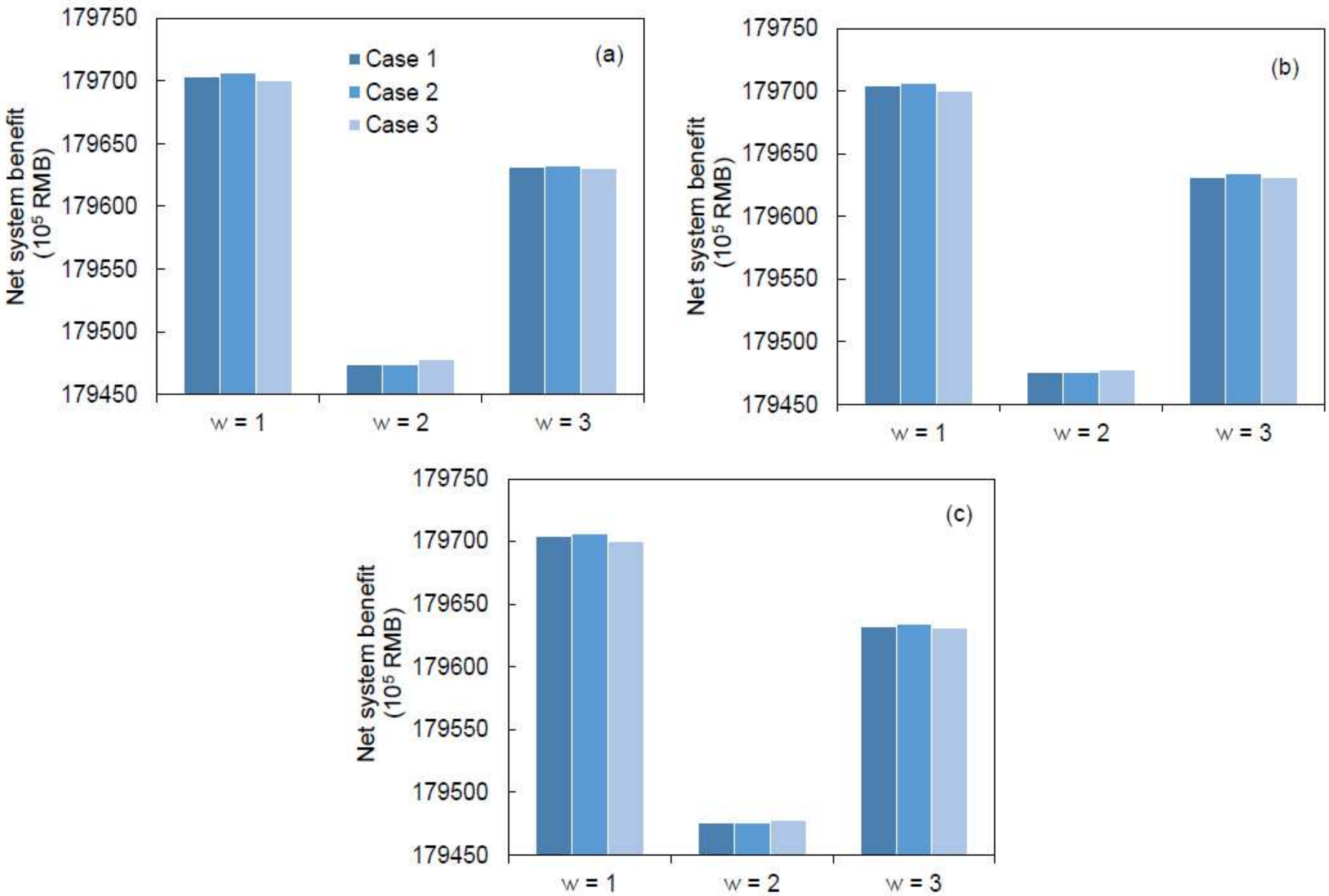


Figure 6

Cumulated distribution functions of NH3-N loadings [(a) low NH3-N loading level for lower bound, (b) medium NH3-N loading level for lower bound, (c) high NH3-N loading level for lower bound, (d) low NH3-N loading level for upper bound, (e) medium NH3-N loading level for upper bound, (f) high NH3-N loading level for upper bound]



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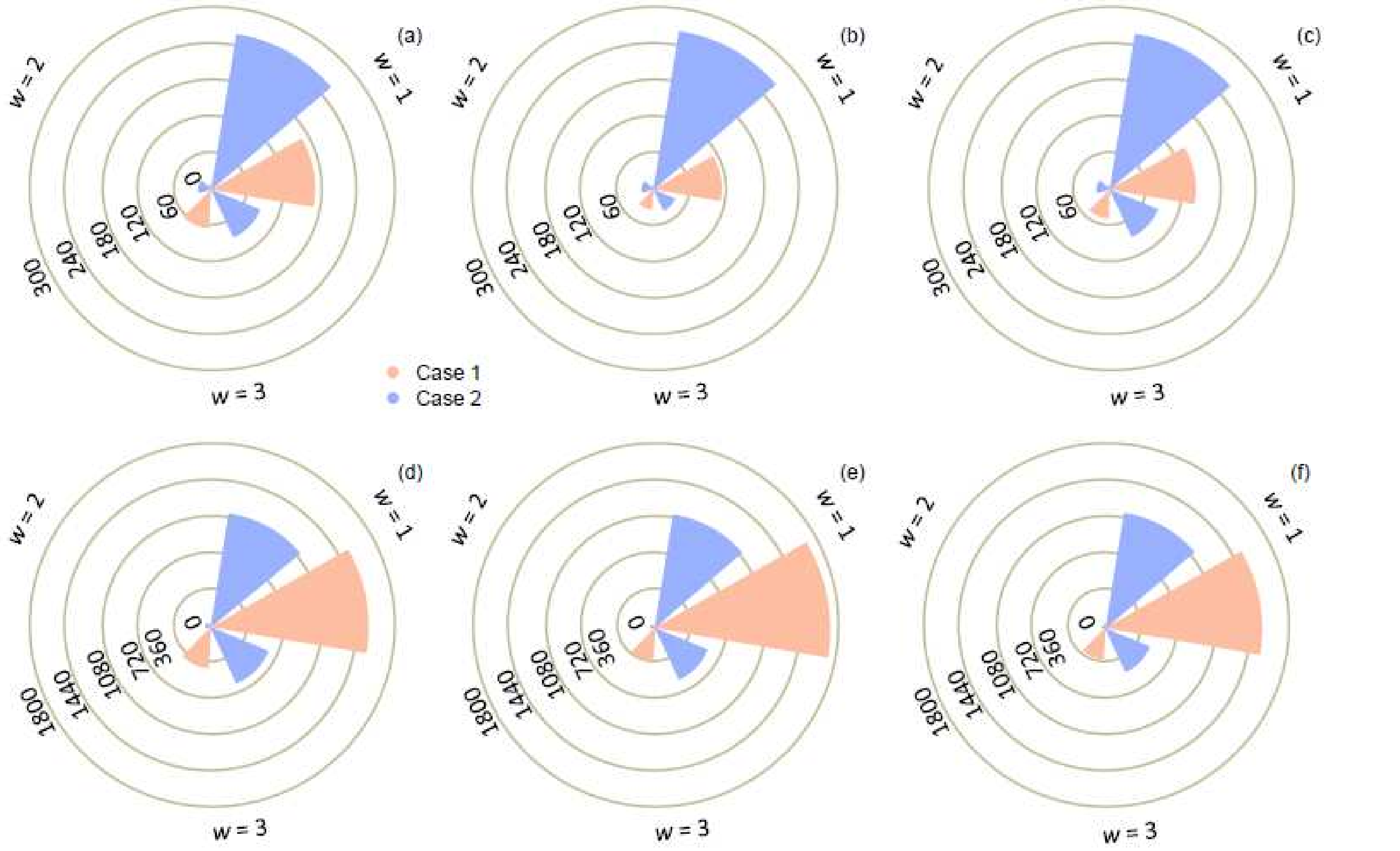
Net system benefits under intra-watershed trading, cross-watershed trading and non-trading cases [(a) p = 0.01, (b) p = 0.05, (c) p = 0.1]



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The total trading amounts under Cases 1 and 2 [(a) TP, p = 0.01; (b) TP, p = 0.05, (c) TP, p = 0.1; (d) NH3-N, p = 0.01; (e) NH3-N, p = 0.05, (f) NH3-N, p = 0.1]

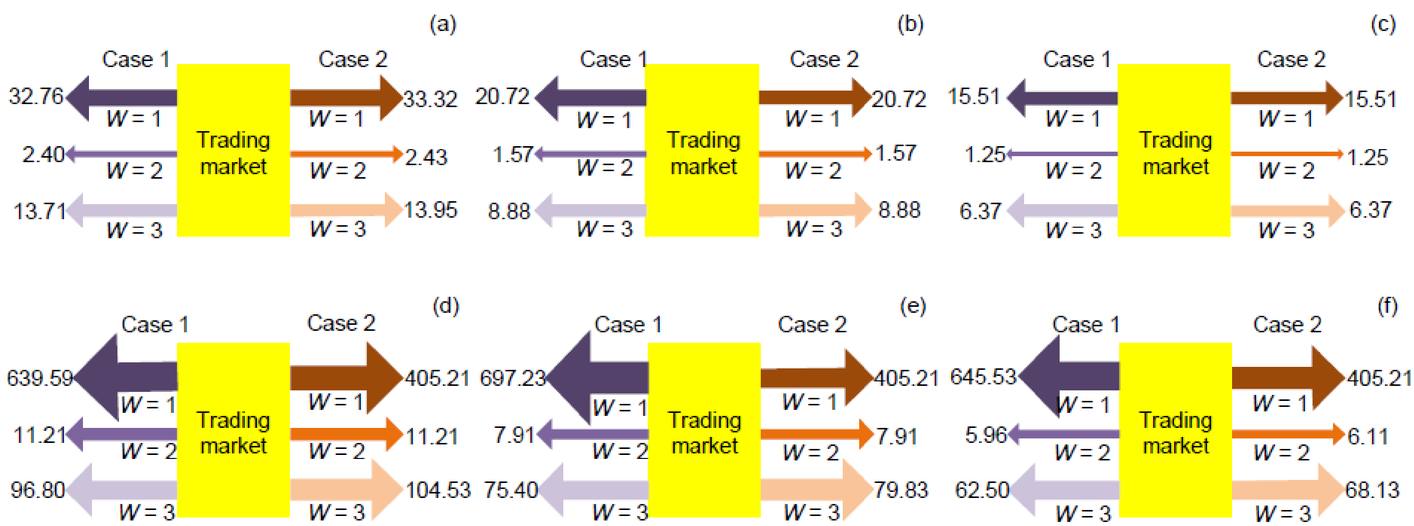

Figure 9

The eliminated trading amounts of tradings under Cases 1 and 2 for TP and NH3-N [(a) TP, p = 0.01; (b) TP, p = 0.05; (c) TP, p = 0.1; (d) NH3-N, p = 0.01; (e) NH3-N, p = 0.05; (f) NH3-N, p = 0.1]

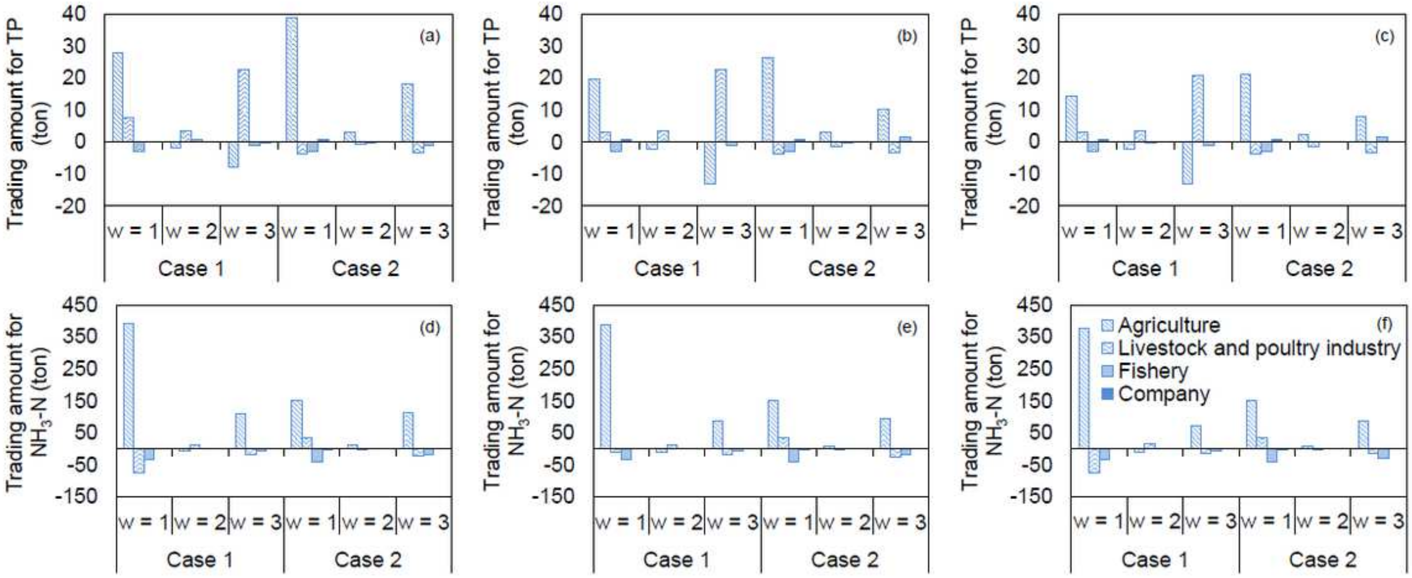

Figure 10

TP and NH3-N detailed trading process for agriculture, livestock and poultry industry, fishery and company [(a) TP, p = 0.01; (b) TP, p = 0.05; (c) TP, p = 0.1; (d) NH3-N, p = 0.01; (e) NH3-N, p = 0.05; (f) NH3-N, p = 0.1]

Supplementary Files

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- GraphicalAbstract.png