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Selected Economic Aspects of Water Quality Trading:

A Primer and Interpretive Literature Review

Richard N. Boisvert, Gregory L. Poe, and Yukako Sado

Department of Applied Economics and Management
College of Agriculture and Life Sciences
Cornell University
Ithaca, NY 14853-7801

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I. Introduction and Motivation

The economic objective of environmental regulatory design is to achieve a targeted reduction of pollution at the lowest possible cost.[2] Conceptually, this "cost–effectiveness" objective can be achieved through voluntary adoption of new technologies, strict regulatory approaches, and/or market-based incentive programs such as tax/subsidy mechanisms or marketable permit systems. Encouraged by the singular success of the highly visible United States (U.S.) acid rain program in accelerating reductions in sulfur dioxide pollution, while also providing substantial savings relative to alternative command-and-control measures, environmental policymakers are increasingly directing their attention to market-based approaches that allow flexibility in meeting caps set on aggregate pollution levels.

That the longstanding academic interest in pollution trading is being translated into actual water policy is evident in the rapid growth in the number of water quality trading initiatives over the past fifteen years: in 1990 three such programs existed in the United States, by 1999 there were 25 programs in various stages of implementation and development, and as of 2004 this number had increased to 70 (Woodward, Kaiser and Wicks; Environomics; Breetz et al.). Water quality trading programs have been established internationally in such diverse locations as Australia, Chile, China and Slovakia (NCEE).

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[1] During a portion of the time that this report was being prepared, Poe also served as a Visiting Fellow at the Crawford School of Economics and Government, Australian National University. The authors also benefited, without implication, from helpful discussions with Richard Woodward and Josef Kardos.

[2] Here we assume, as is appropriate for biophysically determined total maximum daily loads (TMDLs) applied to water quality at a watershed level, that the target level of ambient water quality, and hence total emissions and total abatement of emissions, are exogenously determined through political or other processes. Given this predetermination, economic efficiency is equated with cost-effectiveness. This conditional cost-effectiveness benchmark, however, deviates from a great body of environmental economics literature directed toward identifying the socially optimal level of pollution (or pollution abatement) in which optimality is identified to be the level of pollution in which the marginal benefits of pollution equal the marginal costs (see Baumol and Oates, 1971, 1988). Since explicit consideration of relative benefits and costs is precluded in the Clean Water Act decision-making processes, we instead make the cost-effectiveness criterion paramount in our discussion. It is this cost-effectiveness criterion that underpins the arguments made by Dales in his original proposal for trading pollution rights: "economic analysis, which is all but useless in helping us to decide on a policy, is all but indispensable in helping us decide on the best way of implementing a policy once it has been chosen. The criterion is simply that the best way of implementing a policy is the least costly way…" (1968a, p. 99). As discussed in footnote 9 below, this cost-effective orientation is further bolstered by Montgomery's seminal theoretical paper and subsequent work in this area.

In the United States, the growth of trading initiatives has been fostered by the U.S. Environmental Protection Agency's (EPA's) explicit endorsement of water quality trading. In 1996 the U.S. EPA issued a Draft Framework for Watershed-Based Trading to encourage trading and to assist in evaluating and designing trading programs (U.S. EPA 1996). A final Water Quality Trading Policy was promulgated in 2003 based on the rationale that "market-based approaches such as water quality trading provide greater flexibility and have potential to achieve water quality and environmental benefits greater than would otherwise be achieved under more traditional regulatory approaches" (U.S. EPA 2003, p. 1). The US EPA presently provides substantial funds to support the development of watershed-based water quality trading programs through its Targeted Watersheds Grant Program (US EPA 2006).

Despite this keen interest in such programs, the recent increase in the number of initiatives, and expanded availability of funding, the promise of the significant cost savings for nutrient trading programs has never materialized. With the exception of an extremely limited number of oft-mentioned successes (e.g., Long Island Sound), very few trades have actually occurred (King and Kuch). Tietenberg and Johnstone (2003) observed that, "[i]n a general sense, programs targeting water pollution control have generally not been successful" (p. 33). Speaking more specifically about nutrient trading, Faeth remarked:

> "There are some bright spots, but overall I think real progress has been spotty. There's some good news in a few places, but it's not clear that trading has actually resulted in significantly improved water quality yet. There have been a few trades…[But,] [a]re there any functioning markets up and running? The answer is no (p. 1-2). [3]

Thus, rather than providing the basis for a "how to" template from a stream of successfully implemented programs, the existing water quality initiatives are perhaps best viewed as pilot programs providing an important range of "lessons learned" (Kieser and Feng). The paramount lesson, as Hoag and Hughes-Popp argued some time ago, is that translating theory into practice may necessitate a reexamination of "the main principles associated with water pollution credit trading theory…to identify factors that influence program feasibility" (p. 253). If such efforts are undertaken, King maintains that, "the potential for [water quality] trading might be realized. If not [water quality] trading will probably end up in the overflowing dustbin of well-intentioned economic policies that attracted attention for a while but never delivered." In his similarly guarded conclusions regarding the future of pollution trading, Tietenberg (2004) argued that the "evidence seems to suggest that tradable permits are no panacea, but they do have their niche" (p. 416).

Drawing on these lessons learned, specifically the admonition by King and Kuch that the basic economic obstacles pose a greater problem for trading programs than institutional

[3] To avoid quoting out of context, Faeth's comments were directed primarily at point-non-point trading. Nonetheless, Faeth's dismal observations apply equally to point-point source water quality trading (King and Kuch).

design, we focus much of this review on the basic economic prerequisites necessary to implement a trading program. Briefly, these can be stated as: 1) there must be an economic demand for permits;[4] 2) after accounting for the biophysical fate and transport relations, there must be clear gains from trade deriving from differences in cost structures between firms in the trading scheme; 3) there must be a trading system established that accounts for the biophysical and economic characteristics of the pollutant and ecosystem under consideration; and 4) there needs to be a clear authority to trade, legal foundations to enforce property rights exchanges related to pollution permit or credit trading, and a market structure to facilitate trades.

With an eye toward the phosphorus trading program being investigated for the upper Passaic River Basin, we direct the discussion toward selected economic aspects of point-point source water quality trading programs. In Section II, we review the necessary market conditions for trades to occur, with an emphasis on identifying the basic demand and supply conditions. In Section III, we outline a trading-ratio system designed recently to provide a least-cost solution to achieving water quality targets for a non-uniformly mixed assimilative pollutant. One distinct advantage of this trading-ratio system for water quality trading is that it exploits the property that water flows downhill.

Assuming that these market prerequisites are met and that it is possible to implement a trading system amenable to the characteristics of the watershed, we turn our attention to the range of applicable market structures in Sections IV and V. We bring together our observations, summarize our arguments, and draw some policy conclusions in the final section.

II. Market Foundations: Demand, Supply, and Gains from Trade

To design a market for pollution trading, it is critical at the outset to distinguish between the familiar concept of a well-functioning commodity market with that of a nascent pollution trading program. From an economic perspective, a market is a predictable social and legal arrangement that facilitates the interactions among buyers and sellers to communicate and share information efficiently and to carry out voluntary exchange. Markets are embedded in, and arise from, a nexus of legal and social foundations (Bromley, 1989, 1997). Yet, beyond establishing these prerequisite conditions and related enforcement, the "trade regulator" plays no active role in conventional commodity markets; all that is needed are willing buyers and willing sellers. In such markets, willing buyers (individuals and firms) demand goods at various prices based on their own preferences or profit motives. The supply of goods at various prices derives from the cost of production activities.

[4] Throughout this report, we refer to emissions permits (or allowances), with each permit providing the right to emit a specific amount of pollutants. An alternative tradable commodity is pollution credits. Under a credit system, each discharger is allowed a certain amount of emissions. Should the actual level of pollutants emitted by the discharger fall below the amount allowed, the discharger earns a credit which can be traded to other dischargers seeking to exceed their specified allocation of pollution. While the specifics of allowance and credit programs differ, the general economic principles discussed here with respect to permits apply to both settings.

By stark contrast, the role of the "trade regulator" in pollution markets extends beyond the purview of establishing and enforcing "the rules of the game." In such markets it becomes "important to view trades as three-party transactions involving active participation among buyers, sellers, and trade regulators" (King and Kuch, p.10353). The regulators' actions are central to creating scarcity, and without scarcity, there is no demand. Thus, absent the "trade regulator", there would be no commodity called pollution abatement, because such markets do not arise "naturally" (Woodward and Kaiser). Also, the trade regulator must balance the objective of cost-effectiveness with that of assuring that environmental targets are reached (King and Kuch; Woodward, Kaiser and Wicks). Greater social demands engender more stringent regulations, raise the costs to regulated firms, and, as a result, are often met with increased resistance by those managing the sources of pollutants in their attempts to mollify regulatory efforts (Hahn and Hester; Lai).

For point sources of water pollution, the demand for tradable pollution permits is supported by linkage between two regulatory mechanisms: the Total Maximum Daily Loads (TMDL's) and the National Pollution Discharge Elimination System (NPDES). A TMDL defines ambient water quality in the aggregate, specifying a quantitative expression of the amount of pollutant a waterbody can receive (loading capacity) without causing impairment of the applicable water quality standard for any portion of that water body. By establishing this baseline relative to the status quo with corresponding wasteload allocations to point sources (and load allocations if expanded to include non-point sources), the TMDL defines the aggregate, location-specific amount of pollution reduction that must take place. The NPDES permits are then assigned to individual point sources, defining the amount and the conditions for discharge of pollutants into waterbodies. Once a TMDL is in place, individual NPDES permits should reflect the aggregate waste load allocation.

The relationship between the TMDLs and the NPDES permits can stimulate demand for permits in the following way. Under Principle 3 of the Draft Plan (US EPA 1996), trades are to be "developed within a TMDL or equivalent analytical or management framework." Further, the US EPA supports the incorporation of specific trades into the individual NPDES permits or the use of flexible approaches for the incorporation of provisions for trading in NPDES permits. Together with the assumption that reducing waste is costly, the TMDL and the corresponding discharger-specific NPDES wasteload allocations engender a willingness to pay on the part of some point sources to exceed allocated levels. The specifications within the NPDES permits provide the legal foundations to ensure that point-point source trades are legally enforceable. In essence, under a TMDL program, the NPDES permit has the potential to evolve from its traditional technology-based criteria of "How much should each source be allowed to emit?" to "How should the total pollution load be allocated among various sources?" (Woodward and Kaiser).

These conditions constitute the first corner stone of the market – demand from willing buyers is assured. This stands in stark contrast to point-nonpoint source trading in which the viability of such trades is seriously undermined because there are no mechanisms to guarantee the credits purchased from non-point sources (Faeth; Kieser and Feng).

Given a demand for permits, the potential for market success of point-point source trades rests on two additional conditions: an effective supply of permits and the establishment of effective trading institutions. Assuming profit, or at least cost-minimization motives, firms would be willing to trade away their pollution rights only if they stand to gain monetarily from such a trade. For a transaction to take place, there must be a sufficient difference in abatement costs across firms for there to be significant gains from trade from exchanging rights to pollute.

a. Gains from Trade: Marginal Abatement Costs for Uniformly-Mixed Pollutants.

As underscored in the opening section of this review, the economic objective of environmental regulatory design is to achieve a targeted level (A*) of pollution (or equivalently pollution abatement – R*) at the lowest possible cost. Using economic optimization methods (see Appendix A), and assuming continuity in abatement costs, the solution of this problem involves the application of what environmental economists refer to as the *equimarginal* condition – that is, the desired level of pollution abatement is achieved at the point where the marginal abatement costs are equated across all firms. *Marginal abatement cost* refers to the cost of implementing one more unit of emissions reduction, where the unit is small, such as a pound of nutrient. For example, an extra pound of reduction by a point source could be achieved by increasing the amount of chemicals used in its treatment process (U.S. EPA, 1996). The marginal abatement cost in this simple example would be the cost of the additional chemicals.

In market trading, the nature of differential marginal abatement costs across regulated entities plays a fundamental role in determining the direction of trade, the number of permits traded, and the magnitude of gains from trading pollution permits. Two features are particularly important. The first is that for a fixed level of capital investment, marginal abatement costs tend to rise with successive levels of abatement. With chemical treatment processes, for example, the effectiveness of each small addition of chemicals beyond a certain point is expected to diminish, raising the marginal abatement cost of each successive pound of pollutant abated. The second critical feature is that cost savings from trade increase with the divergence of the marginal abatement cost functions across dischargers. Put differently, if all abatement cost functions were the same across dischargers, we would expect no gains from trade. Alternatively, if there is substantial diversity in marginal abatement cost functions, gains from trade are expected. For instance, there might be some dischargers for whom it is costly to reduce pollutant levels, while for others, their present technology may be such that additional reductions in pollutant levels could be achieved at relatively low cost.

Through a simple example, we can effectively illustrate how this heterogeneity in cost functions, along with the application of the equimarginal principle, can lead to gains from trade relative to conventional command-and-control approaches. To do so, consider the pair of watershed settings presented in Figure 1.[5] In each watershed, we assume that the pollutants discharged have equal effects at the point of measurement, which we shall assume is immediately downstream from Discharger D. This may be due to adjacencies of dischargers, or the pollutant could be characterized by uniform mixing, such as is the case of greenhouse gas emissions.[6] The first column in each of the sub-tables indicates the total number of pounds of pollution abated by each discharger. The second and third columns provide the corresponding marginal costs of abating each additional unit for Discharger D and Discharger U, respectively. For example, the marginal abatement cost of the fourth pound abated in the homogeneous (heterogeneous) setting for Discharger D is $8 ($12).

Prior to any water quality control policy, each discharger emits six pounds of pollutants. Now, suppose that the regulatory agency desires to reduce aggregate levels of pollution at the point of measurement immediately below discharger D to 6 pounds of pollutants. In a watershed where the pollutants are perfectly mixed, this is equivalent to cutting the total pollutants in half (from 12 to six pounds). To provide a basis for assessing the gains from trade, we first assume that no trades are possible; and that abatement responsibilities are to be allocated equally across dischargers. Under these conditions, the total abatement costs in each watershed would be $32:

- in the watershed where costs are homogeneous each discharger would incur total abatement costs of $16 [= $3 (lb. 1) + $5 (lb. 2) + $8 (lb. 3)];
- in the watershed where costs are heterogeneous, Discharger D would incur total abatement costs of $19 [= $2 (lb. 1) + $5 (lb. 2) + $12 (lb. 3)], while the firm with a lower abatement cost schedule, Discharger U, would incur costs of $13[= $4 (lb. 1) + $4 (lb. 2) + $5 (lb. 3)].
- In both watershed settings, the aggregate abatement costs would be equal $32, and the amount of abatement by each discharger would be equal three pounds (resulting in the desired level of six pounds of pollutants). These abatement costs would be shared equally ($16) by the two dischargers in the homogenous case. If the costs are heterogeneous and without trade, Discharger D would discharge the same number of units as Discharger U, but would incur about 60 percent ($19) of the total $32 watershed abatement costs.

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[5]To facilitate the presentation, we examine a situation where both abatement amounts and the cost of each increment of abatement are reported in discrete amounts. In most standard elementary or intermediate economics texts, similar examples are presented graphically utilizing continuous marginal abatement cost functions. Continuous cost functions are also utilized in the mathematical appendices in this review. See Tietenberg (2006) and Sado for more details.

[6] Theoretical presentations of permit trading programs further distinguish between assimilative pollutants and accumulative pollutants. With our charge of addressing phosphorous pollution in the upper Passaic Water Basin, our focus is on assimilative pollutants. See Tietenberg (2006) for a treatment of pollution trading permits for accumulative pollutants.

Figure 1. Marginal Cost Functions and Gains From Trade

Watershed with Homogeneous Costs		
# of lbs. Abated	Marginal Abatement Costs ($/lb.)	
	Discharger D	Discharger U
1	3	3
2	5	5
3	8	8
4	12	12
5	17	17
6	23	23

Watershed with Heterogeneous Costs		
# of lbs. Abated	Marginal Abatement Costs ($/lb.)	
	Discharger D	Discharger U
1	2	4
2	5	4
3	12	5
4	23	5
5	38	6
6	57	6

The important question to ask at this point is: Would it be possible to improve upon this regulatory approach in terms of cost-effectiveness?

In the homogeneous case, the answer is ‘no’ (try any other combination of abatement levels by the two dischargers that sum to six pounds abated and compare the aggregate costs to $32). Since the abatement cost functions are identical for both firms, the equimarginal condition is automatically satisfied at R* equals six, with each firm abating three units, and the marginal cost of the last unit being $8. Hence there is no way to allocate abatement responsibilities in a manner that lowers the aggregate abatement costs for the watershed.

In contrast, because the abatement schedules differ across the two firms in the heterogeneous-cost watershed, there *are* potential gains from trade relative to the equal abatement regulatory status quo. In this case, it is the structure of abatement costs that creates the opportunity for the discharger (Discharger D) with relatively high abatement costs to pay the relatively low-abatement-cost discharger (Discharger U) to undertake some of the high discharger’s abatement duties. In doing so, trades can be undertaken such that each discharger gains relative to the regulatory status quo, and the aggregate costs of abatement are reduced.

To see how this works, we need to compare the willingness to pay to not have to abate the last unit (i.e., lb. 3) for Discharger D with Discharger U’s willingness-to-accept compensation to abate an additional unit (i.e., lb. 4). Discharger D’s third unit of abatement comes at a cost of $12, and hence that discharger would be willing to pay up to $12 not to abate this last unit. This is the *demand side* of the *permit* market. With respect to the *supply of permits*, Discharger U would be willing to abate an extra unit (e.g. a fourth unit) if compensation to do so was equal to or exceeded $5. Hence there are clear opportunities for gains from trade.

If such trade is permitted, Discharger D will pay Discharger U to abate an extra unit of pollution at a price lying between $12/lb. (D's willingness to pay or the demand price) and $5/lb. (U's willingness to accept or the supply price). Now, if such a trade were arranged at $6/lb., both parties would be better off.

- Discharger D would have been willing to pay $12 but only has to pay $6, resulting in a gain of $5.
- Likewise, Discharger U gains $1 because the amount compensated, $6, exceeds that firm's costs of abatement, $5.
- In terms or resources devoted to pollution abatement in the watershed, total abatement costs are reduced by $7 with Discharger D abating two units at a cost of $7 [= $2 (lb. 1) + $5 (lb. 2)] and Discharger U abating four units at a cost of $18 [= $4 (lb. 1) + $4 (lb. 2) + $5 (lb. 3)+ $5 (lb. 4)]. Total watershed abatement cost of $25 for the six units abated.

While the transfer of abatement responsibilities entails a corresponding payment of $6 by Discharger D to Discharge U and thus affects the returns of each discharger, these monies are not regarded as true resource costs to society from a social perspective. They merely represent a transfer of funds from one firm to another.[7] It is important to recognize that in this bargaining situation the price of a permit is not a prioi determinate, as it depends upon the relative bargaining power of the two dischargers.

Note further that after this initial one-unit trade there are no further gains to trade in this watershed. Indeed, the equimarginal principle is satisfied. Discharger D's maximum willingness to pay ($5/lb.) to not have to abate another unit exactly equals the minimum compensation that Discharger U ($5/lb.) would require to abate another unit.

In relative terms, the cost-savings in this example represent a 22% reduction relative to the regulatory scenario, but the savings of this magnitude are strictly an artifact of the hypothetical numbers chosen for illustrative purposes. The reader is cautioned that it is impossible to access whether the 22% reduction demonstrated herein is large or small relative to the gains that may be realized in actual trading programs. All that we know is that this figure is in the range of the cost savings based on *ex ante* comparisons of potential least-cost emission reductions with the costs associated with command–and-control allocations. These e*x ante* analyses typically utilize hypothetical simulation techniques based on engineering models and assumed optimizing behavior. In a review of such studies for air pollution regulation, Tietenberg (2006) finds that the potential cost savings from adopting least-cost approaches range from 6 to 95 percent of the command-and-control benchmark (p. 59-60). With respect to point-point source water quality trading, separate efforts by Rowles and Sado suggest that cost-savings will lie at the lower end of the range of the potential savings identified by Tietenberg. We conjecture

[7] Bear in mind that in adopting a cost-effective approach, one must recognize that there may be other social criteria that are also important in evaluating trades, trading systems, and trading structures as these elements affect the distribution of pollution and the burden on consumers and taxpayers. Similarly, potential "environmental justice" issues have been discussed in general in Drury et al. and Solomon and Lee, and, with specific reference to water quality trading in Goldfarb.

that this relatively low level of savings is due to the fact that abatement technologies of the sources considered in these studies are relatively homogenous.

Unfortunately, as is evident in both Tietenberg's review of actual air emission programs and King and Kuch's assessment of water quality trading efforts, the projected cost savings are typically neither realized nor approximated in practice because of the behavioral responses of participants, market imperfections, and other constraints inhibiting trade. Indeed, King and Kuch's *ex-post* assessment suggests that the cost savings from most efforts to establish water quality programs approach zero. As Woodward notes "with few trades it seems likely that the cost reductions generated through trading are minimal." This disparity between *ex-ante* projections and *ex-post* assessment is evident in Smith's reflection on the earliest application of water quality trading, the Fox River trading scheme introduced by the Wisconsin Department of Natural Resources in 1981:

> "This scheme, covering a number of paper mills and municipal wastewater treatment plants discharging effluent to a heavily polluted stretch of the Fox River, had the potential to achieve considerable cost savings compared to a fixed central directive requiring uniform emissions. A simulation study by O'Neil, David, Moore and Joeres (1983) showed that there would be considerable scope for reducing total abatement cost through the allocation of emissions between sources. Since abatement costs differed between sources by a factor of four, there would be considerable cost savings from such a reallocation. The fact that, in practice, the introduction of the scheme was followed only by a single trade, stood in stark contrast to the predicted theoretical gains, and provided a clear warning that there would be considerable gap between advance forecasts and practical outcomes." (p. 29)

Furthermore, even for successful trading programs, *ex-post* studies of actual cost savings are limited (Tietenberg, 2006) and, for those that have been undertaken, there appears to be a lack of consensus regarding the magnitude of actual cost-savings. For example, due to the varying criteria used, cost savings examined, counterfactual baseline cases, and other methodological differences, estimates of the cost-savings from the much-touted U.S. acid rain trading program under the 1990 Clean Air Act Amendments range widely, from 16%-25% (Keohane), to 25%-34% (Schmalensee et al.), to 43% (Carlson et al.).

In the discussion thus far, we have characterized gains from trade in the most direct terms—the case where high-marginal-abatement-cost dischargers pay low-marginal-abatement-cost dischargers to undertake additional abatement. Applying these concepts to trading permits is easily done, simply by recognizing that instead of specifying pollution reduction in terms of levels of abatement, one can also express this objective in terms of pollution allowed. Hence, if we assume in our example that there are 12 units of pollution at present, i.e. six from each firm, R* could be expressed not as six units abated, but as six units of allowable emission E*. Hence six units of emissions permits will be distributed within the watershed, which for direct comparisons with our previous discussion, we assume are equally distributed across dischargers.[8] In the heterogeneous setting, the two dischargers will trade in a manner consistent with that previously discussed so that Discharger D abates two (emits three) pounds in the least-cost equilibrium, while Discharger U abates four (emits one) pounds. Thus, Discharger U would sell its pollution permit to Discharger D.

b. Gains from Trade: Non-Uniformly Mixed Pollutants, Accounting for Spatial Distribution

The assumption of uniformly mixed pollutants is useful for presenting basic concepts. This assumption too is relevant to some real world cases such as greenhouse gas emissions, and has also been used as an approximation in a number of air pollution trading programs (Tietenberg, 1985, 2006). For many pollutants and media, however, such an assumption is simply inappropriate (Tietenberg, 1978, 1980, 1995). For instance, for nutrient management at the watershed level, the spatial distribution of dischargers relative to receptor sites is critical to program design because the fate and transport of the pollutants must be considered explicitly. Due to dilution, dispersion, and other biophysical interactions, the impact on ambient levels of a pollutant at a given receptor are expected to decline as the distance between the discharger and the receptor increases. At the extreme, receptor sites upstream will be unaffected by the downstream discharger's emissions.

Fortunately, the issue of non-uniform mixing and spatial distribution of pollutants is easily accommodated into the previous framework (for a mathematical treatment, see Appendix B). We can do so by defining a *diffusion (or transfer) coefficient*, d_{ij}, that measures the contribution of one unit of emissions from the i*th* discharger to the total load of effluent at the j*th* receptor (Montgomery; Tietenberg, 1978; Hung and Shaw). Formally, let e_i indicate an amount of emissions from source *i*, and let e_{ij} indicate the corresponding amount measured at the j*th* receptor after discharger *i* emits e_i. Then,

$$d_{ij} = {}^{e_{ij}}\!\big/_{e_i}$$

This coefficient is neccessarily bounded between zero and one, where "zero" indicates that the i*th* discharger has no effect on the j*th* receptor (as in the case of being upstream) and "one" indicates that the unit of pollution from the i*th* source does not diminish in any way by the time it reaches the j*th* receptor. An intermediate coefficient of, say, $d_{ij} = 0.5$ would indicate that one additional unit of pollution for discharger *i* results in one-half a unit of pollution at receptor *j*. For a region or watershed with *I* stationary sources of pollutants and J receptor points, the dispersion of water emissions for the I sources can be specified by an I by J matrix of (linear) unit diffusion coefficients (McGartland and Oates):

[8] In our example, any other initial allocation of four pollution permits across firms will, after trading, result in the same final least cost result indicated in the text. However, since the initial allocation defines who has to pay whom, there will be income effects.

$$D = \begin{bmatrix} & & & \cdot & & & \\ & & & \cdot & & & \\ & & & \cdot & & & \\ \cdot & \cdot & \cdot & d_{ij} & \cdot & \cdot & \cdot \\ & & & \cdot & & & \\ & & & \cdot & & & \\ & & & \cdot & & & \end{bmatrix}$$

When these spatial conditions must be accommodated, the previously described equimarginal principle must be modified:

> "..it is not the marginal costs of emission reduction that are equalized across sources in a cost-effective allocation (as was the case for uniformly mixed assimilative pollutant) it is the marginal costs of pollution reduction at each receptor location that are equalized" (Tietenberg, 2006 p. 34).

This relationship is most readily understood when there is a single receptor site, such as that used in the Long Island Sound in which an "equalization factor" is used to relate each facility's geographic location to its relative impact on the oxygen levels in Western Long Island Sound where the impact of excess nitrogen is most severe (Connecticut Department of Environmental Protection). Similarly the Minnesota River trading program (Hall) and the proposed Lower Boise river trading program (Schary) define the trades and trading ratios throughout their respective watersheds in terms of the impact at a single point of egress.

To add further to an understanding of this modification in the equimarginal principle when there in non-uniform mixing, we continue the previous example of the heterogeneous watershed with two dischargers. The left-hand side of Figure 2 presents the Heterogeneous Watershed from Figure 1, but with two notable, albeit minor changes. The first change, indicated in the title of the left-most column is that, the quantity of pollutant is measured in the area of Discharger D (i.e. @D). The second modification is that diffusion coefficients are now specified. In this case, the diffusion coefficients are both equal to one (e.g. $d_{DD} = d_{UD} = 1$), which is equivalent to uniform mixing. As such, the cost-effective outcome of reducing six units of aggregate emissions is identical to that discussed previously: Discharger D reduces pollution by two pounds and the lower cost Discharger U reduces pollution by four pounds. Recall that this allocation of abatement reduces aggregate pollution costs relative to an equal abatement command-and-control approach.

Compare this result with the watershed conditions described on the right hand side of Figure 2, characterized by non-uniform mixing. Here the diffusion coefficient for Discharger D equals one (e.g. $d_{DD}=1$) as would be expected because water quality measurements are again taken in the area of Discharger D. However, the diffusion coefficient, $d_{UD} = 0.5$. This implies that for every unit of pollution reduced by Discharger

U (where U represents upstream) there is only a 0.5 unit reduction in pollution at the downstream receptor. The effective marginal abatement cost of the n*th* unit of pollution reduction at receptor site D by Discharger U is that associated with the 2*n*th* unit reduction by Discharger U. Stated differently, to reduce one unit at D, Discharger U must reduce two units and incur the additional cost of abating both units. This effective marginal cost is presented in the final column of Figure 2. The last three entries in this column are empty because to achieve these levels of abatement at the point of measurement would require U to abate more than it initially pollutes. We assume that this is impossible in this setting, although such an outcome could exist if offsets from other sources are available to Discharger U.

Under these conditions, application of the equimarginal principle demonstrates that the cost-effective way to reduce six units of pollution at site D is now accomplished through equal abatement of three units by each firm. Hence, in the heterogeneous case there are no longer gains to trade relative to the equal abatement command-and-control regime once spatial distributions are accounted for in this instance. Indeed, it is interesting to note that total abatement in terms of the sum of abatement levels measured at each site is larger: Discharger D abates three units and Discharger U abates six units (equivalent to three units measured at D).

Figure 2: Cost-Effective Solutions Under Uniform and Non-Uniform Mixing

Watershed with Heterogeneous Costs (Uniform Mixing)			Watershed with Heterogeneous Costs (Non-Uniform Mixing)		
# of lbs. Abated (@ D)	Marginal Abatement Costs ($/lb.) $d_{DD}=d_{UD}=1$		# of lbs. Abated (@ D)	Marginal Abatement Costs ($/lb.) $d_{DD}=1$; $d_{UD}=0.5$	
	Discharger D	Discharger U		Discharger D	Discharger U
1	2	4	1	2	8
2	5	4	2	5	10
3	12	5	3	12	12
4	23	5	4	23	-
5	38	6	5	38	-
6	57	6	6	57	-

Although this simple example represents an extreme case where the transfer coefficients eliminate any gains from trade, this will not be true in general, However, by considering this extreme case, we do underscore the lesson to be learned from our illustration: that gains from trade depend not only on the differences in abatement costs across firms, but also on the relative diffusion of transfer coefficients between pairs of upstream and downstream sites. In cases such as this one presented in Figure 2, these effects can be at odds with one another. One effect can act to negate the other if lower cost abaters are also characterized by relatively low diffusion coefficients.

III. Trading Systems

In the previous section, we identified the fundamental characteristic of cost-effective pollution abatement--that of equating marginal abatement costs across firms after accounting for spatial characteristics and transport. The original suggestion that tradable pollution rights could achieve this least-cost allocation of resources was provided independently by Dales (1968a, b) and Crocker. Drawing from Coase's seminal work on property rights, Dales proposed his concept for a market for fully transferable pollution rights within the context of water quality. Crocker's vision of a market pricing system for emission rights was oriented to atmospheric pollution.[9]

a. Ambient Permit Systems and Emission Permit Systems

Motivated by Dales' arguments, as well as a closely related policy proposal to establish markets in BOD bonds or licenses for industrial sources in the Delaware Estuary, Montgomery sought to prove whether or not such conjectures could be supported theoretically. In his seminal paper, Montgomery explored whether competitive market equilibrium in licenses can achieve "externally given standards of environmental quality at least cost to the regulated industries" (p. 396). In exploring licenses, Montgomery took care to distinguish between "pollution" and "emission" licenses. The former is associated with the right to emit pollutants in terms of pollutant concentrations at a set of receptor points. In the present lexicon of tradable permits, this is most frequently referred to as an ambient permit system. Emissions licenses instead confer a right to emit pollutants up to a certain rate. Such licenses correspond to what is now commonly referred to as emission permit systems.

Under an ambient permit system, permits are receptor specific, with the allocation to each receptor site corresponding to the targeted ambient quality at that site. The Montgomery paper provides a theoretical proof for the existence of a competitive market equilibrium, and that moreover, the equilibrium coincides with the least-cost solution. For a result that Tietenberg (2003) calls "remarkable", Montgomery further proved that this least-cost outcome is independent of how the initial permits are allocated across dischargers or sources. That is, theoretically at least, any initial allocation rule across dischargers still engenders the cost-effective allocation after trading.

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[9] Aside from the pollutant type, the Crocker and Dales presentations also differed in terms of the extent of the market. Crocker clearly envisioned a market that would include polluters and pollutees, and hence framed his arguments for a market system to link receptors and emitters in terms of optimal levels of air quality over time. As discussed previously in footnote 1, Dales oriented his arguments toward providing a least-cost solution to achieving a specified level of pollution abatement. In his subsequent theoretical formulation, Montgomery (1972, p. 395) argued "it appears unlikely that markets in rights, containing many sufferers from pollution as participants, will lead to overall Pareto Optimality. They can only serve the more limited but still valuable function of achieving specified levels of environmental quality." With some exceptions (e.g. Farrow et al.) economic discussions subsequent to these initial efforts have centered on the cost-effective aspects of tradable pollution permits, implicitly or explicitly adopting the arguments of Dales and Montgomery.

> "[T]he logic behind this result is rather straight forward. Whatever the initial allocation the transferability of permits allows them ultimately to flow to their highest-valued uses. Since those uses do not depend on the initial allocation, all initial allocations result in the same outcome and that outcome is cost-effective" (Tietenberg 2003, p. 401).

The important implication of this invariance result from the perspective of economic theory is that such independence implies that there need not be a conflict between political feasibility or equity and cost-effectiveness. Further, ambient standards are always met. Unfortunately, Montgomery also demonstrates that this result does not extend to emissions permits. Instead,

> "[a]n extremely restrictive (and sometimes unattainable) condition is required to ensure that the market equilibrium is also the least-cost solution. This finding is particularly disturbing on two counts. First, the environmental authority may not be able to find an initial allocation of permits that ensures an efficient outcome. And second, should such an allocation exist, a substantial degree of flexibility in the choice of this initial allocation may be lost. Such flexibility can be extremely important in designing a system that is politically feasible (as well as efficient)" (Krupnick, Oates, and Van De Verg, p. 234).

To summarize, from a theoretical perspective ambient permit systems have an advantage over emissions permits. Beyond theoretical modeling arguments, however, the relative advantage is less clear. One practical concern about ambient permit systems is:

> "[f]or every receptor a separate market would have to be established. In order to emit one unit, each source would have to keep the appropriate number of disposition permits for each receptor it affects. If a source wants to increase emissions it must obtain additional [ambient] permits for each of the receptors its emission reaches." (Klaassen, p. 48)

This multiplicity of markets is likely to create large burdens on each market participant who must create a portfolio of permits and engage in simultaneous deals across all of the affected receptor points (Krupnick, Oates and Van De Verg; McGartland). This contrasts with emission permit systems in which trades simply involve one-to-one exchanges of rights to emit. Hahn (1986) suggests that having to simultaneously address the consequences on many receptors may lead to thin markets where competitive market price-taking assumptions can no longer be assumed, even as a rough approximation.[10] This is of particular concern to water quality trading as trades are limited to individual watersheds or sub-watersheds (Woodward and Kaiser). While attention to this issue has centered on ambient pollution systems, related concerns about susceptibility to market manipulations have similarly been expressed for emissions permit systems (Hahn, 1986).

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[10] Tietenberg (2006) provides a comprehensive review of the related issue of market power in a chapter devoted to that topic.

Concerns have also been raised about the relationships between each permitting approach and realized water quality. With respect to ambient standards, using the Fox River Discharge Program as a case study, Devlin and Grafton argue that property rights associated with ambient pollution permits are poorly defined unless ambient quality relationships are clearly specified between the emissions of a firm, the emissions of other firms, and relevant receptor sites. Because different firms have different impacts on ambient water quality due to locational or biophysical issues, "what the seller sells" and "what the buyer buys" is typically not clearly defined in past applications of ambient permit systems to water quality. On the other hand, to the extent that they rely on one-to-one trading, trades of emissions permits may create unacceptably high local concentrations or "hot spots" in areas near sources that acquire permits instead of abating (Tietenberg, 1995). To ensure that no violations of ambient targets occur, aggregate levels of abatement may thus have to be higher under emissions permit systems than command-and-control regulations. In turn, this suggests that, depending on local conditions, emissions permit systems may actually increase aggregate abatement relative to command-and-control approaches. Tietenberg (1985) provides compelling empirical examples demonstrating this possibility.

b. Trading Rules:

Neither the emission permit nor ambient permit systems are "optimal from all points of view" (Atkinson and Tietenberg, 1982, p. 103). In an effort to search for more pragmatic alternative permit system designs that will garner the benefits of both the ambient and emission permit systems while minimizing their respective shortcomings, a number of "trading rule" systems have been proposed in the literature. The unifying feature of these structured rules of trade is that emissions are traded under the constraint that ambient targets are not violated. Klaassen and Tietenberg (2006) categorize these rules as follows:

- The pollution offset system (Krupnick, Oates and Van de Verg) meets ambient standards by allowing emissions trading among dischargers as long as they do not violate ambient standards at any receptor.
- The modified pollution offset system (McGartland and Oates) instead only allows trades that meet the following two conditions: ambient standards and pre-trade water quality are not exceeded at any receptor.
- The non-degradation (or constant emissions) offset system (Atkinson and Tietenberg, 1982) only permits trades that meet the following two conditions: ambient standards are not exceeded at any receptor and total emissions do not increase relative to the baseline.

This latter approach has, in effect, been applied through "regulatory tiering" in the U.S. acid rain program in which sulfur emissions are controlled both by the relations designed to achieve local ambient air quality standards as well as by sulfur allowance trading rules (Tietenberg, 2006).

Conceptually, each of these systems is expected to lower transactions costs relative to the ambient permit system because dischargers have only to be concerned with receptors that threaten to violate ambient targets, rather than all receptors that are affected by the discharger's emissions. However, such systems may create prohibitive administrative costs if ambient simulation models have to be conducted before each trade is approved (McGartland, 1988). This necessity elevates the costs to dischargers because they do not know the value of the permit beforehand and whether or not, once an application for a trade has been submitted, the trade will be approved (Hung and Shaw). Further, the right to increase emissions is endogenous or state-dependent: i.e., a trade between two sources affects deposition patterns and alters trading possibilities for other dischargers. Hence prices are endogenous, raising the costs of price discovery. Therefore, in the final analysis, these trading rules may only be useful in cases where, *a priori*, the regulators have simulated the consequences of trades in areas of concern, if diffusion coefficients are made available and if the number of receptors where violations are a concern is small and stable, in the sense that the number of potential violations does not change drastically with trades (Klaassen). As demonstrated by the correspondence between the non-degradation rule and the acid rain program, such policy conditions may be satisfied in specific instances.

b. Zonal Trading Systems

An alternative "feasible" approach to dealing with non-uniform mixing pollutants is a zonal permit approach: "In this approach, the control region is divided into a specific number of zones; each zone is allocated a zonal cap. In pure zonal systems, permits can be traded within each zone on a one-for-one basis, but trading among zones is prohibited (Tietenberg, 2006 p. 89). At one extreme, the emissions permit system mentioned above represents a single zone system, with an exchange rate of unity across dischargers. By incorporating trading ratios, defining trading zones, or combining both, we may modify this administratively simple system.

The single market ambient permit system defines all trades in terms of their effects on the worst case or most constraining receptor. As indicated above, such an approach has been utilized in water quality trading in the Long Island Sound and proposed for trading schemes elsewhere. In these circumstances, the ambient conditions of the other receptors are presumed to be met, as long as the conditions at this single receptor are met. Emissions permits are traded based of their ratios of impacts on water quality at the critical receptor. Such an approach is administratively facile, and provided that the dominance of the critical receptor is assured, is a potential least-cost means of meeting ambient standards. However, if such dominance is not actually the case, in either the short or the long term, then the emergence of hot spots may require that total allowable permits must be ratcheted down to avoid such outcomes. This would reduce any cost advantages from adopting a simpler exchange program.[11] Or in the case of the Minnesota Trading Program, the use of a single binding endpoint may have to be reconsidered (Hall, personal comments accompanying a formal presentation).

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[11] Tietenberg (2006) also raises long-run equilibrium concerns associated with the possibility that firms will relocate to distant points wherein the effect of emissions on the binding receptor is low.

This trading of permits within several zones has certain appeal on the surface.

> "It allows the regulatory agency to choose the size and location of zones, taking into account the spatial distribution of sources and possible differences in allowed [ambient] levels. Therefore it offers more protection for [ambient] targets than emission trading in one zone and reduces control costs. However, this is only the case when the environmental agency has complete and correct knowledge of control costs. With limited information, the cost will be above the cost minimum because emissions cannot be traded among zones. This is because without knowing the cost-minimum solution, the environmental agency does not know how many permits it should allocate to each zone. In addition, there is no protection against violation of the standards, even in small zones, because it is not exactly known where emissions will take place after trading" (Klaassen, p. 59-60).

Simulations based on full information about costs of each firm have demonstrated cost-effectiveness gains relative to standard emission permit programs (because in a single market without trading ratios distant sources over-control). However, Tietenberg (2006) concludes that in realistic circumstances with only limited information about discharger abatement costs, "zonal permit systems with no trading between zones do not appear promising…[they] do not in general provide much of an opportunity either to reduce costs or to control the hot spot problem" (p. 93).

This pessimistic conclusion has led to proposals to expand beyond no-trading zones to allow directional trading (as has been done in the RECLAIM program, see Harrison) or rely on exchange rates between zones. We now turn to one such proposal designed specifically for water quality trading.

c. A Trading-Ratio System for Water Quality

Recognizing that "[t]he fact that water flows to the lowest level uni-directionally is a very specific and useful property of water" (p. 83), Hung and Shaw designed a trading–ratio system that links emission permit trading to ambient water quality. From a theoretical perspective, these authors prove that, by assuming cost-minimizing dischargers and no transactions costs or strategic behavior, their proposed trading-ratio system is cost-effective for both simultaneous and sequential trading equilibria. The fact that, theoretically at least, the cost-effective outcome can be achieved by sequential trades is particularly significant because this concern has been underscored with respect to many of the rules and systems (Hahn 1986; Atkinson and Tietenberg 1991).

The trading-ratio system by Hung and Shaw is based on the assumptions that emissions at a site can be translated into ambient concentrations, and that the impact of these additional emissions on affected sites can be expressed fully by the diffusion coefficients defined above. By definition, the diffusion coefficient for an upstream discharger expressed in terms of a downstream receptor will be bounded by zero and one.

Downstream dischargers will not influence water quality at upstream sources or in other branches of the water body that are upstream from a point of confluence downstream from the source. In these latter cases, the diffusion coefficient between the i*th* source and the j*th* receptor, d_{ij}, will be equal to zero. To describe this system, assume further that the regulatory authorities can express the ambient standards at each receptor in terms of total load E^*_j and that each zone contains only one source.[12]

Hung and Shaw go on to assume that the environmental regulator divides the water basin into n zones, each with its own water quality standard based on the use of water in that zone. Zones are ordered and indexed from the most upstream ($n = 1$) to the most downstream zone ($n = N$).[13] The authority takes the existing load standards E^*_j as the environmental constraint for each zone, and sets the zonal effluent caps one-by-one working from the upstream to downstream zones, making use of the dispersion coefficients and the environmental constraints, "such that the zonal effluent cap is equal to the zonal total load standard minus the effluent load transferred from upstream zones" (p. 87). In cases where zonal effluent caps are all positive, the regulator can assign tradable pollution permits to each discharger corresponding to the zonal effluent cap. For the case of zone 1 there is no inflow of pollutants from upstream dischargers and the regulator sets the number of permits T_1 equal to the load standard E^*_1. However, for downstream zones, T_j is necessarily less than E^*_j because of inflow from upstream dischargers. In effect,

> "this approach endows an upstream zonal permit its downstream effluent rights because its downstream impacts have been fully considered. Dischargers therefore do not need to assemble a portfolio of [permits] for all zones that are affected by their effluents" (p. 88).

In this manner, the trading-ratio system avoids one of the major drawbacks of ambient permit systems.

Given this initial allocation, the regulator can go on to set trading ratios between zones equal to the corresponding dispersion ratios and allow dischargers to trade freely based on these ratios. When this dispersion ratio is also used as the trading ratio, d_{ij} is the increase in the volume of effluent by a discharger in zone j made possible by purchasing one pollution permit, T_i, from any other discharger. In the absence of strategic effects, a rational discharger j will only buy permits from upstream dischargers (i.e. $i < j$). This is because purchases from downstream dischargers (i.e. $i > j$) would not allow an increase in effluents as the respective trading ratio is effectively zero (p. 89).

Under this trading-ratio system, the regulator is assumed to bear responsibility for monitoring and assuring that dischargers equate their effluent levels to the effective number of permits held during any time period: this effective amount equals the initial permit allocation to the discharger, plus any permits purchased (from upstream dischargers) weighted by their corresponding trading-ratios, minus any permits that were

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[12] This latter assumption can be relaxed, but it is useful here for presentation purposes.
[13] Indexing can be adjusted to accommodate multiple branches.

sold by the discharger (to downstream dischargers – these permits are not weighted from the perspective of the seller). One advantage of this system is that the monitoring burden on the regulator is expected to be relatively light for point sources of water pollution. One reason is that there is no need to approve each trade because the trading ratios are *exogenously* predetermined, greatly reducing the administrative costs relative to trading rule approaches. This predetermination of the trading ratios also facilitates transactions because all dischargers can simply refer to a fixed trading-ratio table to find the trading ratios for every possible trade.

Another characteristic of this trading-ratio system is that the sequential setting of effluent caps and permit allocations may result in a permit cap of less than zero in a particular zone (i.e. the inflow from upstream sources exceeds the allowable effluents within a zone). Such a zone is identified as a critical zone, but Hung and Shaw describe a method for redefining allowable upstream dischargers in a cost-effective manner to account for these critical zones and to avoid hot spots.

In summary, Hung and Shaw demonstrate that the trading-ratio system can be cost-effective under standard assumptions. Appropriately implemented, such a system avoids the major disadvantages of ambient permits systems (maintaining a portfolio of permits for each site affected by a discharger's emissions), standard emission permit systems (hot spot issues), and trading rules (high administrative costs and endogeneity of trading ratios). On this basis, we believe that this system is the most promising alternative for meeting ambient water quality standards along the entirety of a water body in cases where there is no dominant receptor.

IV. Incremental Abatement Costs and Trading

Up to this point in the discussion, we have implicitly focused on open market trading conditions driven, conventionally, by trades based on differences in marginal abatement costs. That is, from a particular starting point, say, the initial allocation of permits, dischargers compare their marginal abatement costs for the last units. When there is a noticeable difference in abatement costs across firms, trades will occur in the direction of high marginal-abatement-cost firms paying lower marginal-abatement-cost firms to undertake abatement.

While marginal abatement cost is a useful theoretical construct, actual pollution abatement decisions often do not occur at the margin. Adding additional chemicals or other small changes allow additional abatement control in some instances, but, given initial capital configurations, there can be limits to such opportunities.

> "Generally, pollution controls are feasible to implement in relatively large installments that reduce multiple units of pollutants. Point sources in particular tend to purchase additional loading reduction capability in large increments. For example a wastewater treatment plant upgrade or plant expansion may be designed to treat millions of gallons a day" (US EPA, 1996, p. 3-2).

In addition to involving discrete jumps in costs, rather than smooth, convex marginal costs typically assumed in theory (see footnote 5), these investments involve capital expenditures that last over multiple periods. The discrete nature of these investments creates path dependence in the sense that starting from the initial set of capital investments and permit allocations is likely to deviate from an optimal portfolio of capital investments if every firm were able to start from scratch. The initial investment levels will also affect the optimum additional investment scheduling over time. When the number of trading units is small, these two interrelated factors have consequences for open market trading, and may tend toward favoring bilateral, intertemporal contracts. We briefly comment on these two points below.

a. Lumpy Investments and Capital Costs: Incremental Costs and Trading

Incremental abatement costs are similar to marginal abatement costs, the only difference being the units of change being considered. As above, marginal abatement cost refers to the additional cost associated with increasing abatement by one, usually small, unit. *Incremental cost* is defined as the average cost of incremental reductions. For example if additional abatement cannot be undertaken for small units, such as a pound at a time, but instead requires a discrete capital investment, marginal costs would be incalculable. However, incremental costs could be calculated by dividing the total costs of increasing abatement by the increment of abatement that occurs. If 100 pounds of abatement cost $2,000, the incremental cost would be $20 per unit.

For all intents and purposes, the basic trading principles are still the same as described previously – firms with high incremental abatement costs will tend to buy permits from firms with low incremental abatement costs. However, the fluidity of the market may be curtailed by the lumpiness of the transactions. Units of trade are no longer independent. If these incremental blocks are large relative to the market, there may be incentives to pursue bilateral negotiations and contracts rather than trade single permit. One such example is found in Breetz et al.'s discussion of the trading program in Bear Creek, CO, in which each year a large discharger (Evergreen Metro) reduces phosphorus release in a trade of 40-80 pounds per year so that a smaller discharger (Forest Hills) does not have to undergo a costly upgrade to its facilities:

> "It is estimated that Forest Hills saves over $1.2 million, the cost of an expensive system replacement that would be necessary to meet their allocation without a trade… In exchange for Evergreen Metro reducing their discharge, Forest Hills pays an undisclosed amount of money that has been estimated to be around $5,000 per year" (p. 28)

b. Capital Costs and Trade over Time

In large, fluid pollution permit markets with many traders, such as the nation-wide U.S. acid rain program, the distinction between marginal and incremental cost has little practical significance. This is because a discharger's decision to upgrade its facility is likely to have no noticeable effect on the market supply or demand for permits.

In smaller markets with few trading partners, firms that opt not to upgrade their systems fully are not guaranteed that a supply of permits will be available as a substitute at any price. In a similar manner, firms that choose to upgrade, base their decision, in part, on the presupposition that demand exists for their unused permits. When costly and irreversible capital investments extend over time, the consequences of uncertainty become larger if inter-temporal banking of permits is not allowed.[14] Firms that have relatively recently installed capital equipment seek assurance that an amply supply of permits exists so as to postpone costly, premature upgrades. Firms that undertake upgrades similarly desire that there will be a stable demand for their unused allowances over a period of time.

These arguments suggest that temporal dimensions and security of investments may be critical factors in permit trading, temporal efficiency in investment patterns, and the cost-effectiveness of pollution trading over time (Tietenberg and Johnstone; Vestergaard, Jensen and Jørgensen; Weninger and Just). Evidence from U.S. air quality programs (e.g. Hahn and Hester; Schmalensee et al.) suggests that firms have widely utilized opportunities for internal banking of permits across time in conjunction with investment decisions in the face of declining caps on the aggregate number of permits. Kerr and Newell's retrospective analysis of the U.S. lead phase down program found that the availability of permits allowed less efficient firms to avoid expensive abatement investments by buying permits. In a similar vein, Jones suggests that trading will enhance firms' abilities to time their capital investments optimally, leading to a 40 percent reduction in the present value of capital investments for a phosphorus program in the York Basin.

In summary, there are two implications of investment decisions that bear consideration in the design and organization of markets. First, because different firms are in different stages of their capital investment cycle, there may be benefits in implementing permit systems with declining caps over time as has been done in the U.S. lead phase down and the sulfur dioxide air pollution programs. A similar approach is being utilized in the Long Island Sound water quality trading program (Stacey). Second, in small markets without banking, such as might be expected in most watershed-based trading, certainty in investment decisions may be enhanced by pursuing long-term bilateral negotiations and contracts rather than simply relying on current market conditions and projections of market prices in the future. Simply stated, there may be gains from moving beyond annual market transactions to more structured trading focusing on bilateral negotiations and multiyear contracts[15]. Alternatively, as we discuss below, pollution clearinghouses

[14] Banking allows firms to save pollution permits for future use in trading. Hahn and Hester's analysis of the lead phase down program suggests that banking across years was an effective way of smoothing out pollution abatement and investment costs across years. To our knowledge, however, the opportunity for banking has not been raised as an option in discussions of water quality trading.

[15] However, as discussed in Boisvert et al. (2006), there may be legal impediments to multi-year contracts that extend across licensing periods.

may allow individual dischargers to make more efficient capital abatement investments over time.

V. Market Structures to Exchange Property Rights

As suggested in the preceding discussion, the design of the trading system can, to some extent, be separated from the market structure used to facilitate trades. The trading system defines the basic commodity or rights to be traded. The market structure, also referred to as a trading program, governs the mechanics of exchanges in pollution rights that allow dischargers to satisfy regulatory pollution reduction requirements by arranging to reduce pollution from another discharger.[16]

a. Property Rights[17]

As Dales stressed in his early writings, tradable permit programs are about the exchange of property rights. Property can be conceived of as a stream of benefits over time. Property rights define an individual's (or group's) access to this stream of benefits relative to others (Bromley 1991). In devising tradable permit systems, Devlin and Grafton (see also Grafton et al.) argue that the success of a trading program will depend greatly on how these rights are defined. The most successful trading programs appear to be those that most closely correspond with private rights regimes.

Following Devlin and Grafton, regimes of property rights can be described using six characteristics: exclusivity, divisibility, quality of title, transferability, duration, and flexibility. *Exclusivity* refers to the important characteristic of being able to exclude others from access to the benefit stream. This is necessary for any secure property rights regime. *Divisibility* pertains both to the ability to separate the benefit stream from other activities of the firm and to the degree that the rights in question can be ascribed to small units or increments. *Quality of Title* corresponds to the extent that the right is recognized by law and the corresponding ability to call upon the collective to enforce these rights. *Transferability* indicates the nature of any constraints placed on the ability to transfer those rights to others. *Duration* represents the time horizon over which an individual exercises the right. *Flexibility* refers to how the property right can accommodate changes in both the assets and circumstances of the rights-holder.

A convenient way of subjectively characterizing these dimensions is provided by the hexagonical depiction in Figure 3. In this figure, each side of the hexagon represents one of the six characteristics. The arrows emanating from the center convey the dimensions

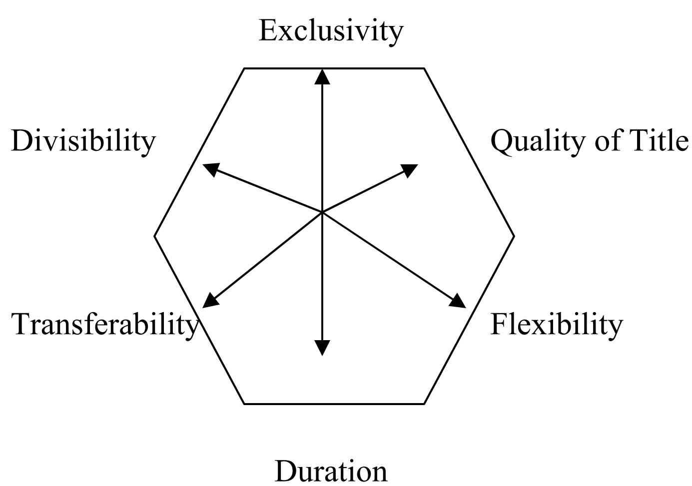
[16] This definition follows closely to that used by Woodward, Kaiser and Wicks and Woodward and Kaiser. However, we limit our "arrangements" to be with "other dischargers" while they more broadly consider opportunities to reduce pollution through "nonstandard means in lieu of reductions in normal effluent streams" (Woodward and Kaiser p. 379). For example, these authors cite the City of Boulder's restoration of a riparian zone to meet associated TMDL and avoid future capital investments in wastewater treatment as an example of such "sole-source offsets." Our focus is more limited to trading of effluents between dischargers.

[17] This sub-section closely follows that of Devlin and Grafton and Grafton et al.

of the characteristic: the longer the arrow pointing to a particular characteristic, the greater is the dimension of the characteristic and the closer that characteristic is to what would be true for a normal, private good. Thus, in Figure 3, the right has full dimension in terms of quality of exclusivity, but a relatively lower dimension in quality of title.

The dimensions presented in Figure 3 reflect those used in Devlin and Grafton's (p. 60-61) discussion of the successful U.S. acid rain program in which allowances to emit SO_2 are for the *exclusive* use of their owner, typically the electricity-producing utilities. They are *transferable* with few restrictions on their ability to be sold. Each unit of pollution is separable from other production activities, and is for one ton, so the dimension of *divisibility* is quite high. Allowances are also *flexible* in the sense that they can accommodate changes and remain a viable asset. For example such allowances remain a valuable commodity even if the owner exits the industry. These authors state that,

Figure 3: Property Rights and their Characteristics (Adapted from Devlin and Grafton)



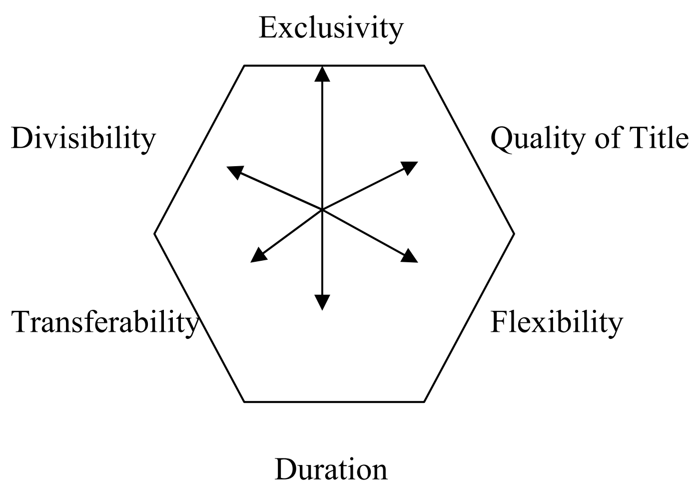
> "As far as the quality of title to these rights is concerned, it would appear to be well developed. However, the right itself does suffer from the same problem as all artificially-created assets in that its value depends crucially on the reliability and the durability of the policy that created it in the first place. So, for instance, the right is durable only insofar as the Clean Air act is not revised again to dismantle the program."

Hence, they subjectively rate the *durability* and *quality of title* marginally less than ideal.

A comparison of Figure 3 with the dimensions depicted in Figure 4 by Devlin and Grafton for the Fox River Discharge Program is particularly instructive. Only one trade occurred in this Fox River program, a result that Devlin and Grafton and others (e.g.

Hahn, 1989) attribute in part "to the complex administrative requirements and regulations associated with trading" (p. 54). In this program, the property right was established over biochemical oxygen demand discharges expressed in ambient terms. Although the right was, in principle transferable, many administrative criteria hampered the actual operation of the market. The quality of title associate with the property right was poor because the relationship between emissions and ambient quality at a receptor site was not clearly specified. The right was also of low duration, since it lasted for only the five-year time horizon of the NPDES permits with no guarantee beyond this period. Finally, the pollution right had some degree of flexibility in the sense that its value depended on, and indeed varied in response to, the activities of surrounding dischargers and the environmental conditions. However, the value of a permit was dependent upon the specific conditions at the seller's and purchaser's monitoring sites, making this property right quite inflexible (Devlin and Grafton, p. 54). In brief, as depicted in Figure 4, the dimensions of the rights associated with the Fox River permit deviated from an optimal regime, and likely contributed to the failure of the trading program.

Figure 4: The Fox River Discharge Program
(Adapted from Devlin and Grafton)



b. Transactions costs

The theoretical models demonstrating the potential cost-effectiveness of alternative trading systems all come with the caveat that there are assumed to be no transactions costs. Transactions costs arise from the transfer of property rights because the parties involved in trades must gather and exchange information about what particular opportunities for trade are possible and on what terms, develop contracts to specify the terms of exchange, and monitor and enforce these contracts and exchanges. A facile acronym for remembering these categories of transactions costs is ICE, representing information, contracting and exchange (Bromley, 1991). Although assumed away in most theoretical presentations, these costs represent resource costs in terms of time or money expended to undertake and enforce an exchange.

Transactions costs act to drive a "margin between the buying and selling price of a commodity in a given market" (Stavins p. 134). For example, in a discussion of the U.S. lead phase down program, Godard states that despite

> "...limited regulatory bureaucracy (no ex ante approval of trades required) and pre-existing routine transactions of various products among participating refineries… in spite of that, transactions costs have been estimated in the range of 10 to 20% of the potential economic gain of the program. This means that if a [trading permit] program is expected to reduce costs of a given environmental achievement by 50%, the actual benefits may not be more than 40%, even when the program is well designed and flexible" (p. 12-13).

By reducing the gains from trade, these costs will affect the level of trading. Kerr and Maré and Gangadaharan estimate that transactions costs reduced the probability of trading by 10-20 percent in the U.S. lead phase down program and by 32 percent in the Los Angeles Basin Regional Clean Air Incentives Market (RECLAIM). Based on this and other evidence provided in Tietenberg and Johnstone, it appears that transactions costs are of "considerable importance" and "a significant factor in many actual trading schemes" (p. 17, p. 23).

c. Market Structures

This recognition of an inverse relationship between transactions costs and the level of trading underscores the importance of considering transactions costs explicitly in designing actual market structures for pollution permit trading systems (Hahn and Hester). According to Woodward and Kaiser, such consideration might enter into discussions of the design of market structures in two ways. One approach has been to view transactions costs as a wedge between the performances of actual trading programs with those of an ideal "frictionless" market. Along these lines, Stavins argues that the existence of such costs drives the much-observed disparity between ex ante and ex post estimates of cost savings. Viewed from this perspective, a natural role for "government is to find ways to reduce transaction costs to move the market closer to the ideal" (Woodward and Kaiser, p. 374).

A second perspective furthered by Woodward and Kaiser is to recognize that transactions costs are inevitable in any market structure and that policy efforts should be directed toward identifying market structures appropriate to specific trading settings. Thus, it is not appropriate to define a market structure in isolation from the particular circumstances of the particular effluent and corresponding market system. Just as different market structures have arisen naturally for exchanging goods -- ranging from commodity exchanges to grocery stores to one-on-one negotiations – one should expect constructed pollution trading systems to differ with trading environments. Within their framework, three different pollution trading market structures are identified: exchange markets, bilateral negotiations, and clearinghouses. To understand these alternative market systems, we draw heavily from the clarifying work of Woodward and co-authors in their discussions of market structure for water quality trading (see Woodward and Kaiser, and Woodward, Kaiser, and Wick)

Exchange markets are what one typically thinks of when envisioning a market trading structure, and it is one that closely corresponds to the market system successfully implemented in the acid rain program. In exchange markets "buyers and sellers meet in a public forum where prices are observed and uniform goods are traded. At any one time, there is a unique market-clearing price…" (Woodward and Kaiser, p. 374). Exchange markets are relatively transparent: entering into a trade simply involves comparing the going price with the marginal cost of provision of a unit (for sellers) or the marginal value of an additional unit (for buyers). If these comparisons are favorable, then the item is exchanged at the going price and transactions costs remain relatively low. The success of such markets, however, rests on the uniformity of the product and the depth of the market. Uniform, or standardized products, enable participants to simply react to price. The depth of the market indicates the extent to which no single participant can influence price; that is, all participants are price takers. Woodward and his co-authors argue that such conditions are not representative of water quality trading opportunities. Because of non-uniform mixing, it is difficult to achieve uniformity of permits or credits. Due to the directional impact of pollutants, trading opportunities are limited and hence markets may be relatively thin (Woodward). Hence, Woodward and Kaiser (p. 376) conclude that "[i]f agencies attempt to force a [water quality trading] program into an exchange framework, the results are likely to be disappointing."

When characteristics of the good are variable and seller specific, the "law of one price" associated with exchange type markets simply does not pertain. Further, when markets are thin, information on prices and the price of characteristics is likely to be limited. As such, ICE transactions costs are expected to be relatively high. Under such conditions, a market based on *bilateral negotiations* "in which each transaction requires substantial interaction between the buyer and the seller to exchange information and negotiate the terms of trade" (Woodward, Kaiser and Wicks) may be a preferred market structure. In the past, bilateral negotiations have emerged as the most common form of water quality trading, and Woodward and Kaiser conclude that this structure is the most suitable and likely the most common form for future water quality trading programs. As we have suggested above, bilateral negotiations have a further advantage. They allow for inter-temporal exchanges to accommodate different patterns of capital investment between dischargers.

Both exchange markets and bilateral negotiations involve direct transactions and contractual links between buyers and sellers. In a third market structure, referred to as a *water-quality clearinghouse*, this direct link between buyers and sellers is broken by an intermediary. Woodward and Kaiser define the clearinghouse market structure as one in which the state or some other entity purchases pollution allowances or pays for pollution reductions and then sells the corresponding permits or credits at a fixed price to dischargers seeking to exceed their load allocation. This approach has the advantage that transactions costs may be reduced because sellers only have to deal with the clearinghouse, and potential buyers simply make decisions based on specified permit prices. Such reductions in costs, however, do come at some disadvantage. Since prices are determined by an intermediary, trades are no longer based on the comparison of marginal costs and benefits. This may lead to inefficiencies. In particular, as has been the case of applications of this approach in the Tar Pamlico Basin and the Long Island Sound water quality trading programs, the exogenously determined price may be such that the markets do not clear. For example, in the Long Island Sound program exogenously set prices for credits have been associated with "over abatement" and an excess of credits purchased relative to those sold. In 2004 this imbalance was absorbed by the State of Connecticut at a cost of $873,068 (Connecticut DEP). Due to the exogenously determined price, some have argued that because of the disconnect between buyers and sellers, a fixed price clearinghouse program resembles an effluent tax-subsidy mechanism (Caton; North Carolina DWQ). Despite these disadvantages and possible reservations, Woodward and Kaiser (p. 379) conclude, "We believe that clearinghouses will find a sustainable niche in [water quality trading]."

It is possible that the similarity of clearinghouse trading structures to tax subsidy mechanisms could be an advantage from the perspective of optimal investment over time. Knowing that additional permits could be purchased at a relatively certain price may be viewed as an advantage over annual exchange markets for firms that seek to postpone investments for a number of periods. Similarly, when overall emissions are being phased down, as in the Long Island Sound trading program, a firm that "over abates" relative to a current standard, in part to anticipate a more restricted allocation in future periods, can do so with the assurance that its excess permits can be sold at a certain price. In essence, to a limited extent, the fact that clearinghouses need not equate supply and demand might allow individual dischargers to capture some of the benefits associated with banking of permits.

d. Is Trading Needed to Achieve Cost-Savings?

The discussion above has centered on identifying alternative market structures to enhance trades. Implicit in this discussion is that trades are needed in order for cost savings to be achieved. Contrary to this view, there is some literature that suggests that this need not be the case. For instance, despite the fact that no external discharger-to-discharger trading has occurred in the Tar-Pamlico Basin Nutrient Trading Program [Environmental Trading Network], this program is widely cited as being a success in terms of cost savings and pollution load reduction.

> "…trades are not necessary for trading programs to realize cost savings and achieve environmental goals. Water quality trading offers a flexible solution for point sources to phase in technology upgrades or optimize existing technology to meet more stringent discharge requirements. This flexibility alone is sometimes enough to introduce substantial load reductions and cost savings. For example, the point source association in the Tar-Pamlico River program, faced with collective load limits for phosphorus and nitrogen, was able to maintain discharge levels below the limits despite population growth; mostly via changes in in-plant management practices." (Kieser and Feng, p. 8).

Woodward similarly concluded that by simply offering the opportunity for trading, with the associated flexibility it entails, may by itself engender cost savings even if trades are "few and infrequent."

VI. Concluding Discussion: Main Points

Below, we provide a summary of the main themes that have emerged from this review. Taken together, the major point is that there are potential gains in cost-effectiveness from implementing water quality trading programs to meet TMDL regulations at the watershed level. These potential gains may be difficult to achieve, however, and it is likely that, because of the specific nature of water quality, watersheds, and the lumpiness of capital investments, any cost savings that actually accrue will not be associated with the establishment of open, exchange-like markets. Instead savings may simply be realized by dischargers independently taking advantage of the flexibility associated with trading programs and to an extent, structured bilateral negotiations between dischargers.

The following summarizes the main points of this review that have led us to reach these conclusions.

1. Translating textbook theory of pollution trading programs into actual practice is difficult. Despite substantial effort to establish water quality trading programs, there has only been a handful of successful trades.

2. The likelihood of success associated with trading is directly proportional to potential gains from trade derived from differences in discharger marginal or incremental abatement costs after accounting for biophysical transport and dispersion. When these differences are not large or pervasive, the gains from developing a watershed wide trading program will be limited. This should be of particular concern in settings in which abatement technologies are fairly homogeneous across dischargers.

3. A trading-ratio system recently presented by Hung and Shaw offers the most appropriate way to meet water quality standards in settings in which there are several spatially distinct, binding ambient water quality standards. When there is a dominant single receptor, and hot spots are not a dominant concern, then a single market ambient permit system, which represents a simple variant of the trading-ratio system, is appropriate.

4. Because of thin markets and the lumpiness of capital investments, exchange markets are expected to have low trading performance for water quality trading programs. Because of non-uniformity in mixing and limited numbers of trading opportunities, a structured bilateral trading approach with contractual relationships across periods appears to have many advantages. To the extent that a central authority is willing to absorb the financial consequences of trade imbalances, a clearinghouse market structure may be desirable.

5. Recall that the objective of environmental regulatory design is to cost-effectively reduce pollution to a specified level. Even if trades are few, there may be notable gains associated with establishing pollution trading programs because of the flexibility embodied in pollution permit programs.

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Appendix A: Cost Effectiveness for Uniformly-Mixed Assimilative Pollutants

Assuming that there are i=1,2…I firms in a uniformly mixing assimilative pollution setting, the optimization problem can be specified formally as:

$$\underset{e_1, e_2, \ldots e_I}{Minimize} \quad \sum_{i=1}^{I} C_i(e_i^o - e_i) \qquad \text{(A.1a)}$$

$$\text{Subject to} \quad \eta + \beta \sum_{i=1}^{I} e_i \leq A^* \qquad \text{(A.1b)}$$

$$e_i \in [0, e_i^o] \quad \forall i \qquad \text{(A.1c)}$$

where

$C_i(.)$ = costs of abatement,
e_i^o = unregulated emissions, firm i,
e_i = emissions under abatement program,
η = natural background levels or other (e.g. non-point sources) pollution sources.
β = factor of proportionality converting emissions levels (e.g. pounds) to ambient concentrations (e.g. mg/l), and
A^* = targeted ambient pollution levels.

Assuming continuity and convexity of the abatement cost function, denoting first derivatives (i.e. marginal cost) with a " ' ", and letting λ be the LaGrangian multiplier (i.e., the shadow price on the ambient constraint), the corresponding necessary and sufficient Kuhn-Tucker conditions for a cost-minimizing solution are:

$$C_i'(e_i^o - e_i) - \lambda\beta \geq 0 \quad \forall i \qquad \text{(A.2a)}$$

$$(e_i^o - e_i)[C_i'(e_i^o - e_i) - \lambda\beta] = 0 \quad \forall i \qquad \text{(A.2b)}$$

$$\eta + \beta \sum_{i=1}^{I} e_i - A^* \leq 0 \qquad \text{(A.2c)}$$

$$\lambda(\eta + \beta \sum_{i=1}^{I} e_i - A^*) = 0 \qquad \text{(A.2d)}$$

$$e_i \in [0, e_i^o] \quad \forall i, \quad \lambda \geq 0 \qquad \text{(A.2e)}$$

Recognizing that λ and β are not indexed by i, equation A.2b implies that a necessary condition for an interior solution with positive abatement is that the marginal costs of abatement are equalized across firms. This is the equimarginal principle discussed in the text. Equation A.2c indicates that either the required target level of ambient quality is met exactly or the shadow price is zero.

Appendix B: Cost Effectiveness for Nonuniformly-Mixed Assimilative Pollutants

Assuming that there are i=1,2…I dischargers, and j=1,2…J receptors in a non-uniformly mixing assimilative pollution setting, the optimization problem can be specified formally as:

$$\underset{e_1, e_2, \ldots e_I}{Minimize} \quad \sum_{i=1}^{I} C_i(e_i^o - e_i) \qquad \text{(B.1a)}$$

$$\text{Subject to} \quad \eta_j + \beta \sum_{i=1}^{I} d_{ij} e_i \le A_j^* \quad \forall j \qquad \text{(B.1b)}$$

$$e_i \in [0, e_i^o] \quad \forall i \qquad \text{(B.1c)}$$

in which the parameters correspond to the definitions in Appendix A, with the exception of:

η_j = natural background levels or other pollution sources at the jth receptor,
d_{ij} = the diffusion coefficient as defined in the text, and
A_j^* = Targeted ambient pollution levels at receptor j.

Assuming continuity and convexity of the abatement cost function, denoting first derivatives with a " ' ", and letting λ_j be the LaGrangian multiplier (i.e. the shadow price on the ambient constraint) corresponding to the jth receptor, the corresponding necessary and sufficient Kuhn-Tucker conditions for a cost-minimizing solution are:

$$C_i'(e_i^o - e_i) - \beta \sum_{j=1}^{J} d_{ij} \lambda_j \ge 0 \quad \forall i \qquad \text{(B.2a)}$$

$$(e_i^o - e_i)[C_i'(e_i^o - e_i) - \beta \sum_{j=1}^{J} d_{ij} \lambda_j] = 0 \quad \forall i \qquad \text{(B.2b)}$$

$$\eta_j + \beta \sum_{i=1}^{I} d_{ij} e_i - A_j^* \le 0 \quad \forall j \qquad \text{(B.2c)}$$

$$\lambda_j(\eta_j + \beta \sum_{i=1}^{I} d_{ij} e_i - A_j^*) = 0 \quad \forall j \qquad \text{(B.2d)}$$

$$e_i \in [0, e_i^o] \quad \forall i, \quad \lambda_j \ge 0 \quad \forall j \qquad \text{(B.2e)}$$

Equation B.2b indicates that for positive levels of abatement, a cost-effective solution requires each firm to equate its marginal costs of abatement to the sum of the shadow prices of the total load constraints for all affected receptors weighted by the corresponding diffusion coefficients. It further implies that in equilibrium firms no longer equate marginal costs of abatement as for uniform-mixing settings. Instead, letting k represent a second discharger, the optimal solution implies the following relationship:

$$\frac{C_i'(e_i^o - e_i)}{C_k'(e_k^o - e_k)} = \frac{\sum_{j=1}^{J} d_{ij} \lambda_j}{\sum_{j=1}^{J} d_{kj} \lambda_j}$$

In the case presented in Figure 2 of the text, where there is one receptor j = d (downstream) and two sources, i = downstream and k = upstream, this implies that the ratio of marginal costs $C_D' / C_U' = d_{DD} / d_{UD} = 1/0.5 = 2$, as indicated.