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The research of river basin ecological compensation based on water emissions trading mechanism

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ABSTRACT

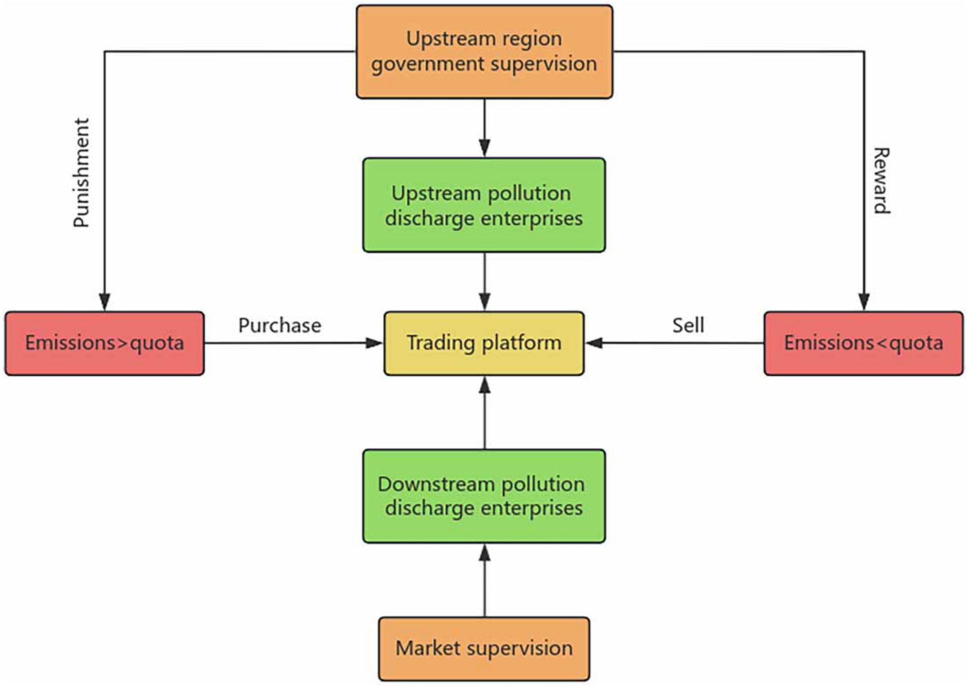
By integrating the successful case of the European Union emissions trading system, this study proposes a water emissions trading system, a novel method of reducing water pollution. Assuming that upstream governments allocate initial quotas to upstream businesses as the compensation standard, this approach defines the foundational principles of market trading mechanisms and establishes a robust watershed ecological compensation model to address challenges in water pollution prevention. To be specific, the government establishes a reasonable initial quota for upstream enterprises, which can be used to limit the emissions of upstream pollution. When enterprises exceed their allocated emissions quota, they face financial penalties. Conversely, these emissions rights can be transformed into profitable assets by participating in the trading market as a form of ecological compensation. Numerical simulations demonstrate that various pollutant emissions from upstream businesses will have various effects on the profits of other businesses. Businesses in the upstream region received reimbursement from the assigned emission rights through the market mechanism, demonstrating that ecological compensation for the watershed can be achieved through the market mechanism. This novel market trading system aims at controlling emissions management from the perspectives of individual enterprises and ultimately optimizing the aquatic environment.

Key words: ecological compensation, pollution control, trading of water emission rights, watershed management

HIGHLIGHT

- The article establishes a water emissions trading mechanism. We establish this mechanism to control the amount of emission from each enterprise. Then we achieve the purpose of optimizing the water environment.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Researchers (Shortle & Dunn 2010; Huang *et al.* 2010; Bao *et al.* 2012; Gorelick *et al.* 1983; Rozell & Reaven 2012) have shown a lot of interest in the issue of controlling water contamination. Until the middle of the 1990s, China had five or fewer domestic wastewater treatment facilities. Most big cities, such as Wuhan and Chongqing, do not treat any household wastewater before it is released into the environment. There is still no Chinese city that has completely treated all of its sewage, highlighting the environmental pollution problem plaguing China's river basins.

The rapid industrialization of cities has increased resource consumption, energy consumption, and pollution emissions (Liu *et al.* 2012). Growing public and international condemnation has compelled governments to take steps to reduce watershed contamination to tolerable levels. Water emissions trading is regarded as a less costly alternative tool compared to traditional administrative control methods (Hung & Shaw 2005; Jamshidi *et al.* 2015). As with many other emissions trading programs, post-event analysis of Chinese emissions trading programs by researchers found small cost savings and lower than expected trading volumes at the start of the program (Atkinson & Tietenberg 1991; Chang & Wang 2010).

In the existing literature, scholars have conducted numerous studies on carbon and sulfur emission rights (Cong & Wei 2010; Lin & Jia 2018; Zetterberg & Wrake 2012; Kumar & Managi 2010; Ren *et al.* 2020; Burtraw & Mansur 1999; Corburn 2001; Kroes *et al.* 2010). Cong & Wei (2010) studied the potential impact of introduction of carbon emissions trading on China's power sector and discusses the impact resulting from different approaches to the allocation of allowances. Lin & Jia (2018) constructed six countermeasure scenarios with various methods for carbon allocation reduction to investigate the impact of these schemes on energy, economy, and the environment. The findings indicate that the emission-based emission trading plan (ETS) quota decrease plan would encourage society to prioritize emission reduction. Zetterberg & Wrake (2012) employed economic analysis to analyze grandfathering, auctioning, and benchmarking systems for distributing emissions permits and then discussed practical experience from European and American schemes.

Ren *et al.* (2020) used 'China's sulfur dioxide (SO_2) emissions trading program' as a quasi-natural experiment to identify the causal effect of this market-based environmental regulation on firm's labor demand. The research findings demonstrated that the market-based environmental regulations in even developing countries could achieve the double dividend of coexistence of environmental protection and employment growth. Kumar & Managi (2010) found that from 1995 to 2007, due to the introduction of the cap-and-trade system, power plants were able to increase their power output and reduce SO_2 and NO_x emissions.

Environmentalists have questioned whether market-based schemes are satisfying their needs for effective and equitable pollution reduction promises as emissions trading systems have grown in popularity as a tool for environmental pollution management on a global scale. Water quality trading (WQT) programs including point-nonpoint trading have been promoted for decades in many countries (e.g., the United States, Japan, Canada) to address water pollution problems (Duke *et al.* 2020). However, China's emission trading system has been gradually improved, the country has the initial foundation to implement emission trading, and the research on water emission trading is extremely immature (Havens & Schelske 2001).

Based on the successful case of EU ETS, this study provides a reference for the existing research by establishing water pollutant emission trading markets and watershed ecological compensation models. Previous studies have already shown the potential of market mechanisms in promoting environmental protection (Zhang *et al.* 2012) and the importance of economic incentives in pollution control (Juan *et al.* 2002). We further demonstrate how the introduction of market mechanisms and trade can achieve economically effective water pollution control at the watershed level. This model innovatively integrates economic incentives with ecological restoration by incorporating ecological compensation into the trading market, thus addressing the dual challenge of economics and environment.

This article is organized as follows. In Section 2, we briefly introduce the basic elements of water emission right trading market and introduce the market operation mechanism and watershed ecological compensation. The model is analyzed in different cases and explained the theoretical results in Section 3 and summarized in Section 4.

2. METHODS

This article mainly draws on the European Union (EU) carbon emission trading system to research the water emission trading mechanism (Brink *et al.* 2016; Anger & Kohler 2010). Incorporating the concept of ecological compensation, the water pollution control model was designed based on the quota. This section mainly elaborates on the fundamental components of the market and the trading mechanism.

2.1. Basic elements

2.1.1. Emission threshold

The social welfare of the downstream region is directly impacted by the pollution emission threshold of the upstream region in addition to its own social welfare level. Our thoughts in this study are therefore focused on the formulation of the emission threshold. Instead of upstream and downstream regional administrations, basin management establishes consistent emission levels (Talmadge *et al.* 1998).

2.1.2. Transaction subject, object, and scope

We study a market where the trading parties are basin-wide water discharge businesses that are located upstream and downstream, and the trading objects are water discharge rights. Not all of the emitters in the basin, nevertheless, are tradeable. Based on variables such as whether the firm has a right to emit, the magnitude of earlier emissions, and the actual size of production, basin management should establish precise market access thresholds and standards (Arabi *et al.* 2007). The EU's participation in the carbon emissions trading scheme is limited to a small number of high carbon output industries. As a result, several businesses with substantial emissions of water pollution are thought to be covered by water emissions trading, including the paper industry, printing and dyeing, nitrogen fertilizers, and others.

2.1.3. Allocation of quotas

A key feature that sets the water emissions trading market apart from the carbon emissions trading market is that it complements the basin ecological compensation mechanism in addition to promoting the reduction of water pollution (Marchal *et al.* 2011). In particular, the basin management only provides the upstream government with a limited number of emission rights, or quotas as discussed, free of charge, under the upstream region's water pollution discharge threshold (Zhang & Hao 2017). This is done as ecological compensation to the upstream region. Following that, the quotas are further distributed to local emitters by upstream governments.

2.2. Market operation mechanism

The suggested basin water emissions trading market operation mechanism is shown in Figure 1 and is based on the analysis of the fundamental components of the water emissions trading market that was done earlier. Upstream emitters purchase emission rights from basin management agencies, and through an offset system, the emission quotas they acquire can be used to lower the emission fees owed for emissions. The remaining quota can also be swapped with other upstream and downstream polluters when the allotted amount is greater than the permitted emissions.

Therefore, by allocating some additional emission rights to upstream emitters, the emissions trading market primarily delivers ecological compensation for upstream regions. In addition, there are two key factors that determine the extent of ecological compensation: First, the quota that the basin management distributed to the regional governments upstream. More effluent costs can be mitigated or more money can be made via market transactions the more quotas there are. Second, how much upstream emitters are permitted to compensate for their polluting emissions by buying their emission rights. Downstream emitters (Yu *et al.* 2016) that there is a higher demand for emission licenses when the amount of offsetting is high. The upstream emission businesses can then sell them for more money and get paid more as a result.

2.3. Hypothesis

(1) Within the basin, there is one rational discharge enterprise in each of the upstream and downstream areas (Jiang *et al.* 2019).
(2) Due to the relatively poor economy of the upstream region, the government of the upstream region can allocate a certain amount of quota to enterprises in the upstream region, while no quota is allocated to enterprises in the downstream region (Marchal *et al.* 2011). After upstream enterprises offset their actual emissions with quotas, they can sell their water emissions rights to other enterprises through a trading market.
(3) Water emissions rights cannot be used past their expiration date (Konishi *et al.* 2015).
(4) Businesses in the downstream are open to trading water emissions rights. In other words, regardless of how many quotas are available for upstream businesses, downstream businesses are eager to purchase them. In addition, downstream businesses can keep reselling the purchased allowances to other businesses while using them to reduce their own emissions payments.

2.4. Basic model

Combined with the operating mechanism of the water emission rights trading market in the basin shown in Figure 2, there are two regions (A, B) in the basin, and watershed management controls the emissions threshold to $Q_i (i = A, B)$. For enterprise j ($j = a, b$), enterprise a obtains quota Q_s $(0 \leq Q_s < Q_A)$. We considered that one unit of pollutant emissions are subject to an emission fee of t. When the emission exceeds the emission threshold Q_i, the excess will be paid in the amount of $2t$ emission fees. It can be seen that when the actual pollutant emissions are at different levels, the environmental benefits R of enterprise

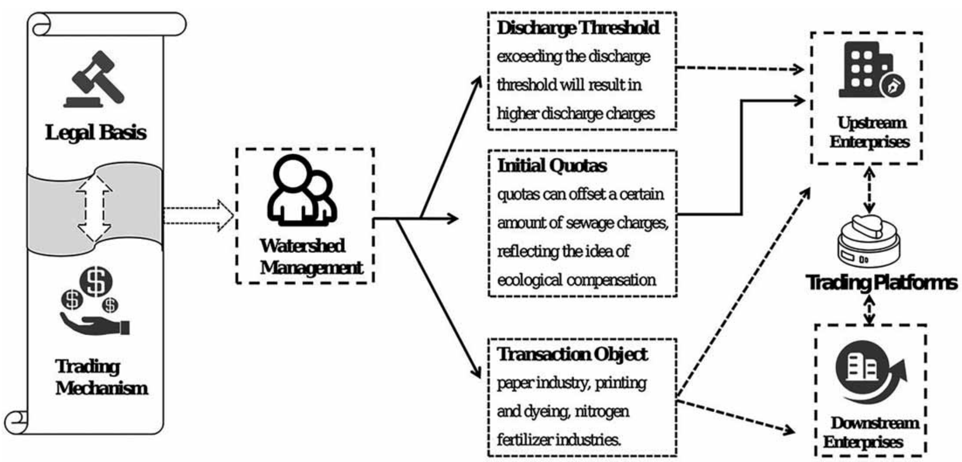


Figure 1 | Policy on market trading platform for emission rights.

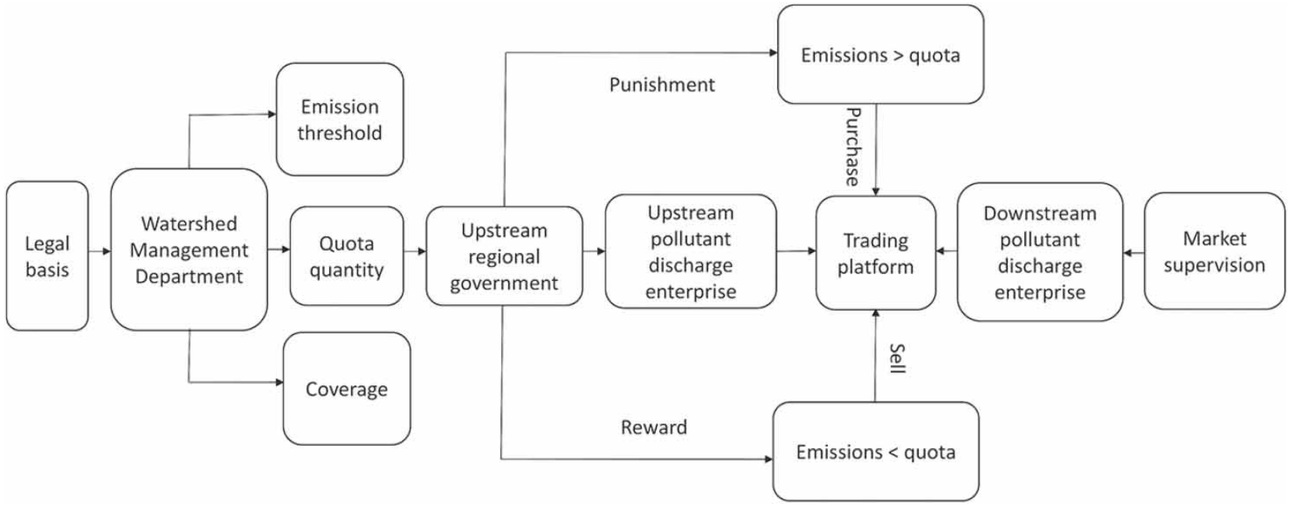


Figure 2 | Operating mechanism of water emission rights trading market in the basin.

will be significantly different. Therefore, R^n (n represents different situations) was analyzed according to the q_a. The basic parameters are set as shown in Table 1.

2.4.1. Case 1: $0 < q_a < Q_s$

In this case, enterprise a may trade the set-off remaining quota ($Q_s - q_a$) in the water emission rights trading market. Correspondingly, enterprise a and enterprise b trade water emissions rights in the water emissions rights trading market. Here, we assume that enterprise b is a rational individual, so the price he can accept for water emissions rights will be less than the emission fees t. And enterprise a can obtain a free quota Q_s, we do not consider the allocation of quotas by the local government to downstream enterprises, and the reason is that upstream regions are relatively economically poor and the downstream regions are economically developed. Of course, both enterprises are rational individuals. We defined that the actual trading price of water emission rights is p ($0 < p < t$), the main situation is shown in Figure 3.

We obtained the benefits of enterprise a as follows:

$$R_a^1 = (Q_s - q_a) \cdot p. \tag{1}$$

Table 1 | Notations and definitions

A	Upstream region
B	Downstream region
Q_s	Initial quota
Q_i	Pollutant emissions threshold of region i
R_j^n	Income of enterprise j, n means different pollution emissions cases of enterprises
q_i	Emissions from region i
a	Upstream enterprise
b	Downstream enterprise
t	Pollutant emissions for fee per unit of pollutant emissions
p_k	Trading price of water emission rights under different circumstances

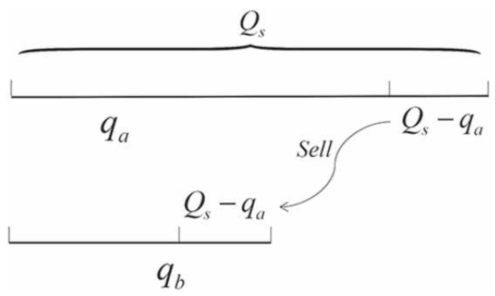


Figure 3 | Trading of water emission rights between enterprise *a* and enterprise *b*.

From Equation (1), $R_a^1 > 0$ shows that in the case of low emissions, enterprise a does not need to pay sewage charges and can also get additional environmental benefits through water emission rights trading. That is to say, the amount of ecological compensation consists of two parts: (i) The exemption of pollutant emissions fee. (ii) Additional benefits obtained through transactions. Under this circumstance, enterprise b can also obtain certain benefits through water pollution rights trading. Compared with when there is no water pollution rights trading, it can reduce the emission fees of R_b^1.

$$R_b^1 = (Q_s - q_a) \cdot (t - p).$$

2.4.2. Case 2: $Q_s < q_a < Q_A$

Under this situation, the quota of water emission rights obtained by enterprise a cannot completely offset its actual emission volume, so it is necessary to pay a certain sewage charge. Since the actual emissions does not exceed the upper limit, the income R_a^2 of enterprise a in case 2 is:

$$R_a^2 = -(q_a - Q_s) \cdot t, \tag{2}$$

Where $R_a^2 < 0$, it means that when enterprise a emissions a lot of pollution, it needs to pay a sewage fees for excessive emissions, and there is no remaining water emissions right to trade with enterprise b. Therefore, the amount of ecological compensation received by enterprise a is only part: underpaid sewage charges Q_s.

2.4.3. Case 3: $q_a > Q_A$

In this case, since the pollution emissions of enterprise a exceeds the threshold of region A, not only does it need to pay the pollution emissions fees within the specified emissions volume but also the government needs to punish it accordingly, and the penalty is $(q_a - Q_A) \cdot 2t$. The details are shown in Figure 4. Thus, the income R_a^3 of enterprise a in this case:

$$R_a^3 = -(q_a - Q_s) \cdot t - (q_a - Q_A) \cdot 2t. \tag{3}$$

2.4.4. Model extensions

As shown in section (Section 2.4), there is only one enterprise that exists in region A. Now, we consider that there are two enterprises (a_1, a_2) in region A, and the actual emissions of enterprise a_1 and a_2 are q_{a_1} and q_{a_2}, respectively. In addition, the upper limit of pollutant emissions Q_A for region A is decomposed into Q_{Aa_1} and Q_{Aa_2}. Corresponding to the pollutant emission thresholds of enterprise a_1 and enterprise a_2, respectively. The quota of water emission rights obtained by the two

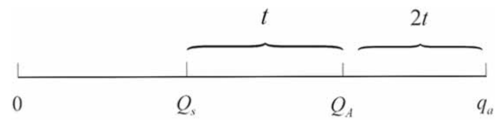


Figure 4 | Enterprise *a* pollution charge situation.

enterprises are Q_{sa_1} and Q_{sa_2}, respectively. Among them, $Q_{sa_1} < Q_{Aa_1}$ and $Q_{sa_2} < Q_{Aa_2}$. Next, we analyze the revenue of each enterprise based on the actual emissions of enterprise a_1 and enterprise a_2.

2.4.5. $0 < q_{a_2} < Q_{sa_2}$

Case 4: $0 < q_{a_1} < Q_{sa_1}$

In this case, enterprises a_1 and a_2 can trade the offset remaining quotas $(Q_{sa_1} - q_{a_1})$ and $(Q_{sa_2} - q_{a_2})$. In the water emission rights trading market and resell the excess emission rights to enterprise b. Moreover, the actual market transaction price of water pollution rights is p_1, which satisfies $0 < p_1 <$ t. Therefore, we obtain the revenue of each enterprise as follows:

$$R_{a_1}^4 = (Q_{sa_1} - q_{a_1}) \cdot p_1, \tag{4}$$

$$R_{a_2}^4 = (Q_{sa_2} - q_{a_2}) \cdot p_1. \tag{5}$$

Similar to the analysis in Section 2.4.1, no enterprises in upstream region A need to pay pollution fees, and they can also obtain additional income through water pollution rights trading, thereby obtaining corresponding ecological compensation. At the same time, enterprise b can pay less for sewage R_b^4:

$$R_b^4 = (Q_s - q_{a_2} - q_{a_1}) \cdot (t - p_1). \tag{6}$$

Case 5: $Q_{sa_1} < q_{a_1} < Q_{Aa_1}$

In this case, the quota of water emission rights obtained by enterprise a_1 can only offset part of the pollution emissions fees. Not only can enterprise a_2 completely offset the pollution emissions fees but also it can resell part of the excess quota to enterprise b or enterprise a_1. Now suppose that enterprise a_2 sells to enterprise a_1 proportion of the remaining quota is α $(0 < \alpha < 1)$. Among them, $(Q_{sa_2} - q_{a_2}) \cdot \alpha \leq q_{a_1} - Q_{sa_1}$ because the quota purchased by enterprise a_1 will not be higher than the difference between the actual emissions and its own quota. Then enterprise b can purchase $1 - \alpha$ proportions remaining quota. Moreover, suppose that the market equilibrium is that the price of water emission rights is $p_2(0 < p_2 <$ t). Thus, the benefits of these enterprises are as follows:

$$R_{a_1}^5 = -[q_{a_1} - \alpha(Q_{sa_2} - q_{a_2})] \cdot t - \alpha(Q_{sa_2} - q_{a_2}) \cdot p_2, \tag{7}$$

$$R_{a_2}^5 = (Q_{sa_2} - q_{a_2}) \cdot p_2. \tag{8}$$

In this case, enterprise b can obtain $1 - \alpha$ proportion water emission rights quota from enterprise a_2, so the emission reduction cost it can got

$$R_b^5 = (Q_{sa_2} - q_{a_2}) \cdot (1 - \alpha) \cdot (t - p_2). \tag{9}$$

Case 6: $q_{a_1} > Q_{Aa_1}$

In this case, the pollutant emissions volume of enterprise a_1 exceeds the threshold Q_{Aa_1}. Although the initial quota allocated by the upstream government can offset certain pollution charges, the government should impose certain penalties on the part with multiple emissions. For enterprise a_2, not only does it not need to pay pollution fees but also it can sell the remaining quota to other enterprises. It should be noted that there are two situations for discussion here: (i) $q_{a_1} - Q_{Aa_1} \geqslant (Q_{sa_2} - q_{a_2}) \cdot \alpha$. (ii) $q_{a_1} - Q_{Aa_1} < (Q_{sa_2} - q_{a_2}) \cdot \alpha$. In addition, we assume that the trading price in the market at this time is p_3 $(0 < p_3 < t)$. Thus, the benefits of these enterprises we given that

(i) $q_{a_1} - Q_{Aa_1} \geqslant (Q_{sa_2} - q_{a_2}) \cdot \alpha$.

In this case, because enterprise a_1 emissions more pollutants than it purchases, even if it can be exempted from some penalties, it still needs to pay a certain fine. Therefore, we give that

$$R_{a_1}^6 = -(Q_{Aa_1} - Q_{sa_1}) \cdot t - \alpha(Q_{sa_2 - q_{a_2}}) \cdot p_3 - [(q_{a_1} - Q_{Aa_1}) - \alpha(Q_{sa_2 - q_{a_2}})] \cdot 2t, \tag{10}$$

$$R_{a_2}^6 = (Q_{sa_2} - q_{a_2}) \cdot p_3. \tag{11}$$

Similarly, the sewage fees underpaid by enterprise b is

$$R_b^6 = (1-\alpha)(Q_{sa_2} - q_{a_2}) \cdot (t - p_3). \tag{12}$$

(ii) $q_{a_1} - Q_{Aa_1} < (Q_{sa_2} - q_{a_2}) \cdot \alpha$.

In this case, enterprise a_1 has purchased too much emission rights. To achieve the ecological compensation standard for upstream enterprises, we assume that enterprise a_1 will sell the excess quota to downstream enterprises at price p_4.

$$R_{a_1}^6 = -(Q_{Aa_1} - Q_{sa_1}) \cdot t - (q_{a_1} - Q_{Aa_1}) \cdot p_3 + [\alpha(Q_{sa_2} - q_{a_2}) - (q_{a_1 - Q_{Aa_1}})] \cdot p_4, \tag{13}$$

$$R_{a_2}^6 = (Q_{sa_2} - q_{a_2}) \cdot p_3. \tag{14}$$

The sewage fees underpaid by enterprise b, we assume that enterprise a resells the excess emission rights to b at price p_4 $(0 < p_4 < p_3)$. Thus, we given that

$$R_b^6 = (1-\alpha)(Q_{sa_2} - q_{a_2}) \cdot (t - p_3) + [\alpha(Q_{sa_2} - q_{a_2}) - (q_{a_1 - Q_{Aa_1}})] \cdot (t - p_4). \tag{15}$$

2.4.6. $Q_{sa_2} < q_{a_2} < Q_{Aa_2}$

Case 7: $0 < q_{a_1} < Q_{sa_1}$

In this case, the quota of enterprise a_1 is greater than its emissions, so he has the remaining quotas to be sold to other enterprises. For enterprise a_2, its emissions are larger than the initial quota and less than the local upper limit. Therefore, he needs to be punished accordingly and pay a certain sewage charge. At this point, we set the market price as p_5. And we assumed that enterprise a_1 sells the remaining quota to enterprise a_2 at proportion $\beta(0 < \beta < 1)$, and then enterprise b will have a quota of $1-\beta$ proportion. Same analysis as Equation (7), $(Q_{sa_1} - q_{a_1}) \cdot \beta \leq q_{a_2} - Q_{sa_2}$. Thus, we given that

$$R_{a_1}^7 = (Q_{sa_1} - q_{a_1}) \cdot p_5, \tag{16}$$

$$R_{a_2}^7 = -[q_{a_2} - (Q_{sa_1} - q_{a_1}) \cdot \beta] \cdot t - (Q_{sa_1} - q_{a_1}) \cdot \beta \cdot p_5, \tag{17}$$

$$R_b^7 = (Q_{sa_1} - q_{a_1}) \cdot (1-\beta) \cdot (t - p_5). \tag{18}$$

Case 8: $Q_{sa_1} < q_{a_1} < Q_{Aa_1}$

In this case, neither enterprise a_1 nor enterprise a_2 has any remaining quota. Therefore, upstream enterprises are required to pay a certain amount of pollution emissions fees, and enterprise b cannot purchase quotas. So, the income of each enterprise is

$$R_{a_1}^8 = -[(q_{a_1} - Q_{sa_1}) \cdot t], \tag{19}$$

$$R_{a_2}^8 = -[(q_{a_2} - Q_{sa_2}) \cdot t], \tag{20}$$

$$R_b^8 = 0. \tag{21}$$

Case 9: $q_{a_1} > Q_{Aa_1}$

In this case, enterprise a_1 has exceeded the emission limit and it will be penalized, while the others have no quota to sell. As a result, their earnings are as follows:

$$R_{a_1}^9 = -[(q_{a_1} - Q_{Aa_1}) \cdot 2t + (Q_{Aa_1} - Q_{sa_1}) \cdot t], \tag{22}$$

$$R_{a_2}^9 = -[(q_{a_2} - Q_{sa_2}) \cdot t], \tag{23}$$

$$R_b^9 = 0. \tag{24}$$

2.4.7. $q_{a_2} > Q_{Aa_2}$

Case 10: $0 < q_{a_1} < Q_{sa_1}$

In this case, enterprise a_2 exceeds its emission threshold and needs to be severely punished. However, compared with enterprise a_1, it has the remaining quota to be sold to enterprise a_2 and enterprise b, so both of them can reduce the sewage charge relatively. In fact, this situation is similar to case 6 (see Section 2.4.5), so we also discuss it in two cases: (i) $q_{a_2} - Q_{Aa_2} \geqslant (Q_{sa_1} - q_{a_1}) \cdot \beta$. (ii) $q_{a_2} - Q_{Aa_2} < (Q_{sa_1} - q_{a_1}) \cdot \beta$. Among them, the market transaction price is set to $p_6(0 < p_6 < t)$. If enterprise a_2 buys more quotas, it can be sold to enterprise b at the price of $p_7(0 < p_7 < p_6)$. Thus, the benefits of these enterprises we given that

(i) $q_{a_2} - Q_{Aa_2} \geqslant (Q_{sa_1} - q_{a_1}) \cdot \beta$.

$$R_{a_1}^{10} = (Q_{sa_1} - q_{a_1}) \cdot p_6, \tag{25}$$

$$R_{a_2}^{10} = -(Q_{Aa_2} - Q_{sa_2}) \cdot t - (Q_{sa_1 - q_{a_1}}) \cdot \beta \cdot p_6 - [(q_{a_2} - Q_{Aa_2}) - (Q_{sa_1 - q_{a_1}}) \cdot \beta] \cdot 2t, \tag{26}$$

$$R_b^{10} = (Q_{sa_1} - q_{a_1}) \cdot (1 - \beta) \cdot (t - p_6). \tag{27}$$

(ii) $q_{a_2} - Q_{Aa_2} < (Q_{sa_1} - q_{a_1}) \cdot \beta$.

$$R_{a_1}^{10} = (Q_{sa_1} - q_{a_1}) \cdot p_6, \tag{28}$$

$$R_{a_2}^{10} = -(Q_{Aa_2} - Q_{sa_2}) \cdot t - (q_{a_2} - Q_{Aa_2}) \cdot p_6 + [(Q_{sa_1} - q_{a_1}) \cdot \beta - (q_{a_2 - Q_{Aa_1}})] \cdot p_7, \tag{29}$$

$$R_b^{10} = (Q_{sa_1} - q_{a_1}) \cdot (1 - \beta) \cdot (t - p_6) + [(Q_{sa_1} - q_{a_1}) \cdot \beta - (q_{a_2 - Q_{Aa_2}})] \cdot (t - p_7). \tag{30}$$

Case 11: $Q_{sa_1} < q_{a_1} < Q_{Aa_1}$

Neither enterprise a_1 nor enterprise a_2 has quota surplus, so we have

$$R_{a_1}^{11} = -[(q_{a_1} - Q_{sa_1}) \cdot t], \tag{31}$$

$$R_{a_2}^{11} = -[(Q_{Aa_2} - Q_{sa_2}) \cdot t + (q_{a_2} - Q_{Aa_2}) \cdot 2t], \tag{32}$$

$$R_b^{11} = 0. \tag{33}$$

Case 12: $q_{a_1} > Q_{Aa_1}$

In this case, the earnings we get from each enterprise are as follows

$$R_{a_1}^{12} = -[(Q_{Aa_1} - Q_{sa_1}) \cdot t + (q_{a_1} - Q_{Aa_1}) \cdot 2t], \tag{34}$$

$$R_{a_2}^{12} = -[(Q_{Aa_2} - Q_{sa_2}) \cdot t + (q_{a_2} - Q_{Aa_2}) \cdot 2t], \tag{35}$$

$$R_b^{12} = 0. \tag{36}$$

The two-enterprise water emissions rights trading model and the three-enterprise water emissions rights trading model were covered in the earlier research. The next section uses numerical simulations to more clearly clarify the issue by analyzing the relationship between upstream businesses' pollution emissions and their revenues in various scenarios.

3. RESULTS AND DISCUSSION

3.1. Result analysis

To further illustrate the impact of the parameters in the model on the earnings of the upstream firms, we will use numerical simulations to analyze the impact of the emissions volume and the trading price on earnings of the firms. Table 2 presents the initial values of each parameter (the assumptions of the parameters are based on the analysis in the previous sections).

According to the previous model and hypothetical parameters, we can obtain Figure 5. From Figure 5, we analyze the relationship between the emissions of upstream enterprise a and its income. With the increase of emissions, it can be seen

Table 2 | Parameter data

Q_s	Q_A	p	t
30	60	7	10

Notes: Q_s is the initial quota allocated by the upstream government to upstream enterprises, Q_A represents the upper limit of pollutant emissions in region A set by the watershed management department, q is the emission of upstream enterprise a, p represents the price traded to other enterprises (b) by upstream enterprises, and t indicates the pollutant emissions price set by the river basin management department.

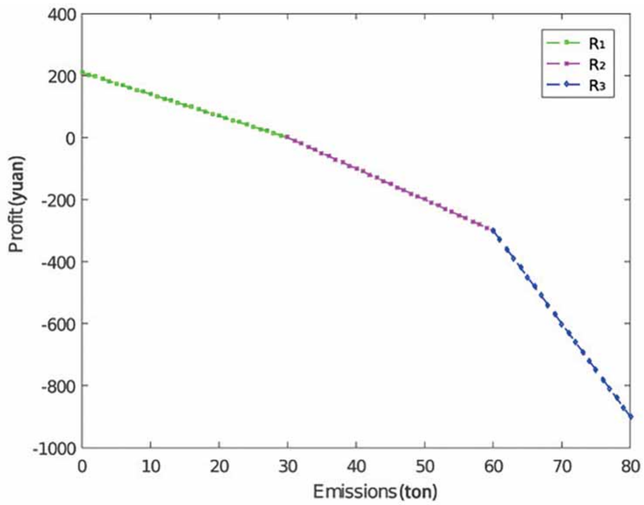


Figure 5 | Relationship between emission and profit of enterprise a.

from $\partial R_a^3/\partial q < \partial R_a^2/\partial q < \partial R_a^1/\partial q$ that the income of enterprise a is declining faster and faster. It demonstrates that the severity of the penalty for firms increases with the level of emissions. As a result, upstream businesses should precisely take into account how their emissions and earnings relate during manufacturing and building. Only in this way, we can maximize our own interests and better develop our enterprises.

3.2. Analysis of extended model results

In this section, we mainly explain the situation of three enterprises. It is relatively complex compared to the two companies. Here, the parameters we assumed are shown in Table 3:

(i) $q_{a_1} - Q_{Aa_1} \geqslant (Q_{sa_2} - q_{a_2}) \cdot \alpha$.

Combined with the previous analysis, we can also make a function diagram of upstream enterprise emissions and their benefits. However, it should be noted that when the emission of enterprise a_1 is greater than the threshold Q_{Aa_1} given by the watershed management department, or when the emission of enterprise a_2 is greater than the threshold Q_{Aa_2} given by the watershed management department, we need to discuss it on a case-by-case basis. Therefore, the function diagrams of the following cases are obtained.

Figures 6 and 7 explain the relationship between the emissions of enterprise a_1 and enterprise a_2 and the income when $0 < q_{a_2} < Q_{sa_2}$, and $q_{a_1} - Q_{Aa_1} \geqslant (Q_{sa_2} - q_{a_2}) \cdot \alpha$. In Figure 6, the images of R_1, R_2, and R_3 are obtained by Equations (4),

Table 3 | Parameter data

Q_{sa_1}	Q_{sa_2}	Q_{Aa_1}	Q_{Aa_2}	t	p_1	p_2	p_3	p_4	p_5	p_6	p_7
16	14	32	28	10	7	6	5	4	7	8	6

Notes: Q_{sa_1} represents the initial quota allocated to enterprise a_1 by the upstream government, Q_{sa_2} represents the initial quota allocated to enterprise a_2 by the upstream government, Q_{Aa_1} indicates that the watershed management department sets the emissions threshold for enterprise a_1, Q_{Aa_2} indicates that the watershed management department sets the emissions threshold for enterprise a_2, q_{a_1} represents the amount of pollution emissionsd by the upstream enterprise a_1, q_{a_2} represents the amount of pollution emissionsd by the upstream enterprise a_2, and p_k ($k = 1, 2, \cdots, 7$) represents the trading price of emissions in different cases, $\alpha = 0.6$, $\beta = 0.7$.

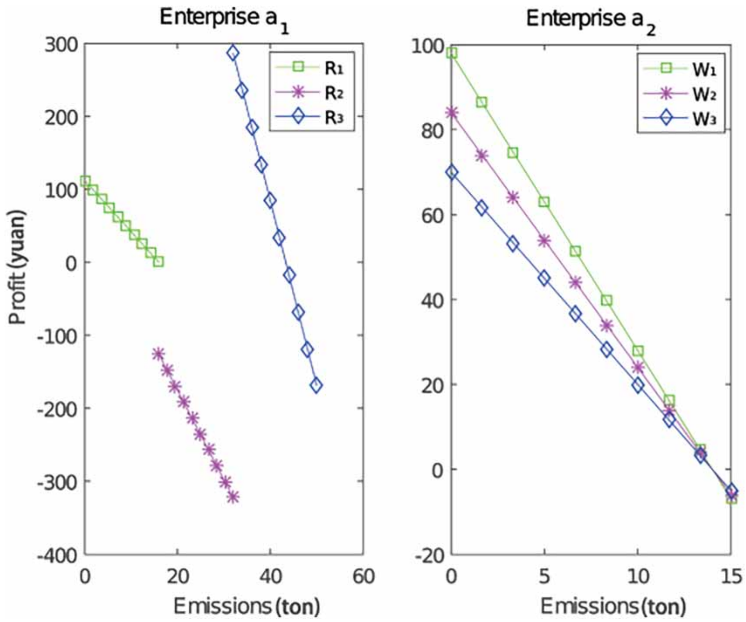


Figure 6 | Relationship between emissions and profits of enterprise a_1 and a_2.

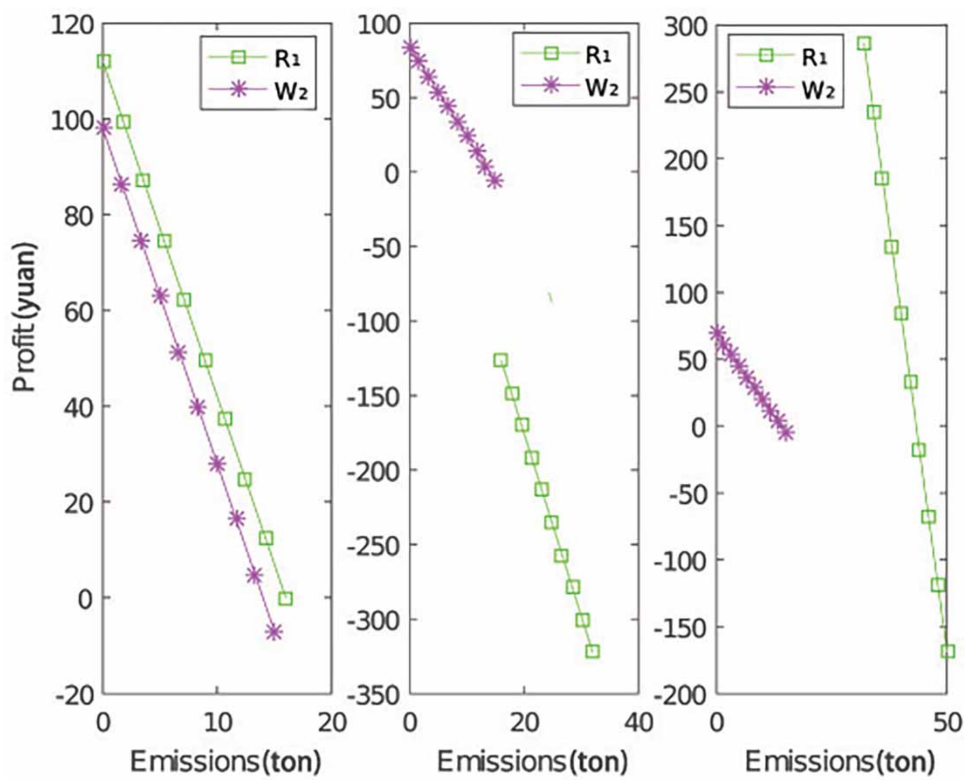


Figure 7 | Comparison of the profit situation of enterprise a_1 and enterprise a_2.

(7), and (10), respectively. Similarly, the images of W_1, W_2, and W_3 are obtained from Equations (5), (8), and (11), respectively. From the analysis of the picture, it shows that $\partial R_{a_1}^6/\partial q_{a_1} < \partial R_{a_1}^5/\partial q_{a_1} < \partial R_{a_1}^4/\partial q_{a_1}$, and on the contrary, $\partial R_{a_2}^6/\partial q_{a_2} > \partial R_{a_2}^5/\partial q_{a_2} > \partial R_{a_2}^4/\partial q_{a_2}$. It means that as corporate a_1 emissions increase, enterprise a_1 earnings will decline faster and faster. However, the revenue of enterprise a_2 will grow faster and faster. This is because the more a_1 emissions, when they exceed their initial quota, are penalized accordingly. However, to avoid paying excessive sewage charges, it will buy a certain amount of pollution from enterprise a_2. As a result, the revenue of enterprise a_2 will increase as the volume of emissions of enterprise a_1 increases.

Figure 7 shows that when the emissions q_{a_1} of enterprise a_1 are at $0 < q_{a_1} < Q_{sa_1}$, the earnings of enterprise a_1 and enterprise a_2 decline at almost the same rate, and the reason is when enterprise a_1 produces emissions, it will offset a certain amount of sewage charges with its own initial quota, resulting in the same result as enterprise a_2. When the emissions q_{a_1} of enterprise a_1 are at $Q_{sa_1} < q_{a_1} < Q_{Aa_1}$, and as shown in the figure, we found that with the increase of emissions, the income of enterprise a_1 decreases faster than that of enterprise a_2. The reason is that enterprise a_1 emits too much pollution and will be punished accordingly, while enterprise a_2 does not have to pay a fine because it has an excess quota. When the emissions q_{a_1} of enterprise a_1 are at $q_{a_1} > Q_{Aa_1}$, we found that the rate of decline in enterprise a_1 revenue is even more drastic.

Next, we will analyze the case: $q_{a_1} - Q_{Aa_1} < (Q_{sa_2} - q_{a_2}) \cdot \alpha$.

(ii) $q_{a_1} - Q_{Aa_1} < (Q_{sa_2} - q_{a_2}) \cdot \alpha$.

In this case, we give an image of $q_{a_1} - Q_{Aa_1} < (Q_{sa_2} - q_{a_2}) \cdot \alpha$, as shown in Figure 8. Through the comparison between the two parties, we found that the images of R_1, R_2, and R_3 have changed.

As shown in Figure 8, it is obvious that the image results of Equations (10) and (13) are different, and the result R_3 of Equation (10) is larger than R_3 of Equation (13). The reason is that the quota that enterprise a_1 buys from enterprise a_2 exceeds its emission capacity, so enterprise a_1 will resell the remaining quota to other enterprises, and this article assumes that it will be resold to downstream enterprise b. As a result, enterprise b will get a certain quota to offset the sewage charges. Therefore, the results of the two cases are different.

Figures 9 and 10 explain the relationship between the emissions of enterprise a_1 and enterprise a_2 and the income when $Q_{sa_2} < q_{a_2} < Q_{Aa_2}$. In Figure 9, the images of R_1, R_2, and R_3 are, respectively, obtained from Equations (16), (19), and (22). Similarly, the images of W_1, W_2, and W_3 are obtained from Equations (17), (20), and (23), respectively. We found that $\frac{\partial R^9_{a_1}}{\partial q_{a_1}} < \frac{\partial R^8_{a_1}}{\partial q_{a_1}} < \frac{\partial R^7_{a_1}}{\partial q_{a_1}}$, by reversing the order, $\frac{\partial R^7_{a_2}}{\partial q_{a_2}} < \frac{\partial R^8_{a_2}}{\partial q_{a_2}} = \frac{\partial R^9_{a_2}}{\partial q_{a_2}}$. As shown in Figure 10, we obtained that only in the case of $Q_{sa_1} < q_{a_1} < Q_{Aa_1}$ and $Q_{sa_2} < q_{a_2} < Q_{Aa_2}$, the enterprise a_1 and a_2, their earnings decline at the same rate. When the emissions of enterprise a_1 are $0 < q_{a_1} < Q_{sa_1}$ and $q_{a_1} > Q_{Aa_1}$, the revenue of enterprise a_1 is falling faster than that of enterprise a_2. Next, we will analyze the case: $q_{a_2} > Q_{Aa_2}$.

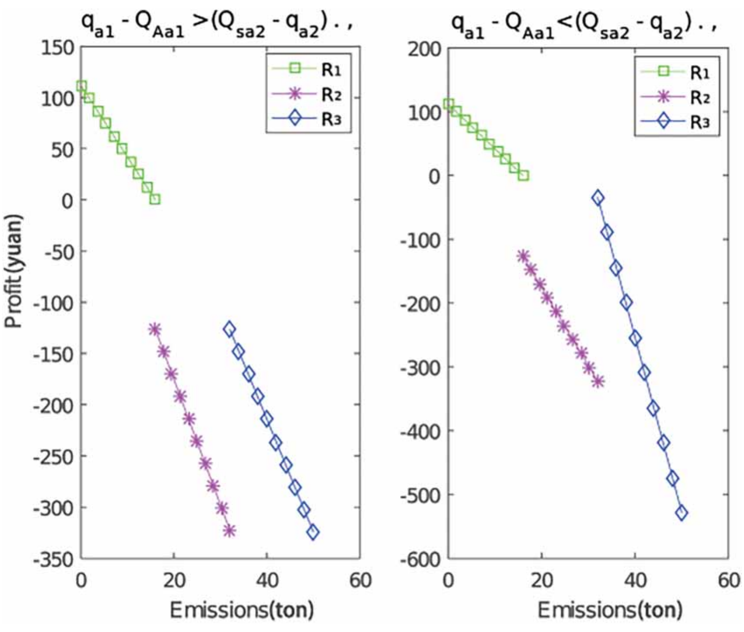


Figure 8 | Comparison of enterprise a_1 purchase quota situation.

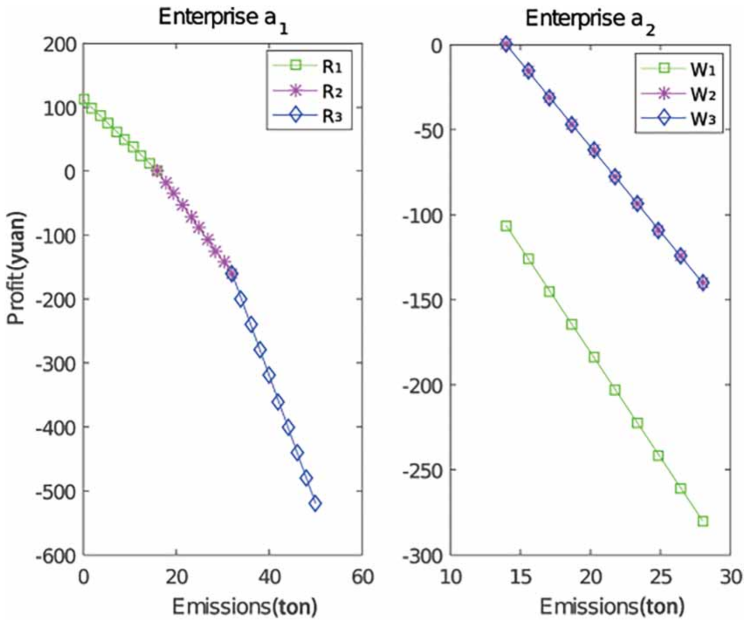


Figure 9 | The relationship between income and emissions of enterprise a_1 and a_2.

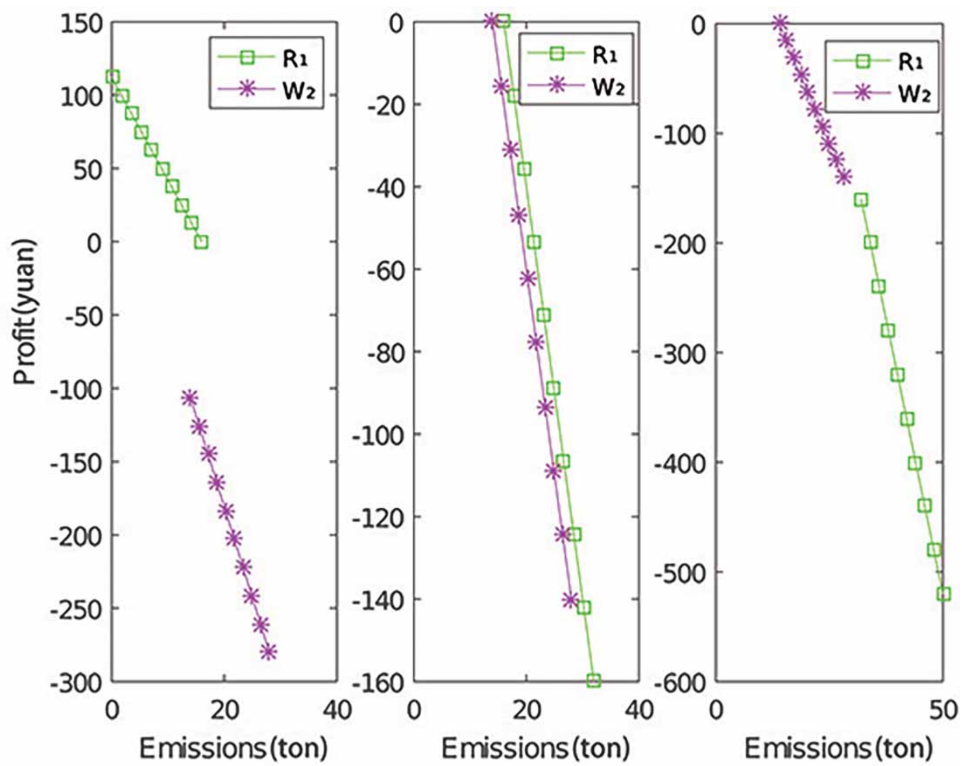


Figure 10 | Comparison of profit and emissions of enterprise a_1 and a_2.

We analyze the situation of enterprise a_2 for the reason that the functional image of enterprise a_1 is relatively simple, as shown in Figure 11. From Figure 12, we see that, except that Equations (25) and (28) get different results, the other cases are exactly the same. This shows that when enterprise a_1 has a surplus quota, enterprise a_2 can buy a certain quota to

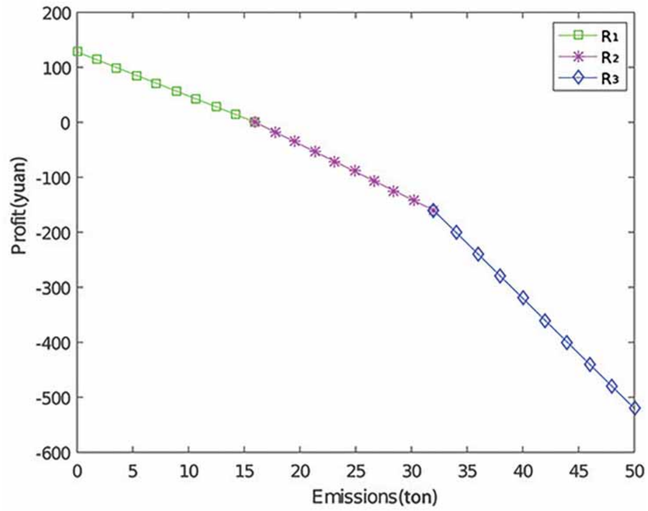


Figure 11 | Relationship between enterprise *a*'s emissions and profits.

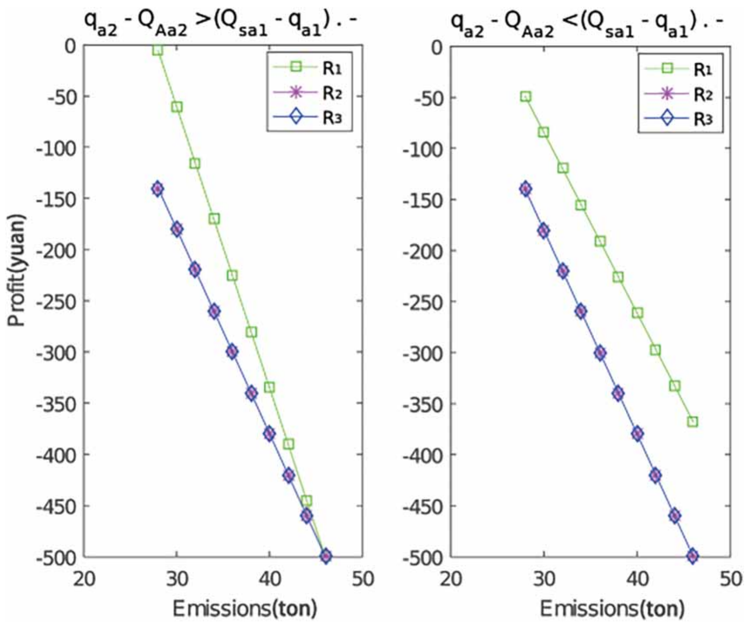


Figure 12 | Comparison of different percentages of quotas purchased by enterprise a_2.

offset the sewage charge, but when enterprise a_1 has no extra quota to sell. This case will result in enterprise a_2 to paying the excess sewage charges.

3.3. Discussion

In the numerical simulation phase, this article firstly analyzes the relationship between the income and emissions of a single upstream enterprise. Then, it focuses on an extended model that includes upstream enterprises a_1 and a_2, as well as a downstream enterprise b. The relationship between profits and emissions is studied under different emission scenarios. Similar to Li & Wang (2018), it suggested that cross-border urban areas should adhere to the principle of 'polluter pays', and cities that excessively use emission rights should pay more ecological compensation. Different from this research, Zhu *et al.* (2022) studied the central government and upstream and downstream governments, and the central government fines or rewards upstream and downstream governments based on pollution emissions. The model proposed in this article aligns more with the purposes of enterprises, which is profit-oriented, profit is a key driver for enterprises to engage in technological innovation. If enterprises know that their investment in pollution control can bring returns, they will take the initiative to implement pollution control measures. However, it may require initial financial subsidies from the government to achieve significant income in the early stages.

4. CONCLUSIONS

This study establishes a watershed ecological compensation model of the water emissions trading market, analyzes, and explains the operation mechanism of the water emissions trading market from the theoretical level, and primarily draws the following conclusions. These conclusions are based on the successful case of EU international carbon emissions trading and the fundamental characteristics of water pollution emissions.

1. The water emissions trading system is a useful new solution to the pollution management issue and a supplement to the already-existing ecological compensation in the basin. This article proposes a synergistic model in which market mechanisms successfully complement each other through combined coordination of government regulation and market processes. Government macro-regulation takes the lead (quota allocation, setting of emissions thresholds, etc.). It has been discovered that the use of water emissions trading for watershed pollution control, along with the knowledge gained through carbon emissions trading, can give government policy makers a fresh viewpoint when addressing water pollution issues.
2. The market mechanism can facilitate ecological compensation in the basin, incentivizing upstream regions to mitigate water pollution. As the emissions from upstream enterprises escalate, the income of these enterprises is rapidly diminishing. From a market operation perspective, the ecological compensation received by upstream enterprises primarily stems from allocated water discharge rights.
3. The allocation of initial quotas to upstream enterprises by the upstream governments is found to be a crucial trade-off process when basin management sets emission thresholds, which has a significant impact on the basin's ecological environment, to effectively control the water pollution emissions of each enterprise. In addition, when the government assigns initial quotas to upstream firms, they benefit by lowering emissions and also make a significant contribution to decreasing water pollution. According to the calculation results, the government can set a more reasonable initial emission quota to reduce pollutant emissions. In addition, businesses can invest in sewage treatment facilities to reduce pollution emissions and increase revenue in the trade market.

In future research, scholars are recommended to include diverse regions, multiple industries, and varying strategic decisions made by companies or governments. In addition, researchers can explore more practical and effective strategies to optimize emissions and allocate initial quotas, taking into account regional characteristics, industrial activities, and government policies. Furthermore, empirical analysis of a particular region will contribute to the development of effective and sustainable water pollution management strategies.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

AUTHOR CONTRIBUTIONS

Lu Zuliang and Xing Lu have participated in the sequence alignment and drafted the manuscript. Xu Ruixiang, Hou Chunjuan, and Yang Yin have made substantial contributions to conception and design.

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