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Water-quality trading: Can we get the prices of pollution right?

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Key Points:

- Water-quality trading is a useful policy approach to protecting water quality
- Trading is hard, especially for branching rivers in which damages are nonlinear
- Simulations show nonlinearity is the lesser problem, emissions limits critical

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Abstract Water-quality trading requires inducing permit prices that account properly for spatially explicit damage relationships. We compare recent work by Hung and Shaw (2005) and Farrow et al. (2005) for river systems exhibiting branching and nonlinear damages. The Hung-Shaw scheme is robust to nonlinear damages, but not to hot spots occurring at the confluence of two branches. The Farrow et al. (2005) scheme is robust to branching, but not to nonlinear damages. We also compare the two schemes to each other. Neither dominates from a welfare perspective, but the comparison appears to tilt in favor of the Farrow et al. scheme.

1. Introduction

Enthusiasm for water-quality trading (WQT) is high in the U.S., at least in certain quarters [*U.S. Environmental Protection Agency*, 2003, 2004]. The experience with sulfur dioxide allowances proved that markets can work for air pollution. Should they not work for water pollution too? So far, where trade in water quality has been attempted the results have not been encouraging, at least according to one important metric: the number of trades has typically been lower than hoped [*Morgan and Wolverton*, 2005; *King and Kuch*, 2003; *Fisher-Vanden and Olmstead*, 2013]. Is this because trading is simply not a viable policy approach for water, or because the existing schemes are not well designed?

Hoping that the problem is with design, not with concept, economists continue to seek new and improved ways of building WQT systems. The aim is to improve their performance and so, perhaps, to achieve the kind of cost savings that accompanied trading for SO_2 under Title IV of the 1990 Clean Air Act Amendments [*Carlson et al*., 2000]. Two recent contributions, by *Farrow et al*. [2005] and by *Hung and Shaw* [2005], follow this strategy. Though quite different in specifics, both offer innovative schemes for trading between point sources on a river system.

The present paper grew out of our efforts to employ these two approaches in a study of trading for temperature in the Vermillion River, a popular trout stream in suburban Minnesota [*Vermillion River Watershed Joint Powers Board*, 2008]. In each case, we encountered difficulties that could be traced to particular features of the respective schemes. The Vermillion trout fishery extends into tributaries, and so the trading system we sought would need to accommodate branching. The biology of trout indicates the existence of threshold temperatures above which the fish are dramatically more susceptible to mortality [*Elliott*, 2000]. The trading system we sought would need to accommodate nonlinear damages.

Our attempt to apply Hung and Shaw revealed a problem in their model that arises when a “hot spot” is located at a confluence of streams. There, the Hung-Shaw method of allocating permits is ill defined. Our attempt to apply Farrow et al. revealed a problem in their model that arises when the damages associated with emissions are nonlinear. There, the Farrow et al. damage coefficients cannot be computed independently. Discovery of these problems led us to investigate the welfare properties of the two systems by incorporating into a single theoretical model the two important features noted above: branching rivers and nonlinear damages. Our purpose is to describe the difficulties we encountered, to explain their source in each case, and to gauge the degree to which they detract from the obvious appeal of the two schemes. Our ultimate finding is that both are likely to serve reasonably well in practice. Attempts to apply them, though, should be carried out with an awareness of the possible pitfalls.

After describing our model, we turn first to an analysis of Hung and Shaw’s trading-ratio system (TRS). The TRS is designed to guarantee that ambient water-quality standards are satisfied at each “zone” of the river system. The regulator first calculates a matrix of physical transfer coefficients, a la *Montgomery* [1972], describing the portion of pollutant emitted at each zone that remains in the river at any downstream zone. Permits are allocated so as to meet the zonal standards without trade, and then trade between sources is executed at the ratio of coefficients. By design, the transfer coefficient from a downstream to an upstream source, or across branches above a point of confluence, is always zero. Thus, upstream sources cannot buy from downstream sources and trade across branches above a point of confluence is prohibited. These restrictions mean that under the TRS some trades that increase social welfare are prohibited. What is more, we find that when a "hot spot" is located at a confluence of streams, the Hung-Shaw method of allocating permits is ill defined. Where this is true, a cost-effective outcome can be guaranteed only if the regulator knows firms' abatement cost functions.

In Farrow et al., whose methodology plays an important role in *Muller and Mendelsohn* [2009], the main constraint is that total monetary damages in the river system cannot exceed a maximum determined by the regulator. (We call this the damage-denominated trading-ratio system, or DTRS.) Each source is assigned a damage coefficient that reflects the integral over its downstream "zone of influence" of marginal damage caused by that source's emissions. Permits are then allocated so that aggregate damages satisfy the overall monetary constraint, and trade can occur between any two sources at the ratio of their damage coefficients. Unlike the TRS, the DTRS is not concerned with water quality at specific points along the river. Also unlike the TRS, trade can occur across branches above a confluence and upstream sources can buy from downstream. When the model is extended to nonlinear damages, though, we find that the Farrow et al. allocation scheme too can be ill defined. This possibility arises because emissions from each source affect the marginal damages of all others. What is more, even if the damage coefficients are computed at the cost-effective optimum, the trading outcome can still fail to achieve that optimum, because here the initial supply of permits goes astray.

These findings suggest that we need to evaluate the welfare properties of the two systems against the same benchmark. To this end, in section 5 we consider the efficient, fully socially optimal, program for a social planner who selects a vector of emissions to minimize the sum of abatement costs and pollution damages. We compare the welfare losses of the two systems, if any, against this efficient benchmark. We find that, when the regulator is able to allocate permits in the first-best manner, the TRS struggles precisely where the DTRS succeeds (in the face of branching), and vice versa (in the face of nonlinearities).

In particular, we find that the TRS outperforms the DTRS if there is no branching but damages are nonlinear. Because the TRS sometimes disallows efficient trades, improvement over a no-trade baseline can be inhibited. For certain configurations of sources above and below a confluence, in particular if the disallowed trades would have been inefficient, this can turn out to be an advantage relative to the DTRS. In contrast, however, when the regulator is unable to allocate permits in the first-best manner, we find that the TRS is generally dominated by the DTRS. In such a case, the regulator can make use of the damage coefficients to encourage efficient trades that increase welfare relative to the second-best initial allocation of permits. The exception occurs when inefficient trades between branches, prohibited by the TRS, are instead allowed by the DTRS. When this occurs, the DTRS is too permissive in that some trades that reduce social welfare are permitted.

These findings suggest that the relative performance of the two systems depends on the distribution of sources in a watershed featuring both branching rivers and nonlinear damages. We investigate this question by constructing a small numerical model and perturbing the geographic distribution of pollution sources. Here again, our results suggest that neither system dominates from a welfare perspective. As expected, the TRS precludes some efficient trades across branches and the DTRS allows some inefficient trades. However, our comparative work tilts in favor of the DTRS: for most of our limited set of configurations of the numerical model, welfare improvement over the second-best allocation is larger for the DTRS than for the TRS. The question of how the two compare in an empirical setting is deferred to future work. We find it encouraging that the efficiency loss from failing to issue the correct number of permits is much greater than the efficiency loss from failing to set the correct trading ratios. This last is what is meant by getting prices right, and it leads us to believe the two systems do indeed represent significant innovations in the water-quality trading literature.

The reader might reasonably ask whether hot spots at confluences, or nonlinear damages, are important concerns in water policy. We believe that they are. Cities tend to rise up in those places where rivers meet. This means that water quality is likely to be compromised by industrial activity, and so a hot spot is more likely, at a confluence. Linear damages, on the other hand, certainly confer a computational advantage upon a model of water-quality trading. But the chemistry and the biology of aquatic systems are sometimes characterized by thresholds or tipping points or other nonlinear relationships between nutrient concentration and outcomes of interest. What is more, the constant marginal abatement benefits that attend linear damages are hardly standard in environmental economics. In textbook treatments [*Baumol and Oates*, 1988, for example] and a host of scholarly articles, the assumption of declining marginal benefits is very much the norm.

2. A Model of Water-Quality Management

Consider the problem of regulating a single pollutant that is emitted by N point sources, indexed by $i=1,\ldots,N$, located along a river system. Let e_i represents emissions from source i, with $\mathbf{e}=(e_1,\ldots,e_i,\ldots,e_N)$, and let $\bar{\mathbf{e}}$ be a vector of baseline or uncontrolled emissions, with $e_i \leq \bar{e}_i$. Let $\mathbf{x}=(x_1,\ldots,x_m,\ldots,x_M)$ be a vector of ambient concentration levels, where x_m denotes concentration at receptor m. Assume, as in *Montgomery* [1972], that there exists a linear mapping $T:\mathcal{R}^N \rightarrow \mathcal{R}^M$ describing the scientific relationship between $\mathbf{e}$ and $\mathbf{x}$, so that $\mathbf{x}=T\mathbf{e}'$, with T an $M \times N$ matrix of nonnegative transfer coefficients. The assumption of a linear mapping from emissions to concentration is not innocuous [*Todd and Mays*, 2005]; we make it in order to place our focus firmly on nonlinear damages. Our framework would be useful also in understanding the implications of a nonlinear T mapping.

Let $S:\mathcal{R}^M \rightarrow \mathcal{R}$, given by $S(\mathbf{x})$, be a differentiable and possibly nonlinear function that describes total economic damages as a function of the vector of concentration levels and assume that $\partial S/\partial x_m > 0$ for all m. It follows that total economic damage as a function of emissions is differentiable and given by $D(\mathbf{e})=S(T\mathbf{e}')$. Define a vector of abatement levels $\mathbf{a}=\bar{\mathbf{e}}-\mathbf{e}$, where by definition $a_i \in [0,\bar{e}_i]$. Each source i is assumed, here and throughout the paper, to have a twice-differentiable abatement cost function $C_i(a_i)$, with $C'_i > 0$, $C''_i > 0$, and $C_i(0)=0$.

The usual approach to modeling an emissions-trading scheme is to specify one variant or another of a cost-effectiveness program. In *Montgomery* [1972], *Krupnick et al*. [1983], and *McGartland and Oates* [1985], for example, the constraint placed on the problem is a vector of environmental standards, one for each receptor. This approach is followed in *Hung and Shaw* [2005]. For a given vector of exogenously determined zonal environmental standards $\bar{\mathbf{X}}$, they specify the following cost-effectiveness program:

$$\mathbf{a}^{\mathrm{HS}}=\arg\min_{\mathbf{a}} \left\{\sum\nolimits_{i=1}^{N} C_i(a_i) | x_m \leq \bar{X}_m,\ \mathbf{x}=T\mathbf{e}',\ \text{ and }\ a_i \in [0,e_i]\right\}. \tag{1}$$

The TRS is designed to solve program (1). We note that the TRS trading scheme is not designed to achieve a socially optimal outcome, a property it shares with earlier work.

An interesting alternative, the innovation of *Farrow et al*. [2005], is to specify a different cost-effectiveness program. Farrow et al. impose a constraint on total monetary damages caused by the vector of emissions. They assume that $D(\mathbf{e})$ is additively separable and linear in emissions: $D(\mathbf{e})=\sum_i d_i e_i$, where d_i is a damage coefficient describing the aggregate damages caused by a unit of emissions from source i. For an exogenously given limit on total monetary damages $\overline{\mathrm{TD}}$, Farrow et al. specify the following cost-effectiveness program:

$$\mathbf{a}^{\mathrm{FSCH}}=\arg\min_{\mathbf{a}} \left\{\sum\nolimits_{i=1}^{N} C_i(a_i) | D(\bar{\mathbf{e}}-\mathbf{a}) \leq \overline{\mathrm{TD}} \text{ and } a_i \in [0,e_i]\right\}. \tag{2}$$

The DTRS is designed to solve program (2). Like the TRS, it is not designed to achieve a socially optimal outcome. As *Muller and Mendelsohn* [2009] observe, $\mathbf{a}^{\mathrm{FSCH}}$ will be socially optimal only if the constraint on total damages, $\overline{\mathrm{TD}}$, is set at the efficient level.

Finally, we define a criterion that can be used to compare the two systems. Following Muller and Mendelsohn, a natural choice is to define the efficient program. A social planner who knows the cost and damage functions and who wishes to maximize social welfare will select an efficient vector of abatement that minimizes the sum of damages and abatement costs:

$$\mathbf{a}^{\text{eff}}=\arg\min_{\mathbf{a}} \left\{\sum_{i=1}^{N} C_i(a_i)+D(\bar{\mathbf{e}}-\mathbf{a})|a_i \in [0, e_i]\right\}. \tag{3}$$

Given that the C_i's and D are continuous and that the constraint set is compact, the Weierstrass theorem ensures that a solution to (3) exists. Let $\mathbf{x}^{\text{eff}}$ denote the associated vector of efficient concentrations and $D^{\text{eff}}=D(\bar{\mathbf{e}}-\mathbf{a}^{\text{eff}})$ the associated level of damages. In order to guarantee uniqueness of the solution to (3), one would need also to impose curvature restrictions on $D(\cdot)$. In the numerical simulation below, local curvature of a sigmoidal damage function yields optima that appear to be unique.

In the next two sections, we show that in the presence of branching (manifest in the T matrix) the TRS equilibrium *may not achieve the solution to (1)*. If damages are nonlinear (manifest in the damage mapping S), the DTRS equilibrium *may not achieve the solution to (2)*. Therefore, one can guarantee neither that the equilibrium under the TRS is equivalent to that under the DTRS, nor that either system delivers the socially optimal vector of emissions. Whether these difficulties are significant in practice is an empirical question to which we turn in section 6.

3. The Trading-Ratio System (TRS)

We begin by sketching the main elements of the TRS. For further details, the reader should consult *Hung and Shaw* [2005]. As in that paper, number the zones (and the sources) so that $i=1$ indicates the most upstream source and N the most downstream, where indexes on two branches above their confluence, though important for bookkeeping purposes, have no ordinal relationship to each other. (With one source per zone, the i and m indexes coincide.) Let the transfer matrix be $T=\{\tau_{ij}\}$, where τ_{ij} measures the water-quality impact of pollution from zone i upon concentration at zone j. Given the unidirectional flow of a river, T has a special characteristic: for any m and n with $m>n$, or for zones on different branches, we must have that $\tau_{mn}=0$. Following Hung and Shaw, we assume that each source influences its own zone in a unitary fashion: $\tau_{ii}=1$ for all i.

Under the TRS, the allocation of tradable discharge permits begins at zone 1 and proceeds from there on down the stream, ensuring along the way that the concentration standard $\bar{X}_i$ is met at each zone. This means that downstream sources may receive few permits or no permits in the initial allocation. This makes good economic sense, in that an efficient outcome should "fill the river" with pollution up to the standard at each receptor. Failing to do this will lead to higher aggregate abatement costs.

Given a vector $\bar{\mathbf{X}}$ of zonal concentration standards from (1), the TRS regulator uses the τ_{ij} to allocate zonal permits $\bar{\mathbf{Z}}$ so that the standards are met if no trade occurs. Define $\bar{Z}_1=\bar{X}_1$ and, for $j>1$, define $\bar{Z}_j=\bar{X}_j-\sum_{i=1}^{j-1}\tau_{ij}\bar{Z}_i$. It is possible that, for a given j, we might find that $\tau_{(j-1)j}\bar{X}_{j-1}>\bar{X}_j$. That is, the level of pollution arriving from upstream when the standard is exactly met there exceeds zone j's standard even if $e_j=0$. In this case, zone j is called a *critical zone*. The TRS allocation scheme sets $\bar{Z}_j=0$ and, in turn, reduces the allocation of permits to the upstream zone (or, possibly more than one upstream zone) to the point at which zone j is no longer critical: $\bar{Z}_{j-1}=(\bar{X}_j/\tau_{(j-1)j})-\sum_{k=1}^{j-2}\tau_{kj-1}\bar{Z}_k$.

This allocation scheme ensures that the water-quality impacts of all upstream zonal standards on a given zone are accounted for via the upstream transfer coefficients. Note that in using the TRS procedure, the regulator takes as given the set of zones $\{i\}$, the zonal environmental standards $\bar{\mathbf{X}}$, and the transfer coefficients T. Each discharger is then allowed to trade freely in a watershed-wide permit market according to the transfer coefficients T, so long as its emissions do not exceed the permits it holds.

Formally, each source i solves:

$$\min_{r_{ki},r_{si},r_{sj}} \quad C_i(a_i)-p_i r_{si}+\sum_j p_j r_{ji}, \tag{4a}$$

$$\text{s.t.}\ \bar{Z}_i \geq (\bar{e}_i-r_{ki})-\sum_{j=1}^{i-1}\tau_{ji}r_{ji}, \tag{4b}$$

$$a_i=r_{ki}+r_{si}, \tag{4c}$$

$$r_{si}=\sum_{j=i+1}^{n} r_{ij}, \tag{4d}$$

$$r_{ki}, r_{si}, r_{sj} \geq 0, \tag{4e}$$

where p_i and p_j are the market prices of permits from sources i and j, r_{ji} is the amount of pollution control purchased from source j to offset pollution at source i, r_{ki} is the amount of pollution control from source i that is kept by source i to meet the zonal standard $\bar{Z}_i$, and r_{si} is the amount of pollution control sold by source i. As Hung and Shaw observe, the TRS possesses two advantages over earlier trading schemes. The first is that each discharger must participate in only a single watershed-wide permit market, so that transaction costs are low. (Contrast this feature with the ambient-permit system of *Montgomery* [1972], where each polluter must hold permits for each of the receptor markets it affects.) The second is that the regulator allocates initial zonal discharge permits $\bar{\mathbf{Z}}$ in such a way that the ambient environmental constraints $\bar{\mathbf{X}}$ are satisfied exactly at the initial allocation.

One can rewrite (4b) to obtain Hung and Shaw's trading constraint (their equation (5)):

$$e_i \leq \bar{Z}_i + \sum\nolimits_{j=1}^{i-1} \tau_{ji} r_{ji} - \sum\nolimits_{j=i+1}^{n} r_{ij}, \tag{5}$$

where r_{ij} is the net amount of zonal discharge permits sold by source i to source j. This constraint means that any discharger can buy permits only from upstream zones and sell permits only to downstream zones. Because sources can trade permits at exchange rates τ_{ij}, in any TRS equilibrium (including the boundary case), for any $j > i$, the two permit prices must satisfy

$$\tau_{ij} p_j = p_i. \tag{6}$$

The economic implications of this equality are substantial. If a high-cost source is located upstream of, or on a different branch from, a low-cost source, because $\tau_{ij} = 0$ for $i > j$ this constraint strictly prohibits trade between them even if the trade would reduce costs. This might seem justifiable at first on the grounds that water flows downstream, so that any downstream pollution reduction or a reduction on a different branch has no effect on the concentration at the upstream location. However, if damages are nonlinear the downstream marginal damages of pollution from the high-cost (upstream) source can be comparable to those of the low-cost (downstream) source. In this case, increased abatement by the low-cost source in exchange for decreased abatement by the high-cost source might be Pareto improving. But this trade is infeasible under the TRS because of its prohibition on cross-branch or upstream sales, and so the TRS can fail to achieve the least cost outcome. We shall return to this point in section 6 when presenting the results of our numerical work.

We now turn to the main result of this section. The question is whether the TRS equilibrium is guaranteed to achieve the cost-effective outcome $\mathbf{a}^{HS}$. Proposition 1 shows that the answer is no. There are situations, perhaps not unusual in actual practice, in which the outcome of the TRS is either indeterminate (the permit-allocation scheme breaks down) or not cost effective (it fails to solve program (1)). All proofs appear in Appendix A.

Proposition 1. *Consider a river system in which there exists a critical zone at the confluence of upstream branches. Then the TRS permit-allocation scheme is indeterminate. The TRS equilibrium is not guaranteed to achieve the cost-effective solution to program (1) unless the regulator knows the cost functions of at least some upstream sources.*

Proposition 1 implies that the TRS cannot always be relied upon to deliver the cost-effective outcome even if the ambient environmental constraints, the $\bar{\mathbf{X}}$, are set optimally. One might ask whether the given condition, in which a critical zone lies at a confluence of branches, is likely to be met in practice. We believe it is not at all unusual. In a branching river, confluence zone m is critical if $\sum\nolimits_{m-1_i} \tau_{(m-1_i)m} \bar{X}_{m-1_i} > \bar{X}_m$, where $\{m-1_i\}_i$ is the collection of indices directly upstream of zone m, along all contributing branches. Economic activity and population both tend to concentrate around the confluence of rivers. The water quality there is often important for both aquatic species and people living nearby. Thus, a zone of confluence might be more likely than others to be critical.

4. The Damage-denominated Trading-Ratio System (DTRS)

We turn now to an examination of the Farrow et al. DTRS. The fundamental regulatory constraint in the DTRS is a single limit on aggregate monetary damages, here denoted $\overline{\mathrm{TD}}$, rather than a set of physical environmental standards. Hung and Shaw's TRS is deeply concerned over hot spots, but, given the exogenous nature of the vector of standards, ignores damages. The DTRS, on the other hand, is deeply concerned over damages but is concerned with hot spots only to the extent that damages are high in some places along the river. The DTRS trading ratios are themselves based upon marginal damages, rather than upon physical transfer coefficients. Each source i's marginal damage d_i is calculated by integrating its contribution to monetary damages over that source's "zone of influence." Having calculated marginal damages for each source, the regulator distributes permits $\bar{L}_i$ (in terms of emissions at the point of discharge) in such a way that aggregate damages meet the overall monetary constraint at the initial allocation: $\sum_i d_i \bar{L}_i = \overline{\text{TD}}$. Trade is allowed between any two sources, but at the ratio of their marginal damages. The aggregate limit on damages will be satisfied in the face of any permissible trade at these ratios.

Given the vector **d** of marginal damages and a vector **e** of emissions, Farrow et al. (and also *Muller and Mendelsohn* [2009]) assume that aggregate damages are linear: $D(\mathbf{e}) = \sum_{i=1}^{n} d_i e_i$. It is this quantity that must not exceed $\overline{\text{TD}}$. The assumed linearity of the damage function means that each d_i is independent of emissions from other sources.

Each source i solves the following cost-minimization program:

$$\min_{r_{ki}, r_{si}, r_{sj}} \quad C_i(a_i) - p_i r_{si} + \sum_j p_j r_{ji}, \tag{7a}$$

$$\text{s.t. } (\bar{e}_i - r_{ki}) - \sum_j \frac{d_j}{d_i} r_{ji} \le \bar{L}_i, \tag{7b}$$

$$a_i = r_{ki} + r_{si}, \tag{7c}$$

$$r_{ki}, r_{si}, r_{sj} \ge 0, \tag{7d}$$

where p_i and p_j are the market prices for permits from sources i and j, r_{ji} is the amount of pollution control purchased from source j to offset pollution at source i, r_{ki} is the amount of pollution control from source i that is kept by that source to meet its emissions standard $\bar{L}_i$, and r_{si} is the amount of pollution control sold by source i.

Note that substituting $e_i = \bar{e}_i - a_i$ and $r_{ki} = a_i - r_{si}$ into (7b), one obtains an analog of (5), the Hung-Shaw trading constraint:

$$e_i \le \bar{L}_i + \sum_j \frac{d_j}{d_i} r_{ji} - r_{si}.$$

This constraint means that each source can trade with any other source, according to the marginal damage ratios, so long as the level of its discharge does not exceed the sum of the original discharge limits $\bar{L}_i$ and the net purchase of damage-denominated permits $\sum_j (d_j/d_i) r_{sj} - r_{si}$. Because sources can trade permits at the exchange rates d_j/d_i, the spatially explicit prices of permits in equilibrium (including the boundary case) satisfy the following analog of (6):

$$\frac{d_j}{d_i} p_j = p_i. \tag{8}$$

Note that unlike in the TRS, one can be sure that $d_i \ne 0$ in practice for all i: a source for which $d_i = 0$ would not be part of the trading system. Therefore, each source can trade with any other source, including those located upstream or downstream or on different branches of the river.

Farrow et al. derived the first-order necessary (and sufficient) conditions for each source's optimization problem, from which the following *interior* equilibrium condition is derived:

$$\frac{C'_i(a_i)}{C'_j(a_j)} = \frac{d_i}{d_j} = \frac{p_i}{p_j}. \tag{9}$$

In fact, in equilibrium the right equality in (9) (and therefore also (8)) must be satisfied for every pair i and j, not just those who actually trade. Unlimited arbitrage opportunities would arise if it were violated for any pair. To see this, note that if (8) does not hold, say, if $p_i/d_i > p_j/d_j$, then any source k who buys permits from j and sells them to i can secure such profits. But this cannot be an equilibrium with a finite supply of permits.

Take as given a vector of baseline emissions $\bar{\mathbf{e}}$, a vector of initial permits $\bar{\mathbf{L}}$, and a vector of trading ratios $\mathbf{d}$. The complete characterization of the Farrow et al. equilibrium conditions is given in (10a)–(11c). These expressions, which we use in our numerical example, are stated for completeness. Thus, we provide only a sketch of their derivation. The first set, equations (10a)–(10c), characterize an *interior* equilibrium. Letting $R_i(p_i)$ denote i's abatement decision function given p_i, we have

$$a_i^* = R_i(p_i^*), \tag{10a}$$

$$\sum\nolimits_i d_i\left[\bar{e}_i - R_i(p_i^*) - \bar{L}_i\right] = 0, \tag{10b}$$

$$\frac{p_i^*}{d_i} = \frac{p_j^*}{d_j} \quad \text{for all } i, j. \tag{10c}$$

Equation (10c), which like the right equality in (9) serves as a no-arbitrage condition, ensures that each source i faces the same effective price in all zonal markets j: $p_i = p_j(d_i/d_j)$. Source i is therefore indifferent from which sources it buys permits or to which sources it sells. It follows that source i abates such that $C'_i(a_i) = p_i$. Because $C'_i(a_i)$ is strictly increasing, the interior optimal abatement a_i^* is unique. Thus, $p_i = p_j(d_i/d_j)$ for all j.

Equations (11a)–(11c) characterize the vector of equilibrium traded quantities, $\left\{ r_{ki}^*, r_{si}^*, \sum_j \frac{d_j}{d_i} r_{ji}^* \right\}_{i,j}$, while accounting for the relevant corners:

$$r_{ki}^* = \begin{cases} \bar{L}_i & \text{if } \bar{e}_i - R_i(p_i^*) \le \bar{L}_i \\ 0 & \text{if } \bar{e}_i - R_i(p_i^*) > \bar{L}_i \end{cases}, \tag{11a}$$

$$r_{si}^* = \begin{cases} \bar{L}_i - \bar{e}_i + R_i(p_i^*) & \text{if } \bar{e}_i - R_i(p_i^*) \le \bar{L}_i \\ 0 & \text{if } \bar{e}_i - R_i(p_i^*) > \bar{L}_i \end{cases}, \tag{11b}$$

$$\sum\nolimits_j \frac{d_j}{d_i} r_{ji}^* = \begin{cases} 0 & \text{if } \bar{e}_i - R_i(p_i^*) \le \bar{L}_i \\ \bar{e}_i - R_i(p_i^*) - \bar{L}_i & \text{if } \bar{e}_i - R_i(p_i^*) > \bar{L}_i \end{cases}, \tag{11c}$$

Source i's excess demand function may be obtained as follows. Given p_i, source i would choose abatement R_i so that $C'_i = p_i$. Thus, R_i is a well-defined function. The excess demand for permits from source i is $z_i(p_i; \bar{e}_i, \bar{L}_i) = \bar{e}_i - R_i(p_i) - \bar{L}_i$. If $z_i > 0$, then i must buy permits. If $z_i < 0$, it sells its excess permits. All permits sold to and purchased from i must be exchanged at the ratio d_i/d_j with permits from any source j. This means that the common units of exchange are $d_i z_i$, and so the market clears in equilibrium if equations (10a)–(11c) hold. For a given vector $\{\bar{e}_i, \bar{L}_i, d_i\}_i$ and n sources, this gives us n equations in n unknown prices $\{p_i^*\}_i$. Thus, the equilibrium is exactly identified.

This characterization of market equilibrium turns out to be useful for the simulations in section 6. There may be nontrivial boundary equilibria in which $a_i^* = 0$ or $a_i^* = \bar{e}_i$. These boundary cases can be dealt with by defining $R_i(p_i^*) = 0$ if $C'_i(a_i) > p_i^*$ for all $a_i \in [0, \bar{e}_i]$ and $R_i(p_i^*) = \bar{e}_i$ if $C'_i(a_i) < p_i^*$ for all $a_i \in [0, \bar{e}_i]$. The rest of the equilibrium conditions are intact.

Our next result is analogous to Proposition 1. The question is whether the DTRS equilibrium is guaranteed to achieve the solution to program (2) if damages are nonlinear. Proposition 2 shows that the answer is no.

Proposition 2. *Suppose that aggregate environmental damages are a nonlinear function of pollution concentration, so that at the cost-effective solution* $\mathbf{e}^{\text{FSCH}}$ *we have*

$$D(\mathbf{e}^{\text{FSCH}}) \neq \sum\nolimits_i \frac{\partial D(\mathbf{e}^{\text{FSCH}})}{\partial e_i} e_i^{\text{FSCH}}.$$

Then the DTRS equilibrium does not achieve the cost-effective solution to program (2), even if the d_i *are evaluated at the optimum.*

Because Farrow et al.'s system assumes linear damages, the result that the DTRS breaks down in the face of nonlinear damages is perhaps not surprising, though it has not evidently been noted before. More surprising is that with nonlinear damages the DTRS fails to achieve the cost-effective solution even if the regulator evaluates the trading ratios at the efficient allocation. The DTRS equilibrium can get not only the price ratios, but also the aggregate market-clearing condition, wrong. Whether this is significant in practice is an empirical question.

As is evident from the proof, the difficulty with the DTRS stems from the fact that the initial allocation of permits follows Farrow et al.'s original allocation rule (A1). A natural question arises: what would happen if one were to use a different allocation rule? For example, the regulator could allocate permits so that $D(\bar{L}_1,\ldots,\bar{L}_n)=\overline{\mathrm{TD}}$. Here one encounters an insuperable difficulty: there is no allocation rule the regulator could rely upon in this case. Indeed, the problem is similar to that of the TRS. To see this, suppose that the regulator agreed upon the desired level of aggregate damage, $\overline{\mathrm{TD}}$. Because the damage function is nonlinear, there will inevitably exist many vectors $\bar{\mathbf{L}}$ such that $D(\bar{L}_1,\ldots,\bar{L}_n)=\overline{\mathrm{TD}}$. The regulator's problem is indeterminate. (Recall that D is the composition function $D(\mathbf{e})=S(T\mathbf{e})$.)

In the following section, we investigate how the TRS and DTRS perform, relative to the efficient solution as well as to each other, if the initial allocation of permits follows such a rule.

5. Equilibrium Comparisons

Given the performance of the TRS and the DTRS, respectively, in the face of branching and nonlinear damages, a natural question is whether it is possible to say which of the two is preferred, based either on theoretical arguments or on empirical evidence. In this section, we explore this question theoretically, always bearing in mind that empirical considerations in any given situation will likely be decisive.

The comparative question really does matter, for at least two reasons. One is that, as we have shown, the initial allocation of zonal standards under the TRS is indeterminate in the presence of branching. The initial allocation of permits under the DTRS is indeterminate in the presence of nonlinear damages. One would like to know whether either of these difficulties is cause for concern and, if so, which is the greater. The other is that the informational requirements in applying the two schemes might appear to be different: the DTRS incorporates information on damages while the TRS does not. We will see that, in fact, the information needed to deploy either scheme is the same.

Proposition 3 shows how the TRS and the DTRS can both be derived directly from the efficient program found in (3). Thus, the two alternatives can be compared on the same efficiency grounds within our framework.

Proposition 3. *Under the conditions imposed upon the C_i and D, the following are true:*

1. *Given the efficient solution $\mathbf{a}^{\mathrm{eff}}$, there exists a constraint vector $\bar{\mathbf{X}}^{\mathrm{eff}}$ in terms of pollution concentrations such that the solution $\mathbf{a}^{\mathrm{HS}}$ to program (1) subject to $\bar{\mathbf{X}}^{\mathrm{eff}}$ is the optimal solution $\mathbf{a}^{\mathrm{eff}}$; and*
2. *Given the efficient solution $\mathbf{a}^{\mathrm{eff}}$, there exists a constraint value $\overline{\mathrm{TD}}^{\mathrm{eff}}$ in terms of total damages such that the solution $\mathbf{a}^{\mathrm{FSCH}}$ to program (2) subject to $\overline{\mathrm{TD}}^{\mathrm{eff}}$ is the optimal solution $\mathbf{a}^{\mathrm{eff}}$.*

Proposition 3 establishes the practical equivalence of the two cost-effective programs in a situation in which the regulator has perfect knowledge of T and D. (Note that in order to achieve the social optimum the by either system, the regulator must also know the $C_i(a_i)$.) In that case, it does not matter whether the policy is constrained by $\bar{\mathbf{X}}$ or by $\overline{\mathrm{TD}}$. Suppose, though, that the regulator has imperfect information on one of these elements. Even if there is no branching and damages are linear, the informational requirements of the two trading mechanisms are quite different. A regulator wishing to implement the TRS must estimate the transfer coefficients in T while a regulator wishing to implement the DTRS must estimate the damage coefficients, the d_i. Thus, for our comparative work, we must define the requisite policy choice for a regulator who wishes to achieve $\mathbf{e}^{\mathrm{eff}}$ in each system. Under the TRS, the regulator must select zonal environmental standards at the efficient levels: $\bar{\mathbf{X}}^{FB}=T\mathbf{e}^{\mathrm{eff}}$. Under the DTRS, the regulator must constrain total damages at the efficient level: $\overline{\mathrm{TD}}^{FB}=D(\mathbf{e}^{\mathrm{eff}})$. Let us call any distribution of permits consistent with $\bar{\mathbf{X}}^{FB}$ under the TRS, or $\overline{\mathrm{TD}}^{FB}$ under the DTRS, the "first-best" allocation.

Given our Proposition 3, we shall employ the following criterion for judging which of the two schemes outperforms the other.

Definition 1. Given two feasible abatement vectors $\mathbf{a}$ and $\mathbf{a}^{'}$, say that $\mathbf{a}$ is **at least as efficient as $\mathbf{a}'$** if $\sum_i C_i(a_i)+D(\bar{\mathbf{e}}-\mathbf{a}) \leq \sum_i C_i(a^{'}_i)+D(\bar{\mathbf{e}}-\mathbf{a}^{'})$.

To prepare for our final results, we first establish that the TRS equilibrium achieves the efficient outcome, if it achieves it at all, *with no trade*. To see this, consider a branchless river system. Note that as in the proof of Proposition 3, the efficient environmental constraints are found by setting $\bar{\mathbf{X}}^{\text{eff}}=T(\bar{\mathbf{e}}-\mathbf{a}^{\text{eff}})$. Then as Hung and Shaw show, in a branchless river the constraint set arising from $\bar{\mathbf{Z}}$ is equivalent to that arising from $\bar{\mathbf{X}}^{\text{eff}}$ and the TRS equilibrium achieves the cost-effective outcome. But because the cost-effective outcome must coincide with the efficient outcome, which also coincides with the initial allocation, and because it is assumed that there is only one discharger in each zone, this implies that discharging pollution so as to satisfy $\bar{\mathbf{Z}}$ exactly, without engaging in any trade, is also cost-minimizing. Put another way, the regulator cannot implement the efficient optimum in a decentralized manner. This claim, whose proof is obvious and so is omitted, is stated in the following result.

Proposition 4. *Suppose that in program (1), the zonal environmental constraints $\bar{\mathbf{X}}$ are set at the efficient levels and that there is only one discharger in each zone. Then if the TRS trading achieves the cost-effective optimum of program (1), it is achieved with no trade.*

The next result follows in a straightforward manner from Propositions 1, 2, and 3, and so the proof is omitted.

Proposition 5. *Suppose the regulator allocates permits in the first-best manner. Then the following are true:*

1. *If the watershed is characterized by a branchless river but a nonlinear damage function S, the equilibrium under the TRS scheme is at least as efficient as that under the DTRS scheme.*
2. *If the watershed is characterized by a branching river but a linear damage function S, the equilibrium under the DTRS scheme is at least as efficient as that under the TRS scheme.*

This result may come as a surprise. Why can the DTRS not outperform the TRS when environmental damages are nonlinear, even though the DTRS incorporates some information about variation in marginal damages whereas the TRS does not? The answer is precisely that when the regulatory benchmark is the efficient outcome, the regulator *must* commit herself to an initial allocation of permits that meets the constraints $\bar{\mathbf{X}}^{FB}$ (for the TRS) or $\overline{\text{TD}}^{FB}$ (for the DTRS). The difficulty with the DTRS when damages are nonlinear is with the dependence of the d_i's upon the entire vector of emissions. The price signals offered by the physical transfer coefficients under the TRS, which are independent of abatement decisions, are consistent with the first-best outcome. The price signals offered by the variable damage coefficients, the $d^{'}_i$, are not.

In practice, even a perfectly informed regulator might face informational or political constraints that drive the allocation of permits away from the first-best allocation. Selecting a useful criterion for comparison becomes more difficult in this case. The reason is that, as may be seen in (A3), when damages are nonlinear it can be the case that the realized damages at a DTRS equilibrium actually exceed the constraint value of $\overline{\text{TD}}$ that generated the permit allocation. Thus, just how one chooses the appropriate "second-best" standards, $\bar{\mathbf{X}}^{SB}$ or $\overline{\text{TD}}^{SB}$, so as to allow a legitimate comparison between the TRS outcome and the DTRS outcome is not at all obvious. The TRS equilibrium is sure to produce the desired level of damages, but the DTRS equilibrium is not.

A reasonable alternative might be to compare equilibria *given an initial allocation of permits*. Assuming that there is one discharger in each zone, and that $\tau_{ii}=1$ for all i as in section 3, specifying the initial allocation in terms of zonal standards $\bar{\mathbf{X}}$ under the TRS is equivalent to specifying the initial allocation $\bar{\mathbf{L}}$ under the DTRS. Permits would then be allocated at $\bar{\mathbf{X}}^{SB}=\bar{\mathbf{L}}^{SB}$ so that

$$S(\bar{\mathbf{X}}^{SB})=D(\bar{\mathbf{L}}^{SB}) \neq D(\mathbf{e}^{\text{eff}}).$$

In this case, we would be comparing the performance of the two trading systems relative to a no-trading baseline. The following result offers some evidence that the comparison leans more in favor of the DTRS than the TRS.

Proposition 6. *Suppose the regulator allocates permits in a second-best manner. Then the following are true:*

1. *If the watershed is characterized by a branchless river but a nonlinear damage function S, the equilibrium under the DTRS scheme can be more efficient than that under the TRS scheme; and*
2. *If the watershed is characterized by a branching river but a linear damage function S, the equilibrium under the DTRS scheme is no less efficient than that under the TRS scheme.*

A caveat is in order. One may be tempted to interpret this result as saying that the DTRS dominates the TRS under this second-best condition. However, that interpretation could be misleading. First, it seems implausible that the regulator would be able to choose d_i's with sufficient accuracy to ensure that equation (A4) are satisfied. Second, many river systems are likely to be characterized by *both* branching and nonlinear damages. We need to examine the relative performance of the two systems when both properties are present. The following section uses a numerical model to explore this question.

6. A Numerical Model

In this section, we develop and solve a small numerical model aimed at providing an answer to this question: which of the systems, TRS or DTRS, performs better, relative to each other and to the efficient outcome, when river systems are characterized by both branching and nonlinear damages? Our answer comes in two forms. One is that neither system dominates, and that which performs better depends on the distribution of firms' abatement costs. The other is that even in the presence of both branching and nonlinear damages the TRS and the DTRS perform well so long as the total quantity of permits issued is close to the optimal level. Getting prices right (that is, setting the correct trading ratios) is much less important than getting the quantity right.

For purposes of this numerical exercise, we suppose that a regulator knows the damages caused by water pollution. She also knows enough of the science to be able to specify the transfer coefficients correctly. The regulator is imperfectly informed about abatement cost functions, however, and so cannot compute the socially optimal vector of emissions. Put another way, our regulator is unable to set either $\bar{\mathbf{X}}$ (for the TRS) or $\overline{\mathrm{TD}}$ (for the DTRS) at the efficient levels. We start out, though, by giving our regulator a helpful nudge. That is, we set the total number of permits equal to the socially optimal level. Any divergence between the social optimum and the outcomes of the TRS or the DTRS, then, cannot be due to getting the quantity of permits wrong. It must be because the trading schemes provide incorrect price incentives. At the end of the section, we consider the added inefficiency that results from an incorrect quantity of permits.

The details of our numerical model are adapted from the *U.S. Environmental Protection Agency (U.S. EPA)*'s [2002] tool for modeling water-quality impacts, the NWPCAM, which is also the basis for the empirical application in *Farrow et al*. [2005]. Let x_{mi} be source *i*'s contribution to the pollution concentration at location *m* downstream. Then x_{mi} is a function of the emissions e_i at source *i*, stream flow *Q*, and an exponential decay term:

$$x_{mi} = \frac{e_i}{Q} \exp\left(-\hat{k}\,\delta_{mi}\right), \tag{12}$$

with $x_{mi}=0$ if *m* is upstream of *i*. In (12), which simplifies the Farrow et al. version slightly, $\hat{k}$ is the decay parameter and δ_{mi} is distance in river miles. The pollution concentration at location *m* is the sum of contributions from all upstream sources: $x_m = \sum_i x_{mi}$. This model can incorporate branching in the river. If two sources, *i* and *j*, are located along two different branches upstream of a confluence, the impacts of emissions from *i* and *j* on concentrations at location *k* below the confluence are simply x_{ki} and x_{kj}. In this framework, the effect of changes in concentration at location *i* on concentration at any downstream location *j* is linear:

$$\tau_{ij} \stackrel{def}{=} \frac{dx_j}{dx_i} = \exp\left(-\hat{k}\,\delta_{ij}\right), \tag{13}$$

where the τ_{ij} are the transfer coefficients.

In order for our model to capture the effects of interest, it must be able to accommodate both nonlinear damages and critical zones where branching occurs. The latter is straightforward, but the specific form of nonlinearity is crucial and requires a bit of explanation. Consider first the linear specification of damages found in Farrow et al., who assumed that marginal damages are constant at each location:

$\partial D/\partial x_m = \text{WTP} \times H_m$, where WTP is the constant per-capita marginal damages from changes in water quality and H_m is the population at location m. According to this specification, damages from each source's emissions are given by $D_i(e_i) = d_i e_i$, where d_i is constant and independent of e_i:

$$d_i = \sum_{m=1}^{M} \text{WTP} \times H_m \times \tau_{mi} \times \frac{1}{Q}.$$

To justify the constant marginal willingness to pay (WTP), *Farrow et al*. [2005, p. 197] argue that water quality is inversely related to pollution concentrations and that "the household marginal willingness to pay for a small improvement in water quality, WTP, is constant . . . over the range of water-quality conditions considered in this study."

Linearity may often be a reasonable assumption, but we argue that there are important cases where it is not. One source of nonlinearity is curvature in the biology or chemistry of aquatic systems. The relevant science, including that for fish and for algae, indicates that the underlying biology can be nonlinear as a function of water quality [see *Elliott*, 2000; *Schnoor*, 1996; *Anderson et al*., 2002]. In such cases, economic damages may be expected to be nonlinear too.

The effect of thresholds can also be important. In many watersheds in the U.S., water quality is already impaired, so that a further increase in pollution concentrations might drive conditions above a particular concentration threshold. Indeed, our communications with water practitioners and policymakers reveal that their primary concern is often related to this nonlinear biological response around hot spots. This concern is one of the important political factors that has plagued water-quality trading in many watersheds. Understanding how a trading scheme performs in the face of nonlinearity, we argue, is essential.

To model the nonlinear biological responses that allow for the type of threshold effects highlighted above, we consider a logistic damage response to pollution concentrations at each location m:

$$S_m(x_m) = \frac{b}{1+\exp\left(-a(x_m - c)\right)} \quad \text{for all } m = 1, \ldots, M, \tag{14}$$

where a is a damage-sensitivity parameter, b a scale parameter, and c a concentration threshold. The total economic damages are then given by $D(\mathbf{e}) = \sum_m S_m(x_m)$. Logistic models are commonly used in biology and ecology for modeling the response of species' mortality or population size to pollution. Though in biology, the parameters a and c often depend on a variety of environmental factors, for simplicity of analysis we treat them as constants that do not vary by time or location. The parameter b is a scaling parameter that transforms biological damages into monetary economic damages, which we also assume are constant. With these assumptions, marginal aggregate damages with respect to emissions from any source i depend not only upon emissions from that source but also upon emissions from other sources, both downstream and upstream of i (that is, $\partial D/\partial e_i = \sum_m (\partial S_m/\partial x_m)(\partial x_m/\partial e_i)$). When there is a branch in a river system, marginal damages also depend on the emissions from sources located along the other branches.

The parameter values of the model can vary widely by pollutant and watershed. Because our goal is to obtain generic efficiency properties of the two trading systems, we decided to choose representative parameter values for the water-quality model (12) and then choose a set of parameters a, b, and c that generate interior optima for at least two out of three sources given the assumed cost parameters (see below). The value of $\hat{k} = 0.005$ is chosen based on three parameters: the mean of the decay rates for seven representative water pollutants [*U.S. EPA*, 2002], the average water temperature of 20°C, and the stream velocity of 1.5 miles/h. The scale parameter b and the threshold parameter c are important in generating interior solutions. We thus started with arbitrary values $a = 5$ and $c = 5$ and then searched for the associated value of b. The parameters used for the simulation are summarized in Table 1.

6.1. Simulation Scenarios

We assume that the river has a main stem M and a single branch B. The river has a maximum length of 200 river miles along the main stem ($m^M \in [0, 200]$) and 50 river miles along the branch ($m^B \in [0, 50]$) above a confluence at $m^M = 100$ (or at $m^B = 50$). There are three polluting sources. Source 1 is located in the most upstream point of the main stem ($m^M = 0$), source 2 at the confluence ($m^M = 100$ or $m^B = 50$), and source 3 at the most upstream point of the branch (see Figure 1). There is one pollution source i in each

Table 1. Parameters for Water-Quality Model

	Parameter	Units	Value
k	Decay rate	$mile^{-1}$	0.005
Q	Stream flow	ft^3/s	10
a	Damage parameter	None	5
b	Damage-scale parameter	None	6.7
c	Concentration threshold	mg/L	5

zone i, as in *Hung and Shaw* [2005]. Thus there are three zones, each zone facing zonal environmental standard $\bar{X}_i$ and receiving zonal permits $\bar{Z}_i = \bar{L}_i$. The firms have quadratic abatement cost functions of the form

$$C_i(a_i) = \frac{a_i^2}{\alpha_i}, \tag{15}$$

with $a_i \in [0, \bar{e}_i]$ and $\alpha_i > 0$.

Given the transfer coefficients as in (13), the damage function in (14), and the cost functions in (15), we first compute the socially optimal vector of emissions, $\mathbf{e}^{\text{eff}}$. Again, our regulator does not know cost functions, and so cannot solve for this optimum. A fair comparison of outcomes of the TRS and the DTRS to the optimum, though, requires that we set the total number of permits at the optimal level. The optimal total is then allocated equally across the three sources: $\bar{L}_1 = \bar{L}_2 = \bar{L}_3 = \sum e_i^{\text{eff}}/3$. This choice of an initial allocation is only one of an infinite number of possibilities, but it has the advantage of reflecting equal required reductions in the absence of trade.

Under the TRS, this means that zonal environmental standards, the $\bar{X}$'s, are allocated so that

$$\bar{X}_1 = \bar{L}_1, \quad \bar{X}_3 = \bar{L}_3, \quad \text{and} \quad \bar{X}_2 = \bar{L}_2 + \tau_{12}\bar{X}_1 + \tau_{32}\bar{X}_3.$$

We chose this allocation rule for two reasons. The first is that we are interested in the relative performance of the two trading systems under conditions that can be compared to the social optimum. The second is that, were we instead to allocate permits so as to ensure that water quality is equal in all zones, by design we would have a critical zone at confluence zone 2. This would mean in turn that the problem of indeterminate allocation would arise (see Proposition 1).

Under the TRS, the correct transfer coefficients are known to the regulator and are announced to the polluters. Under the DTRS, the regulator does not know the social optimum, and so she evaluates the d_i's at the initial allocation. In each of these setups, we simulate the trading outcomes for two sets of cost parameters:

$$\text{Case A}: \quad \alpha_1 = 7.5, \quad \alpha_2 = 15, \quad \alpha_3 = 7.5 \quad \text{and}$$
$$\text{Case B}: \quad \alpha_1 = 15.0, \quad \alpha_2 = 7.5, \quad \alpha_3 = 15.0.$$

For each case, we also compute the social costs at the initial allocation of permits, as the no-trading baseline. These two cases represent only a fraction of the infinity of possible arrangements, but they do provide some useful insights.

6.2. Simulation Results

Case A. In this case, a low-cost firm is located downstream of two high-cost firms. At the socially optimal outcome, the low-cost firm (source 2) abates completely while source 1 emits more than source 3 even though they have the same marginal costs and the same baseline emissions (Table 2). This occurs because marginal damages at the optimum increase more in source 3's emissions than in source 1's emissions. Recall that the TRS mechanism precludes upstream sales and trade across branches. Because the potential seller (the low-cost firm 2) is located downstream, that source cannot trade at all. Moreover, the socially optimal trade between the two upstream firms is also precluded. As a result, firms incur higher abatement costs under the TRS than at the optimal outcome. On the other hand, the DTRS does allow trades among any of the three sources. Because of this, the DTRS performs substantially better than the TRS (and therefore, the no-trading baseline).

A difficulty with the DTRS, however, is that in our simulation the d_i do not appear to be good approximations to the assumed marginal damages at the optimum. This point is demonstrated in Figure 2, which plots marginal damages as a function of each source's emissions, holding other sources' emissions at the optimum. Figure 2 also shows each source's marginal cost and trading coefficient. The social optimum occurs where each firm's marginal damages are equated with its marginal cost and the overall constraint is satisfied. Interestingly, the equilibrium does not occur where each source's marginal cost equals its trading coefficient d_i. This is because each source makes its abatement and trading decisions so that its marginal cost equals the spatially explicit price it faces, $p_i = (d_j/d_i)p_j$. Thus, when the d_i's do not closely approximate actual

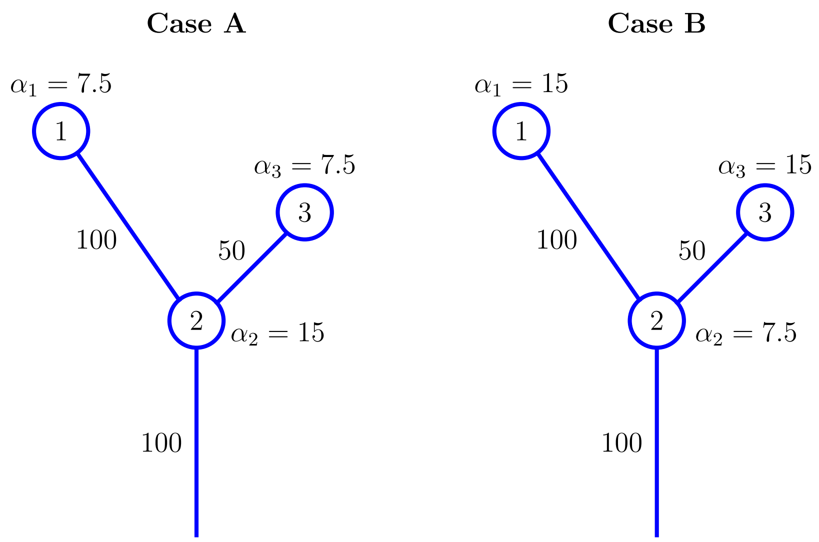

Figure 1. Hypothetical river system.

marginal damages, the trading outcome under DTRS may not equate marginal damages with marginal costs. In actual practice, of course, it might be true that damages are nearly linear, so that the DTRS is more nearly optimal than in our example.

Note also that in the DTRS equilibrium the sum of emissions can exceed the sum of initial emissions permits: $\sum e_i^{\mathrm{DTRS}} > \sum e_i^{\mathrm{eff}}$. This is because neither the individual polluters nor the equilibrium market-clearing condition are constrained by $\sum e_i^{\mathrm{DTRS}} \leq \sum e_i^{\mathrm{eff}}$. In the DTRS, the common unit of exchange is $d_i e_i$ rather than e_i itself. Thus, the discipline imposed on the equilibrium is that $\sum d_i e_i^{\mathrm{DTRS}} \leq \sum d_i \bar{L}_i$. Because sources can emit more than the socially optimal total, environmental damages are higher, but abatement costs are lower, at the DTRS equilibrium than at the social optimum. Lastly, note that Figure 2 illustrates that with nonlinear damages the first-order conditions are not sufficient. In the top right plot, we see that the marginal damage curve for source 3 crosses its marginal cost curve twice. Also, though not plotted, each source has infinitely many marginal damage curves corresponding to different emissions levels by other sources.

Case B. In this case, a high-cost firm is located downstream of two low-cost firms. At the social optimum, source 3 abates all of its emissions while source 2 emits the most (Table 2). Efficient trades should occur under the TRS, because this system allows the high-cost downstream source to buy permits from the two low-cost upstream sources. Indeed, this is exactly what happened in the simulation. Each firm is allocated 18.5 units of discharge permits initially in both the TRS and the DTRS. In the TRS equilibrium, firm 2 bought 14.4 units from source 3 to increase its emissions to 32.9 while firm 3 sold 18.5 units at the trading ratio $\tau_{32} \approx 0.78$ (i.e., $18.5 \times \tau_{32} = 14.4$ units for source 2). Note that under the TRS, the downstream firm has a choice of buying permits from either source 1 or source 3. Therefore, source 2 buys from the partner with the lowest effective permit price.

It follows then that the effective equilibrium prices are equalized across space: $p_1 = \tau_{12} p_2 = \tau_{32} p_2 = p_3$. At this equilibrium price, source 1 has no incentive to sell its permits to source 2 and thus ends up emitting exactly at the initial allocation. The trading outcome in the DTRS is similar. Source 3 abates completely and sells its permits mostly to source 2. A difference occurs, though, because source 3 also sells its permits to source 1. As we have noted, under the DTRS firms located in different branches are allowed to trade, and the equilibrium prices satisfy $p_1 = (d_1/d_2) p_2 = (d_1/d_3) p_3$. It turns out that at these equilibrium prices, it is cheaper for source 1 to buy permits

Table 2. Simulation Results

	Outcome	e_1	e_2	e_3	Damage	Cost	Total
Case A							
	No trade	23.7	23.7	23.7	511	1942	2454
	TRS	23.7	23.7	23.7	511	1942	2454
	DTRS	48.9	0.0	34.4	530	1589	2119
	Optimum	42.0	0.0	29.0	60	1787	1848
Case B							
	No trade	18.5	18.5	18.5	10	1771	1782
	TRS	18.5	32.0	0.0	10	1710	1720
	DTRS	20.5	31.4	0.0	9	1716	1725
	Optimum	21.0	34.5	0.0	42	1655	1697

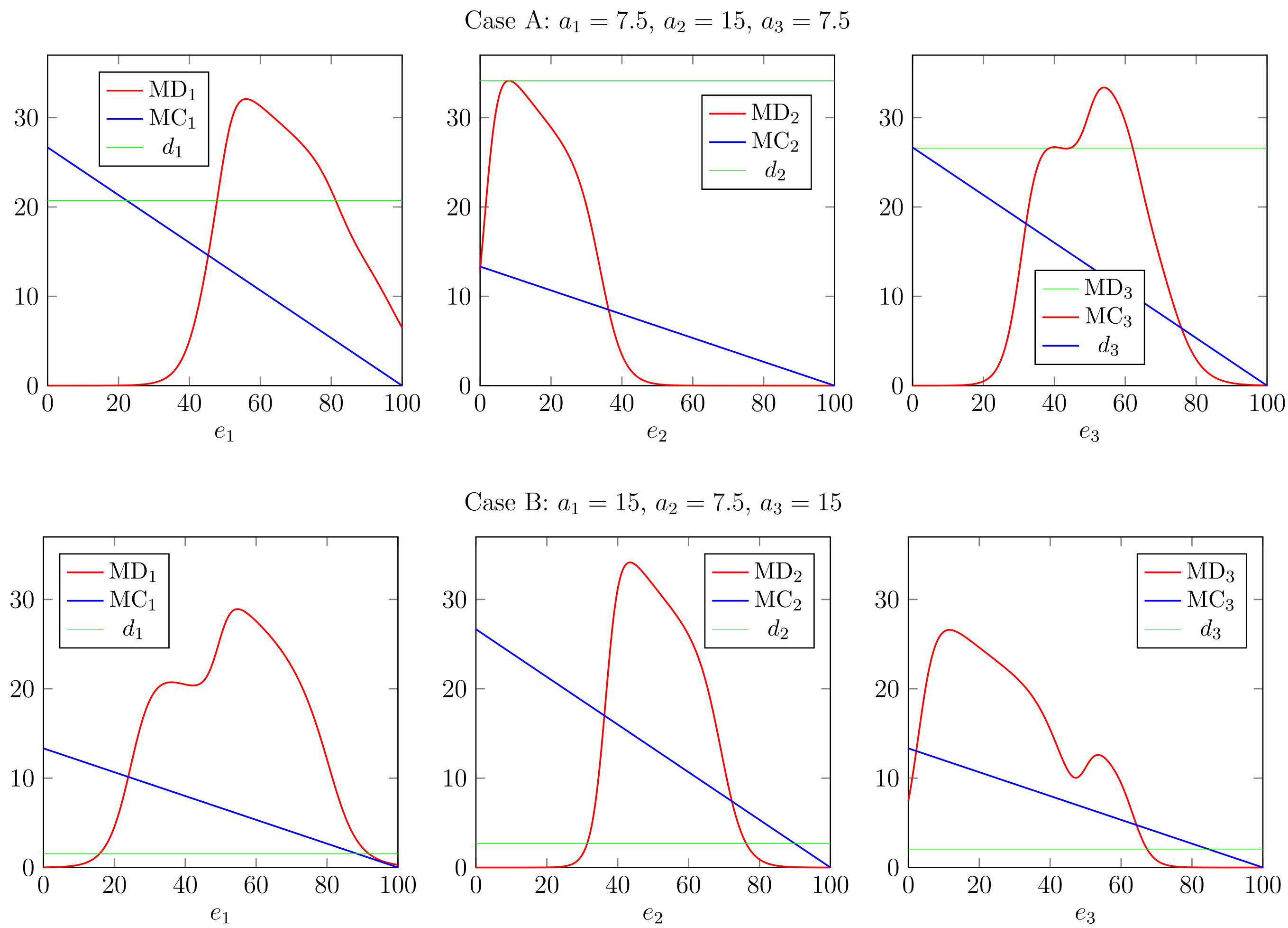

Figure 2. Marginal damages, marginal costs, and trading coefficients. Top plots: Case A ($a_1 = 7.5$, $a_2 = 15$, $a_3 = 7.5$). Bottom plots: Case B ($a_1 = 15$, $a_2 = 7.5$, $a_3 = 15$). Horizontal axis measures emissions for each source, with other sources' emissions held at the efficient levels.

from source 3. As a result, source 1's equilibrium emissions are slightly higher under the DTRS than under the TRS while source 2's equilibrium emissions are lower under the DTRS than under the TRS. The extra trade between source 1 and source 3, however, decreased efficiency slightly compared to the TRS equilibrium. This is because the damage-denominated trading coefficients, the d_i's, are poor approximations of the true marginal damages at the optimum, as shown in Figure 2. In this case, therefore, the DTRS encouraged inefficient trades. Note, however, that both TRS and DTRS reduce deadweight loss relative to the no-trading baseline, and closely approximate the social optimum in this case.

6.3. Prices Versus Quantities

On one hand, our numerical analysis suggests the impossibility of getting prices right in watersheds with branches and nonlinearities that significantly influence marginal damages. Neither the TRS nor the DTRS succeeds in providing the correct price signals. On the other hand, our analysis also indicates that in some cases the equilibria approximate the social optimum quite closely. We obtained these results by setting the total supply of permits equal to the socially optimal level. A natural question then is, which causes the greater efficiency loss: not getting the quantity of permits right, or not getting the price of permits right? We investigate this question by simulating the trading outcomes for varying levels of the total supply of permits (in percentage reduction from the baseline discharge level) and again allocating permits in equal number to each discharger.

In order to make the relevant comparison, we compute two measures of efficiency loss. Let $\mathbf{a}^T(A)$ denote the equilibrium abatement vector that emerges under trading scheme T, which can be either the TRS or the

DTRS. In either case, the equilibrium is subject to the constraint that $\sum \bar{L}_i = A$ for some value A. The first measure is efficiency loss when the quantity of permits is correct, that is, equal to the sum of efficient emissions levels. It is given by

$$L_T^{\text{eff}} = \frac{[C(\mathbf{a}^T(\sum e_i^{\text{eff}})) + D(\mathbf{a}^T(\sum e_i^{\text{eff}}))] - [C(\mathbf{a}^{\text{eff}}) + D(\mathbf{a}^{\text{eff}})]}{[C(\mathbf{a}^{\text{eff}}) + D(\mathbf{a}^{\text{eff}})]}. \tag{16}$$

The first term in the numerator is social cost after trading when the total number of permits is equal to the efficient level of total emissions. The denominator is social cost at the efficient outcome.

The second measure is the maximum efficiency loss due to misspecifying the total supply of permits, which is given by

$$L_T^{\max} = \max_{0 \le A \le \sum_i \bar{e}_i} \frac{[C(\mathbf{a}^T(A)) + D(\mathbf{a}^T(A))] - [C(\mathbf{a}^{\text{eff}}) + D(\mathbf{a}^{\text{eff}})]}{[C(\mathbf{a}^{\text{eff}}) + D(\mathbf{a}^{\text{eff}})]}. \tag{17}$$

The results are shown in Figure 3, where the dashed light blue line in the rightmost plots is drawn at the minimum of $C+D$. The monetary value corresponds to the efficient level of aggregate emissions, in both cases about 80% of the initial total. First, the relative performance of the two systems varies, in an unsystematic way, with the supply of permits. In Case A, where a low-cost source is located downstream of two high-cost sources, the DTRS performed substantially better than TRS when the total supply of permits was kept to the socially optimal level. This is because the TRS prohibited any trade from taking place. (The curves with no trading coincide with the TRS curves in Case A.) However, when the total supply of permits is reduced to 60–70% of the baseline discharge level, the TRS performs better than the DTRS despite the fact that no trading still takes place under the TRS. This occurs because the efficiency loss due to the TRS precluding trading was outweighed by the efficiency loss due to the DTRS encouraging inefficient trades, which increased environmental damages substantially relative to no trade.

In contrast, in Case B, in which a high-cost source is located downstream of two low-cost sources, the DTRS performed slightly better than the TRS for all levels of initial permit supplies. In this case, TRS and DTRS provide similar price signals so that the magnitude of the efficiency loss due to environmental damages is similar between the two systems (see the left plot of Case B in Figure 3). However, because the DTRS offers more flexibility in trading, it reduces abatement costs a bit more than does the TRS. This effect dominates the relative performance of the two systems.

Second, total economic costs $C+D$ do not exhibit a simple convex relationship with respect to the total supply of permits under the two systems. This is because neither environmental damages nor abatement cost has a simple relationship to the supply of permits. Despite the fact that environmental damages are defined as a decreasing function of emissions or pollution concentrations, environmental damages in the trading equilibrium are not necessarily a decreasing function of the *reduction in the total supply of permits*, and analogously, despite the fact that abatement costs are a convex function of *abatement levels*, total abatement costs are not necessarily a convex function of the *reduction in the total supply of permits*. These effects are especially strong in the DTRS, because the damage-denominated trading coefficients are based on marginal damages at the initial allocation, and thus depend endogenously on the initial supply of permits. Somewhat counter-intuitively, these trading coefficients can either decrease or increase efficiency relative to the TRS. On one hand, the trading coefficient can decrease efficiency by providing incorrect trading margins, which adversely affects environmental damages. On the other hand, however, the trading coefficients can improve efficiency by providing flexibility for trading partners, which reduces abatement costs.

Lastly, at least in the current model, getting the quantity of permits right appears to be more important than getting the prices of permits right. In Case A, the estimated efficiency losses, computed according to equation (17), are only 18.2% and 0.1% of the total economic damages, respectively, for TRS and DTRS when the socially optimal number of permits is issued. (In Case B, the corresponding results are 3.6% for TRS and 0.03% for DTRS.) In contrast, the maximum efficiency losses due to misspecifying the total supply of permits, computed according to equation (17), are 80.9% and 97.8% of the total economic damages, respectively, for TRS and DTRS. (In Case B, the corresponding results are 80.3% for TRS and 78.1% for DTRS.) It is important to emphasize that this result is not a direct consequence of the logistic damage response we

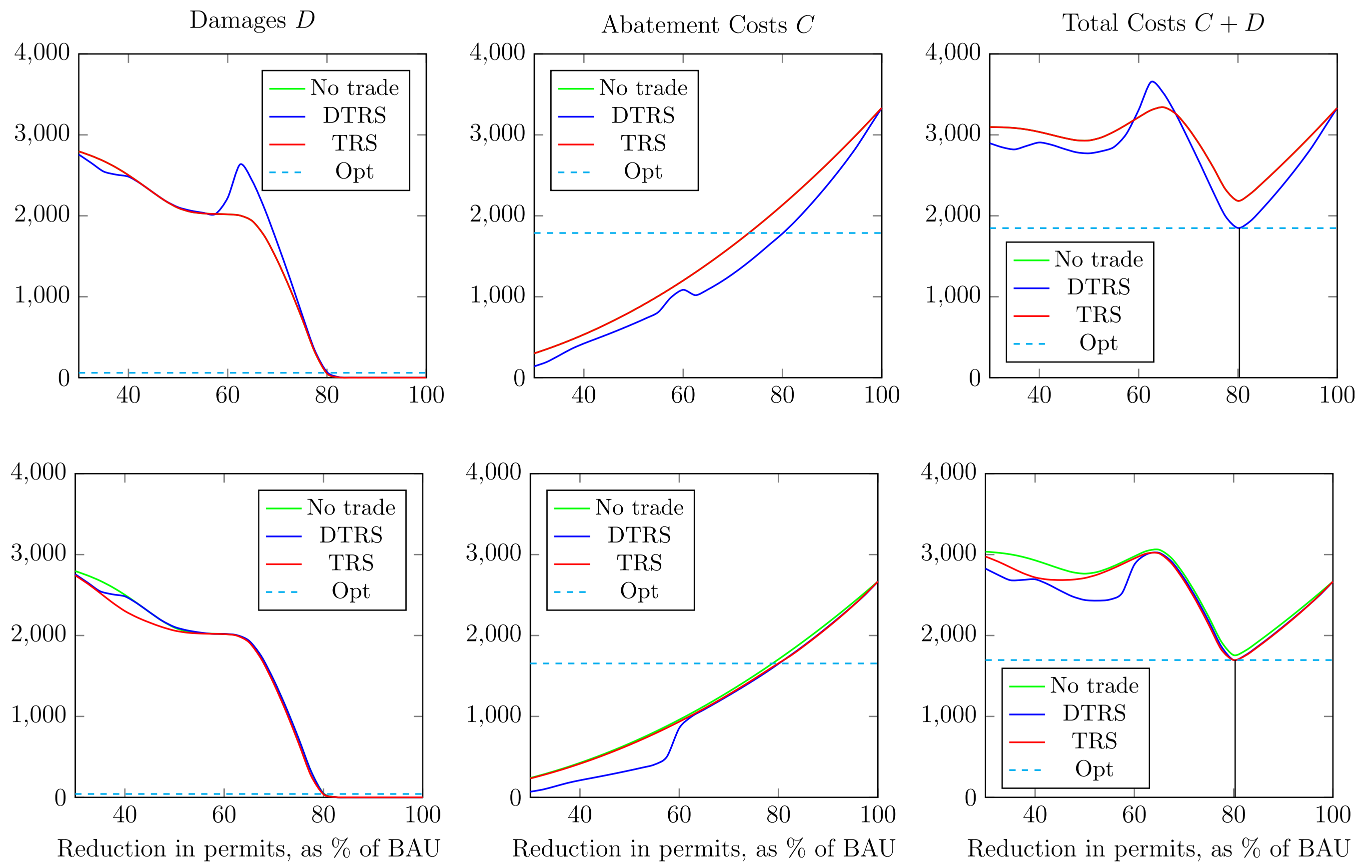

Figure 3. Performance of TRS and DTRS compared. Top plots: Case A ($a_1 = 7.5, a_2 = 15, a_3 = 7.5$). Bottom plots: Case B ($a_1 = 15, a_2 = 7.5, a_3 = 15$). Horizontal axis measures reduction in permit allocation as a percent of business-as-usual emissions total.

assumed in (14). Rather it stems from the simultaneous effects of misspecifying the quantity of pollution as well as the incorrect price signals that arise from it.

7. Discussion

In this paper, we examined the efficiency properties of two recently developed water-quality trading models, the trading-ratio system (TRS) proposed in *Hung and Shaw* [2005] and the damage-denominated trading-ratio system (DTRS) proposed in *Farrow et al.* [2005]. We showed that neither system is sure to achieve the cost-effectiveness optimum (and thus the efficient outcome). More specifically, the TRS encounters difficulties when the river has critical zones at a confluence. The DTRS encounters difficulties when damages are nonlinear. We derived these results under the first-best scenario in which the regulator knows the efficient vector of environmental constraints (for TRS) and the efficient damage constraint (for DTRS). Furthermore, in a second-best scenario where the regulator cannot set these constraints at the efficient levels, neither system dominates in terms of efficiency, because the TRS excludes efficient trades while the DTRS promotes inefficient trades. In this sense, our results indicate the impossibility of getting the spatially explicit prices of pollution right under either system.

Our computational model also contains some encouraging findings: the welfare losses associated with the two systems are dwarfed by those associated with choosing the incorrect number of permits. Thus, getting quantities right is more important than getting prices right. The two effects interact in interesting ways, though. The magnitude of inefficiency due to incorrect price signals appears to depend on the total supply of permits. Thus our paper suggests the importance of getting the quantity of pollution right even while striving to get the spatial prices of pollution right.

Our main message, then, is that either scheme can perform well so long as the aggregate supply of permits is set carefully. We have not provided an alternative scheme that addresses the difficulties we have found.

That project is left for future work and we believe fruitful work might lie along either of two lines. One is to investigate empirically the geographic distribution of polluting sources and the degree and nature of nonlinearity in environmental damages in actual watersheds, and for key water pollutants. It may be the case that the concerns raised here are minor in comparison to the benefits conferred by improved water quality.

Second, *Antweiler* [2012] has developed a powerful iterative approach to permit-trading policy for air quality. The idea of the scheme is for the regulator to adjust the number of permits issued each period, based on each polluter's marginal contribution to environmental damages at its current emissions level. As long as social welfare is globally concave, this iterative process would eventually converge to the social optimum. Our conjecture is that this iterative scheme could potentially be embedded in either the TRS or the DTRS. Future studies might investigate the performance of the iterative approach, with any of the three schemes, for watersheds characterized by both nonlinear damages and branching rivers.

Appendix A: Proofs of Propositions

Proof of Proposition 1. Suppose that $\mathbf{e}^{\mathrm{HS}}$ is the solution vector for program (1). By assumption, we must have a critical zone at the confluence receptor m: $\sum_{m-1_i} \tau_{(m-1_i)m}\bar{X}_{m-1_i} > \bar{X}_m$, where $\{m-1_i\}_i$ is the collection of indices immediately upstream of zone m, along two or more branches. We know that at the optimum, given our assumption that $C'_i > 0$,

$$\bar{X}_m = \sum_{m-1_i} \tau_{(m-1_i)m} e^{\mathrm{HS}}_{m-1_i}.$$

Suppose, without loss of generality, that there are only two zones upstream of the critical confluence, one on each of two tributaries. Call these zones a and b. By assumption,

$$\bar{X}_m = \tau_{am} e_a^{\mathrm{HS}} + \tau_{bm} e_b^{\mathrm{HS}}.$$

On the other hand, without knowing individual sources' cost functions, information on $\mathbf{e}^{\mathrm{HS}}$ is not available to the TRS regulator. Therefore, she must, without knowledge of $\mathbf{e}^{\mathrm{HS}}$, allocate zonal discharge load standards $\bar{Z}$'s such that $\bar{Z}_m = 0$ and

$$\bar{X}_m = \tau_{am}\bar{Z}_a + \tau_{bm}\bar{Z}_b.$$

Because there is only one constraint equation for two zonal standards, the allocation is indeterminate. It is trivial to see that if the TRS allocates $\bar{Z}$'s in such a way that, for example, $e_a^{\mathrm{HS}} > \bar{Z}_a$ and $\bar{Z}_b = (\bar{X}_m - \tau_{am}\bar{Z}_a)/\tau_{bm} > e_b^{\mathrm{HS}}$, then the trading equilibrium can never achieve $\mathbf{e}^{\mathrm{HS}}$. Similar arguments apply when there are more than two upstream zones. This completes the proof. ■

Proof of Proposition 2. We offer a proof for the case of an interior optimum of (2). Note that at the interior optimum, the emission vector $\mathbf{e}^{\mathrm{FSCH}}$ must satisfy the necessary (but not sufficient) condition:

$$\frac{\partial D(\mathbf{e}^{\mathrm{FSCH}})/\partial e_i}{\partial D(\mathbf{e}^{\mathrm{FSCH}})/\partial e_j} = \frac{C'_i(a_i^{\mathrm{FSCH}})}{C'_j(a_j^{\mathrm{FSCH}})} \quad \text{for all } i, j,$$

where $e_i^{\mathrm{FSCH}} = \bar{e}_i - a_i^{\mathrm{FSCH}}$. On the other hand, according to equation (9), at an interior equilibrium, we have

$$\frac{d_i}{d_j} = \frac{C'_i(a_i^{\mathrm{FSCH}})}{C'_j(a_j^{\mathrm{FSCH}})} \quad \text{for all } i, j.$$

Thus, in order for the trading equilibrium to achieve the cost-effective solution, the regulator must evaluate the exchange rates (the d's) at the optimum: $d_i^{\mathrm{FSCH}} = \partial D(\mathbf{e}^{\mathrm{FSCH}})/\partial e_i$. Under the DTRS, the regulator allocates $\bar{L}$'s in such a way that:

$$\sum_i d_i^{\mathrm{FSCH}} \bar{L}_i = \overline{\mathrm{TD}} = D(\mathbf{e}^{\mathrm{FSCH}}). \quad \text{(A1)}$$

We now ask whether there exists some initial allocation $\bar{\mathbf{L}}$, satisfying (A1), such that the resulting equilibrium would achieve the cost-effective solution. We claim that such an allocation does not exist. Suppose, by way of contradiction, there exists such an allocation $\bar{\mathbf{L}}$ and that the resulting trading equilibrium is also cost-effective: $\mathbf{e}^{\text{DTRS}}=\mathbf{e}^{\text{FSCH}}$. Because the equilibrium must satisfy the market-clearing condition (10b), we have

$$\sum_i d_i^{\text{FSCH}}\bar{L}_i=\sum_i d_i^{\text{FSCH}}e_i^{\text{DTRS}}. \tag{A2}$$

However, because the aggregate damage function is nonlinear, we have

$$\sum_i d_i^{\text{FSCH}}e_i^{\text{FSCH}}\neq D(\mathbf{e}^{\text{FSCH}}). \tag{A3}$$

Combining (A1), (A2), and (A3), we see that

$$\sum_i d_i^{\text{FSCH}}\bar{L}_i=\sum_i d_i^{\text{FSCH}}e_i^{\text{DTRS}}=D(\mathbf{e}^{\text{FSCH}})\neq\sum_i d_i^{\text{FSCH}}e_i^{\text{FSCH}}.$$

which contradicts that $\mathbf{e}^{\text{DTRS}}=\mathbf{e}^{\text{FSCH}}$. This completes the proof. ■

Proof of Proposition 3. To see (i), given the efficient solution $\mathbf{a}^{\text{eff}}$, let the constraint vector $\bar{\mathbf{X}}^{\text{eff}}$ be defined as

$$\bar{\mathbf{X}}^{\text{eff}}=T(\bar{\mathbf{e}}-\mathbf{a}^{\text{eff}})'.$$

Suppose by way of contradiction that $\mathbf{a}^{\text{HS}}$ solves (1) subject to $\bar{\mathbf{X}}=\bar{\mathbf{X}}^{\text{eff}}$, but $\mathbf{a}^{\text{HS}}\neq\mathbf{a}^{\text{eff}}$. Because D is increasing in $\mathbf{x}$, and because $\mathbf{x}^{\text{eff}}=T(\bar{\mathbf{e}}-\mathbf{a}^{\text{eff}})'=\bar{\mathbf{X}}^{\text{eff}}$, we have

$$\sum_i C_i(a_i^{\text{eff}})+D(\mathbf{x}^{\text{eff}})<\sum_i C_i(a_i^{\text{HS}})+D(\mathbf{x}^{\text{HS}})\leq\sum_i C_i(a_i^{\text{HS}})+D(\mathbf{x}^{\text{eff}}),$$

where the first inequality follows from $\mathbf{a}^{\text{HS}}\neq\mathbf{a}^{\text{eff}}$ and the second inequality follows because $\mathbf{x}^{\text{HS}}\leq\mathbf{x}^{\text{eff}}$ implies $D(\mathbf{x}^{\text{HS}})\leq D(\mathbf{x}^{\text{eff}})$. But this inequality implies that there exists $\mathbf{a}^{\text{eff}}\neq\mathbf{a}^{\text{HS}}$ such that $\sum_i C_i(a_i^{\text{eff}})<\sum_i C_i(a_i^{\text{HS}})$ with $\mathbf{x}^{\text{eff}}=\bar{\mathbf{X}}^{\text{eff}}$, a contradiction.

The proof of (ii) is analogous, with the constraint value $\overline{\text{TD}}^{\text{eff}}$ defined as $\overline{\text{TD}}^{\text{eff}}=D(\bar{\mathbf{e}}-\mathbf{a}^{\text{eff}})$. ■

Proof of Proposition 6. (i) Let $\bar{\mathbf{Z}}^{SB}$ denote the second-best allocation of permits under the TRS and define $\bar{\mathbf{X}}^{SB}=T\bar{\mathbf{Z}}^{SB}$. In a branchless river, Hung and Shaw's result applies and so the TRS equilibrium achieves the solution $\mathbf{a}^{SB}$ to the cost-effective program (1) given $\mathbf{X}^{SB}$. By definition, $\mathbf{a}^{SB}$ is not the same as $\mathbf{a}^{\text{eff}}$. Thus there exists some abatement vector $\mathbf{a}'$ such that

$$\sum_i C_i(a_i^{SB})+D(\mathbf{x}^{SB})>\sum_i C_i(a'_i)+D(\mathbf{x}')\geq\sum_i C_i(a_i^{\text{eff}})+D(\mathbf{x}^{\text{eff}}).$$

On the other hand, an interior DTRS equilibrium satisfies

$$\frac{C'_i(a_i^{DTRS})}{C'_j(a_j^{DTRS})}=\frac{d_i}{d_j}=\frac{p_i}{p_j}, \tag{A4a}$$

$$\sum d_i\bar{L}_i^{SB}=\sum d_i(\bar{e}_i-a_i^{DTRS}). \tag{A4b}$$

Here the notation a_i^{DTRS} is distinct from our earlier a_i^{FSCH} in that the former, employed in equation (A4), may not solve (2). Now, replace $\mathbf{a}^{\text{DTRS}}$ with $\mathbf{a}'$. It is easy to see that given $(\bar{\mathbf{L}}^{SB},\bar{\mathbf{e}},\mathbf{a}')$, this system of equations can be solved for $\mathbf{d}$. It follows then that there exists a vector of trading ratios $\mathbf{d}$ such that the DTRS equilibrium arising from $(\bar{\mathbf{L}}^{SB},\bar{\mathbf{e}},\mathbf{d}')$ achieves $\mathbf{a}'$.

(ii) Define $\overline{\text{TD}}^{SB}=S(\bar{\mathbf{X}}^{SB})=D(\bar{\mathbf{L}}^{SB})$. We know from Farrow et al. that when damages are linear, the DTRS mechanism achieves the solution $\mathbf{a}^{SB}$ to the cost-effective program (2) given $\overline{\text{TD}}^{SB}$. On the other hand, there exists a cost-effective program (1) that achieves $\mathbf{a}^{SB}$. Proposition 1 shows that the TRS scheme may fail to achieve $\mathbf{a}^{SB}$ if the branching river has a critical zone at the confluence. Now, unlike in part (*i*), the TRS requires polluting sources to still obey $\bar{\mathbf{X}}^{SB}$. It thus follows that

$$\sum_i C_i(a_i^{TRS})+D(\mathbf{x}^{TRS})>\sum_i C_i(a_i^{DTRS})+D(\mathbf{x}^{DTRS})=\sum_i C_i(a_i^{SB})+D(\mathbf{x}^{SB}).$$

This completes the proof. ■

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