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

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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 as well as yield considerable economic and environmental benefits can be under additional challenges. 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 Mosuhihe 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 can alleviate environmental contamination as well as yield considerable economic and environmental benefits; while it can be under additional challenges (Santhi et al. 2006; Sith et al. 2019; Alnahit et al. 2020; Saby et al. 2021). A good control of single watershed may be not adequate for environmental management of the bay. The mutually independent management for multiple watersheds may lead to high costs. Multi-watershed management can make best use of resources and reduce costs.

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 (Stephenson et al. 2010; Zeng et al. 2016; Mahjoobi 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. (2019a, b) 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. The cross-watershed trading policy has a favorable role in promoting the development of green economy under certain conditions (Wang and Pang 2019; Zhang and Li 2019). Cross-watershed trading, as one of mechanisms of multi-watershed trading, can make best use
of environmental capacity by enabling discharge permit transaction among pollution sources with surplus discharge permits and excess pollutions in different watersheds. Thus it has the potential to obtain the optimized water quality and economic benefits. Nevertheless, there have been few studies addressing the design 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. 2019a, b). 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 integrated model framework with Bayesian inference coupling simulation efforts and optimization approaches is desired to be developed for improving the accuracy in nutrient fate modeling as well as accounting for uncertainties in multi-watershed effluent trading design.

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 framework includes uncertainty analysis of SWAT model with MCMC, constraint-violation risk-based two-stage stochastic programming (CRTSP) and mechanism analysis. 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 combines TSP, CCP and interval parameter linear programming (ILP) optimization approaches, which is aimed to disclosing optimal industry scales and trading processes as well as identifying the best trading mechanism. The mechanism analysis can help select the best mechanism according to the performance of net system benefits, excess nutrient emissions, trading amount 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. The innovation of this research lies in the design of multi-watershed effluent trading programs as well as identifying optimal trading mechanisms considering uncertainties in nutrient fate simulation and effluent trading planning. The importances of the research are as follows: (i) discharge permits can be transferred across watersheds and environmental capacity can be fully used; thus environmental cost can be reduced; (ii) the optimal trading schemes can be disclosed under the impact of environmental allowance levels and water availability levels considering the balance of system benefit and risks; (iii) the question of whether to conduct cross-watershed trading can be answered based on the quantitative analysis.

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 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 2009; Sheng et al. 2019; Xu et al. 2020):
(1) Each Markov chain’s initial value is derived from
determined the parametric prior distribution, denoted
as $\phi^i (i = 1, 2, ..., N)$.

(2) The initial value’s likelihood of each chain can be
calculated:
$$\pi (\phi^i) = f (\phi^i | \delta)$$  

(3) Candidate samples are generated by mutation oper-
ation. 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 $Z_{j+1}$ is computed. If the recep-
tance rate $x(\phi_j, Z_{j+1}) > U$ (sampling from uniform
distribution $U(0, 1)$), otherwise refuse. The Inter-
Quartile-Range (IQR) method can remove the use-
less 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 distribu-
tion of the parameter is stably converged. The for-
ula for $R_{stat}$ is:
$$R_{stat} = \sqrt{(1 - \frac{1}{J}) + \frac{N + 1B}{NW} \frac{1}{J}}$$  
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 algo-
rithm is used for uncertainty analysis for parameters
in SWAT model. Nutrient (e.g. NH$_3$-N and TP)
migration equations 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 deci-
sion 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):

$$\text{Max } f = \sum_{j=1}^{n} c_j x_j^\pm - \sum_{j=1}^{n} \sum_{h=1}^{v} p_h d_j y_j^\pm$$  

Subject to:

$$\sum_{j=1}^{n} a_j^\pm x_j^\pm \leq b_r^\pm, r = 1, 2, ..., m_1$$  

$$\sum_{j=1}^{n} a_j^\pm x_j^\pm + \sum_{j=1}^{n} a_j^\pm y_j^\pm \geq \omega_t, t = 1, 2, ..., m_2$$  

$$x_j^\pm \geq 0, j = 1, 2, ...n_1$$  

$$y_j^\pm \geq 0, j = 1, 2, ...n_2; h = 1, 2, ...v$$

where superscripts “−” and “+” represent the lower and
upper bounds of an interval parameter or variable,
respectively; $j$ denotes the pollution sources; $r$ and $t$
are marks of constraints; $h$ represents the probability level; $f^\pm$, $c_j^\pm$, $d_j^\pm$, $a_j^\pm$, $b_r^\pm$, $x_j^\pm$, $y_j^\pm$, and $\omega_t$ are interval coef-
ficients/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, $b_r^\pm = [b_r^-, b_r^+]$.

However, the right-hand side parameters (e.g.
environmental capacity) are of randomness, leading to system risk
of excess emission. Chance-constrained programming
(CCP) can deal with the random uncertainties and analyze
constraint-violation risk effectively (Zhu et al. 2012; Piao
et al. 2014), as follows:

$$\text{Max } f = C(t) X$$  

Subject to:
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 $x_u \in [0, 1]$ for each constraint $u$ and imposes a condition that the constraint is satisfied with at least a probability of $1 - x_u$ (Xie et al. 2011). When $A(t)$ are deterministic and $b_u(t)$ are stochastic, constraint (4b) becomes linear:

$$A_u X \geq b_u(t)^{1-x_u}$$

Equation (5) is equivalent to Eq. (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:

$$\text{Max } f^+ = \sum_{j=1}^{n_1} c_j^+ x_j^+ - \sum_{j=1}^{n_2} \sum_{h=1}^{v} p_h d_j^+ y_{jh}^+$$

Subject to:

$$\sum_{j=1}^{n_1} a_j^+ x_j^+ \leq b_r^+, r = 1, 2, ..., m_1$$

$$\sum_{j=1}^{n_1} a_j^+ x_j^+ + \sum_{j=1}^{n_2} a_j^+ y_{jh}^+ \geq (w_r^+)^{1-x_u}, t = 1, 2, ..., m_2$$

$$x_j^+ \geq 0, j = 1, 2, ..., n_1$$

$$y_{jh}^+ \geq o, j = 1, 2, ..., n_2; h = 1, 2, ..., v$$

In above model, $(w_r^+)^{1-x_u}$ is the stochastic coefficient under period $t$ and under constraint-violation probability $x_u$. 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 longest of all the rivers flowing into Jiaozhou Bay, with a length of more than 140 km. And the total area is 4631 km², which is located between latitudes of 36°10’N-37°12’N and longitudes 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 °C 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 km² with an average annual precipitation of 680 mm in Jimo city. Moshui River is typical seasonal river with the maximum runoff of 500 m³/s and an average annual flow of 0.22188 billion m³. The main soil of the upper reaches is sandy loam and loam in the middle and lower reaches. In addition, the upper reach is characterized by great topographic inequality (Qiao et al. 2012). Moshuihe watershed flows through Jimo city into Jiaozhou Bay, which includes seven tributaries including Liucun River, Longquan River, Tuqiao River, Xialalicun River, Hongzi River, Aimin River and Xiliufeng 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, Dagouhe 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. NH₃-N and TP are two main contaminants for the watersheds. The amount of TP flowing into Jiaozhou Bay through Dagouhe watershed accounts for 55.34% of total TP loading to the Bay. The amount of NH₃-N accounts for 24.18% of total NH₃-N loading to Jiaozhou Bay (Li et al. 2009). On the other hand, Dagouhe 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 to improve the capability of the model in dealing with complexities in effluent trading planning.
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 inefficiency of environmental management and even lead to the issue of hot spots. Instead, effluent trading can help allocate discharge permits and achieve optimal economic benefits or enhanced environmental benefits. In addition, the pollution sources that are not easy to mitigate or who choose to heighten production can purchase the unused permits from the others, without paying huge environmental penalties. TP and NH₃-N are selected as water quality indicators. As shown in Fig. 2, the left and right scale bars indicate the measurement accuracy of Daguhe and Moshuihe watersheds, respectively. 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; Zhao et al. 2018). The pink, yellow, green and purple river networks represent Laixi reach (Reach I), Pingdu reach (Reach II), Jiaozhou reach (Reach III) and Daguhejimo reach (Reach IV), respectively. Laixi reach includes Laixi mainstream of Dagu River, half of Xiaogu River and Wugu River. Pingdu reach includes Pingdu mainstream of Dagu River, half of Xiaogu River and Luoyao River. Jiaozhou reach includes Jiaozhou mainstream of Dagu River and Nanjiaolai River. Daguhejimo reach includes Jimo mainstream of Dagu River and Liuhao River. Second, 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 NH₃-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.
follows:

Under Case 2, the effluent trading scheme can be formulated as follows:

\[
\text{Max } f = \sum_{i=1}^{5} \sum_{j=1}^{5} A_{ij} f (X_{ij} - \Delta X_{ij}) + \sum_{i=1}^{5} \sum_{j=1}^{5} B_{ij} f (W_{ij} - \Delta W_{ij}) + \sum_{i=1}^{5} \sum_{j=1}^{5} C_{ij} f (X_{ij} - \Delta X_{ij}) + \sum_{i=1}^{5} \sum_{j=1}^{5} D_{ij} f (W_{ij} - \Delta W_{ij})
\]

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 Appendix B. The model of effluent trading scheme under Case 2 can be formulated as follows:

\[
\sum_{i=1}^{5} \sum_{j=1}^{5} A_{ij} f (X_{ij} - \Delta X_{ij}) + \sum_{i=1}^{5} \sum_{j=1}^{5} B_{ij} f (W_{ij} - \Delta W_{ij}) + \sum_{i=1}^{5} \sum_{j=1}^{5} C_{ij} f (X_{ij} - \Delta X_{ij}) + \sum_{i=1}^{5} \sum_{j=1}^{5} D_{ij} f (W_{ij} - \Delta W_{ij})
\]

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 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

\[
\sum_{i=1}^{11} (X_{ij} - \Delta X_{ij}) \cdot CWPA_{ij} \leq ACEP_{ij}
\]

\[
\sum_{r=1}^{4} (N_{nr} + \Delta N_{nr} \cdot r_{mr}) \cdot CWPR_{r} \leq LCEP_{rw}
\]
(Z_p^- \Delta Z_p \cdot s_{pw}) \cdot DWP^\pm \cdot CWPP^\pm \\
- EDPP_{pw}^\pm \leq SCEN_{pw} \tag{7d}

(Y_m^- \Delta Y_m \cdot \epsilon_{mn} \cdot DWM^\pm \cdot CWPM^\pm \\
- EDPC_{mn}^\pm \leq CCEP_{mnw} \tag{7e}

2. Constraints for NH\(_3\)-N permit reallocation

\[ \sum_{j=1}^{11} (X_j^- + \Delta X_j \cdot o_{jw}) \cdot CWNA_j^\pm - EDNA_{jw}^\pm \leq ACEN_{jw} \tag{7f} \]

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

\[ (Z_p^- \Delta Z_p \cdot s_{pw}) \cdot DWP^\pm \cdot CNWP^\pm \\
- EDNP_{pw}^\pm \leq SCEN_{pw} \tag{7h} \]

\[ (Y_m^- \Delta Y_m \cdot \epsilon_{mn} \cdot DWM^\pm \cdot CWNM_{m}^\pm \\
- EDNC_{mnw}^\pm \leq CCEN_{mnw} \tag{7i} \]

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 Dagou and Moshiuhe watersheds are equal to that the initial discharge permits plus the purchasing permits, and minus the selling permits.

3. Constraints for TP trading rules

\[ \sum_{p'=1}^{3} TP_{pp'}w + \sum_{i=1}^{5} TP_{psiw} + \sum_{m=1}^{3} TP_{spm} + \sum_{m=1}^{7} TP_{spmw} \leq TTP_{pw} + \sum_{p'=1}^{3} TP_{p'pw}/ip_{i} + \sum_{n=1}^{3} TP_{bpnw}/ip_{ip} \tag{7j} \]

\[ \sum_{n'=1}^{3} TP_{np'w} + \sum_{i=1}^{5} TP_{nsiw} + \sum_{p=1}^{3} TP_{nspw} + \sum_{m=1}^{7} TP_{spmw} \leq TNN_{nw} + \sum_{n'=1}^{3} TN_{n'iw} + \sum_{m=1}^{7} TN_{iaw} \tag{7k} \]
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

\[
\begin{align*}
\sum_{m=1}^{7} TN_{mw} + \sum_{i=1}^{5} TNs_{mw} + \sum_{n=1}^{3} TN_{nmw} + \sum_{p=1}^{3} TNs_{mpw} & \leq TNM_{mw} + \sum_{m=1}^{7} TN_{mw} / m_{iw} + \sum_{i=1}^{5} TNb_{mw} / m_{im} \\
+ \sum_{n=1}^{3} TNb_{mw} / m_{nm} + \sum_{p=1}^{3} TNb_{mpw} / m_{pm} & \leq \sum_{m=1}^{7} TN_{mw} + \sum_{i=1}^{5} TNs_{mw} + \sum_{n=1}^{3} TN_{nmw} + \sum_{p=1}^{3} TNs_{mpw} \quad (7q)
\end{align*}
\]

5. Constraints for TP environmental limit

\[
\begin{align*}
ACEP_{iw} & \leq TPA_{iw}, \quad LCEP_{nw} \leq TPL_{mw} \quad (7r) \\
SCEP_{pw} & \leq TPS_{pw}, \quad CCEP_{nw} \leq TPC_{mw} \quad (7s)
\end{align*}
\]

\[
\begin{align*}
ACEP_{iw} + LCEP_{nw} + SCEP_{pw} & \leq TPGF_{qw} \quad \forall i = n \quad (7t) \\
ACEP_{iw} & \leq TPGF_{qw} \quad i = 4, \quad q = 4 \quad (7u)
\end{align*}
\]

\[
\begin{align*}
ACEP_{5w} + CCEP_{3w} + CCEP_{4w} + CCEP_{5w} + CCEP_{nw} & \leq TPWF_{1w} \quad (7v) \\
CCEP_{1w} + CCEP_{2w} + CCEP_{7w} & \leq TPWF_{2w} \quad (7b)
\end{align*}
\]

\[
\begin{align*}
\sum_{i=1}^{4} ACEP_{iw} + \sum_{n=1}^{3} LCEP_{nw} + \sum_{p=1}^{3} SCEP_{pw} & \leq TPGF_{qw}^{1-pw} \quad (7f)
\end{align*}
\]

\[
\begin{align*}
ACEP_{iw} & \leq TPGF_{qw} \quad i = 4, \quad q = 4 \quad (7u)
\end{align*}
\]

\[
\begin{align*}
ACEP_{5w} + CCEP_{3w} + CCEP_{4w} + CCEP_{5w} + CCEP_{nw} & \leq TPWF_{1w} \quad (7v)
\end{align*}
\]

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 Daguhu 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

\[
\begin{align*}
ACEP_{iw} + LCEP_{nw} + SCEP_{pw} & \leq TPGF_{qw} \quad \forall i = n \\
= p, \quad i = 1, 2, 3, \quad q \neq 4
\end{align*}
\]

\[
\begin{align*}
\sum_{i=1}^{4} ACEP_{iw} + \sum_{n=1}^{3} LCEP_{nw} + \sum_{p=1}^{3} SCEP_{pw} & \leq TPGF_{qw}^{1-pw}
\end{align*}
\]

\[
\begin{align*}
\sum_{i=1}^{4} ACEP_{iw} + \sum_{n=1}^{3} LCEP_{nw} + \sum_{p=1}^{3} SCEP_{pw} & \leq TPGF_{qw}^{1-pw}
\end{align*}
\]

\[
\begin{align*}
\sum_{i=1}^{4} ACEP_{iw} + \sum_{n=1}^{3} LCEP_{nw} + \sum_{p=1}^{3} SCEP_{pw} & \leq TPGF_{qw}^{1-pw}
\end{align*}
\]

\[
\begin{align*}
\sum_{i=1}^{4} ACEP_{iw} + \sum_{n=1}^{3} LCEP_{nw} + \sum_{p=1}^{3} SCEP_{pw} & \leq TPGF_{qw}^{1-pw}
\end{align*}
\]

6. Constraints for NH$_3$-N environmental limit

\[
\begin{align*}
ACEN_{iw} & \leq TNA_{iw}, \quad LCEN_{nw} \leq TNL_{mw} \quad (7z) \\
SCEN_{pw} & \leq TNS_{pw}, \quad CCEN_{nw} \leq TNC_{mw} \quad (7aa)
\end{align*}
\]

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
\[ 0 \leq o_{pm} \leq 1, \quad 0 \leq r_{new} \leq 1, \quad 0 \leq s_{pm} \leq 1, \quad 0 \leq e_{nmc} \leq 1 \]

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 \( TP_{buy} = TP_{sell} \), 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 D.

4 Technical and non-negativity constraints

4.1 Data collection

In this study, hydrology and water quality are simulated and predicted. Hydrology data is obtained from Nancun hydrological station; water quality data is obtained from Xielaqiao observation station (Wang et al. 2014; Liu 2009; Wu 2013). A range of general meteorological data associated with model inputs are demanded for water quality simulation, including maximum and minimum temperature and daily rainfall data during the period of 1991–2018. These datas are from China Meteorological Data Service Center (Qingdao station: No. 54857), with latitude and longitude of 36°04’ and 120°20’. 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.

5 Results and discussion

5.1 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 for the emissions of TP and NH$_3$-N in optimized model 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 Metropolis) 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. And the sensitivities of TP and NH$_3$-N parameters in SWAT model are described by T-Stat and P-Values, which is illustrated in Figs. 3 and 4. T-Stat provides a measure of sensitivity, with larger absolute values indicating more sensitive. P-Values determine the significance of the sensitivity. A value close to zero has more significance.

The marginal posterior probability density distributions for the parameters of TP and NH$_3$-N are highlighted as shown in Figs. 5 and 6. And the vertical axis is Frequency and the horizontal axis is parameter value. The posterior distribution of sensitive parameters is obtained based on prior distribution and MCMC with DREAM method. The distributions of CH_N(2), LAT_TTIME and CN2 for TP are close to normal distribution with a relative symmetric distribution. The distributions of ALPHA_BF and CH_K2 for TP are close to multimodal distribution. The distributions of BC2 for NH$_3$-N are close to normal distribution with a relative symmetric distribution. The distributions of CN2 and CH_K2 for NH$_3$-N are close to multimodal distribution. The posterior distributions of the other parameters for TP and NH$_3$-N are not normally distributed associated with skewness. The prediction intervals of TP and NH$_3$-N loadings are acquired by running SWAT model for years 1991–2025 (Figs. 5 and 6) based on the posterior distribution of the above sensitive parameters. The observed data for TP and NH$_3$-N loadings are highlighted with blue circles. The results depict that 66.7% and 85.7%
of the observed TP and NH$_3$-N loadings are captured by the uncertain predictions on an annual scale, 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 7 shows the cumulative probability distribution function (CDFs) under

| Parameter | Description                                                                 | Limit value range | Units          |
|-----------|------------------------------------------------------------------------------|-------------------|---------------|
| TP        | CH$_N$(2) Manning’s “n” value for the main channel                           | 0                 | 0.3           |
|           | ALPHA$_BF$ Baseflow recession factor                                         | 0                 | 1             |
|           | 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 °C | 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           |

Fig. 3 The sensitivities of TP parameters in SWAT model
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 8 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. Figure 4 The sensitivities of NH$_3$-N parameters in SWAT model

![Diagram showing sensitivities of NH$_3$-N parameters in SWAT model](image)

The sensitivities of NH$_3$-N parameters in SWAT model

**Table 2** shows loading distributions and the associated probabilities for TP and NH$_3$-N, respectively. The two probabilities measure the low, medium and high probabilities of TP and NH$_3$-N, which are obtained based on the probability distribution of the upper and lower bounds of TP and NH$_3$-N emissions, respectively. In this study, Bayesian inference with DREAM algorithm generates interval predictions for nutrient loadings, which can reflect uncertainties in important parameters and the associated practical processes. Then the propagation from parameter

![Diagram showing prediction intervals of TP loading](image)

**Fig. 5** The prediction intervals of TP loading [(a) CH_N(2), (b) ALPHA_BF, (c) USLE_P, (d) REVAPMN, (e) CH_K2, (f) GW_REVAP, (g) LAT_TTIME, (h) GWSOLP, (i) SOL_AWC, (j) CN2]
uncertainties to effluent trading planning can be addressed and the decision-making in the trading can thus be more accurate compared with traditional certainty water quality prediction. Therefore, the interval predictions of TP and NH$_3$-N loadings can improve the accuracy of decision making.

5.2 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 Appendix C Tables 5, 6, 7, 8, the results are provided in forms of “selling amount/purchasing amount”. The selling and purchasing amount would be different because of the existence of trading ratio. Tables 5 and 6 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 within one reach and across different reaches in a 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 6. 74.9 ton of NH$_3$-N permits would be eliminated in this trading section because of trading ratio. Tables 7 and 8 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 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 8). The detailed trading processes under $p = 0.01$ in medium level of water availability are shown in Appendix C, Tables 9, 10, 11, 12.

Figure 9 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) 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) and 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

| 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         |
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 $w = 1$.

The accuracy of effluent trading schemes would be affected by the temporal and spatial heterogeneity of water availability level and environmental capacity. The total excess pollution emissions, the total trading amounts and the net system benefits would change with the variation of the two factors. The two factors can affect the effluent trading design; thus their impact on effluent trading should be analyzed. The performances of trading system under the three environmental allowance-violation risks ($p$) are compared and investigated. Table 3 shows the excess TP and NH$_3$-N emissions from agriculture under different $p$. The results indicate that generally the 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 4 shows the total excess TP and NH$_3$-N emissions under 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 emission under $p = 0.01$ would be 1.18 ton lower than that under $p = 0.1$. Fig. 10 shows the net system benefits under 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 $w = 1$, the net system benefits under $p = 0.01$ would be RMB¥1.3592 × 10$^6$ lower than that under $p = 0.1$. Figure 11 shows the total TP and NH$_3$-N trading amounts under 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

### Table 3: The 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   |
|            | $p = 0.05$  | 0       | 183.34  | 60.78   |
|            | $p = 0.1$   | 0       | 183.34  | 60.78   |
| Case 2     | $p = 0.01$  | 0       | 188.49  | 84.14   |
|            | $p = 0.05$  | 0       | 188.28  | 76.333  |
|            | $p = 0.1$   | 0       | 187.80  | 73.81   |
| Case 3     | $p = 0.01$  | 0       | 185.35  | 69.87   |
|            | $p = 0.05$  | 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       |
|            | $p = 0.05$  | 250.53  | 0       |
|            | $p = 0.1$   | 249.27  | 0       |
| Case 2     | $p = 0.01$  | 0       | 273.34  | 0       |
|            | $p = 0.05$  | 0       | 270.04  | 0       |
|            | $p = 0.1$   | 0       | 268.24  | 0       |
| Case 3     | $p = 0.01$  | 0       | 259.57  | 0       |
|            | $p = 0.05$  | 0       | 259.57  | 0       |
|            | $p = 0.1$   | 0       | 259.57  | 0       |

Fig. 9 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, $p = 0.1$]
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.

The total trading amounts, excess total TP and NH$_3$-N emissions and system net benefits are compared and investigated under three levels for water availability ($w$). From the results in Fig. 11, the total TP and NH$_3$-N trading amounts under low water availability level would be lower than those under high water availability level. For example, under Case 2 and when $p$ takes 0.01, the NH$_3$-N trading amount under $w = 2$ would be 1084.24 ton lower than that under $w = 1$. 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 4). For example, when $p = 0.01$ under Case 2, the total excess NH$_3$-N emissions under low water availability level would be 581.55 ton higher than that under high water availability level. What’s more, the net system benefits would be increased accordingly (Fig. 10). For example, when $p = 0.01$ under Case 2, the net system benefits under $w = 1$ would be RMB¥ 23.224 $\times 10^6$ higher than that under $w = 2$. Above the results indicate that the total trading amounts would be increased when the level of water

### Table 4 Total excess TP and NH$_3$-N emissions under three cases (ton)

| Case | Probability | $w = 1$ | $w = 2$ | $w = 3$ |
|------|-------------|--------|--------|--------|
| TP   | $p = 0.01$  | 243.16 | 521.48 | 383.11 |
|      | $p = 0.05$  | 238.63 | 520.62 | 383.46 |
|      | $p = 0.1$   | 238.63 | 520.30 | 380.95 |
|      | $p = 0.01$  | 231.96 | 521.48 | 380.46 |
|      | $p = 0.05$  | 231.96 | 520.62 | 375.40 |
|      | $p = 0.1$   | 231.96 | 520.30 | 372.88 |
|      | $p = 0.01$  | 240.82 | 519.05 | 370.46 |
|      | $p = 0.05$  | 240.82 | 519.05 | 370.46 |
|      | $p = 0.1$   | 240.82 | 519.05 | 370.46 |
| NH$_3$-N | $p = 0.01$  | 614.11 | 1195.66 | 732.82 |
|      | $p = 0.05$  | 614.11 | 1192.36 | 732.82 |
|      | $p = 0.1$   | 614.11 | 1190.56 | 732.82 |
|      | $p = 0.01$  | 614.11 | 1195.66 | 732.82 |
|      | $p = 0.05$  | 614.11 | 1192.36 | 732.82 |
|      | $p = 0.1$   | 614.11 | 1190.56 | 732.82 |
|      | $p = 0.01$  | 627.93 | 1184.46 | 750.31 |
|      | $p = 0.05$  | 627.93 | 1184.46 | 750.31 |
|      | $p = 0.1$   | 627.93 | 1184.46 | 750.31 |

Fig. 10 Net system benefits under intra-watershed trading, cross-watershed trading and non-trading cases [(a) $p = 0.01$, (b) $p = 0.05$, (c) $p = 0.1$]
availability is raised. After that, the total excess TP and NH₃-N emissions would be decreased and net system benefits would be increased.

The trading optimization provides schemes of trading scale, main seller and purchaser as well as detailed trading processes under uncertainties. The results can reveal the optimal trading schemes considering the balance of benefit objectives and the associated risks through comparative study concerning different environmental allowance levels and water availability levels. In addition, the impact of environmental capacity and water availability on effluent trading is explored through comparative study.

5.3 Interactive effects between the water availability level and trading mechanism

Firstly, from the results in Table 4, the total excess TP and NH₃-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 emission under Case 1 (Case 2) is 2.19 ton (8.86 ton) lower than that under Case 3. Figure 11 depicts the amounts of the eliminated TP and NH₃-N permits from trading market under three levels for water availability as well as Cases 1 and 2. The eliminated TP and NH₃-N permits imply the reduced emission permits under Cases 1 or 2 compared with Case 3. From the results, there are some eliminated TP and NH₃-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 Fig. 10, 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 benefit under Case 1 (Case 2) are RMB¥ 0.411 × 10⁶ (RMB¥ 0.611 × 10⁶) higher than that under 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 NH₃-N emissions under Cases 1 and 2 would be higher than those under Case 3 when \( w = 2 \) (Table 4). For example, when \( p = 0.1 \) and \( w = 2 \), the total excess TP emissions under Cases 1 (Case 2) are 1.25 ton (1.25 ton) higher than that under Case 3. In addition, the increased amounts of total excess TP and NH₃-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 \( w = 2 \).
(Fig. 10). For example, when \( p = 0.1 \) and \( w = 2 \), the net system benefit under Case 1 (Case 2) is RMB¥ 0.190 \( \times 10^6 \) (RMB¥ 0.190 \( \times 10^6 \)) lower than that under 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 4). 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 Fig. 12, 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 \( w = 3 \) (Fig. 10). For example, when \( p = 0.1 \) and \( w = 3 \), the net system benefit under Case 1 (Case 2) is RMB¥ 0.122 \( \times 10^6 \) (RMB¥ 0.364 \( \times 10^6 \)) higher than that under 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.

From the results in Table 4, 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 case. The results illustrate that the eliminated TP permits under Case 1 would almost be equivalent to those under Case 2 when \( w = 1 \) (Fig. 12). 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 4). However, the eliminated NH\(_3\)-N permits under Case 1 would be increased by [234.39, 292.02] ton compared with Case 2 (Fig. 12). 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 Fig. 10, 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 benefit under Case 1 would be RMB¥ 0.336 \( \times 10^6 \) lower than that under Case 2. 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 4, 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 \( w = 3 \) (Fig. 12). The above results imply the TP

![Fig. 12](image_url)
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 4). And the eliminated NH$_3$-N permits under Case 1 would be decreased by [4.43, 7.73] ton compared with Case 2 when $w = 3$ (Fig. 12). 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 benefit under Case 1 would be RMB¥ $0.313 \times 10^6$ lower than that under 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.

From the results in Fig. 11, 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 (NH$_3$-N) trading amount under Case 1 would be 12.32 ton (18.81 ton) lower than that 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.

In this study, the optimal trading mechanism would be determined by comparing the excess pollutant emissions, the eliminated permits from the trading market, the total trading amounts and net system benefits under Cases 1 and 2 as well as different water availability levels. Optimal effluent trading mechanism under different water availability levels provides stakeholders with a better understanding whether cross-watershed trading mechanism is efficient in multi-watershed nonpoint source pollution management. The results provide a solid scientific basis for nonpoint source pollution management as well as effective sustainable development for multi-watershed region.

### 5.4 Discussion

Zhang et al. (2017) applied an integrated modeling framework with SWAT and effluent trading model for planning effluent trading in Xiangxihe Watershed. Zeng et al. (2017) developed an effluent trading model based on Laplace criterion for the water quality management in Kaidu-kongque River Watershed. In the above researches, the tradings are limited within watershed boundaries. Comparing to such traditional single-watershed effluent trading modeling efforts, cross-watershed trading has the advantages as follows: (i) Cross-watershed trading case can make best use of resources of environmental capacity, leading to the lower excess pollution emissions and higher net system benefits. For example, the total excess TP emission under cross-watershed trading case would be 5.36 ton lower than those under the traditional single-watershed trading (represented by intra-watershed trading case) under medium water availability level. Meanwhile, the eliminated TP permits due to trading ratio would be almost equivalent to those under the traditional trading, implying that more discharge permits in the cross-watershed trading market are used. The total excess NH$_3$-N emission under cross-watershed trading case would be no less than that of traditional trading under medium water availability level. But its eliminated NH$_3$-N permits are 6.08 ton more than those of traditional trading. This indicates that the excess NH$_3$-N emission and the associated environmental penalties would not increase with less available permits under cross-watershed trading case. In addition, the efficient use of environmental capacity brings about higher net system benefits under cross-watershed trading. For example, the net system benefits under cross-watershed trading case would be RMB¥ $268 \times 10^3$ higher than those under traditional trading under medium water availability level. (ii) The optimal effluent trading mechanism can be obtained based on above discussion. The cross-watershed trading planning would be the optimal scheme under medium and high water availability levels. The excess pollution emissions (net system benefits) under trading schemes would be higher (lower) than those under non-trading case. Thus the non-trading scheme would be appropriate under low water availability level.

Two vital factors on the trading process are examined in this study, i.e. environmental allowance-violation risk level and water availability level. The high level of environmental allowance would lead to the less excess pollution emissions, and higher net system benefits, and vice versa. For example, under cross-watershed trading and medium water availability level, the total excess TP emission under the lowest environmental allowance ($p = 0.01$) would be 7.581 ton higher than that under the highest environmental allowance ($p = 0.1$). The corresponding net system benefit under the lowest environmental allowance would be RMB¥ $2.2743 \times 10^6$ lower than that under the highest environmental allowance. In addition, high water availability level leads to more supply for discharge permits and trading amounts. The total excess pollution emissions would then be reduced, and the net system benefits would be increased. For example, under cross-watershed trading and the lowest environmental allowance, the NH$_3$-N trading amount under
low water availability level would be 1230.57 ton lower than that under high water availability level. This is due to the existence of demand and more supply for pollution permits when the level of water availability is high. The demand derives from the existence of excess TP and NH₃-N emissions of pollution sources. The surplus TP (NH₃-N) discharge permits under high water availability level bring about the supply. In fact, the total surplus TP (NH₃-N) permits under high water availability level would be 0.76 ton (1287.49 ton) more than that under low water availability level before trading. And the corresponding total excess NH₃-N emission under low water availability level would be 1909.89 ton higher than that under high water availability level. At last, the corresponding net system benefit under low water availability level would be RMB¥ 61.976 × 10⁶ lower than that under high water availability level. This implies that the effluent trading would be promoted and system benefit would be increased under high level of water availability.

6 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 incorporates 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 considering interaction between trading mechanism and water availability level.

In this study, BS-METM has been applied to multi-watershed effluent trading design for two agricultural watersheds, i.e., Daguhe and Moshuihe watersheds, China. TP and NH₃-N are selected as water quality indicators. The optimized industry scales and trading processes are obtained. The effects of 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 NH₃-N emissions and trading amounts as well as the increased net system benefits; (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 NH₃-N permits; high water availability level also corresponds to high net system benefits; (iii) the total TP and NH₃-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) non-trading case would be recommended in low water availability level because there is almost no surplus pollution discharge permits; in medium and high water availability level, cross-watershed trading case would be recommended, with increased net system benefits of RMB¥ [200, 336] × 10⁶ and [80, 242] × 10⁶ compared with intra-watershed trading case for the two levels; strict environmental management of NH₃-N should be strengthened due to less eliminated discharge permits under cross-watershed trading.

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. 2019a, b):

\[
f_{\text{post}}(\theta | y_{\text{obs}}) = \frac{f_{\text{prl}}(\theta) \cdot f_{M}(y_{\text{obs}} | \theta)}{\int f_{\text{prl}}(\theta) \cdot f_{M}(y_{\text{obs}} | \theta) \, d\theta}
\]

where \(f_{\text{post}}(\theta | y_{\text{obs}})\) represents the posterior distribution of parameter set \(\theta\) that is dated from the prior distribution \(f_{\text{prl}}(\theta)\) conditioned on observed data \(y_{\text{obs}}\); \(f_{M}(y_{\text{obs}} | \theta)\) 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):

\[
f_{M}(y_{\text{obs}} | \theta_M) = \prod_{i} \frac{1}{\sqrt{2\pi\sigma_e}} \exp \left( -\frac{(y_i - y_{\text{obs}, t})^2}{2\sigma_e^2} \right)
\]

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

Phosphorus (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:

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

$$NO_{3,\text{surf}} = \frac{\beta_{NO_3}Q_{\text{surf}}NO_3}{w_{\text{mobile}}} \left[1 - \exp\left(-\frac{w_{\text{mobile}}}{(1 - \theta_c) SAT_{ly}}\right)\right]$$

where $NO_{3,\text{surf}}$ is the nitrate removed in surface runoff (kg/ha); $\beta_{NO_3}$ represents the nitrate percolation coefficient; $NO_3_{ly}$ is the amount of nitrate in the soil layer (kg/ha); $w_{\text{mobile}}$ represents the amount of mobile water in the layer (mm H$_2$O); $\theta_c$ is the fraction of porosity from which anions are excluded; $SAT_{ly}$ is the water content of the soil layer; $Q_{\text{lat,ly}}$ represents the water discharged from the layer by lateral flow (mm H$_2$O); and $w_{\text{perc,ly}}$ denotes the amount of water percolating to the underlying soil layer (mm H$_2$O). 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:

$$orgN_{\text{surf}} = \frac{0.001conc_{orgN}e_{\text{sedn,sed}}}{\text{area}_{\text{hru}}}$$

where $orgN_{\text{surf}}$ 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 $e_{\text{sedn}}$ 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:

$$orgP_{\text{surf}} = \frac{0.001conc_{orgP}e_{\text{sedp,sed}}}{\text{area}_{\text{hru}}}$$

where $orgP_{\text{surf}}$ 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 $e_{\text{sedp}}$ 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:

$$P_{\text{surf}} = \frac{10P_{\text{soluble,surf}}Q_{\text{surf}}}{\rho_b k_d,\text{surf}}$$

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

### Appendix B

#### 1. Intra-watershed trading case:

Max $f = \sum_{i=1}^{3} \sum_{j=1}^{7} AB^i \cdot (X_{ij}^- + \Delta X_{ij} \cdot \epsilon_{ijw})$

+ $\sum_{n=1}^{3} \sum_{r=1}^{7} W_{ir}^- \cdot (N_{ir}^- + \Delta N_{ir} \cdot r_{irw})$

+ $\sum_{p=1}^{3} \sum_{w=1}^{7} SB_{pw}^- \cdot (Z_p^- + \Delta Z_p \cdot s_{pw})$

+ $\sum_{m=1}^{3} \sum_{w=1}^{7} CB_{mw}^- \cdot (Y_m^- + \Delta Y_m \cdot e_{mw})$

- $\sum_{i=1}^{3} \sum_{k=1}^{7} h_k \cdot EDPA_{sw}^- \cdot PF^i$

- $\sum_{n=1}^{3} \sum_{p=1}^{7} EDPR_{sw}^- \cdot PF^i$

- $\sum_{p=1}^{7} EDPP_{sw}^- \cdot PF^i$

- $\sum_{m=1}^{3} \sum_{w=1}^{7} EDP_{sw}^- \cdot PF^i$

- $\sum_{i=1}^{3} \sum_{k=1}^{7} k_s \cdot EDNA_{sw}^- \cdot NF^i$

- $\sum_{n=1}^{3} \sum_{w=1}^{7} EDNR_{sw}^- \cdot NF^i$

- $\sum_{p=1}^{7} EDNF_{sw}^- \cdot NF^i$

- $\sum_{m=1}^{3} \sum_{w=1}^{7} EDNC_{sw}^- \cdot NF^i$

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 system net benefits and the environmental penalties of agriculture, livestock and poultry industry, fishery and company. The constraints to be complied with can be divided into the following groups:

(a) Constraints for TP permit reallocation
\[
\sum_{j=1}^{11} (X_{ij}^{+} + \Delta X_{ij} \cdot o_{ijw}) \cdot CWPA_{k}^{+} - EDPA_{iskw}^{+} \leq ACEP_{iw} \quad \text{B2}
\]

\[
\sum_{r=1}^{4} (N_{nr}^{+} + \Delta N_{nr} \cdot r_{nrw}) \cdot CWPR_{r}^{+} - EDPR_{nmw}^{+} \leq LCEP_{mw} \quad \text{B3}
\]

\[
\sum_{r=1}^{4} (N_{nr}^{+} + \Delta N_{nr} \cdot r_{nrw}) \cdot CWPR_{r}^{+} - EDPR_{nmw}^{+} \leq LCEP_{mw} \quad \text{B3}
\]

\[
(Z_{n}^{+} + \Delta Z_{n} \cdot s_{pwm}) \cdot DWP_{r}^{+} \cdot CWPP_{r}^{+} - EDPP_{npw}^{+} \leq SCEP_{pw} \quad \text{B4}
\]

\[
(\sum_{i=1}^{11} (X_{ij}^{+} + \Delta X_{ij} \cdot o_{ijw}) \cdot CWNA_{k}^{+} - EDNA_{iskw}^{+} \leq ACEN_{iw} \quad \text{B6}
\]

\[
\sum_{r=1}^{4} (N_{nr}^{+} + \Delta N_{nr} \cdot r_{nrw}) \cdot CWNA_{k}^{+} - EDNA_{iskw}^{+} \leq ACEN_{iw} \quad \text{B6}
\]

\[
(Y_{n}^{+} + \Delta Y_{n} \cdot e_{mwm}) \cdot DWM_{m}^{+} \cdot CWPM_{m}^{+} - EDPC_{nmw}^{+} \leq CCEP_{mw} \quad \text{B5}
\]

\[
(Y_{n}^{+} + \Delta Y_{n} \cdot e_{mwm}) \cdot DWM_{m}^{+} \cdot CWPM_{m}^{+} - EDPC_{nmw}^{+} \leq CCEP_{mw} \quad \text{B5}
\]

Constraints (B2)–(B5) and (B6)–(B9) represent the trading process of TP and NH3-N discharge permits for 18 pollution sources, respectively. Through the trading, the reallocation of discharge permits can be optimized to obtain the maximum net benefits and minimum environmental penalties. In addition, the reallocated TP and NH3-N discharge permits for each pollution source in Daguhe watershed and Moshuihe watershed respectively are equal to the initial discharge permits plus the purchasing permits, and minus the selling permits.

(c) Constraints for TP trading rules

\[
\sum_{i=1}^{3} TPN_{iw}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \leq TPN_{nw}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \quad \text{B11}
\]

\[
\sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \leq TPN_{nw}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \quad \text{B11}
\]

\[
\sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \leq TPN_{nw}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \quad \text{B11}
\]

\[
\sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \leq TPN_{nw}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \quad \text{B11}
\]

\[
\sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \leq TPN_{nw}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \quad \text{B11}
\]

\[
\sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \leq TPN_{nw}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \quad \text{B11}
\]

\[
\sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \leq TPN_{nw}^{+} + \sum_{i=1}^{3} TPS_{iwm}^{+} + \sum_{p=1}^{3} TPS_{npw}^{+} \quad \text{B11}
\]
\begin{equation}
\sum_{p=1}^{3} TN_{pw} + \sum_{i=1}^{4} TNs_{pw} + \sum_{n=1}^{3} TNS_{pw} \leq TNP_{pw} + \sum_{p=1}^{3} TN_{pw} p/m_{p} + \sum_{n=1}^{3} TNP_{pw} m/n_{p} + \sum_{i=1}^{4} TNP_{pw} m_{i} (B17)
\end{equation}

\begin{equation}
\sum_{m=1}^{7} TNS_{mw} \leq TNL_{iw} + \sum_{m=1}^{7} TNb_{mw} / m_{m} \quad i = 5 (B18)
\end{equation}

\begin{equation}
\sum_{m=1}^{7} TN_{mw} / m_{m} + \sum_{m=1}^{7} TNs_{mw} \leq TM_{uw} \quad i = 5 (B19)
\end{equation}

Constraints (B10)–(B14) and (B15)–(B19) can contribute to the trading of TP and NH3-N discharge permits for pollution sources in Daguhe watershed and Moshuihe watershed, respectively. And following the trading rules that the discharge permits sold by the pollution sources should be larger than the sum of the discharge permits they purchase and possess.

(e) Constraints for TP environmental limit.

\begin{equation}
ACE_{iw} \leq TPA_{iw}, \quad LCE_{iw} \leq TPL_{iw} \quad (B20)
\end{equation}

\begin{equation}
SCE_{iw} \leq TPS_{iw}, \quad CCE_{iw} \leq TPC_{iw} \quad (B21)
\end{equation}

\begin{equation}
ACE_{iw} + LCE_{iw} + SCE_{iw} \leq TPGF_{iw} \quad \forall i = n = p, \quad i = 1, 2, 3, \quad q \neq 4 \quad (B22)
\end{equation}

\begin{equation}
ACE_{iw} \leq TPGF_{qw} \quad i = 4, \quad q = 4 \quad (B23)
\end{equation}

\begin{equation}
ACE_{iw} + CCE_{iw} + ACE_{iw} + SCE_{iw} \leq TPGF_{qw} \quad \forall i = n = p, \quad i = 1, 2, 3, \quad q \neq 4 \quad (B24)
\end{equation}

\begin{equation}
ACE_{iw} \leq TPGF_{qw} \quad i = 4, \quad q = 4 \quad (B25)
\end{equation}

\begin{equation}
\sum_{i=1}^{4} ACE_{iw} \leq ACE_{iw} + \sum_{n=1}^{3} LCE_{iw} + \sum_{p=1}^{3} SCE_{iw} \leq TPGF_{iw} \quad (B26)
\end{equation}

\begin{equation}
ACE_{iw} \leq TPS_{iw} \quad i = 5 \quad (B27)
\end{equation}

(f) Constraints for NH3-N environmental limit.

\begin{equation}
ACEN_{iw} \leq TNA_{iw}, \quad LCEN_{iw} \leq TNL_{iw} \quad (B28)
\end{equation}

\begin{equation}
SCEN_{iw} \leq TNS_{iw}, \quad CCEN_{iw} \leq TNC_{iw} \quad (B29)
\end{equation}

The environmental limits for TP and NH3-N are set for the four industries, the four reaches in Daguhe watershed, the two reaches in Moshuihe watershed, the whole Daguhe watershed and the whole Moshuihe watershed in constraints (B20)–(B27) and (B28)–(B35).

(g) Energy and protein requirements constraints

\begin{equation}
\sum_{i=1}^{4} \sum_{j=1}^{11} AP_{q}^{+} \cdot (X_{q}^{i} + \Delta X_{q}^{i} \cdot o_{jw}) \cdot PE_{j} - \sum_{n=1}^{3} \sum_{r=1}^{4} LE_{r} \cdot (N_{r}^{n} + \Delta N_{r}^{n} \cdot r_{nwr}) - \sum_{n=1}^{3} \sum_{r=1}^{4} LE_{r} \cdot (N_{r}^{n} + \Delta N_{r}^{n} \cdot r_{nwr}) \leq 0 \quad (B36)
\end{equation}

\begin{equation}
\sum_{i=1}^{4} \sum_{j=1}^{11} AP_{q}^{+} \cdot (X_{q}^{i} + \Delta X_{q}^{i} \cdot o_{jw}) \cdot CE_{j} - \sum_{n=1}^{3} \sum_{r=1}^{4} LE_{r} \cdot (N_{r}^{n} + \Delta N_{r}^{n} \cdot r_{nwr}) - \sum_{n=1}^{3} \sum_{r=1}^{4} LE_{r} \cdot (N_{r}^{n} + \Delta N_{r}^{n} \cdot r_{nwr}) \leq 0 \quad (B37)
\end{equation}

\begin{equation}
\sum_{j=1}^{11} AP_{q}^{+} \cdot (X_{q}^{i} + \Delta X_{q}^{i} \cdot o_{jw}) \cdot PE_{j} - MP \cdot NE \geq 0 \quad i = 5 \quad (B38)
\end{equation}

\begin{equation}
\sum_{j=1}^{11} AP_{q}^{+} \cdot (X_{q}^{i} + \Delta X_{q}^{i} \cdot o_{jw}) \cdot CE_{j} - MP \cdot NP \geq 0 \quad i = 5 \quad (B39)
\end{equation}

Constraints (B36) and (B37) represent that the energy and digestible protein content from crops in Daguhe watershed should be larger than the demand of humans and livestock, respectively. Constraints (B38) and (B39) represent that the energy and digestible protein content from crops in Moshuihe watershed should be larger than the demand of humans, respectively.

(h) Technical and non-negativity constraint
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 pollution 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 pollution source, respectively; the pollution 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; within the same watershed, the TP and NH$_3$-N emission permits should be lower than the initial pollutant discharge permit of the source.

2. Non-trading case:

Max $= \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} AB_{ijw}^\pm \cdot (X_{ij} + \Delta X_{ij} \cdot \alpha_{ijw}) + \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} W_{ijw}^\pm \cdot (N_{ijw} + \Delta N_{ijw} \cdot \tau_{ijw})$

\[+ \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} CB_{ijw}^\pm \cdot (Z_{ij} + \Delta Z_{ij} \cdot s_{ijw}) + \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} CB_{ijw}^\pm \cdot (Y_{ij} + \Delta Y_{ij} \cdot e_{ijw})
\]

\[- \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} \sum_{k=1}^{3} h_k \cdot EDPA_{ijkw}^\pm \cdot PF^\pm - \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} EDPR_{ijkw}^\pm \cdot PF^\pm
\]

\[- \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} \sum_{k=1}^{3} k \cdot EDNAV_{ijkw}^\pm \cdot NF^\pm - \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} EDNR_{ijkw}^\pm \cdot NF^\pm
\]

\[- \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} EDNP_{ijkw}^\pm \cdot NF^\pm - \sum_{i=1}^{5} \sum_{j=1}^{11} \sum_{w=1}^{3} EDNC_{ijkw}^\pm \cdot NF^\pm
\]

\[(B41)\]

(a) Constraints for TP environmental limit

\[\sum_{j=1}^{11} (X_{ij} + \Delta X_{ij} \cdot \alpha_{ijw}) \cdot CWPA_{ik}^\pm \cdot EDPA_{ijkw}^\pm \leq TP\bar{I}_{iw} \ (B42)\]

\[\sum_{r=1}^{4} (N_{irw} + \Delta N_{irw} \cdot r_{irmw}) \cdot CWPR_{irw} \cdot EDPR_{irmw} \leq TPN_{mw} \ (B43)\]

\[(Y_{im} + \Delta Y_{im} \cdot e_{imw}) \cdot DWM_{imw}^\pm \cdot CWPM_{imw}^\pm - EDPC_{imw}^\pm \leq TPM_{imw} \ (B45)\]

\[\sum_{j=1}^{11} (X_{ij} + \Delta X_{ij} \cdot \alpha_{ijw}) \cdot CWPA_{ik}^\pm \cdot EDPA_{ijkw}^\pm + \sum_{r=1}^{4} (N_{irw} + \Delta N_{irw} \cdot r_{irmw}) \cdot CWPR_{irw} = (Z_{p} + \Delta Z_{p} \cdot s_{pw}) \cdot DWP^\pm \cdot CWPP^\pm - EDPP^\pm \leq TP\bar{F}_{pw} \]
\[
\sum_{j=1}^{4} \sum_{j=1}^{11} \left( X_j + \Delta X_j \cdot o_{jw} \right) \cdot \text{CWPA}_j - \text{EDPA}_{\text{sw}}^j
\]
\[
+ \sum_{i=1}^{3} \sum_{n=1}^{4} \left( N_{wr} + \Delta N_{wr} \cdot r_{sw} \right) \cdot \text{CWPR}_r - \text{EDPR}_{\text{sw}}^r
\]
\[
+ \sum_{p=1}^{3} \left( Z_p + \Delta Z_p \cdot s_{pw} \right) \cdot \text{DWP}^p - \text{CWPP}^p - \text{EDPP}_{\text{sw}}^p \leq \text{TPG}_{1}^{1-p}
\]
\[\text{(B52)}\]
\[
\sum_{j=1}^{11} \left( X_j + \Delta X_j \cdot o_{jw} \right) \cdot \text{CWPA}_j - \text{EDPA}_{\text{sw}}^j
\]
\[
+ \sum_{n=1}^{7} \left( Y_{m} + \Delta Y_{m} \cdot e_{mw} \right) \cdot \text{DWM}_m - \text{CWPM}_m - \text{EDPC}_{\text{sw}}^m \leq \text{TPW}_i
\]
\[\text{i=5}\]
\[\text{(B53)}\]
\[
\sum_{j=1}^{5} \sum_{j=1}^{11} \left( X_j + \Delta X_j \cdot o_{jw} \right) \cdot \text{CWPA}_j - \text{EDPA}_{\text{sw}}^j
\]
\[
+ \sum_{n=1}^{3} \sum_{r=1}^{4} \left( N_{nr} + \Delta N_{nr} \cdot r_{sw} \right) \cdot \text{CWPR}_r - \text{EDPR}_{\text{sw}}^r
\]
\[
+ \sum_{p=1}^{3} \left( Z_p + \Delta Z_p \cdot s_{pw} \right) \cdot \text{DWP}^p - \text{CWPP}^p - \text{EDPP}_{\text{pw}}^p \leq \text{TPG}_{1}^{1-p}
\]
\[\text{(B54)}\]
\[
\sum_{j=1}^{11} \left( X_j + \Delta X_j \cdot o_{jw} \right) \cdot \text{CWNA}_{s}^j - \text{EDNA}_{\text{sw}}^j \leq \text{TNI}_{1w}
\]
\[\text{(B55)}\]
\[
\sum_{i=1}^{4} \sum_{r=1}^{4} \left( N_{nr} + \Delta N_{nr} \cdot r_{sw} \right) \cdot \text{CWNR}_{r} - \text{EDNR}_{\text{sw}}^r \leq \text{TNN}_{\text{sw}}
\]
\[\text{(B56)}\]
\[
\sum_{i=1}^{4} \sum_{j=1}^{11} \left( X_j + \Delta X_j \cdot o_{jw} \right) \cdot \text{CWNA}_{s}^j - \text{EDNA}_{\text{sw}}^j
\]
\[
+ \sum_{i=1}^{4} \sum_{n=1}^{3} \sum_{r=1}^{4} \left( N_{nr} + \Delta N_{nr} \cdot r_{sw} \right) \cdot \text{CWNR}_{r} - \text{EDNR}_{\text{sw}}^r
\]
\[
+ \sum_{p=1}^{3} \left( Z_p + \Delta Z_p \cdot s_{pw} \right) \cdot \text{DWP}^p - \text{CWNP}^p - \text{EDNP}_{\text{pw}}^p \leq \text{TNG}_{1}^{1-p}
\]
\[\text{(B57)}\]
\[
\sum_{j=1}^{11} \left( X_j + \Delta X_j \cdot o_{jw} \right) \cdot \text{CWNA}_{s}^j - \text{EDNA}_{\text{sw}}^j
\]
\[
+ \sum_{i=1}^{4} \sum_{n=1}^{3} \sum_{r=1}^{4} \left( N_{nr} + \Delta N_{nr} \cdot r_{sw} \right) \cdot \text{CWNR}_{r} - \text{EDNR}_{\text{sw}}^r
\]
\[
+ \sum_{p=1}^{3} \left( Z_p + \Delta Z_p \cdot s_{pw} \right) \cdot \text{DWP}^p - \text{CWNP}^p - \text{EDNP}_{\text{pw}}^p \leq \text{TNG}_{1}^{1-p}
\]
\[\text{(B58)}\]
\[
\sum_{j=1}^{11} \left( X_j + \Delta X_j \cdot o_{jw} \right) \cdot \text{CWNA}_{s}^j - \text{EDNA}_{\text{sw}}^j
\]
\[
+ \sum_{i=1}^{4} \sum_{n=1}^{3} \sum_{r=1}^{4} \left( N_{nr} + \Delta N_{nr} \cdot r_{sw} \right) \cdot \text{CWNR}_{r} - \text{EDNR}_{\text{sw}}^r
\]
\[
+ \sum_{p=1}^{3} \left( Z_p + \Delta Z_p \cdot s_{pw} \right) \cdot \text{DWP}^p - \text{CWNP}^p - \text{EDNP}_{\text{sw}}^p \leq \text{TNG}_{1}^{1-p}
\]
\[\text{(B59)}\]
Table 5  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     | 0/0     | 0/0     | 3.42/2.63 |
| $p = 1$          | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     |
| $p = 2$          | 3.34/3.34 | 7.89/6.16 | 0/0     | 0/0     | 4.47/3.64 | 0/0     | 0/0     | 0/0     |
| $p = 3$          | 0/0     | 0.52/0.31 | 0/0     | 0/0     | 0/0     | 0/0     | 4.47/3.64 | 0/0     |
| $m = 1$          | /       | /       | /       | /       | /       | /       | /       | /       |
| $m = 2$          | /       | /       | /       | /       | /       | /       | /       | /       |
| $m = 3$          | /       | /       | /       | /       | /       | /       | /       | /       |
| $m = 4$          | /       | /       | /       | /       | 0.01/0.01 | /       | /       | /       |
| $m = 5$          | /       | /       | /       | /       | 0.01/0.01 | /       | /       | /       |
| $m = 6$          | /       | /       | /       | /       | 0.01/0.01 | /       | /       | /       |
| $m = 7$          | /       | /       | /       | /       | 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     |
| $n = 1$          | 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     |
| $m = 2$          | /       | /       | 0/0     | 0/0     | 0/0     | 0.01/0.01 | 0.02/0.01 | 0/0     |
| $m = 3$          | /       | /       | 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     |
| $m = 5$          | /       | /       | 0/0     | 0.15/0.15 | 0/0     | 0/0     | 0/0     | 0/0     |
| $m = 6$          | /       | /       | 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     |
Table 6  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    | 0/0    | 0/0    | 0/0    | 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    |
| $i = 5$          | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    |
| $n = 1$          | 154.6/54.82 | 154.6/79.7 | 32.28/11.17 | 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    |
| $n = 3$          | 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    | 0/0    |
| $p = 2$          | 0/0    | 39.43/30.8 | 0/0    | 10.43/7.73 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| $p = 3$          | 34.12/34.12 | 34.12/18.95 | 34.12/19.06 | 0/0 | 0/0 | 0/0 | 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    | 0/0    | 0/0    | 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    | 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    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    |
| $n = 2$          | 120.04/114.33 | 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    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    |
| $p = 3$          | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    |
| $m = 1$          | 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    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    |
Table 7 The detailed trading process for TP under Case 2 when \( p = 0.01 \) and \( w = 1 \)

| Seller/purchaser | \( i = 1 \) | \( i = 2 \) | \( i = 3 \) | \( i = 4 \) | \( i = 5 \) | \( n = 1 \) | \( n = 2 \) | \( n = 3 \) | \( p = 1 \) |
|------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| \( m = 3 \)      | 0/0        | 0/0        | 0/0        | 0/0        | 0.01/0.01  | 0/0        | 0/0        | 0/0        | 0.02/0.02  |
| \( m = 4 \)      | 0/0        | 0/0        | 0/0        | 0/0        | 0.01/0.01  | 0/0        | 0/0        | 0/0        | 0.06/0.06  |
| \( m = 5 \)      | 0/0        | 0/0        | 0/0        | 0/0        | 0.08/0.08  | 0/0        | 0/0        | 0/0        | 0.07/0.07  |
| \( m = 6 \)      | 0/0        | 0/0        | 0/0        | 0.01/0.01  | 0/0        | 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        | 0/0        |

(continued)
Table 8 The detailed trading process for NH₃-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   | 381.4/381.4   | 13.44/13.44  | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| i = 4            | 134.08/134.08 | 0/0   | 0/0   | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| i = 5            | 0/0   | 0/0   | 0/0   | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| i = 6            | 0/0   | 0/0   | 0/0   | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| i = 7            | 0/0   | 0/0   | 0.51/0.51 | 0.97/0.97 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
Table 9 The detailed trading process for TP under Case 1 and $p = 0.01$ in medium level of water availability ($w = 3$)

| 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    | 0/0    | 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    | 3.39/3.39 |
| $i = 5$          | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    |
| $n = 1$          | 0/0    | 0/0    | 9.89/4.51 | 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    |
| $n = 3$          | 5.05/5.05 | 0/0 | 6.28/4.69 | 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    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    |
| $p = 3$          | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0.02/0.01 | 0/0    | 0/0    |
| $m = 1$          | /      | /      | /      | /      | /      | /      | /      | /      | /      |
| $m = 2$          | /      | /      | /      | /      | /      | /      | /      | /      | /      |
| $m = 3$          | /      | /      | /      | /      | /      | /      | /      | /      | /      |
| $m = 4$          | /      | /      | /      | /      | /      | /      | /      | /      | /      |
| $m = 5$          | /      | /      | /      | /      | 0.01/0.01 | /      | /      | /      | /      |
| $m = 6$          | /      | /      | /      | /      | /      | /      | /      | /      | /      |
| $m = 7$          | /      | /      | /      | /      | /      | /      | /      | /      | /      |
| 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    | /      | /      | /      | /      | /      | /      | /      |
| $i = 4$          | 2.95/2.95 | 0/0 | /      | /      | /      | /      | /      | /      | /      |
| $i = 5$          | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0.02/0.01 | 0/0    | 0/0    | 0/0    |
| $n = 1$          | 0/0    | 0/0    | /      | /      | /      | /      | /      | /      | /      |
| $n = 2$          | 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    | 0/0    | 0/0    | 0.02/0.02 | 0/0    | 0/0    | 0/0    |
| $m = 2$          | /      | /      | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    | 0/0    |
Table 10 The detailed trading process for NH$_3$-N under Case 1 and $p = 0.01$ in medium level of water availability ($w = 3$)

| 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     | 0/0     | 98.21/98.21 | 0/0     | 35.07/32.47 | 0/0     |
| $i = 2$          | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0.00/8.00   | 0/0     | 0/0     | 0/0     |
| $i = 3$          | 0/0     | 0/0     | 0/0     | 0/0     | 29.83/21.15 | 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     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     |
| $n = 1$          | 0/0     | 0/0     | 61.84/31.88 | 43.19/14.95 | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     |
| $n = 2$          | 0/0     | 0/0     | 31.39/16.7 | 0/0     | 0/0     | 10.44/7.4   | 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     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     |
| $p = 3$          | 12.94/12.94 | 12.94/7.19 | 0/0     | 0/0     | 5.70/5.70   | 0/0     | 12.94/12.94 | 2.26/2.26 | 0/0     |
| $m = 1$          | /       | /       | /       | /       | 0.92/0.92   | /       | /       | /       | /       |
| $m = 2$          | /       | /       | /       | /       | 1.38/1.38   | /       | /       | /       | /       |
| $m = 3$          | /       | /       | /       | /       | 0/0        | /       | /       | /       | /       |
| $m = 4$          | /       | /       | /       | /       | 0.05/0.05   | /       | /       | /       | /       |
| $m = 5$          | /       | /       | /       | /       | 0.14/0.14   | /       | /       | /       | /       |
| $m = 6$          | /       | /       | /       | /       | 0.01/0.01   | /       | /       | /       | /       |
| $m = 7$          | /       | /       | /       | /       | 11.64/11.64 | /       | /       | /       | /       |

| 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     | 48.21/48.21 | /       | /       | /       | /       | /       | /       | /       |
| $i = 5$          | 0/0     | 0/0     | 17.05/13.64 | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     |
| $n = 1$          | 0/0     | 0/0     | /       | /       | /       | /       | /       | /       | /       |
| $n = 2$          | 1.9/1.81 | 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     | 1.38/1.38 | 0/0     | 0/0     | 0.14/0.07 | 0.02/0.02 | 11.64/11.64 |
| $m = 2$          | /       | /       | 0/0     | 0/0     | 0/0     | 0/0     | 0.05/0.05 | 0.14/0.07 | 0.02/0.02 |
| $m = 3$          | /       | /       | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0.01/0.01 |
| $m = 4$          | /       | /       | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0.02/0.02 |
| $m = 5$          | /       | /       | 0/0     | 0/0     | 0/0     | 0.05/0.05 | 0/0     | 0/0     | 0.01/0.01 |
| $m = 6$          | /       | /       | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0/0     | 0.09/0.09 |
| $m = 7$          | /       | /       | 0/0     | 0.21/0.21 | 0/0     | 0/0     | 0.14/0.07 | 0.02/0.02 | 0/0     |
Table 11 The detailed trading process for TP under Case 2 and \( p = 0.01 \) in medium level of water availability \((w = 3)\)

| 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         | 0/0         | 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         | 1.29/1.29   | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         |
| \( i = 5 \)      | 0/0         | 0/0         | 0/0         | 0.28/0.28   | 0/0         | 0/0         | 0/0         | 1.1/1.1     | 8.35/8.35   |
| \( n = 1 \)      | 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         |
| \( n = 3 \)      | 0.56/0.56   | 0/0         | 5.33/3.98   | 0/0         | 0/0         | 1.29/1.29   | 0/0         | 0/0         | 0.47/0.47   |
| \( p = 1 \)      | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         |
| \( p = 2 \)      | 0/0         | 0/0         | 3.25/3.25   | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         |
| \( p = 3 \)      | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         |
| \( m = 1 \)      | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         |
| \( m = 2 \)      | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 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         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 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         | 0/0         | 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         | 0/0         | 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         |
| \( i = 5 \)      | 4.19/4.19   | 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         | 0.02/0.02   | 0/0         | 0/0         | 0/0         |
| \( p = 2 \)      | 0/0         | 0.15/0.15   | 0.09/0.09   | 0/0         | 0/0         | 0/0         | 0.01/0.01   | 0/0         | 0.32/0.32   |
| \( p = 3 \)      | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         |
| \( m = 1 \)      | 0/0         | 0.05/0.05   | 0/0         | 0.05/0.05   | 0/0         | 0/0         | 0/0         | 0.01/0.01   | 0.05/0.05   |
| \( m = 2 \)      | 0/0         | 0.08/0.08   | 0.07/0.07   | 0/0         | 0/0         | 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         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         |
| \( m = 5 \)      | 0/0         | 0/0         | 0/0         | 0.01/0.01   | 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         | 0/0         | 0.39/0.39   | 0/0         | 0/0         | 0/0         | 0/0         | 0/0         |
Table 12 The detailed trading process for NH$_3$-N under Case 2 and $p = 0.01$ in medium level of water availability ($w = 3$)

| 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      | 0/0      | 0/0      | 0/0      | 0/0      | 59.12/54.74 |
| $i = 2$           | 0/0      | 0/0      | 0/0      | 7.80/7.43 | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
| $i = 3$           | 0/0      | 0/0      | 0/0      | 0/0      | 144.65/144.65 | 0/0      | 0/0      | 0/0      | 0/0      |
| $i = 4$           | 0/0      | 0/0      | 0/0      | 0/0      | 82.79/82.79 | 0/0      | 0/0      | 0/0      | 0/0      |
| $i = 5$           | 0/0      | 0/0      | 0/0      | 44.92/44.92 | 0/0      | 62.66/62.66 | 0/0      | 62.66/62.66 | 0/0      |
| $n = 1$           | 0/0      | 0/0      | 15.54/8.01 | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
| $n = 2$           | 0/0      | 0/0      | 49.55/49.55 | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
| $n = 3$           | 0/0      | 0/0      | 31.39/23.43 | 31.39/23.43 | 0/0      | 16.83/11.94 | 0/0      | 0/0      | 0/0      |
| $p = 1$           | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 18.39/9.2 | 20.31/14.72 | 0/0      | 0/0      |
| $p = 2$           | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 16.27/16.27 |
| $p = 3$           | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 12.94/12.94 |
| $m = 1$           | 0/0      | 0.92/0.77 | 0.92/0.92 | 0.92/0.92 | 0.92/0.92 | 0/0      | 0/0      | 0/0      | 0.92/0.92 |
| $m = 2$           | 1.38/1.38 | 1.38/1.15 | 1.38/1.38 | 1.38/1.38 | 1.38/1.38 | 0/0      | 0/0      | 0/0      | 1.38/1.38 |
| $m = 3$           | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
| $m = 4$           | 0.05/0.05 | 0.05/0.05 | 0.05/0.05 | 0.05/0.05 | 0.05/0.05 | 0/0      | 0.05/0.04 | 0/0      | 0.05/0.04 |
| $m = 5$           | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
| $m = 6$           | 0.02/0.02 | 0.02/0.02 | 0.02/0.02 | 0.02/0.02 | 0.02/0.02 | 0/0      | 0/0      | 0/0      | 0.02/0.02 |
| $m = 7$           | 0/0      | 0/0      | 0/0      | 11.64/9.7 | 0/0      | 0/0      | 0/0      | 0/0      | 0.92/0.92 |
| 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      | 0/0      | 0/0      | 0/0      | 0/0      |
| $i = 2$           | 8.37/8.37 | 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      |
| $i = 5$           | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
| $n = 1$           | 0/0      | 39.44/25.94 | 0/0      | 0/0      | 0.81/0.81 | 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      | 31.39/27.06 |
| $n = 3$           | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
| $p = 1$           | 20.31/9.67 | 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      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
| $m = 1$           | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0.92/0.92 |
| $m = 2$           | 1.38/1.38 | 1.38/1.38 | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0.11/0.11 |
| $m = 3$           | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
| $m = 4$           | 0.05/0.05 | 0.05/0.05 | 0.05/0.05 | 0.05/0.05 | 0.05/0.05 | 0/0      | 0/0      | 0/0      | 0.05/0.05 |
| $m = 5$           | 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      | 4.97/4.97 | 11.09/11.09 | 0/0      | 0/0      | 0/0      | 0/0      |
| $m = 7$           | 0/0      | 0/0      | 4.97/4.97 | 11.09/11.09 | 0/0      | 0/0      | 0/0      | 0/0      | 0/0      |
\[
\sum_{i=1}^{n} \sum_{j=1}^{m} (X_{ij} + \Delta X_{ij} \cdot \alpha_{ijw}) \cdot CWN_{ijw}^\pm - EDN_{ijw}^\pm \\
+ \sum_{\mu=1}^{3} \sum_{\nu=1}^{4} (N_{i\mu}^\pm + \Delta N_{i\mu} \cdot r_{\text{new}}) \cdot CWN_{i\muw}^\pm - EDN_{i\muw}^\pm \\
+ \sum_{p=1}^{3} (Z_{p}^\pm + \Delta Z_{p} \cdot s_{\text{pw}}) \cdot DW_{p}^\pm \cdot CWN_{p}^\pm - EDN_{p}^\pm \\
+ \sum_{w=1}^{7} (Y_{w} - \Delta Y_{w} \cdot \epsilon_{\text{new}}) \cdot DWM_{w}^\pm \cdot CWN_{w}^\pm - EDN_{w}^\pm \leq TNT_{w}^\pm
\]

(B67)

(c) Energy and protein requirements constraints
\[
\sum_{i=1}^{n} \sum_{j=1}^{m} AP_{ijw}^\pm \cdot (X_{ij} + \Delta X_{ij} \cdot \alpha_{ijw}) \cdot PE_{j}
\]

(B68)

- \sum_{i=1}^{n} \sum_{j=1}^{m} LE_{ijw} \cdot (N_{i\mu}^\pm + \Delta N_{i\mu} \cdot r_{\text{new}}) \cdot DP_{ij} \cdot NE_{ij} - MP_{ij} \cdot NE_{ij} \geq 0

\sum_{i=1}^{n} \sum_{j=1}^{m} AP_{ijw}^\pm \cdot (X_{ij} + \Delta X_{ij} \cdot \alpha_{ijw}) \cdot CE_{j}
\]

- \sum_{i=1}^{n} \sum_{j=1}^{m} LP_{ijw} \cdot (N_{i\mu}^\pm + \Delta N_{i\mu} \cdot r_{\text{new}}) \cdot DP_{ij} \cdot NP_{ij} - MP_{ij} \cdot NP_{ij} \geq 0

(B69)

(d) Technical and non-negativity constraints
\[
0 \leq \alpha_{ijw} \leq 1, \ 0 \leq r_{\text{new}} \leq 1, \ 0 \leq s_{\text{pw}} \leq 1, \ 0 \leq \epsilon_{\text{new}} \leq 1
\]

(B70)

Besides, the technology and non-negative constraints comprise the excess TP and NH$_3$-N emission of each pollution source. And 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.

**Appendix C**

See Tables 5, 6, 7, 8, 9, 10, 11, and 12.

**Appendix D**

- **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 peanut, \(j = 2\) for corn, \(j = 3\) for Chinese cabbage, \(j = 4\) for celery, \(j = 5\) for carrot, \(j = 7\) for potato, \(j = 8\) for apple, \(j = 9\) for grape, \(j = 10\) for peach, \(j = 11\) for pear.

- **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 livestock and poultry, \(r = 1, 2, 3, 4\); \(r = 1\) 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 Helo Chemical Co., Ltd, \(m = 4\) for Qingdao Zeyukai Sheng 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.

- **q** Other agricultural zone except zone \(i\), \(q = 1\) for Qingdao Agriculture Co., Ltd, \(q = 2\) for Qingdao Pingdu Agriculture Co., Ltd, \(q = 3\) for Qingdao Jiaozhou Agriculture Co., Ltd.
- **o** Other livestock and poultry industry zone except zone \(n\), \(o = 1\) for Qingdao Livestock and Poultry Industry Co., Ltd, \(o = 2\) for Qingdao Jiaozhou Livestock and Poultry Industry Co., Ltd.

- **k** Other species of livestock and poultry except \(r\), \(k = 1\) for Qingdao Livestock and Poultry Industry Co., Ltd, \(k = 2\) for Qingdao Pingdu Livestock and Poultry Industry Co., Ltd.

- **s** Other fishery zone except zone \(p\), \(s = 1\) for Qingdao Fishery Co., Ltd, \(s = 2\) for Qingdao Jiaozhou Fishery Co., Ltd.

- **h** Other company except company \(m\), \(h = 1\) for Qingdao Manufacturing Co., Ltd, \(h = 2\) for Qingdao Jiaozhou Manufacturing Co., Ltd.

- **q** The level of water availability, \(q = 1\) for high level, \(q = 2\) for low level, \(q = 3\) for medium level.

- **w** Reaches in Daguhe watershed, \(w = 1\) for Pingdu reach, \(w = 2\) for Jiaozhou reach.

- **o** Reaches in Moshuihe watershed, \(o = 1\) for Laixi reach, \(o = 2\) for Pingdu reach, \(o = 3\) for Jiaozhou reach.

- **AB_{i}^{j}** Production level of crop \(j\) in agricultural zone \(i\) (kg/ha).
- **AP_{i}^{j}** Production level of crop \(j\) in agricultural zone \(i\) (RMB¥/ha).

- **SB_{i}^{j}** Lower bound and range of area target for crop \(j\) in zone \(i\) (ha).

- **CB_{i}^{j}** 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.

- **p** Net benefit of zone \(p\) (RMB¥/ha).

- **k** Net benefit of crop \(j\) in agricultural zone \(i\) (kg/ha).

- **o** Net benefit of crop \(j\) in agricultural zone \(i\) (RMB¥/ha).
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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 \( \text{NH}_{3}-\text{N} \) 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 \( \text{NH}_{3}-\text{N} \) effluents exceeding to discharge permits from pollution source (RMB¥/ton)

\( EDP_{A}^{w}, \ EDP_{P}^{w}, \ EDP_{A}^{p}, \ EDP_{P}^{p} \)

Excess annual TP loading for agricultural zone \( i \), livestock and poultry industry zone \( n \), fishery zone \( p \) and company \( m \) (ton)

\( EDN_{A}^{w}, \ EDN_{P}^{w}, \ EDN_{A}^{p}, \ EDN_{P}^{p} \)

Excess annual \( \text{NH}_{3}-\text{N} \) loading for agricultural zone \( i \), livestock and poultry industry zone \( n \), fishery zone \( p \) and company \( m \) (ton)

\( DWP^{w}, \ DWA^{w} \)

Effluent generation rate of fishery zone and company \( m \) (m³/ha; m³/ton, item)

\( CWPA^{w}, \ CWPR^{w}, \ CWPP^{w}, \ CWPM^{w} \)

TP generation rate of agricultural zone \( i \), livestock \( r \), fishery zone \( p \) and company \( m \) (ton/ha; ton/ton; m³/ton; m³/m³)

\( CWNA^{w}, \ CWNR^{w}, \ CWNP^{w}, \ CWNM^{w} \)

\( \text{NH}_{3}-\text{N} \) generation rate of agricultural zone \( i \), livestock \( r \), fishery zone \( p \) and company \( m \) in level \( w \), respectively (ton/ha; ton/tm; m³/ha; m³/ton)

\( TPi_{m}, \ TPi_{n}, \ TPm_{m}, \ TPm_{m} \)

TP discharge permit allocated to agricultural zone \( i \), livestock and poultry industry zone \( n \), fishery zone \( p \) and company \( m \) in level \( w \), respectively (ton)

\( TNI_{m}, \ TNP_{m}, \ TNP_{m}, \ TNP_{m} \)

NH\(_{3}\)-N discharge permit allocated to agricultural zone \( i \), livestock and poultry industry zone \( n \), fishery zone \( p \) and company \( m \) in level \( w \), respectively (ton)

\( ACEP_{A}, \ LCEP_{A}, \ SCEP_{P}, \ CCEP_{P} \)

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)

\( ACEN_{A}, \ LCEN_{A}, \ SCEN_{P}, \ CCEN_{P} \)

\( \text{NH}_{3}\)-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)

\( TPi_{m}, \ TPi_{n}, \ TPm_{m}, \ TPm_{m} \)

TP discharge permit sold to agricultural zone \( i \) from agricultural zone \( j \), livestock and poultry industry zone \( n \), fishery zone \( p \) and company \( m \) (ton)

\( TPi_{m}, \ TPi_{n}, \ TPm_{m}, \ TPm_{m} \)

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 \( m \) (ton)

\( TPi_{m}, \ TPi_{n}, \ TPm_{m}, \ TPm_{m} \)

TP discharge permit sold to livestock and poultry industry zone \( n \) from agricultural zone \( i \), livestock and poultry industry zone \( n' \), agricultural zone \( i \), fishery zone \( p \) and company \( m \) (ton)
zone $i$, livestock and poultry industry zone $n$ and company $m$, respectively (ton)

$T_{Nh_{m,n}}, T_{Nh_{m,n}^{sm}}, T_{Nh_{m,n}^{smw}}$

$NH_3$-N discharge permit in company $m$ purchased from agricultural zone $i$, livestock and poultry industry zone $n$ and fishery zone $p$, respectively (ton)

$T_{Nh_{m,n}^{sm}}, T_{Nh_{m,n}^{smw}}$

$NH_3$-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)

$\eta_{pi}, \eta_{ni}, \eta_{pi}, \eta_{nm}$

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

$\eta_{n,m}, \eta_{m,n}, \eta_{pm}, \eta_{mp}$

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

$\eta_{pi}', \eta_{ni}', \eta_{pi}', \eta_{nm'}$

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

$\eta_{0,j}, \eta_{0,m}, \eta_{0,p}, \eta_{0,mn}$

$NH_3$-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

$\delta_{0,j}, \delta_{0,m}, \delta_{0,p}, \delta_{0,mn}$

$NH_3$-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

$\delta_{0,j}', \delta_{0,m}', \delta_{0,p}', \delta_{0,mn'}$

$NH_3$-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

$\delta_{0,j}, \delta_{0,m}, \delta_{0,p}, \delta_{0,mn}$

$NH_3$-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

$\delta_{0,j}', \delta_{0,m}', \delta_{0,p}', \delta_{0,mn'}$

$NH_3$-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

$p_n$

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/a)

$DP$

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)

$CE_r$

The quantity of digestible protein per kg of crop $j$ (g/kg)

$L_P$

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)

$TPA_{iw}, TPL_{m,w}, TPS_{pn}, TPC_{mnw}$

Allowance of TP emission for agricultural zones, livestock and poultry industry zones, fishery zones and companies within the two watersheds in level $w$ (ton)

$TNA_{iw}, TNL_{m,w}, TNS_{pn}, TNC_{mnw}$

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)

$TPG_{iw}$

Allowance of TP emission in Daguhe watershed in level $w$ (ton)

$TNG_{iw}$

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)

$TPW_{iw}$

Allowance of TP emission in Moshuihe watershed in level $w$ (ton)

$TNW_{iw}$

Allowance of $NH_3$-N emission in Moshuihe watershed in level $w$ (ton)

$TPWF_{qw}$

Allowance of TP emission in reach $q$, Moshuihe watershed in level $w$ (ton)

$TNWF_{qw}$

Allowance of $NH_3$-N emission in reach $q$, Moshuihe watershed in level $w$ (ton)

$TPT_{iw}$

Allowance of TP emission in both watersheds in level $w$ (ton)

$TN_{iw}$

Allowance of $NH_3$-N emission in both watersheds in level $w$ (ton)

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Declarations

Conflict of 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. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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