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Framework Design and Influencing Factor Analysis of a Water Environmental Functional Zone-Based Effluent Trading System

Lei Chen[1] · Zhaoxing Han[1,2] · Shuang Li[1] · Zhenyao Shen[1]

Abstracts The efficacy of traditional effluent trading systems is questionable due to their neglect of seasonal hydrological variation and the creation of upstream hot spots within a watershed. Besides, few studies have been conducted to distinguish the impacts of each influencing factor on effluent trading systems outputs. In this study, a water environmental functional zone-based effluent trading systems framework was configured and a comprehensive analysis of its influencing factors was conducted. This proposed water environmental functional zone-based effluent trading systems was then applied for the control of chemical oxygen demand in the Beiyun River watershed, Beijing, China. Optimal trading results highlighted the integration of water quality constraints and different hydrological seasons, especially for downstream dischargers. The optimal trading of each discharger, in terms of pollutant reduction load and abatement cost, is greatly influenced by environmental and political factors such as background water quality, the location of river assessment points, and tradable discharge permits. In addition, the initial permit allowance has little influence on the market as a whole but does impact the individual discharger. These results provide information that is critical to understanding the impact of policy design on the functionality of an effluent trading systems.

Abbreviations

ETS	effluent trading system
COD	chemical oxygen demand
WEFZ	water environmental functional zone
YTZ, YDZ, XSM, SD, SGD, and CH	Yantan Zha, Yunhe Dajie Zha, Xiaoshan miao Outlet, Shangdian Outlet, Shagudui, Chenhe, respectively.

✉ Zhenyao Shen
zyshen@bnu.edu.cn
chenlei1982bnu@bnu.edu.cn

[1] State Key Laboratory of Water Environment, School of Environment, Beijing Normal University, Beijing 100875, P.R. China

[2] Transport Planning and Research Institute Ministry of Transport of the People's Republic of China, Beijing, Dongcheng, China

Introduction

Pollutant effluents vary qualitatively and quantitatively among dischargers, which results in huge differences among polluters in the costs of achieving their effluent limits (Doyle et al. 2014; Jarvie and Solomon 1998). As a creative market approach, effluent trading systems (ETSs) have been implemented since the 1970s, with nutrients, chemical oxygen demand (COD) and sulfur dioxide as the target pollutants (Bier 2010; Ning and Chang 2007). In general, ETSs are voluntary economic processes that provides an opportunity for dischargers to reduce the costs related to meeting the required discharge limitation. On a watershed basis, an ETS allows for the transfer or exchange of credits among dischargers to achieve at least an equivalent, but less costly, watershed management regime (Obropta and Rusciano 2006; Zhang and Wang 2002).

In general, a permissible discharge baseline is set based on the water environmental capacity of the targeted water

body, and a credit is then created for each discharger that reduces its actual discharge below the allowable limits (Sado et al. 2010). Previous deterministic ETS programs, which might be more computationally tractable, are usually applied using annual-scale loadings or water environmental capacity (Cox et al. 2013; Mesbah et al. 2009). This assumption has often led to conservative results that did not quantitatively characterize the seasonal variation in watershed hydrology and water quality (WQ), which is driven by random weather-related variables—i.e., rainfall (Lentz et al. 2014; Mesbah et al. 2009). Due to the variation of the water environmental capacity within a year, the emission control targets during each hydrological period differ, leading to the divergence of tradable permits (Chen et al. 2014; Horan et al. 2002; Karr and Schlosser 1978; Su et al. 2011). The spatial distribution of pollution sources also has significant impacts on the trading results. Trading-ratio mechanisms, i.e., attenuation or delivery ratios, have been proposed to achieve WQ goals and maintain the flexibility of a trading exchange (Keller et al. 2014). The bound term, which tend to focus on specific river sections, e.g., the watershed outlets, downstream reservoirs or lakes, is also used (Doyle et al. 2014; Keller et al. 2014). However, some specific areas, such as the upstream section of a river, may have serious water pollution as a result of trading, thereby causing a local WQ dispute. Thus, it is useful to design a new ETS framework in response to seasonal changes in the magnitudes of flow rates and the water environmental capacity, as well as the creation of upstream hot spots (localized high-pollution areas) within a watershed.

A typical water environmental functional zone (WEFZ) is defined as a series of water bodies with similar WQ standards based on their regional natural properties and social demands (Su et al. 2011; Shen et al. 2015). Since 2002, all river segments in China have been assigned the WEFZ boundaries by the Chinese Ministry of Environment Protection. In this sense, the WEFZ can be regarded as a basic spatial unit for implementing WQ standards, quantifying pollution levels, and designating the exchange of credits. In our previous study (Han et al. 2011), a WEFZ-based ETS was developed by taking both temporal and spatial limits into account. However, that study was mainly theoretical and lacked sufficient information regarding the related operational procedures. Moreover, as watershed processes and policy designs are very complex, the success of an ETS program will be determined by various influencing factors. Thus, it is important to consider many aspects of ETS design, i.e., the initial allocations of water environmental capacity, the transport fate of certain pollutants, the characteristics of the targeted river, as well as the marginal abatement costs (Corrales et al. 2013; Lentz et al. 2014; Li et al. 2014; Zhang et al. 2011). However, to our knowledge, few studies have been conducted to distinguish the impacts of each of these influencing factors on ETS outputs.

This study aims to configure a WEFZ-based ETS framework and present a comprehensive analysis of its influencing factors. First, an integrated simulation and optimization framework was proposed for determining the optimal abatement loads and costs at the WEFZ scale. Then, the sensitivies of related environmental and policy factors were analyzed to provide a more holistic ETS program. This proposed framework was tested for controlling COD in the Beiyun River watershed, Beijing, China.

Materials and Method

Study Site

The Beiyun River is a key sub-watershed of the Hai River Basin and the northern section of the Chinese Grand Canal. It originates from Yan Mountain in the northern Beijing, drains through Hebei province and flows into Tianjin Haihe River. In this study, we focused on the river system that traverses the southeastern Beijing, which has a total length of 41.9 km and encompasses a drainage area of 189.9 km^2 (92.3 % of all river systems in this region). There is a semi-humid and warm continental monsoon climate with rainy summers and dry winters. The average annual rainfall is recorded as 643 mm, 84 % of which occurs between June and September. During the period 1961–2010, the average annual flow volume and runoff depth of this river is 1491×10^4 m^3 and 85.2 mm, respectively, while the average flow was 29.45 m^3/s and 7.36 m^3/s during the wet and dry period, respectively.

According to the national WQ standard, the Beiyun River is identified as landscape water (class IV WEFZ), and it is also regarded as the major wastewater discharge and flood channel for the main city of Beijing. Water related projects, such as flood gates and pumping stations, have been built and used to release flood and augment the supply of water during the wet and the dry season, respectively. However, these projects have no doubt adversely influenced the river system by altering its downstream river flux and creating barriers to up-downstream transfer of sediment, nutrients, and organisms. Besides, Beijing is one of the largest cities in the world facing serious water shortage and water environment deterioration. There are many effluent outlets along the river, resulting in severe WQ problems in the region. Even with the implementation of watershed programs, eutrophication remains a major problem due to increasing COD loads from local industry and sewage dischargers. This increase in COD has already produced taste and odor problems from the decomposition of algae and
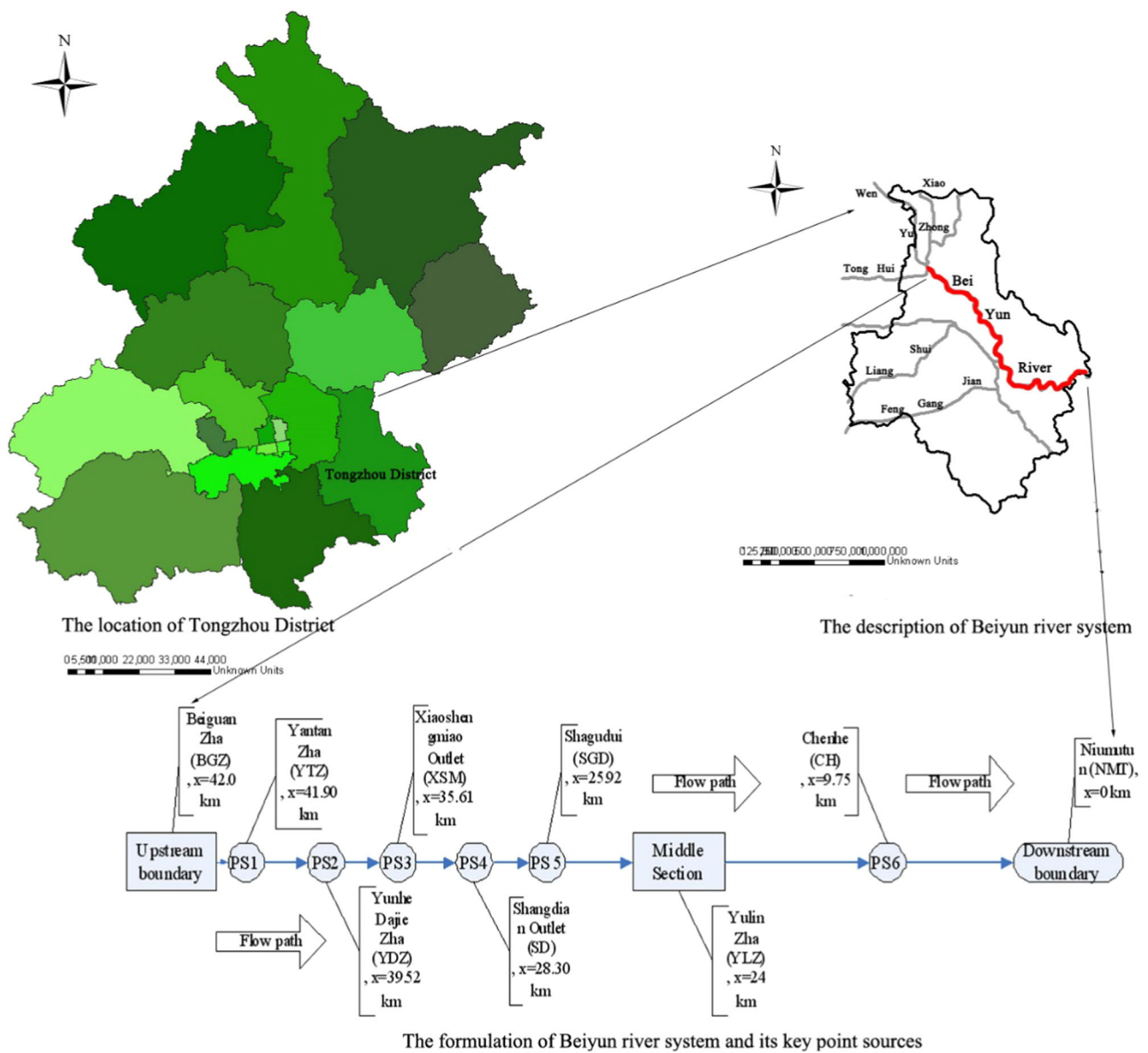
Fig. 1 Location and formulation of the Beiyun river system

harms aquatic organisms via the consumption of dissolved oxygen (Kardos and Obropta 2011). In this study, 6 key point sources (YT, YHDJ, XSM, SDW, SGD, and CH, from upstream to downstream), all of which fall along the 41.9-km-long river, were selected. Based on the characteristics of the water pollution in the Beiyun River, COD was selected for this WEFZ-based ETS. To simplify the complexity of the proposed ETS, agriculture and urban nonpoint source pollution was treated as part of the COD concentration along the river. This consideration is reasonable because the control of pollutant-enriched runoff has not been required for current watershed policy. The downstream boundary of the

local WEFZ, in terms of Niumutun (Fig. 1) was set as the initial river assessment point.

Design of the WEFZ-Based ETS

Designing the integrated WEFZ-based ETS involves a five-step analysis in an iterative scheme.

Calculation of Seasonal Water Environmental Capacity

In the first step, the total acceptable COD loads during a certain hydrological period were calculated based on the seasonal water environmental capacity, which was defined

Table 1 The design of water environmental capacity and initial allocation of abatement loads

Period	River section	Design flow (m³/s)	Design rate (m/s)	Water environmental capacity (tons)	Point source	COD emission (tons)	Initial discharge permits (tons)	Abatement loads (tons)
Flood season	YTZ–YDZ	27.62	0.49	49.54	YTZ	226.52	275.60	−49.08
	YDZ–XSM	27.62	0.49	81.54	YDZ	302.27	367.76	−65.49
	XSM–SD	27.62	0.49	153.06	XSM	42.46	51.66	−9.20
	SD–SGD	27.62	0.49	49.54	SD	44.66	54.34	−9.68
	SGD–YLZ	29.45	0.50	39.94	SGD	72.42	88.11	−15.69
	YLZ–CH	29.45	0.50	311.62	CH	49.21	59.87	−10.66
	CH–DB	29.45	0.50	212.10	—	—	—	—
	Total			897.34	—	737.55	897.34	−159.80
Non-flood season	YTZ–YDZ	5.53	0.13	72.71	YTZ	453.04	379.18	73.86
	YDZ–XSM	5.53	0.13	120.25	YDZ	604.54	505.98	98.56
	XSM–SD	5.53	0.13	228.18	XSM	84.92	71.075	13.84
	SD–SGD	5.53	0.13	72.71	SD	89.32	74.76	14.56
	SGD–YLZ	7.36	0.20	58.54	SGD	144.85	121.23	23.62
	YLZ–CH	7.36	0.20	407.29	CH	98.43	82.38	16.05
	CH–DB	7.36	0.20	274.95	—	—	—	—
	Total			1234.61	—	1475.09	1234.61	240.49

Note: YTZ, YDZ, XSM, SD, SGD, and CH represent the point sources Yantan Zha, Yunhe Dajie Zha, Xiaoshengmiao Outlet, Shangdian Outlet, Shagudui Outlet, and Chenhe Outlet, respectively; YLZ and DB represent the middle river section (Yulin Zha) and downstream boundary (Niumutun), respectively

as the assimilative capacity of a specific pollutant within the receiving water body (local WEFZ). For simplicity, the locations of point sources were used as the boundaries for river segments, while the entire watershed system was divided into seven river sections (Fig. 1) and the entire water environmental capacity was defined as the sum of the capacity of each river section. The classic one-dimensional method was employed using the following equation (Han et al. 2011):

$$W = 31.54c_s\left[\exp\left(\frac{kl}{86.4u}\right) - 1\right](Q + q) \qquad (1)$$

where W represents the water environmental capacity of the targeted water body (tone); 31.54 is used for unit conversion; c_s is the WQ target (mg/L); Q and q are the river flow and emission flow (m³/s), respectively; k is the degradation coefficient (s⁻¹); l is the reach length (km); and u is the water velocity (m³/s).

Based on the state WQ standard (GB3838-2002), the targeted COD concentration was set as 30 mg/L at the WEFZ boundary. Generally, flow rates create the largest uncertainty in this stage. With a 50-year local record of the Beiyun River (from 1961 to 2010), a thorough investigation

of stream volumes, flow rates, and water levels was performed, revealing that flow variations are distinct between wet (June–September) or dry (October–May) seasons, while these variations are relatively low during each season. This pattern suggests that the calculation of the water environmental capacity should be considered separately for high and low flow seasons in this region. Specifically, the designed stream volume is derived based on the actual series of hydrological data in Beiyun river (shown in Table 1), and the correlation coefficient between flow rate and volume is 0.82.

$$y = 0.2195 \times \ln(x) - 0.2417 \qquad (2)$$

where y and x represent the flow rate (m/s) and stream volume (m³/s), respectively.

The Initial Allocation of the Discharge Permission

During the second-step analysis, allowances are defined as the seasonal-limited permissions to discharge a fixed amount of COD, while the sum of issued allowances should be equal to the seasonal WEFZ-based water environmental capacity. As the COD load is dominated by 6 point sources

Table 2 The abatement cost function and the values of R_d

River section	R_d	Point source	Abatement cost function	Marginal abatement cost function
YTZ–YDZ	0.96	YTZ	$C(y_1) = 0.1 \times y_1^{3.27}$	$C(y_1) = 0.327 \times y_1^{2.27}$
YDZ–XSM	0.94	YDZ	$C(y_2) = 0.04 \times y_2^{3.47}$	$C(y_2) = 0.139 \times y_2^{2.47}$
XSM–SD	0.89	XSM	$C(y_3) = 0.08 \times y_3^{4.11}$	$C(y_3) = 0.329 \times y_3^{3.11}$
SD–SGD	0.96	SD	$C(y_4) = 0.1 \times y_4^{3.96}$	$C(y_4) = 0.396 \times y_4^{2.96}$
SGD–YLZ	0.97	SGD	$C(y_5) = 0.09 \times y_5^{3.51}$	$C(y_5) = 0.316 \times y_5^{2.51}$
YLZ–CH	0.86	CH	$C(y_6) = 0.05 \times y_6^{4.06}$	$C(y_6) = 0.203 \times y_6^{3.06}$
CH–DB	0.90			

in this region, the calculated seasonal permits were distributed between these point sources. The discharge report for each point source was reviewed, and their effluents of COD during each season are shown in Table 1.

Incorporation of WQ Response

The third step involves the use of models to establish the linkages between the upstream point sources and WQ at certain river sections. Many models could be used to simulate the fate and transport of specific pollutants within the river system (Fleifle et al. 2014; Hsieh et al. 2007; Wang et al. 2004). In the present study (Han et al. 2011), a classic one-dimensional WQ model, which is based on the law of conservation of matter, was utilized for predicting the COD concentrations at specific river assessment sections under stable conditions.

$$E_x \frac{\partial^2 \rho}{\partial x^2} - u_x \frac{\partial \rho}{\partial x} - K\rho = 0 \qquad (3)$$

For a degradable pollutant, the solution for ρ is as follows:

$$\rho = \rho_i \exp\left[\frac{u_x x}{2E_x}\left(1 - \sqrt{1 + \frac{4KE_x}{u_x^2}}\right)\right] \qquad (4)$$

where ρ_i and ρ are the emission load from emission point i and remaining load at x, respectively (tons); x is the length of delivery from the emission point i (m); u_x is the average flow rate (m/d or m/s); E_x is the vertical mixing coefficient (m²/d or m²/s); and K is the degradable coefficient of the pollutant (1/d or 1/s).

Given that the unit load of pollutant is discharged from the upstream point sources, the transfer coefficient was used to represent the remaining pollutant loads at specific river assessment river sections (Han et al. 2011). These coefficients are based on the distances between the point sources and the targeted river location, the geography of the designated rivers, and the river's biophysical conditions (Sado et al. 2010). Hence, the trading ratios, which were drawn from a series of pairwise simulations and represent the fate of targeted pollutants within certain WEFZ sections,

could be used for the subsequent optimization analysis. The WQ at the upstream boundary was assumed to be acceptable (30 mg/L). If the COD concentration at the downstream boundary was lower than 30 mg/L, the WQ was considered to be safe for the local WEFZ, as well as the next WEFZ. The calculated transfer coefficient is shown in Table 2, and the WQ constraints for a series of river segments can be expressed as follows:

$$R_i = \frac{\rho}{\rho_i} = \exp\left[\frac{u_x x}{2E_x}\left(1 - \sqrt{1 + \frac{4KE_x}{u_x^2}}\right)\right] \qquad (5)$$

$$\sum_{i=1}^{n} (e_i - y_i) \times R_i \times R_{i+1} \times \cdots \times R_n \leq A * q \qquad (6)$$

where e_i and y_i represent the initial emission and abatement loads from emission point i, respectively (tons); R_i is the transfer coefficient; A and q are the targeted WQ standard (mg/L) and design flow at downstream boundary (m³/s), respectively; and n is the number of downstream segments.

Estimation of Abatement Costs

The fourth step focuses on the estimation of abatement costs during the ETS program. In this study, the abatement cost is defined as the sum of the local capital and operation/maintenance costs, as well as the possible technology improvement. As shown in Table 2, the model described by Wang et al. (2008) was used as the basic abatement cost function, which was required for the following optimization process. To achieve higher levels of treatment, a filtration process must be used and the costs for technical upgrading were also reflected in these functions. In so doing, the costs of wastewater treatment were assumed to increase progressively with the abatement load and the continuous marginal cost function for each point source was derived.

Optimization of the WEFZ-Based ETS Market

During the final-stage analysis, an optimization algorithm was applied to identify the cost-effective trading scheme. For simplicity, we only focused on the abatement load and its associated costs, while the detailed transaction process of

Table 3 Optimal trading results and the impacts of environmental factors

Point sources	No trading		WEFZ-ETS		Traditional ETS		Increase of background COD by 10 %	Decrease of background COD by 10 %	Upstream move of assessment point by 5 %		Upstream move of assessment point by 8 %		Upstream move of assessment point by 10 %	
	Load (tons)	Cost (10^4¥)	Load (tons)	Cost (10^4¥)	Load (tons)	Cost (10^4¥)	Load (tons)	Load (tons)	Load (tons)	Cost (10^4¥)	Load (tons)	Cost (10^4¥)	Load (tons)	Cost (10^4¥)
YTZ	73.86	12.87	61.27	6.99	63.75	7.95	244.93	63.75	68.53	10.08	72.07	11.88	75.55	13.86
YDZ	98.56	33.13	63.16	7.07	64.42	7.57	225.66	64.42	69.99	10.10	73.31	11.86	76.56	13.79
XSM	13.84	0.39	20.80	2.09	20.72	2.06	57.19	20.72	22.57	2.93	23.42	3.40	24.24	3.92
SDW	14.56	0.40	23.7	2.78	22.69	2.34	68.58	22.69	25.82	3.90	26.84	4.55	27.83	5.25
SGD	23.62	0.59	46.49	6.41	43.44	5.05	144.85	43.44	51.44	9.14	53.84	10.72	56.18	12.46
CH	16.05	0.39	28.59	4.08	25.48	2.56	79.90	25.48	31.06	5.72	32.24	6.66	33.39	7.67
Total	240.49	47.77	244.01	29.42	240.49	27.53	821.12	240.49	269.41	41.86	281.71	49.07	293.75	56.95

Note: Load and cost represent the abatement pollutant load and the corresponding abatement cost, respectively

discharge permits was neglected. In this study, only multi-lateral simultaneous trading was considered for the WEFZ-based ETS market. A linear program, involving one decision variable and four constraints, was written using General Algebraic Modeling System software (Corrales et al. 2014). The optimization objective, represented in Eq. (7), was designed to minimize the abatement costs at the WEFZ scale, and the four constraints were used to develop trade-off curves among abatement costs, WQ, and the water environmental capacity (Luo et al. 2005). The non-negativity constraint, Eq. (8), ensures that the decision variables are nonnegative, and the technical constraint, Eq. (9), provides the specific removal efficiency from the perspective of management. In addition, the bound term constraints (Eqs. (10) and (11)) ensure that the transfer of discharge permits complies with the allowable concentration limits at the downstream WEFZ boundary, as well as with the required water environmental capacity within the WEFZ section.

objective function : $\quad Min. \sum_i^n C(y_i) \qquad$ (7)

nonnegativity constraint : $\quad y_i \geq 0 \qquad$ (8)

technical constraint : $\quad e_i \geq y_i \qquad$ (9)

water quality constraint :
$$\sum_i^n (e_i - y_i) \times R_i \ldots \times R_n + m \leq A \times q \qquad (10)$$

water environmental capacity constraint :
$$\sum_i^n (e_i - y_i) \leq WEC \qquad (11)$$

where $c(y_i)$ is the abatement function for each point source (RMB); and *WEC* represents the water environmental capacity during a certain period (tons); m is the background concentration of COD in the river (mg/L); $i = 1, 2, \ldots, 6$ (tons).

The required input data to run this linear programming optimization model were as follows: (1) initial COD effluents; (2) the allowable effluent for each point source, which can be obtained from Table 1; (3) the transfer coefficient between each point source and targeted river section boundary; and (4) the capital and operating cost for the COD abatement from Table 2.

Results and Discussion

The Optimal Results of the WEFZ-Based ETS

Trading Results

As shown in Table 1, before trading, the water environmental capacity was quantified as 897 and 1234 tons for the wet and dry seasons, respectively, and the initial downstream COD concentration was calculated as 26 and 31 mg/L. In this sense, the total emission (737 tons) was less than the water environmental capacity limit during the wet season, indicating that control of COD was unnecessary during this period. Conversely, during the dry season, the initial emissions (1475 tons) surpassed the water environmental capacity (1234 tons); thus, COD must be more stringently regulated during this period. Therefore, only the dry season was selected as the candidate period for the WEFZ-based ETS, and the required reduction was 233 tons, which is 16 % of the initial emission.

Tables 3 represents a list of potential permit buyers and sellers after trading, as well as their respective abatement loads and cost savings. Overall, the COD emission was reduced to 1231 tons and the total number of exchanged COD credits was 99 tons, corresponding to 41 % of the initial abatement requirement. The abatement cost was

294×10^3 ¥ for the WEFZ-based ETS program, indicating a total cost savings of 38 % compared to the initial permissible discharge baseline scenario. In addition, it is important to emphasize that cost savings vary substantially among dischargers. In total, 2 buyers and 4 sellers were identified, and the abatement loads and costs for YTZ, YDZ, XSM, SDW, SGD, and CH changed by −17 %, −35 %, 50 %, 62 %, 96 %, and 78 % and by −45 %, −78 %, 433 %, 588 %, 977 % and 942 % from the baseline, respectively. The imperfect substitution between sellers and buyers is related to the differences in their impacts on the ambient WQ, which might the driving force for the trading between point sources (Horan and Shortle 2011). The most obvious variations could be observed for those downstream point sources because their emissions occur closer to the river assessment point.

Comparison Between WEFZ-Based and Previous ETSs

In this section, the trading results of the WEFZ-based ETS were compared to those of the non-WEFZ-based ETS, in which only the water environmental capacity was considered as the pre-defined optimization constraints. As shown in Table 3, after the implementation of a non-WEFZ-based ETS, the abatement loads changed by −3 %, −32 %, 25 %, 36 %, 86 %, and 35 % for YTZ, YDZ, XSM, SDW, SGD, and CH, respectively, from the baseline. Differ from the WEFZ-based ETS, that is based on the contributions of point sources on the downstream WQ, the non-WEFZ-based ETS is still in accordance with the principle of marginal abatement cost of point sources. Compared to the WEFZ-based ETS, the discharge credit was transferred from upstream to downstream point sources with 119 tons of the total exchanged credit, which is greater by 8 % than that of the WEFZ-based ETS. Specifically, more obvious differences in abatement loads between these two approaches could be observed at the downstream point sources. Compare to the initial permissible baseline, the emission abatement of the downstream point sources, in terms of SDW, SGD, and CH, increased by 82 % and 68 % for the WEFZ-based and non-WEFZ-based ETS, respectively. This increase can be explained by the fact that river flows downhill and the upstream credit allocations would affect downstream allocable permits (Dodds and Oakes 2008; Miller et al. 2013). In this sense, downstream point sources would have greater impacts on the WQ of the WEFZ boundary; thus, the WEFZ-based ETS showed greater impacts on those point sources (Miller et al. 2013; Wengrove and Ballestero 2012). If the non-WEFZ-based ETS was used, the downstream COD was only reduced to 30.024 mg/L, which still exceeded the required standard. Thus, although the water environmental capacity constraint is satisfied, there is a low degree of certainty that WQ

targets will be reached. The impact of the WQ constraint would also be reflected by the total abatement cost, which results in savings of 38 % for the non-WEFZ-based ETS and 42 % for the WEFZ-based ETS from the permissible baseline. These results indicate that the WEFZ-based ETS programs would lead to increasing abatement costs and less economically efficient markets by seeking a high level of environmental efficiency (Woodward et al. 2002). For example, a 4 % higher abatement cost would be required to regulate WQ under the COD standard within an ETS market.

Design of the WEFZ-Based Trading Ratio

Generally, substitution between point source emissions can be addressed by the application of trade ratios, which specify the minimum credits required to offset a unit of another point source emissions (Horan and Shortle 2011; Nguyen et al. 2013; Sado et al. 2010). Ideally, a trading ratio should be calculated based on the transfer coefficients of COD loads from each pair of point sources (seller and buyer). Within the WEFZ-based ETS, the trading ratio was determined in an alternative manner by quantifying the impacts of each point source on the WQ at a certain river section. Using the downstream WEFZ boundary, the trading results can be revised as follows:

$$\frac{\partial C(y_i)}{\partial y_i} = d_i \times \lambda \tag{12}$$

where d_i is the delivery coefficient; $d_i = R_i \times R_{i+1}...R_n$, with the calculated R_i presented in Table 2; and λ is the Lagrangian coefficient.

For each paired point sources,

$$\frac{\partial C(y_i)}{\partial y_i \times d_i} = \frac{\partial C(y_{i+1})}{\partial y_{i+1} \times d_{i+1}} \tag{13}$$

Therefore, d_i/d_j represents the trading ratio between the ith and jth point source. Assuming that the marginal abatement cost of the ith point source is x, the credit price is identified as $x \times d_i/d_j$ if the ith point source wants to sell credits to the jth point source.

Based on the optimal results of the WEFZ-based ETS, the marginal abatement cost and delivery coefficient were quantified as 0.37, 0.39, 0.41, 0.46, 0.48, and 0.58 and as 0.59, 0.61, 0.65, 0.72, 0.75, and 0.90 for YTZ, YDZ, XSM, SD, SGD, CH, respectively. Larger delivery coefficients are found for downstream point sources, indicating that more than one upstream credit is required to offset one unit of downstream emission. Thus, WQ constraints could be reflected by a set of trading ratios calculated based on the fate and transport process of pollutants within the river system (Doyle et al. 2014; Keller et al. 2014). This solution is innovative because these ratios are calculated by the

aggregation of the regulations for both WQ and water environmental capacity limits, which reflect the contributions of point sources to the WQ instead of their marginal abatement cost.

Impact of Influencing Factors

For simplicity, we do not formally analyze how each factor may affect trading results at first. In this section, the following four influencing factors were examined: (1) the background COD, (2) the initial allocation of permission, (3) the location of the river assessment point, and (4) the tradable commodity. The selection of these factors was because they are the most sensitive factors on ETS outputs (Lentz et al. 2014; Zhang et al. 2011).

Impact of Background COD Concentration

For simplicity, a static COD concentration (calculated as 24.9 mg/L) was used at the downstream WEFZ boundary. As presented in Table 3, if the background COD increased by 10 % (27 mg/L), the abatement load and corresponding cost increased by 188 % and 7265 %, respectively. This finding indicates that background concentrations would have a great impact on the satisfaction of downstream WQ constraints, as well as on the optimal trading results. It should be noted that if the background COD concentration is 24.9 mg/L and the WQ standard is 30 mg/L, there is going to be very little margin for discharge and the impact of background concentration is going to be very sensitive. Logically, the abatement costs increase by a large amount when almost all the COD load have to be removed. With respect to individual point source, the largest change was observed at the YTZ and YDZ locations because these two point sources were identified as key dischargers in this region, with an initial reduction requirement of 167.27 tons (71.70 % of total abatement). Moreover, if the background COD is reduced by 10 % (22.4 mg/L), the downstream WQ problem is avoided even in the baseline scenario; thus, the WQ constraints would be always satisfied and optimal trading results would be mainly derived from the water environmental capacity constraints. This result indicates that when the background WQ had been improved, the constraint conditions would shift from WQ to the water environmental capacity and the WEFZ-based ETS would transform into a traditional ETS.

Impact of Initial Permission Allocation

For the WEFZ-based ETS, the credit is generally defined based on the permissible discharge baseline for a particular pollutant. However, the credit can be allocated equally among all existing sources or proportionally based on the current loadings (Corrales et al. 2014; Ghosh et al. 2011). Initially, only the proportional idea was used, and these two approaches for initial permission allocation are further compared in this section. As shown in Table 3, the allocation approach has great impacts on the initial permits for each point source and transferable credits among the 6 point sources. The equally allocated transferable permits were 21, 23, −19, −16, 6, and −11 tons for YTZ, YDZ, XSM, SD, SGD, and CH, respectively, and the proportionally allocated transferable permits were −12, −35, 7, 9, 23, and 13 tons. The roles of the two key point sources (YTZ and YDZ) changed from seller to buyer within the ETS market due to differences in marginal abatement cost. Conversely, there were few changes in the total abatement loads and abatement cost in response to the choice of permit allocation approach because the transaction cost was set at 0 for simplicity in this study. These results indicated that the initial permit allocation has little impact on the ETS market as a whole but has considerable influence on the individual point source.

Impact of the Location of River Assessment River Sections

Within the WEFZ-based ETS framework, the discharge permit level is based on its effects on WQ along the river. However, the choice of a particular river assessment point does not guarantee the improvement of WQ at other river sections (Munafo et al. 2005). Based on the calculated results, almost 94 % of the Beiyun River system still exceeds the required standard and the WQ at key river sections was 28, 32, 32, 32, 33, and 30 mg/L, indicating that the hot spot problem exists within the river system. To solve this problem, a sensitivity analysis was designed by moving the river assessment point upstream by 5 %, 8 %, and 10 % in length from the WEFZ boundary. New rules were set as no violations of WQ standards at these upstream targeted sections. As shown in Table 3, the total abatement loads and costs increased by 12.03 %, 17.14 %, and 22.15 % and by 42 %, 66 %, and 93 % for these scenarios, respectively. The damaged river length decreased by 8.74 %, 11.15 %, and 13.56 %, respectively, showing an improvement in WQ along the entire river network. In addition, the choice of assessment point had greater impacts on the abatement loads of the nearby point sources; thus, the use of multiple river sections might be an effective approach to avoid hot spots (Shabman and Stephenson 2007). Theoretically, the WEFZ-based ETS can be designed to improve WQ at all river sections collectively. However, it should be noted that every 1 % decrease in the damaged river length would result in an additional increase of abatement cost. For the Beiyun River, the marginal abatement cost increased by 4.06, 2.99, and 3.27×10^4 ¥ for the 5 %, 8 %, and 10 % scenarios, respectively. Thus, the 8 % upstream movement of the
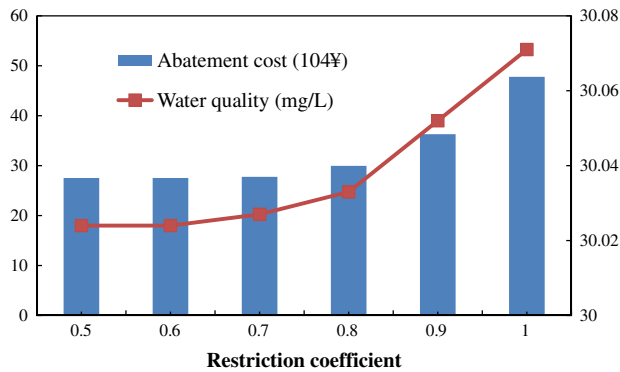
Fig. 2 Abatement loads and costs using various restriction coefficients

assessment point would be the most cost-effective scheme that balances abatement costs and WQ improvement.

Impact of Tradable Discharge Permits

In Section 3.1, point sources are assumed to be willing and able to minimize the abatement cost by fully exploiting the trading opportunity within the ETS market. However, due to political or informational constraints, specific restrictions are often imposed on tradable discharge permits (Corrales et al. 2013; Stephenson and Shabman 2011). In this sense, Eq. 8 was replaced by the following:

$$y_i \geq \alpha \times (e_i - a_i) \qquad (14)$$

where α and a_i are the restriction coefficients ($0 \leq \alpha \leq 1$) and the initial discharge permit, respectively, while $\alpha \times (e_i - a_i)$ represents the tradable discharge permit of each point source.

As shown in Fig. 2, when α was less than 0.6, the restriction coefficient showed little impact on the total abatement loads of COD, the abatement costs, or the downstream WQ because the trades of discharge permits are still based on the marginal abatement cost within the ETS market. However, if α was larger than 0.6, the downstream WQ deteriorated gradually (from 30.00 to 30.07 mg/L) in response to the increase in the restriction coefficient. As the value of α increases, the abatement cost also rises and the role of point sources might change accordingly. This effect occurs because if the regulation of point sources is made more stringent (e.g., less tradable discharge permits), the trading market becomes thinner (shifts toward fewer point sources), which in turn reduces the feasibility of the WEFZ-based ETS (Doyle et al. 2014). Specifically, when α increases to 1.0, the maximum abatement cost is reached and the WEFZ-based ETS is transformed to the permissible discharge baseline. In addition, after trading, the permits of YLZ and CH would transfer to the upstream point sources due to their spatial proximity to the downstream boundary

of the WEFZ market. However, as the value of α increases, their final effluent increases and the downstream WQ deteriorates accordingly. This pattern creates a situation in which the overall load to the stream is reduced but water criteria are exceeded immediately downstream of the point source due to the localized loading input (Doyle et al. 2014; Kardos and Obropta 2011; Mesbah et al. 2009). In other words, downstream hot spots would inevitably occur when the tradable discharge permits are limited.

Conclusion

In this study, a WEFZ-based ETS was proposed for the cost-effective control of multiple-point sources by taking the WQ limits and water environmental capacity limits into account. Compared to previous ETS approaches, WQ at each river assessment point was improved by using the WEFZ-based ETS. The separate consideration of two hydrological seasons also illustrates critical steps for developing cost-effective ETS schemes. In addition, the results indicate that the design of influencing factors is important to the success of the ETS market, i.e., for the abatement loads and costs. Addressing these factors ensures the robustness of the WEFZ-based ETS. The initial permit allowance has little impact on the market as a whole but does influence individual point sources. When the background WQ deteriorated or the assessment point was moved upstream from the WEFZ boundary, the constraining factors of the ETS market changed from the WQ limits to the water environmental capacity limits. If the tradable discharge permits are limited, the WEFZ-based ETS changes to the permissible discharge baseline. These results can be extended to other forms of ETS programs and the control of other contaminants and may have broader applications for determining ETS market structure.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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