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A trading-ratio system for trading water pollution discharge permits

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Abstract

The fact that water flows to the lowest level uni-directionally is a very specific and useful property of water. By utilizing this property, we design a trading-ratio system (TRS) of tradable discharge permits for water pollution control. Such a trading-ratio system has three main characteristics: (1) the zonal effluent cap is set by taking into account the water pollutant loads transferred from the upstream zones; (2) the trading ratios are set equal to the exogenous transfer coefficients among zones; and (3) permits are freely tradable among dischargers according to the trading ratios. This paper shows that the TRS can take care of the location effect of a discharge and can achieve the predetermined standards of environmental quality at minimum aggregate abatement costs. Problems with hot spots and free riding can be avoided, and the burdens on both dischargers and the environmental authority should be relatively light.

Keywords: Trading ratio; Water pollution; Tradable discharge permit; Location effect; Transfer coefficient; Cost-effectiveness; Hot spot; Sequential bilateral trading procedure; Transaction cost; Free rider

1. Introduction

The tradable discharge permit (TDP) has been introduced for about three decades as a cost-effective economic incentive instrument to meet a set of predetermined environmental quality

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standards. The design of a trading system depends rather crucially on the nature of the pollutant being regulated and traded. Tietenberg [20] has categorized pollutants into three different classes, namely, uniformly mixed assimilative pollutants, uniformly mixed accumulative pollutants and non-uniformly mixed assimilative pollutants; and has discussed the different ways in which they are implemented in detail.[1]

In the case of a uniformly mixed pollutant, either accumulative (e.g., carbon dioxide) or assimilative (e.g., volatile organic compounds, VOCs), a simple emission trading system on a one-to-one basis will improve efficiency by equalizing marginal abatement costs across dischargers. However, a TDP system for non-uniformly mixed pollutants, either accumulative (e.g., heavy metals) or assimilative (e.g., sulfur dioxide in the air and biochemical oxygen demand (BOD) in water), is much more complicated and has become the focus of the TDP literature. This is because the extent and the spatial pattern of damage to the environment depend not only upon the level of emissions, but also upon the locations and transfer characteristics of the emissions. Basically, three important TDP systems for non-uniformly mixed pollutants have been proposed and discussed extensively in the literature. They are the ambient-permit system (APS, [18]),[2] the pollution-offset system (POS, [14]),[3] and the exchange-rate emission trading system (ERS, [8,9,12,13]).

First, under the APS, permits are issued for each receptor point. To increase emissions, every discharger must obtain an appropriate amount of permits for those receptors that are affected by his emissions. The trading ratios (exchange rates) are exogenously determined by the transfer coefficient matrix. Montgomery [18] demonstrates that, by issuing permits for each receptor point, the competitive equilibrium for an ambient market exists and coincides with the cost-minimum attainment of a set of predetermined environmental quality standards.[4] It is obvious that the APS suffers from the problem of high transaction costs because every discharger must assemble a portfolio of permits from each of the receptor points that are affected by his emissions (see e.g., [2,11,12,14,16]). In addition, Krupnick et al. [14] show that the APS also suffers from a rather restrictive (and usually unattainable) condition in that the initial allocation of permits must make the pollution constraint binding at all receptor points to ensure the market equilibrium coincides with the least-cost solution.

Second, Krupnick et al. [14] propose the POS. Under the POS, dischargers are free to trade as long as a beforehand simulation of the environmental quality model shows that the proposed transaction would not violate the predetermined environmental quality standard at any receptor point. If the simulation shows that a proposed transaction will violate the binding environmental

[1]However, he does not consider the class of non-uniformly mixed accumulative pollutants (such as lead).

[2]Montgomery [18] explores both an APS and an emission permit system (EPS). Because EPS has both theoretical problems in that it may not yield an efficient solution and practical problems in that it could be quite susceptible to market manipulation [11], we shall not consider EPS in the analysis that follows.

[3]McGartland and Oates [17] develop a modified offset system (MOS) which considers both the predetermined standards and current environmental quality to prevent any deterioration in areas already cleaner than the standards. Because the nature of MOS is the same as that of POS, we shall not study it specifically in the following discussion.

[4]Recently, Weber [23] has modeled the optimal allocation of both surface water rights and pollution rights along a river with water quality constraints. Of the two, the pollution right trading system is essentially a Montgomery-style APS for cumulative impacts of pollutants on water quality. Non-assimilative pollutants are sufficient but not necessary for her results.

quality standard at any receptor point, then emissions must trade at a rate equal to the ratio of the two sources' transfer coefficients. Thus, the exchange rates are endogenously given in the environmental quality simulation model. Free riding and its accompanying high transaction costs, as well as uncertainty in trades resulting from simulations are, however, serious problems with the POS [11,16].

Third, under the ERS [8,9,12,13], the environmental authority first calculates and sets exchange rates ex ante, which are equal to the ratios of the dischargers' marginal abatement costs in the least-cost solution. Dischargers then trade with each other according to these exogenous exchange rates. The burden on the environmental authority is very high, however. The authority must have full information regarding dischargers' abatement cost functions in order to set exchange rates and choose the initial distribution that will yield the cost effective distribution as a result of trading. In addition, some environmental constraints not previously violated by the initial distribution may be violated after trading takes place [9,12, Chapter 9].

This paper proposes and explores an alternative scheme, namely, the trading-ratio system (TRS), to specifically incorporate location effect into TDP trading for non-uniformly mixed pollutants in water. Although the general principles of TDP systems hold regardless of whether water or air pollutants are being regulated, we believe that differences in the characteristics of water and air make the design and choice of TDP trading systems vary. While air pollutants are usually dispersed multi-directionally by wind, water pollutants always flow to the lowest level uni-directionally. This is a very specific and useful property of water that allows the environmental authority to take into account the water pollutant loads transferred from the upstream zones when prescribing effluent caps for different zones, and to set the trading ratios equal to the exogenous transfer coefficients among zones. By doing so, if a discharger wishes to increase his effluent, he only needs to buy the zonal TDPs of the same or upstream zones to offset this increase, and does not need to buy TDPs from all zones that are affected by his effluent as is the case under the APS.

We show in this paper that the TRS is an ideal trading system for water pollution control. It is a cost-effective instrument that meets predetermined environmental quality standards with the least aggregate abatement costs. It can avoid the well-known problems of high transaction costs resulting from assembling a portfolio of permits under the APS, high transaction costs arising from approving trades by simulating trades beforehand and free riding under the POS, and the possibility of violating the environmental quality standards under the ERS.

Before we spell out the details of the TRS and validate its cost-effectiveness in Section 3, we shall first define a formal setting of cost minimization given environmental constraints as the benchmark in Section 2. In Section 4, issues related to transaction costs, hot spots, and the free rider problem are discussed and compared among the TRS, APS, POS, and ERS to examine their feasibility for water pollution control. We summarize and draw conclusions in Section 5.

2. Formal statement of cost-effectiveness: the benchmark

The efficiency criterion requires that pollution control instruments be set so as to equate the marginal abatement cost with the marginal damage caused by the emissions. To be consistent with the efficiency criterion, however, the instruments pose a heavy information burden and are so complex that their use has been rather limited in practice. A general compromise is the goal of cost-effectiveness which is that of achieving an environmental target with minimized abatement costs [2,21].

Suppose there is a river basin. To reduce the transaction costs associated with maintaining its water quality, the environmental authority first divides the river basin into a number of zones and specifies water quality (concentration) standards for each zone that must be met according to the major water usages in that zone.[5] A zone can be defined as an area in which the dispersion characteristics of effluents and the environmental effects of any unit of effluent are very close. Then, by using a water quality model, the zonal water quality standards can be converted into the total load standards of effluents that cannot be violated within each zone.[6]

Suppose the environmental authority divides the river basin into n zones ($n \in N^+$) and orders these zones by their locations. The most upstream zone is indexed by 1 and the most downstream zone, by n. For the sake of symbolic simplification, we assume that there is only one representative discharger in each zone and the first discharger is located in the first zone, etc. This symbolic simplification will not lose any of the generality.

For an environmental authority, to cope with the location effects of non-uniformly mixed water pollutants, the mathematical formulation of the cost-effective solution that minimizes the aggregate abatement costs of n dischargers to achieve the environmental standards is given by (e.g., [9,18,20]):

$$\min_{e_1, e_2, \ldots, e_n} \sum_{i=1}^{n} c_i(e_i^0 - e_i) \tag{1}$$

subject to the total load standards:[7]

$$\sum_{i=1}^{n} t_{ij} e_i \leqslant E_j, \; j = 1, \ldots, n \tag{2}$$

$$e_i \in \left[0, \; e_i^0\right], \tag{3}$$

[5]The zonal approach is used extensively by environmental authorities around the world to reduce the transaction costs of air and water pollution control. One extreme of the zonal approach is a system based on the one-discharger-one-zone principle in a basin. The other extreme of the zonal approach is a very simple pollution control system with only one zone in a basin. The nice thing about the TRS is that it is a valid system for the full spectrum between the two extremes of the zonal approach. In addition, since the TRS can reduce transaction costs substantially, the optimal number of zones using the zonal approach that come with the TRS should be larger than that without it. Thus, the zonal approach comes closer to the optimal differential environmental quality in different locations.

[6]Note that it is not necessary for the water quality standard and the total load standard to be the same for each zone and all the time. The environmental authority could, for example, prescribe more stringent water quality standards and total load standards in densely populated areas and protection areas of drinking water sources, or more lenient total load standards during seasons in which the assimilative capacity of the river is stronger.

[7]We assume no background pollution in each zone. Since background depositions are parameters, this assumption does not result in loss of generality.

where $c_i(\cdot)$ is the abatement costs of discharger i, assumed to be increasing and strictly convex, e_i^0 the primary effluent level of discharger i, e_i the effluent level of discharger i, E_j the total load standard in zone j, t_{ij} the transfer coefficient which indicates the contribution that one unit of effluent from discharger i (or the zone in which he is located) makes to the total load of effluent in zone j. $0 \leqslant t_{ij} \leqslant 1$.

A necessary condition for an interior solution with strictly positive effluent is

$$c_i'(e_i^0 - e_i^{\text{eff}}) = \sum_{j=1}^{n} \mu_j t_{ij}, \quad \forall i, \tag{4}$$

where $c_i'(\cdot)$ is the marginal abatement cost of discharger i, e_i^{eff} the cost-effective effluent levels of discharger i, μ_j the shadow price of the total load standard E_j ($\geqslant 0$ for binding zones, $=0$, otherwise).

Eq. (4) states that, in a cost-effective effluent solution, any discharger's marginal abatement costs should be equal to the sum of the shadow prices of the total load constraints for all affected zones (μ_j) weighted by their own transfer coefficients (t_{ij}). The shadow price in one zone with its environmental constraint binding shows the increase in the aggregate abatement cost of reducing the total load of that zone by one unit.

In principle, this cost-effective solution is the benchmark for any TDP trading system to achieve. Montgomery [18] has shown that such an optimal vector of effluents exists.

It is also noteworthy that, because the transfer coefficients for pollution from the downstream dischargers to the upstream zones are zero ($t_{ij} = 0$ for $i > j$), the environmental constraints (Eq. (2)) for water pollution are simpler than those for air pollution.

3. Trading discharge permits with the trading-ratio system

In this section, we first design a trading-ratio system specifically for water pollution control in a river basin, and then prove that the market equilibrium under the TRS can attain the benchmark, i.e. the cost-effective goal.

3.1. The trading-ratio system

The trading-ratio system is designed as follows:

1. The environmental authority takes the existing zonal total load standards (E_j) as the environmental constraints for each zone.
   The zonal total load standards are converted directly from the water quality standards for every zone.
2. The environmental authority sets the zonal effluent caps one by one from the upstream to the downstream zones such that the zonal effluent cap is equal to the zonal total load standard minus the effluent load transferred from the upstream zones. Then, the authority converts the caps into their equivalent amounts of zonal tradable discharge permits (zonal TDPs, $\bar{T}_j$).
   The zonal TDPs ($\bar{T}_j$) are defined in terms of their original zonal locations. The environmental authority sets $\bar{T}_1 = E_1$ for the first zone, and lets the effluent cap for zone j be set equal to

$\bar{T}_j = E_j - \sum_{k=1}^{j-1} t_{kj}\bar{T}_k$, where k $(<j)$ denotes zones upstream to zone j.[8] Moreover, one zone, say, zone j, is defined as a critical zone if $t_{(j-1)j}E_{j-1} > E_j$. In this case, the total load standard of the critical zone becomes the binding constraint for its immediate upstream zone, i.e. the authority sets $\bar{T}_j = 0$ and $\bar{T}_{j-1} = E_j/t_{(j-1)j} - \sum_{k=1}^{j-2} t_{kj}\bar{T}_k$.

This cap setting approach is specific to the TRS and has two very important features. First, the environmental constraint is set binding in every zone initially. For the TDP trading systems with exogenous trading ratios (e.g., APS, ERS, and TRS), whether or not the initial allocation of permits makes the environmental constraint binding at all receptor points has an effect on whether or not the market equilibrium coincides with the cost-effective solution (see e.g., [12,14,18]).[9] When the environmental constraints are not binding initially, the market equilibrium will not be the cost-effective solution. However, under either the APS or the ERS, it is very difficult to have an initial allocation of TDPs such that the environmental constraint is binding for all receptor points simultaneously. The situation is even worse as the number of receptor points becomes large.

Under the TRS, by utilizing the uni-directional nature of water pollution, the cap setting approach can easily make the environmental constraint binding for every zone. The zonal effluent caps are set one by one from the upstream to the downstream zones. The authority only needs to have information regarding the transfer coefficients and environmental constraints.

Second, a TDP is bundled with its downstream effluent rights. The cap setting approach under the TRS deducts the water pollutant loads transferred from the upstream zones to set the zonal effluent cap. This approach endows an upstream zonal TDP with its downstream effluent rights because its downstream impacts have been fully considered. Dischargers therefore do not need to assemble a portfolio of TDPs of all zones that are affected by their effluents. The effluent trades that follow are simplified.[10]

3. The environmental authority allocates zonal TDPs to dischargers in the zone. Discharger i's initial allocation of TDPs is $\bar{T}_i$.[11]

   In general, the number of dischargers in a zone should be greater than or equal to one, although we assume that there is only one representative discharger in each zone. In any case, zonal dischargers share the zonal TDPs. If there is more than one discharger in a zone, it makes no difference how the zonal TDPs are allocated among dischargers within each zone.

[8]Note that determining zonal effluent caps one by one from the upstream to the downstream zones does not mean that the upstream zones will certainly be allocated more effluent caps. How much the zonal effluent cap of a zone will in fact depend on the zone's water quality standard. For example, if a zone is located in an upstream source water protection area, its water quality standard should be tighter, and it therefore follows that there will be a lower total load standard and a lower zonal effluent cap for the zone. In addition, by changing the zones' water quality standards, the authority has freedom to change the initial allocation of zonal TDPs. The TRS will maintain these water quality standards and zonal total load standards at the least cost.

[9]The POS is free from the initial allocation problem because dischargers can always obtain additional permits from the environmental authority so long as the environmental quality standard is not violated at any receptor point [14, p. 241].

[10]Basically, this advantage is the same as that of the APS if polluters group the ambient-based permits and sell them as a single commodity [16].

[11]The initial allocation of TDPs can be conducted through grandfathering or an auction.

4. The environmental authority sets the trading ratios (t_{kj}) equal to the transfer coefficients and promulgates ex ante.
   The transfer coefficient t_{kj} indicates the contribution that one unit of effluent from zone k makes to the total effluent load in zone j. When it becomes the trading ratio, t_{kj} is the effluent volume a discharger in zone j can increase if he buys one unit of $\bar{T}_k$ from any other discharger. Each discharger can read the trading-ratio table promulgated by the authority to find the trading ratios for his trades.
5. Dischargers trade with each other freely based on the trading ratios. The environmental authority will exercise monitoring and compliance functions to ensure compliance.[12]
   According to the exogenous trading ratios, dischargers trade with each other freely. At the end of a promulgated trading period, say, one year or one season, the environmental authority should ensure compliance, i.e. every discharger's actual effluents must be less than or equal to the effective amount of TDPs that he owns. This requirement means that the trading constraints under the TRS are

$$e_i \leqslant \bar{T}_i + \sum_{k=1}^{i-1} t_{ki} T_{ki} - \sum_{k=i+1}^{n} T_{ik} \quad \text{for dischargers} \quad i = 1, \ldots, n \tag{5}$$

and

$$T_{ik},\ T_{ki} \geqslant 0. \tag{6}$$

The right-hand side of Eq. (5), i.e. the effective amount of TDPs that discharger i owns, is composed of three elements: (1) the initial TDP allocation, (2) the TDPs he bought weighted by trading ratios, and (3) the TDPs he sold. T_{ki} is the net amount of $\bar{T}_k$ that discharger i buys. In principle, the first subscript of the trading amount T denotes the zonal TDPs traded, and the second, the buyer. Assuming the absence of strategic behavior, a rational discharger will not buy downstream zonal TDPs because he cannot increase effluents by doing so since the trading ratio is zero.

For zones with an aggregate primary effluent lower than the zonal effluent cap, zonal dischargers are allocated an abundance of TDPs that they can sell.[13] New dischargers or existing dischargers with higher abatement costs in other zones will buy such dischargers out. If there were still an excess supply of permits, the price of permits would be zero.

3.2. Cost-effectiveness of market equilibrium

In this section, we will show that the TRS can attain the goal of cost-effectiveness in two kinds of trading procedure, i.e. the simultaneous trading procedure, and the sequential bilateral trading

[12] The TRS system belongs to the group of allowance-based TDP trading systems. According to Tietenberg et al. [22], in general, past allowance-based TDP trading programs, such as the Acid Rain Program in the United States and the Regional Clean Air Incentives Market (RECLAIM) in Los Angeles, California, have performed better than credit-based TDP trading programs.

[13] Or, the environmental authority could play the role of a TDP holder and join in the TDP trades that follow. Or else, the authority could reset the cleaner present situation as the environmental constraint as in the case of the modified offset system [17].

procedure. In order to prove the cost-effectiveness of the two kinds of trading procedures in Sections 3.2.1 and 3.2.2, respectively, we need to prove that the cost-effective model in which the environmental authority minimizes the aggregate abatement costs subject to environmental constraints is exactly the same as the model in which the environmental authority minimizes aggregate abatement costs subject to the trading constraints under the TRS in Proposition 1.

Proposition 1. *The cost-effective model in which the environmental authority minimizes the aggregate abatement costs subject to environmental constraints is the same as the model in which the environmental authority minimizes aggregate abatement costs subject to the trading constraints under the TRS.*

Proof. Let us denote the set of effluents that satisfies the constraints under the TRS (Eqs. (5) and (6)) as Ω^{TRS}; the set of effluents that satisfies the constraints of the cost-effective model (Eq. (2)), Ω^{eff}.

Step 1: Prove $\Omega^{\mathrm{TRS}} \subseteq \Omega^{\mathrm{eff}}$.

Here we show that constraints (5) and (6) imply that constraint (2) is satisfied.

For any $\boldsymbol{e} = (e_1, \ldots, e_n) \in \Omega^{\mathrm{TRS}}$, $e_j - \sum_{k=1}^{j-1} t_{kj} T_{kj} + \sum_{k>j}^{n} T_{jk} \leqslant \bar{T}_j$, $j = 1, \ldots, n$.

Let

$$A_j \equiv \bar{T}_j - \left(e_j - \sum_{k=1}^{j-1} t_{kj} T_{kj} + \sum_{k>j}^{n} T_{jk} \right) \geqslant 0$$

then

$$e_j - \sum_{k=1}^{j-1} t_{kj} T_{kj} + \sum_{k>j}^{n} T_{jk} + A_j = \bar{T}_j.$$

According to the zonal effluent cap setting approach of the TRS, $\bar{T}_j = E_j - \sum_{i=1}^{j-1} t_{ij} \bar{T}_i$, thus

$$e_j - \sum_{k=1}^{j-1} t_{kj} T_{kj} + \sum_{k>j}^{n} T_{jk} + A_j + \sum_{i=1}^{j-1} t_{ij} \bar{T}_i = E_j. \tag{7}$$

By using the trading constraint, $e_i - \sum_{k=1}^{i-1} t_{ki} T_{ki} + \sum_{k>i}^{n} T_{ik} \leqslant \bar{T}_i$, we can rearrange (7) as

$$e_j - \sum_{k=1}^{j-1} t_{kj} T_{kj} + \sum_{k>j}^{n} T_{jk} + A_j + \sum_{i=1}^{j-1} t_{ij} \left(e_i - \sum_{k=1}^{i-1} t_{ki} T_{ki} + \sum_{k>i}^{n} T_{ik} \right) \leqslant E_j.$$

Equivalently,

$$\sum_{i=1}^{j} t_{ij} e_i + A_j + \sum_{k>j}^{n} T_{jk} + \sum_{i=1}^{j-1} t_{ij} \sum_{k>j}^{n} T_{ik} \leqslant E_j.$$

Because $A_j \geqslant 0$ and $T_{jk},\ T_{ik} \geqslant 0$,

$$\sum_{i=1}^{j} t_{ij} e_i \leqslant E_j, \quad j = 1, \ldots, n. \tag{8}$$

This equation is exactly the environmental constraint (Eq. (2)).[14] Therefore, for any $\boldsymbol{e} \in \Omega^{\text{TRS}}$, we have $\boldsymbol{e} \in \Omega^{\text{eff}}$. Thus, we have shown that $\Omega^{\text{TRS}} \subseteq \Omega^{\text{eff}}$.

Step 2: Prove $\Omega^{\text{eff}} \subseteq \Omega^{\text{TRS}}$.

Here we show that, given constraints (2), we can find at least a set of non-negative T's that imply that constraints (5)–(6) are satisfied. For any $\boldsymbol{e} = (e_1, \ldots, e_n) \in \Omega^{\text{eff}}$, $\sum_{i=1}^{n} t_{ij} e_i \leqslant E_j$, $j = 1, \ldots, n$.

Because $E_j = \bar{T}_j + \sum_{i=1}^{j-1} t_{ij} \bar{T}_i$, $e_j + \sum_{i=1}^{j-1} t_{ij} e_i \leqslant \bar{T}_j + \sum_{i=1}^{j-1} t_{ij} \bar{T}_i$.

Equivalently,

$$e_j - \sum_{i=1}^{j-1} t_{ij}(\bar{T}_i - e_i) \leqslant \bar{T}_j. \tag{9}$$

By adding $\bar{T}_j - e_j + \sum_{i=1}^{j-1} t_{ij}(\bar{T}_i - e_i) \geqslant 0$ to the left-hand side of Eq. (9), we have

$$e_j - \sum_{i=1}^{j-1} t_{ij}(\bar{T}_i - e_i) + \left[\bar{T}_j - e_j + \sum_{i=1}^{j-1} t_{ij}(\bar{T}_i - e_i)\right] = \bar{T}_j \leqslant \bar{T}_j.$$

Therefore,

$$e_j - \sum_{i=1}^{j-1} t_{ij}(\bar{T}_i - e_i) + \sum_{i=1}^{j} t_{ij}(\bar{T}_i - e_i) \leqslant \bar{T}_j. \tag{10}$$

There exists a set of T's:

$$T_{j(j+1)} \equiv \bar{T}_j + \sum_{i=1}^{j-1} t_{ij}(\bar{T}_i - e_i) - e_j = \sum_{i=1}^{j} t_{ij}(\bar{T}_i - e_i) \geqslant 0 \text{ (by Eq. (9))},$$

$$T_{(j-1)j} = \sum_{i=1}^{j-1} t_{i(j-1)}(\bar{T}_i - e_i) \geqslant 0,$$

$$T_{jk}\big|_{k=j+2,\ldots,n} \equiv 0 \geqslant 0, \quad \text{and} \quad T_{kj}\big|_{k=1,\ldots,j-2} \equiv 0 \geqslant 0,$$

such that constraint (6) is satisfied and Eq. (10) becomes

$$e_j - t_{(j-1)j} T_{(j-1)j} + T_{j(j+1)} - \sum_{k=1}^{j-2} t_{kj} T_{kj} + \sum_{k=j+2}^{n} T_{jk} \leqslant \bar{T}_j.$$

That is,

$$e_j - \sum_{k=1}^{j-1} t_{kj} T_{kj} + \sum_{k=j+1}^{n} T_{jk} \leqslant \bar{T}_j, \; j = 1, \ldots, n.$$

This equation is exactly the TRS trading constraints (Eq. (5)). Thus, for any $\boldsymbol{e} \in \Omega^{\text{eff}}$, we have $\boldsymbol{e} \in \Omega^{\text{TRS}}$. We have shown $\Omega^{\text{eff}} \subseteq \Omega^{\text{TRS}}$.

[14]The only visual difference is that the upper limitation of summation is n in Eq. (2), and j in Eq. (8). This is not a real difference, however. Eq. (2) can be decomposed as $\sum_{i=1}^{j} t_{ij} e_i + \sum_{i>j}^{n} t_{ij} e_i \leqslant E_j$, where the second part is zero because t_{ij} is equal to zero for $i > j$, i.e. downstream effluent does not have any effect on upstream zones.

Since $\Omega^{\mathrm{TRS}} \subseteq \Omega^{\mathrm{eff}}$ and $\Omega^{\mathrm{eff}} \subseteq \Omega^{\mathrm{TRS}}$, we have $\Omega^{\mathrm{TRS}} = \Omega^{\mathrm{eff}}$.

Because the trading constraints under the TRS are exactly the same as the environmental constraint under the cost-effective model, the cost-effective model (Eqs. (1)–(3)) can be rewritten as

$$\min_{e_i,\, T_{ik},\, T_{ki}} \quad \sum_{i=1}^{n} c_i(e_i^0 - e_i) \tag{11}$$

$$\text{s.t.} \quad e_i - \sum_{k=1}^{i-1} t_{ki} T_{ki} + \sum_{k>i}^{n} T_{ik} \leqslant \bar{T}_i, \quad i = 1, \ldots, n. \tag{12}$$

$$T_{ki},\ T_{ik} \geqslant 0, \tag{13}$$

$$e_i \in [0,\ e_i^0]. \qquad \square \tag{14}$$

The model of Eqs. (11)–(14) can be interpreted as if the environmental authority wishes to minimize aggregate abatement costs given the trading-ratio system by choosing $\boldsymbol{e}$ and $\boldsymbol{T}$. The necessary conditions for interior solutions with strictly positive effluents and TDP exchanges are

$$c_i'(e_i^0 - e_i^{\mathrm{TRS}}) = \lambda_i, \quad \forall i, \tag{15}$$

$$\lambda_i = t_{ik} \lambda_k \quad (i < k), \tag{16}$$

where $c_i'(\cdot)$ is the marginal abatement costs of discharger i, e_i^{TRS} the post-exchange effluent level of discharger i, λ_i the shadow price of discharger i's initial TDP allocation ($\geqslant 0$ for binding constraints, $=0$, otherwise).

Eq. (15) shows that the environmental authority would ensure that every discharger's marginal abatement cost is equal to the shadow price of the zonal TDP.[15] Eq. (16) shows that the environmental authority will choose the TDP exchanges such that the ratio of dischargers' marginal abatement costs equals the trading ratio (Eq. (16) can be rewritten as $c_i'(e_i^0 - e_i^{\mathrm{TRS}}) = t_{ik} c_k'(e_k^0 - e_k^{\mathrm{TRS}})$ by using Eq. (15)).

An important result of Proposition 1 that will be used later is that $\boldsymbol{e}^{\mathrm{TRS}}$ is the same as $\boldsymbol{e}^{\mathrm{eff}}$.

3.2.1. Simultaneous trading procedure

Faced with the need to choose a nonnegative level of effluent and quantity of permits traded, a discharger must minimize his total cost which is composed of abatement costs and net expenditures on TDPs. Discharger i's choice can be characterized as

$$\min_{e_i,\, T_{ik},\, T_{ki}} c_i(e_i^0 - e_i) + \sum_{k=1}^{i-1} P_i(t_{ki} T_{ki}) - \sum_{k>i}^{n} P_i T_{ik}, \tag{17}$$

[15] If the discharger's trading constraint is non-binding, i.e. if the discharger's excess TDPs are not taken away, the shadow price is zero. In this case, the discharger will not abate and will emit up to his primary effluent level.

where P_i is the price of TDPs that prevails in zone i. Since the revenue from selling permits is equal to the expenditure incurred in buying permits for an equivalent environmental effect, $P_iT_{ik} = P_kt_{ik}T_{ik}$. By substituting $P_kt_{ik}T_{ik}$ for P_iT_{ik} in Eq. (17) and assuming the discharger's TDP trading constraint is binding, i.e. $e_i - \sum_{k=1}^{i-1} t_{ki}T_{ki} + \sum_{k>i}^{n} T_{ik} = \bar{T}_i$ such that $\sum_{k=1}^{i-1} t_{ki}T_{ki} = e_i + \sum_{k>i}^{n} T_{ik} - \bar{T}_i$, Eq. (17) may be rewritten as

$$\min_{e_i,\, T_{ik}} c_i(e_i^0 - e_i) + P_i\left(e_i + \sum_{k>i}^{n} T_{ik} - \bar{T}_i\right) - \sum_{k>i}^{n} P_kt_{ik}T_{ik}. \tag{18}$$

The necessary conditions for interior solutions with strictly positive effluent and TDP trades are

$$c_i'(e_i^0 - e_i^{\mathrm{mkt}}) = P_i, \quad i = 1, \ldots, n, \tag{19}$$

$$P_i = t_{ik}P_k \quad (i < k), \tag{20}$$

where e_i^{mkt} is the market equilibrium effluent level of discharger i.

In equilibrium, the discharger will abate himself until his marginal abatement cost equals the price of the TDPs, and the selling price of the TDPs is equal to their buying price times the trading ratio.

Proposition 2. *Assuming cost-minimizing dischargers and no transaction costs or strategic behavior, the simultaneous-trading market equilibrium under the trading-ratio system can achieve the goal of cost-effectiveness.*

Proof. Based on Proposition 1, $\boldsymbol{e}^{\mathrm{TRS}}$ is the same as $\boldsymbol{e}^{\mathrm{eff}}$. Then, if the market equilibrium solution ($\boldsymbol{e}^{\mathrm{mkt}}$) is $\boldsymbol{e}^{\mathrm{TRS}}$, the market equilibrium solution under the TRS can achieve cost-effectiveness.

Supposing this is not the case (i.e. $\boldsymbol{e}^{\mathrm{mkt}} \neq \boldsymbol{e}^{\mathrm{TRS}}$), there exists an $\boldsymbol{e}'$ which is feasible under the TRS trading constraint such that $\sum_{i=1}^{n} c_i(e_i^0 - e_i') < \sum_{i=1}^{n} c_i(e_i^0 - e_i^{\mathrm{mkt}})$.

Because ($\boldsymbol{e}^{\mathrm{mkt}}$, $\boldsymbol{T}^{\mathrm{mkt}}$, $\boldsymbol{P}$) is the market equilibrium,

$$c_i(e_i^0 - e_i^{\mathrm{mkt}}) + \sum_{k=1}^{i-1} P_i(t_{ki}T_{ki}^{\mathrm{mkt}}) - \sum_{k>i}^{n} P_iT_{ik}^{\mathrm{mkt}} < c_i(e_i^0 - e_i') + \sum_{k=1}^{i-1} P_i(t_{ki}T_{ki}') - \sum_{k>i}^{n} P_iT_{ik}'$$

for $i = 1, \ldots, n$. Summing over $i = 1, \ldots, n$ we have[16]

$$\sum_{i=1}^{n} c_i(e_i^0 - e_i^{\mathrm{mkt}}) < \sum_{i=1}^{n} c_i(e_i^0 - e_i'),$$

which is a contradiction. Therefore, $\boldsymbol{e}^{\mathrm{mkt}} = \boldsymbol{e}^{\mathrm{TRS}} = \boldsymbol{e}^{\mathrm{eff}}$, i.e. the market equilibrium solution under the TRS can achieve the cost-effectiveness.

[16] ${}^{n}_{i=1}\left(\sum_{k=1}^{i-1} P_i(t_{ki}T_{ki}^{\mathrm{mkt}}) - \sum_{k>i}^{n} P_iT_{ik}^{\mathrm{mkt}}\right) = 0$ because the TDP market clears in equilibrium. ${}^{n}_{i=1}\left(\sum_{k=1}^{i-1} P_i(t_{ki}T_{ki}') - \sum_{k>i}^{n} P_iT_{ik}'\right) = 0$ because there exists the relationship $P_i = t_{ik}P_k$, $(i < k)$ for TDP equilibrium prices. If we expand ${}^{n}_{i=1}\left(\sum_{k=1}^{i-1} P_i(t_{ki}T_{ki}') - \sum_{k>i}^{n} P_iT_{ik}'\right)$ and factor out identical TDP terms, then the value of every term will cancel out because of the equilibrium price relationship. Take a simple two-discharger case for example, ${}^{n}_{i=1}\left(\sum_{k=1}^{i-1} P_i(t_{ki}T_{ki}') - \sum_{k>i}^{n} P_iT_{ik}'\right) = -P_1T_{12}' + P_2(t_{12}T_{12}') = -(P_1 - t_{12}P_2)T_{12}' = 0$.

3.2.2. Sequential bilateral trading procedure

A trading system that promises cost-effectiveness by means of a sequential bilateral trading procedure is more practical. In reality, trades are made sequentially, and usually bilaterally, at changing non-equilibrium prices [1]. This bilateral trading procedure can take place because of the existence of well-defined property rights under the TRS, as in the case of Coasian bargaining [4].

Under the TRS, every discharger has his own TDPs that allow him to discharge a certain amount of effluent. Among the dischargers, any two dischargers with different marginal abatement costs have incentives to trade with each other because the one with higher marginal abatement costs can reduce his abatement costs by trading, while the one with lower marginal abatement costs can earn profit from trading.

Proposition 3. *Assuming cost-minimizing dischargers, and no transaction costs or strategic behavior, the trading-ratio system can achieve the goal of cost-effectiveness through a sequential bilateral trading procedure.*

Proof. Following Xepapadeas's proof for Coasian bargaining [24, pp. 32–33], we assume that a downstream discharger k has higher marginal costs than an upstream discharger i. Thus, discharger k is willing to offer discharger i a payment X for an increase in effluents $(e_k - \hat{e}_k)$ if and only if $c_k(e_k^0 - e_k) + X \leqslant c_k(e_k^0 - \hat{e}_k)$. Here, $\hat{e}$ is the effluent allowed by the TDPs that a discharger owns at the time the trade takes place. Then, discharger i's problem is to solve the problem:[17]

$$\begin{aligned} \min_{e_i,\, e_k,\, X} \quad & c_i(e_i^0 - e_i) - X \\ \text{s.t.} \quad & c_k(e_k^0 - e_k) + X \leqslant c_k(e_k^0 - \hat{e}_k), \\ & t_{ik}(\hat{e}_i - e_i) = (e_k - \hat{e}_k). \end{aligned}$$

The second constraint states that the trading equation between two dischargers under the TRS, i.e., the decrease in the effluent of discharger i $(\hat{e}_i - e_i)$ weighted by the trading ratio (t_{ik}) is equal to the increase in the effluent of discharger k $(e_k - \hat{e}_k)$. In the above problem the first constraint is binding at any solution, thus $X = c_k(e_k^0 - \hat{e}_k) - c_k(e_k^0 - e_k)$. By substituting for X in the objective function, the problem facing discharger i is to choose the levels of (e_i, e_k) that solve:

$$\begin{aligned} \min_{e_i,\, e_k} \quad & c_i(e_i^0 - e_i) + c_k(e_k^0 - e_k) - c_k(e_k^0 - \hat{e}_k) \\ \text{s.t.} \quad & t_{ik}(\hat{e}_i - e_i) = (e_k - \hat{e}_k). \end{aligned}$$

The first-order condition is $c_i'(e_i^0 - e_i) = t_{ik} c_k'(e_k^0 - e_k)$, which is the same as the first-order condition of the cost minimization problem for the environmental authority given the trading-ratio system (Eqs. (15) and (16)). Since this equation must hold for each trade between any pair of dischargers (i, k) at any time, the effluent solution of the sequential bilateral trading procedure can therefore converge to the cost-effective solution. □

[17] In the objective function, e_k is also a control variable of discharger i. This is because discharger i has the property right of the TDPs that they wish to trade. By controlling the amount of TDPs traded, discharger i controls e_k.

3.3. Mathematical simulations

To illustrate how the TRS works, mathematical simulations are performed in a simple case. Suppose there are four zones in a river basin ordered as 1, 2, 3, and 4 from upstream to downstream and that there is only one discharger in each zone. The transfer coefficients are calculated based on the water quality model of the river basin and listed in Table 1. The information regarding the zonal primary effluents and zonal total load standards are provided in the second and third columns of Table 2.

Under the TRS, the environmental authority first takes the existing total load standards as the environmental constraints, i.e. 80, 80, 140, and 100 tons for zones 1 to 4, respectively. Second, the

Table 1
Table of transfer coefficients/trading-ratios (t_{kj})[a]

Zone k	Zone j			
	Zone 1	Zone 2	Zone 3	Zone 4
Zone 1	1	0[b]	0.4	0.32
Zone 2	0[b]	1	0.6	0.48
Zone 3	0	0	1	0.8
Zone 4	0	0	0	1

[a]Zone j indicates the zone where a buyer is located. Zone k indicates the zone whose zonal TDPs ($\bar{T}_k$) a buyer wants to buy.
[b]In this example, Zones 1 and 2 are located at different upstream branches. Their effluents do not contribute to each other's total load of effluent.

Table 2
Simulations of the environmental authority's cost minimization problem

Zone j (discharger i)	Primary effluents[a]	Zonal total load standards (E_j)[a]	Zonal effluent caps/zonal TDPs ($\bar{T}_j$)[b]	Initial TDP allocation ($\bar{T}_i$)[b]	Effluents under the model of equations (11)–(14)[a]	Effluents under the model of equations (1)–(3)[a]
Zone 1 (discharger 1)	100	80	80	80	79.079	79.079
Zone 2 (discharger 2)	60	80	80	80	38.059	38.059
Zone 3 (discharger 3)	100	140	45	45	70.066	70.066
Zone 4 (discharger 4)	30	100	0	0	0.374	0.374
Total abatement costs ($)					327.2065	327.2065

[a]Tons.
[b]Units.

authority sets the zonal effluent caps and zonal TDPs ($\bar{T}_j$)[18] one by one from the upstream to the downstream zones according to the cap setting approach as 80, 80, 45, and 0 tons for Zones 1–4, respectively.[19]

Third, the environmental authority allocates all zonal TDPs to dischargers within that zone. Because there is only one discharger in each zone, the discharger's initial TDP allocation is the zonal TDPs. Fourth, the trading ratios are set equal to the transfer coefficients and promulgated in a trading-ratio table as in Table 1 by the environmental authority. Any discharger can read Table 1 to know the trading ratio by referring to the zone where he is located and the zone whose zonal TDPs he wants to buy. For example, discharger 4 (located in Zone 4) proposes buying $\bar{T}_2$ from discharger 2. Both parties to the trade can read Table 2 and find that their trading ratio, t_{24}, is 0.48. That is, discharger 4 can buy one unit of $\bar{T}_2$ from discharger 2 to discharge 0.48 tons of effluent. On the other hand, the trading ratio for discharger 2 to buy $\bar{T}_4$ is zero, since effluent from Zone 4 has no effect on Zone 2 ($t_{42} = 0$).

Fifth, dischargers trade with each other freely according to the exogenous trading ratios. Each discharger only needs to make sure that his final effluent is less than or equal to the effective amount of TDPs that he owns at the end of a trading period. The environmental authority must make periodic inspections to ensure that dischargers comply with the rule.

Assuming the abatement cost function of discharger i is $c_i = 50 + 0.5 \times (85 - e_i) + \alpha_i \times (85 - e_i)^2$, the marginal abatement cost is then $c_i' = 0.5 + 2 \times \alpha_i(85 - e_i)$, where ($\alpha_1$, α_2, α_3, α_4) is (0.01, 0.02, 0.03, 0.04). Under these settings, both optimization problems under the model of Eqs. (1)–(3) and the model of Eqs. (11)–(14) are solved using GAMS, a mathematical programming package.

The simulated results are presented in the last two columns of Table 2. We see that the optimal effluents and aggregate abatement costs under both models are the same. That is, the environmental authority can achieve the goal of cost-effectiveness given the TRS.

A sequential bilateral trading procedure under the TRS is simulated, too. Two trading sequences are simulated: (1) the trade with the highest marginal cost savings which comes first, and (2) the sequence that is completely random. In the first case, the marginal cost savings are defined as the difference between the marginal abatement costs, weighted by the trading ratio, of any two dischargers. The trade with the highest marginal cost savings is always selected and implemented first. In the second case, the sequence of trades is completely random, which reflects the situation of imperfect information regarding costs in practice. In both sequences, the trading procedure stops if the total abatement costs are not reduced any further by trades on three consecutive occasions.

The simulated results are presented in Table 3. The results show that sequential bilateral trading procedures do not inhibit the TRS from achieving the goal of cost-effectiveness.

[18]Suppose the environmental authority converts the zonal effluent caps to zonal TDPs on a one-ton-to-one-unit basis.

[19]Here $T_1 = E_1 = 80$ and $T_2 = E_2 = 80$ because both Zones 1 and 2 are located at different upstream branches and are not affected by any other zone's effluent. As for Zone 3, originally, $T_3 = E_3 - t_{13}\bar{T}_1 - t_{23}\bar{T}_2 = 140 - 0.4 \times 80 - 0.6 \times 80 = 60$. However, because this zonal effluent cap will cause the total load standard of Zone 4 (E_4) to be violated ($t_{34}E_3 = 0.8 \times 140 = 112 > 100 = E_4$), i.e. Zone 4 is a critical zone and its total load standard becomes the binding constraint for Zone 3. Therefore, $T_3 = E_4/t_{34} - (t_{13}\bar{T}_1 + t_{23}\bar{T}_2) = 100/0.8 - (0.4 \times 80 + 0.6 \times 80) = 45$.

Table 3
Simulations of the sequential bilateral trading procedure under the TRS

Round	Sequence 1: the highest marginal cost savings come first			Sequence 2: random sequence		
	Traders (seller, buyer)	Effluents (tons)	Total abatement costs ($)	Traders (seller, buyer)	Effluents (tons)	Total abatement costs ($)
1	(2, 3)	(38.117, 70.130)	327.2208	(1, 4)	(79.007, 0.318)	383.2361
2	(1, 4)	(79.007, 0.318)	327.2069	(2, 3)	(38.117, 70.130)	327.2069
3	(3, 4)	(70.063, 0.371)	327.2067	(2, 1)	(38.117, 79.007)	327.2069
4	(2, 4)	(38.076, 0.391)	327.2066	(2, 4)	(38.040, 0.355)	327.2067
5	(4, 3)	(0.382, 70.074)	327.2066	(3, 1)	(70.130, 79.007)	327.2067
6	(4, 1)	(0.363, 79.065)	327.2065	(3, 4)	(70.084, 0.391)	327.2066
7	(3, 4)	(70.064, 0.372)	327.2065	(4, 4)	(0.391, 0.391)	327.2066
8	(2, 1)	(38.076, 79.065)	327.2065	(3, 1)	(70.084, 79.007)	327.2066
Post-trade effluents (e_1, e_2, e_3, e_4)	(79.065, 38.076, 70.064, 0.372)			(79.007, 38.040, 70.084, 0.391)		

After eight rounds of trading, both sequences converge and the post-trade effluents are the same as the optimal solutions of the cost-effective model (see the figures in the last column of Table 2).[20]

In addition, we see some trades taking place in which downstream dischargers sell permits to upstream dischargers in the process of trading. For example, in Sequence 1, discharger 4 sells permits to discharger 3 and discharger 1 in rounds 5 and 6, respectively. Here the things that discharger 4 sells to discharger 3 (1) in round 5 (6) are in fact Zone 1's zonal TDPs ($\bar{T}_1$).[21] This is particularly noteworthy because by defining TDPs in terms of their original zonal locations, the TRS can avoid the path-dependent problem.[22] If a downstream discharger buys upstream zonal TDPs in a previous trade, the midstream discharger can buy upstream zonal TDPs from the downstream discharger in later trades.

In practice, however, because of the inflexibility in abatement investment, the sequential bilateral trades cannot work as perfectly as in the simulation. A two-stage multi-agent decentralized market (MADIC) system suggested by Ermoliev et al. [7] might be a way to prevent non-optimal trades from inhibiting cost-minimizing achievements. The MADIC system separates trades into the trading and implementation periods.

[20] There are tiny discrepancies among the results of different simulation models due to mathematical rounding in the simulated trading process.

[21] We do not present these in Table 3 for the sake of simplification.

[22] The path-dependent problem is emphasized by, for example, Tietenberg [21]: "in which early trades can rule out later ones which would have been more cost-effective" (p. 108).

4. Further thoughts and comparisons

In addition to cost-effectiveness and the sequential, bilateral trading procedure, issues such as transaction costs, hot spots, and free riding are all important concerns in determining the performance of alternative TDP trading systems.[23]

4.1. Transaction costs

In order to keep the trading scheme simple, it is better for the trading ratios/exchange rates to be exogenously determined and promulgated ex ante [9]. From this point of view, the transaction costs associated with the POS are higher because its trading ratios are endogenous. When a dispersion model needs to be run before each trade is approved, the administrative costs will be very high [12,16]. Meanwhile, the transaction costs for dischargers are also very high because they must engage in troublesome paperwork and do not know the trading ratios beforehand or whether the trade will be approved. The willingness to trade will therefore be suppressed because the approval process creates uncertainty for them [22].[24]

In the case of the ERS, the exchange rates are explicitly equal to the ratios of the marginal abatement costs in the least-cost solution. While the exogenous exchange rates reduce the transaction costs significantly, solving the cost-minimization problem to determine the optimal exchange rate requires not only information regarding the dispersion characteristics of emissions, but also information regarding dischargers' abatement costs. The burden placed upon the environmental authority is therefore very heavy, and it is highly likely that dischargers will cheat in terms of the control cost information that they provide. Incorrect cost information may bias the trading results and result in high enforcement and monitoring costs.

Several authors have pointed out that the transaction costs associated with the APS are very high (e.g., [2,11,12,14,16]), even though the trading ratios are determined exogenously by the transfer coefficients. The problem of high transaction costs arises due to the difficulties associated with each discharger having to assemble a portfolio of permits for each affected receptor. When there are many receptors, the transaction costs become a very serious problem which in turn makes the APS an unpractical system.[25] Moreover, thin markets may give rise to non-price-taking behavior and result in even higher transaction costs [11,12].

Under the TRS, the trading rules are simple and, therefore, the transaction costs are lower. First, the trading ratios are given as the exogenous transfer coefficients and known by the environmental authority and dischargers ex ante. Second, the zonal TDPs are bundled with downstream effluent rights. A discharger does not need to assemble a portfolio of TDPs for all affected receptors.

[23]Market power should also be an important issue to be concerned about. It is, however, a quite complicated issue related to many factors, such as transaction costs, market participation, product–market competition, new dischargers, permit allocating approaches (e.g., auctions or grandfathering), and shutdown TDPs, etc. [5,10,20]. We will not discuss the differences in market power among the four trading systems.

[24]As the number of receptor points increases, the simulation will become even more complicated. Uncertainties relating to the exchange rates and doubts over whether a trade will be verified are increased too.

[25]A small number of receptors and the grouping and selling of the ambient-based permits could make the APS more practical. However, the reduction in the number of receptors might cause the hot spot problem (see Section 4.2).

In addition, because the trades are easy to process, market thinness should not be a problem and, thus the market power problem under the TRS should be less serious Ceteris paribus. The incentives for interest groups consisting of both dischargers and recipients to seek rents can be lowered too because the straightforward allocation rule of the TRS reduces the chance for administrative maneuvering.

4.2. Number of receptor points/zones and hot spots

The pollution control laws for water or air pollution in most countries generally require that the environmental quality standards be met in *all* locations. Most trading systems are designed, however, in terms of a given and fixed set of receptor points at which the attainment of predetermined levels of environmental quality is required. When the number of receptor points is small, environmental quality in some locations (other than the receptor points) may become worse after trading, i.e. hot spots, and that in certain other locations may become better after trading.

To prevent the occurrence of localized hot spots, a relatively fine mesh of receptor points will be needed. A large number of receptors implies relatively high transaction costs for the APS and the POS, however [2,14].

Under the ERS, some places will become hot spots after trading. This is because the exchange rates are determined by the ratios of the marginal costs in the least-cost solution, and these cannot guarantee the environmental quality.

Under the TRS, by dividing a river basin into a larger number of zones, each of which is defined as an area in which the environmental effects of the effluent of a particular pollutant are the same, we can require that the environmental quality standards be met in all locations. By doing so, the TRS does not become any more complicated. There are two reasons for this. First, the trading ratios are predetermined by the transfer coefficients. They are promulgated and can be easily read by dischargers. No matter how many zones exist, the number of trading ratios discharger faces is equal to the number of dischargers minus one, and the sequential, bilateral trading procedure still works. The transaction costs are therefore essentially unchanged as the number of zones increases to a relatively large number.

Second, it is not necessary to establish water quality monitoring stations in every zone which might be very expensive. The monitors could be established only in critical zones. The authority merely needs to review the amounts of TDPs that dischargers own and their effluents at the end of each trading period. If dischargers' effluents are less than or equal to the effective amount of TDPs they own, the environmental quality within each zone will not be violated.

4.3. Free rider problem

McGartland [16] points out that, under the POS, because dischargers can always obtain additional emission rights from the environmental authority if they do not violate ambient standards, dischargers would like to be free riders. Suppose there is a trade of discharger A that improves the environmental quality of the zone in which both dischargers A and B are located. Discharger B can then be a free rider to increase effluent at no cost if environmental standards are not violated. The free rider problem will impede some TDP trading such that the cost-effectiveness will be difficult to attain. In addition, since the TDPs being traded are

Table 4
Summary of effects of alternative trading systems

Trading systems	Effects				
	Trading ratios (exchange rates)	Transaction costs	Hot spots	Free riding	Environmental constraint
APS	Exogenous	High	Yes	No	Difficult to set as binding
POS	Endogenous	High	Yes	Yes	Easy to set as binding
ERS	Exogenous	High	Yes	No	Difficult to set as binding
TRS	Exogenous	Lower	No	No	Easy to set as binding

state-dependent, i.e. their definition depends on the actions of other dischargers [11], high transaction costs may therefore arise.

Under the TRS, because all zonal TDPs are allocated and any additional increase in effluent should come with more permit purchases as in the case of the APS and ERS, the free rider problem is avoided. Some might think that the selling of upstream zonal TDPs to downstream dischargers would make the upstream and midstream zones cleaner and give dischargers located there the opportunity to be free riders, so that they can increase their effluent without violating the environmental standards where they are located. This is not permissible, however, since downstream zones are still binding after trading, and any increase in effluent in the upstream or midstream zones will lead to a violation of the environmental quality standards in the downstream zones.[26]

Table 4 summarizes the discussion in this section. We can see that the TRS always performs better than other effluent trading systems in terms of each of the issues discussed. Under the TRS, transaction costs are lower, there are no problems with hot spots and free riding, and its cap setting approach can easily make the environmental constraints binding initially.

5. Conclusions

In the literature, several trading systems such as the APS, POS, and ERS have been designed for cost-effective pollution control. These economic instruments, however, might not be appropriate for water pollution control.

With water having the specific property of flowing in one direction, water pollution allows us to design a trading-ratio system (TRS) that is specifically for its control. As discussed above, the

[26]An upstream discharger can also not increase effluents by buying downstream zonal TDPs because the trading ratios of these kinds of trades are zero. To sum up, there are no third-party effects resulting from any non-adjacent TDP trade.

TRS has the property of being able to achieve the goal of cost-effectiveness, i.e. attain the predetermined standards of environmental quality in all locations with minimum aggregate abatement costs. Such cost-effectiveness can also be arrived at by means of a sequential bilateral trading procedure, which is in actual fact a more realistic trading sequence.

TDP systems provide dischargers with an opportunity to reduce their abatement costs. However, if the system is designed in such a way that it is too complicated and not sufficiently clear-cut ex ante, the transaction costs will be very high and dischargers' willingness to trade will be frustrated. Under the TRS, dischargers may trade with each other freely based on exogenous and predetermined trading ratios. This means that trades need not be verified beforehand as under the POS. Besides, by taking the pollution loads transferred from the upstream zones into consideration when setting the zonal effluent caps, dischargers need not assemble a portfolio of permits as under the APS. Trades are therefore easier for dischargers to engage in. The administrative costs borne by the authority are also lower under the TRS. Officials only need information regarding the transfer coefficients and do not need any information whatsoever regarding the abatement costs as under the ERS.

In addition, since environmental quality standards can be met in all locations and some places might become cleaner because of trades, environmentalists, the general public, and officials all benefit from the TRS. For example, in the case where a downstream discharger buys upstream zonal TDPs, the reduction in the upstream effluent makes both the upstream and midstream zones cleaner.

Although the TRS is specifically related to water pollution control, it could be applied to air pollution control in cases where the direction of the pollutant dispersion is clear and fixed. Simulations based on the TRS may also be conducted to empirically examine its cost-effectiveness.[27] Moreover, the TRS can be extended to trades between point and nonpoint sources and multiple-period, multiple-pollutant TDP trades as long as appropriate transfer coefficients and trading ratios can be set. These topics deserve further research in the future.

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