

Effects of Important Factors on Effluent Trading: A Bayesian Estimation-Based Inexact Two-Stage Stochastic Programming Method

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Abstract: We proposed a Bayesian estimation-based inexact two-stage stochastic programming (BITSP) for identifying factors' effect on effluent trading. BITSP incorporates nutrient fate modeling with Bayesian estimation and inexact two-stage stochastic programming (ITSP). Based on the water quality protocols, Bayesian estimation is used to analyze parameter uncertainty of nutrient modeling as well as provide the random inputs for the optimization process. ITSP can then be used for dealing with multiple uncertainties associated with randomness and intervals. A case study for water management in the Xiangxihe watershed is conducted. Results reveal that strict environmental limits increase the desire for permit trading program. The results also reveal that treatment rate have an obvious effect on effluent trading through changing the buying and selling behavior of point sources

1. Introduction

A number of research efforts have been conducted for recognizing optimal factors, such as treatment rate of dischargers, environmental limit, the assign of river assessment points, and market scale [1-5]. Doyle et al. [6] proposed a coupled hydrologic-economic modeling approach for optimizing the scale of markets for water quality trading. Chen et al. [7] developed a water environmental functional zone-based effluent trading systems framework for analyzing the effect of background water quality, the location of river assessment points, and tradable discharge permits. Environmental limit and treatment rate are central regulatory features for the permit trading program. Environmental limit regulates the pollutant emission within the watershed. Environmental penalties would be paid when it is exceeded. Treatment rate denotes the rate of pollutants that are treated by the point sources. The treatment can generate discharge permit for store or sale. Previously, few research works were conducted on effluent trading models to analyze such central regulatory features.

Therefore, this study aims to develop a Bayesian estimation-based inexact two-stage stochastic programming (BITSP) for identifying important factors' effect. BITSP incorporates nutrient fate modeling with Bayesian estimation, and inexact two-stage stochastic programming (ITSP). We conduct a real case study for the application of BITSP in the Xiangxihe watershed. The modeling



approach will (i) address multiple uncertainties expressed as intervals and probability distribution functions; (ii) disclose the effect of important factors in effluent trading.

2. Case study

The Xiangxihe River is located in Hubei province, China (30°57'N to 31°34'N, and 110°25'E to 111°06'E). The point and nonpoint sources pollute the river. Firstly, nutrients from farmlands that are distributed on the hillside can adhere to eroded soil and be dissolved in surface runoff, then transport into the river. This can cause serious agricultural nonpoint source pollution (NPS) pollution. Secondly, phosphorus minings distribute densely within the watershed. Water can percolate from the phosphate waste rocks; this can lead to point pollution [8]. Thirdly, many phosphorus-related industries are situated near the river, with 1.97 million ton of wastewater sluiced into the Xiangxihe River annually, containing large amounts of phosphoric chemicals. In this study, total phosphorus (TP) is selected as the main water quality indicator. Nonflood season (i.e. November to May of the following year) and flood season (i.e. June to October) are considered as the two planning periods. Multiple main crops are also taken into consideration associated with different irrigation water, fertilizer application, and agricultural benefit. The effluent trading design problem can be solved through the BITSP method. The BITSP model incorporates SWAT, Bayesian estimation, and ITSP within a framework. The formulation of BITSP is presented in the "Appendix".

3. Results and discussion

In this study, six levels of environmental limit for the whole watershed are examined through varying the multiplier (ε) for the limits. Figure 1 illustrates the detailed trading process for agricultural zones, chemical plants and phosphorus mining companies. Blue bars represent the purchasing amount; while red bars represent the selling amount. From the results, the trading process would not change when ε takes 1, 0.95 and 0.9. When ε is less than 0.85, the purchasing and selling amount would be increased as the multiplier is reduced. For example, chemical plants would sell 26.04 ton, 28.57 ton and 47.62 ton discharge permit when ε takes 0.85, 0.8 and 0.75, respectively. The total trading amount would increase from 56.17 ton ($\varepsilon = 0.85$) to 134.96 ton ($\varepsilon = 0.75$) during nonflood period. The reduced multiplier represents the more strict environmental allowance. The results can be due to the reason that strict environmental limits lead to high level of environmental penalties; this increase the desire for permit trading program.

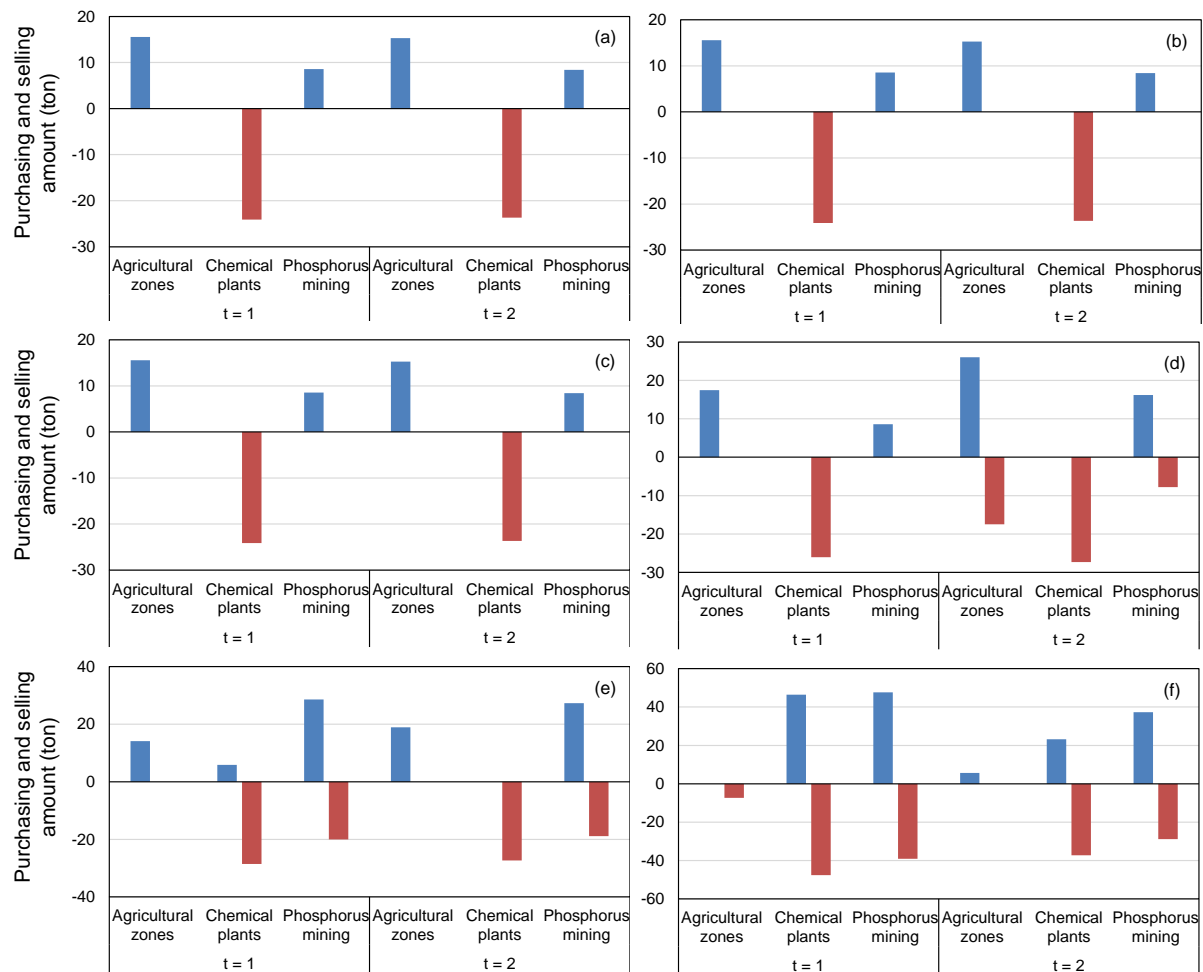


Figure 1. The detailed trading process for agricultural zones, chemical plants and phosphorus mining companies [(a) $\varepsilon = 1$, (b) $\varepsilon = 0.95$, (c) $\varepsilon = 0.9$, (d) $\varepsilon = 0.85$, (e) $\varepsilon = 0.8$, (f) $\varepsilon = 0.75$]

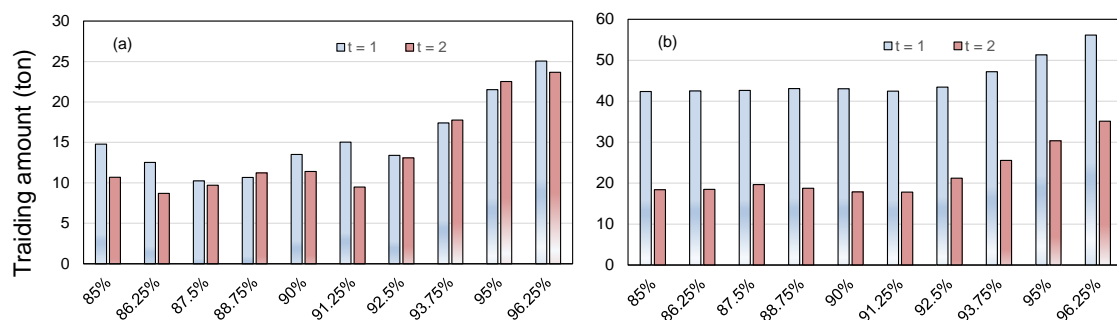


Figure 2. Total trading amount under different treatment rate [(a) $\varepsilon = 1$, (b) $\varepsilon = 0.85$]

Figure 2 illustrates the total trading amount when waste water generated from chemical plants is handled with different treatment rates when environmental limit is at the two levels ($\varepsilon = 1$ and $\varepsilon = 0.85$). From the results, the trading amount would fluctuates as treatment rate is raised. For example, in nonflood season, the trading amount would decrease from 14.79 ton ($\eta = 85\%$) to 10.23 ton ($\eta = 87.5\%$), then increase to 13.40 ton ($\eta = 92.5\%$), and rise to 15.04 ton ($\eta = 91.25\%$). As

treatment rate rise, the plants would purchase less permits because higher treatment rate can bring about more permits for the plants. This can account for the decrease of total trading amount. When treatment rate is further raised, more permits would be generated and the plants can thus sell more permits to other pollution sources to obtain benefit. This can explain the rising trend of total trading amount when treatment rate is larger than 92.75%. In addition, similar changing rules can be found when environmental limit is more strict ($\varepsilon = 0.85$); while the trading amount is less fluctuant.

4. Conclusions

In this study, a Bayesian estimation-based inexact two-stage stochastic programming (BITSP) method is proposed for identifying the effect of important trading factors. The BITSP model incorporates SWAT, Bayesian estimation, and ITSP within a framework. BITSP can help (i) address multiple uncertainties presented as intervals and probability distribution functions; and (ii) disclose the effect of important factors in effluent trading. We conduct a real case study for the application of BITSP in the Xiangxihe watershed. Results reveal that strict environmental limits increase the desire for permit trading program. The results also reveal that treatment rate have an obvious effect on effluent trading through changing the buying and selling behavior of point sources.

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Appendix

The formulation of the BITSP:

$$\begin{aligned} \text{Max } f^{\pm} = & \sum_{i=1}^4 \sum_{j=1}^9 \sum_{t=1}^2 AP_{ijt}^{\pm} AB_{ij}^{\pm} (x_{ij}^{-} + \Delta x_{ij} o_{ijt}) \\ & - \sum_{i=1}^4 \sum_{k=1}^3 \sum_{t=1}^2 p_k CA_t^{\pm} D_{ikt}^{\pm} + \sum_{s=1}^5 \sum_{t=1}^2 CB_{st}^{\pm} (Y_{st}^{-} + \Delta Y_{st} z_{st}) \\ & - \sum_{s=1}^5 \sum_{t=1}^2 \left[k_{1s}^{\pm} + k_{2s}^{\pm} (\eta_{Cs}^{\pm})^{k_{3s}^{\pm}} \right] [WG_s^{\pm}]^{k_{4s}^{\pm}} - \sum_{t=1}^2 SP_t^{\pm} SPM_t \\ & - \sum_{s=1}^5 \sum_{t=1}^2 W_{st}^{\pm} CEH_t^{\pm} + \sum_{m=1}^6 \sum_{t=1}^2 PB_{mt}^{\pm} (V_{mt}^{-} + \Delta V_{mt} b_{mt}) - \sum_{m=1}^6 \sum_{t=1}^2 F_{mt}^{\pm} CEK_t^{\pm} \end{aligned} \quad (1a)$$

Subject to:

$$\left\{ \begin{aligned} & \sum_{s=1}^5 \sum_{i=1}^4 [PAP_t(s, i) + PAS_t(i, s)] + \sum_{m=1}^6 \sum_{i=1}^4 [PAP_t(m, i) + PAS_t(i, m)] \\ & + \sum_{m=1}^6 \sum_{s=1}^5 [PCP_t(m, s) + PCS_t(s, m)] + \sum_{n=1}^3 \sum_{i=1}^4 PAP_t(n, i) \\ & + \sum_{y=1}^4 \sum_{s=1}^5 PCP_t(y, s) + \sum_{f=1}^5 \sum_{m=1}^6 PMP_t(f, m) \end{aligned} \right\} = SPM_t \quad (1b)$$

$$\begin{aligned}
ACE_{it} &= AA_{it} + \sum_{n=1}^3 PAP_t(n, i)/T_A(n, i) - \sum_{n=1}^3 PAS_t(i, n) \\
&+ \sum_{s=1}^5 PAP_t(s, i)/T_A(s, i) - \sum_{s=1}^5 PAS_t(i, s) \\
&+ \sum_{m=1}^6 PAP_t(m, i)/T_A(m, i) - \sum_{m=1}^6 PAS_t(i, m)
\end{aligned} \tag{1c}$$

$$\begin{aligned}
CCE_{st} &= AC_{st} + \sum_{y=1}^4 PCP_t(y, s)/T_C(y, s) - \sum_{y=1}^4 PCS_t(s, y) \\
&+ \sum_{i=1}^4 PCP_t(i, s)/T_C(i, s) - \sum_{i=1}^4 PCS_t(s, i) \\
&+ \sum_{m=1}^6 PCP_t(m, s)/T_C(m, s) - \sum_{m=1}^6 PCS_t(s, m)
\end{aligned} \tag{1d}$$

$$\begin{aligned}
MCE_{mt} &= AM_{mt} + \sum_{f=1}^5 PMP_t(f, m)/T_M(f, m) - \sum_{f=1}^5 PMS_t(m, f) \\
&+ \sum_{i=1}^4 PMP_t(i, m)/T_M(i, m) - \sum_{i=1}^4 PMS_t(m, i) \\
&+ \sum_{s=1}^5 PMP_t(s, m)/T_M(s, m) - \sum_{s=1}^5 PMS_t(m, s)
\end{aligned} \tag{1e}$$

$$\begin{aligned}
AA_{it} &+ \sum_{n=1}^3 PAP_t(n, i)/T_A(n, i) + \sum_{s=1}^5 PAP_t(s, i)/T_A(s, i) \\
&+ \sum_{m=1}^6 PAP_t(m, i)/T_A(m, i) \geq \sum_{n=1}^3 PAS_t(i, n) + \sum_{s=1}^5 PAS_t(i, s) + \sum_{m=1}^6 PAS_t(i, m)
\end{aligned} \tag{1f}$$

$$\begin{aligned}
AC_{st} &+ \sum_{y=1}^4 PCP_t(y, s)/T_C(y, s) + \sum_{i=1}^4 PCP_t(i, s)/T_C(i, s) \\
&+ \sum_{m=1}^6 PCP_t(m, s)/T_C(m, s) \geq \sum_{y=1}^4 PCS_t(s, y) + \sum_{i=1}^4 PCS_t(s, i) + \sum_{m=1}^6 PCS_t(s, m)
\end{aligned} \tag{1g}$$

$$\begin{aligned}
AM_{mt} &+ \sum_{f=1}^5 PMP_t(f, m)/T_M(f, m) + \sum_{i=1}^4 PMP_t(i, m)/T_M(i, m) \\
&+ \sum_{s=1}^5 PMP_t(s, m)/T_M(s, m) \geq \sum_{f=1}^5 PMS_t(m, f) + \sum_{i=1}^4 PMS_t(m, i) + \sum_{s=1}^5 PMS_t(m, s)
\end{aligned} \tag{1h}$$

$$(V_{mt}^- + \Delta V_{mt} b_{mt}) MG_{mt}^\pm - F_{mt}^\pm \leq MCE_{mt} \quad \rho C_s^\pm (Y_{st}^- + \Delta Y_{st} z_{st}) (1 - \eta_{Cs}^\pm) - W_{st}^\pm \leq CCE_{st} \tag{1i}$$

$$e_k^\pm \left(\sum_{j=1}^9 (x_{ij}^- + \Delta x_{ij} o_{ijt}) \right) - D_{ikt}^\pm \leq ACE_{it} \quad ACE_{it} \leq TA_t \quad CCE_{st} \leq TC_t \quad MCE_{mt} \leq TM_t \tag{1j}$$

$$\sum_{i=1}^4 ACE_{it} + \sum_{s=1}^5 CCE_{st} + \sum_{m=1}^6 MCE_{mt} \leq T_t \quad ACE_{2t} + CCE_{2t} \leq T_{1,t} \quad ACE_{3t} + \sum_{s=3}^5 CCE_{st} \leq T_{III,t} \tag{1k}$$

$$ACE_{1t} + CCE_{1t} + \sum_{m=1}^3 MCE_{mt} \leq T_{II,t} \quad \sum_{m=4}^6 MCE_{st} \leq T_{IV,t} \quad ACE_{4t} \leq T_{V,t} \tag{1l}$$

$$PAP_t(s, i) = PAS_t(i, s) \geq 0 \quad PAS_t(s, i) = PAP_t(i, s) \geq 0 \tag{1m}$$

$$PAP_t(m, i) = PAS_t(i, m) \geq 0 \quad PAS_t(m, i) = PAP_t(i, m) \geq 0 \tag{1n}$$

$$PCP_t(m, s) = PCS_t(s, m) \geq 0 \quad PCS_t(m, s) = PCP_t(s, m) \geq 0 \quad (1o)$$

$$PAP_t(n, i) = PAS_t(i, n) \geq 0 \quad PCP_t(y, s) = PCS_t(s, y) \geq 0 \quad (1p)$$

$$PMP_t(f, m) = PMS_t(m, f) \geq 0 \quad 0 \leq D_{ikt}^{\pm} \leq e_k^{\pm} \left(\sum_j (x_{ij}^- + \Delta x_{ij} o_{ijt}) \right) \quad (1q)$$

$$0 \leq o_{ijt} \leq 1 \quad 0 \leq z_{st} \leq 1 \quad 0 \leq b_{mt} \leq 1 \quad 0 \leq W_{st}^{\pm} \leq \rho C_s^{\pm} (Y_{st}^- + \Delta Y_{st} z_{st}) (1 - \eta_{Cs}^{\pm}) \quad (1r)$$

$$0 \leq F_{mt}^{\pm} \leq (V_{mt}^- + \Delta V_{mt} b_{mt}) MG_{mt}^{\pm} \quad (1s)$$

The detailed nomenclatures for the variables and parameters can be found in Zhang et al. [9]. The values of e_k^{\pm} are obtained based on analysis of the propagation of parameter uncertainty by using MCMC. Model (1) can be transformed into two submodels corresponding to lower and upper bounds of the objective function values, as recommended in Huang and Loucks [10].

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