Efficiency and Political Economy of Pollution Control with Ancillary Benefits: An Application to NOx Control in the Chesapeake Bay Airshed

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Abstract

This paper examines implications for cost-effective allocation of pollution controls when preferences of coalitions organized along regional lines, or according to preferences for air vs. water quality improvements, are accounted for. Results are compared to a base case in which NOx emissions reductions must satisfy only a water quality standard, and total costs are minimized over emissions sources. Relative to base-case result that marginal control costs must be equal across sources, stronger relative preferences for air imply shifting of control toward sources that produce greater ancillary benefits to air quality. Regional differences may require side payments to induce cooperation where benefits are low, but this will not affect how controls themselves should be allocated.

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I. INTRODUCTION

It is now accepted that emissions of nitrogen oxides into the air are a major source of nutrient enrichment in the Chesapeake Bay, comprising anywhere from 10% to 40% of the Bay's nitrogen oxide (NOx) loadings. As a result, policies to reduce air emissions of NOx have become an important focus of attempts to reduce Bay nutrient levels. Because air emission reductions have an impact on both air and water quality, important issues arise about the efficient level of control of air sources, about the allocation of the costs of control between air and water, and about the political economy of achieving an efficient or cost-effective allocation.

Although there has been considerable work on the allocation of costs when there are multiple beneficiaries of improvements in a single environmental medium (P. Young *et al.*, 1982 in the case of water benefits), there has been little work examining the efficient allocation of controls across multiple sources, or when multiple media are affected by those controls, or of the allocation of the *costs* of control. Unlike conventional optimization problems that are solved for the efficient outcome, and for which the distributional effects that follow are simply described, in our analysis the distributional concerns are represented in the model and can

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influence the efficient outcome. The analysis of cost allocation transforms the problem into one of political economy rather than of efficiency.

The Chesapeake Bay case provides a unique opportunity to examine these issues, and to do so in a unified analytical framework. Insights about appropriate ways to allocate costs will have bearing on the current policy debate about how to assign the costs of controlling airborne NOx when both air and water media are affected. The assignment of costs may directly influence, in turn, the amount of emissions control that is instituted at each source -- for it is these allocated (or assigned) costs which enter into the cost-effectiveness calculations that determine the optimal amount emissions controls at each source.

Previous studies on the effects of air emissions controls on water quality have assigned all of the costs of control to the water benefits, ignoring the impacts of these controls on air quality through reduced ambient ozone and particulate levels. (In an appendix we present E.H. Pechan and Associates' (1996) estimated costs of nitrate reduction in the Chesapeake Bay.) This overstates the costs of reducing water pollution through air emissions controls. How control costs should be allocated, between air and water as well as between disparate emissions sources, and how much control should be undertaken at each source, remain unanswered questions.

This paper takes some first steps toward resolving some of these issues. We develop several models of optimal emissions control under various constraints. We construct a model where the only environmental standard is on the water side, but where ancillary air benefits from emissions control are recognized and accounted for. We also examine the case where NOx emissions control must achieve both air and water quality standards. We derive as a basis for comparison the optimal control strategy for water quality improvements under a simple *cost-minimization* regime that ignores ancillary benefits in air quality and is constrained only by the water standard.

Because a significant number of the NOx sources affecting the Chesapeake Bay are far upwind of it, and will enjoy fewer of the benefits from controls on their emissions, there may be more resistance from upwind regions to controlling emissions for improved Bay water quality. We address this possibility by adding political economy constraints to the problem. A different kind of political economy constraint is used to represent differing preferences for improvements in air quality *versus* water quality. This allows us to investigate the influence of control cost allocations within a source (over the joint air and water benefits it produces) upon optimal levels and distribution of emissions controls across sources. Cost allocations are not limited to such accounting exercises, but can also involve side payments between sources. The kind of cost allocation method used will depend on the preferences of those facing the control costs. The "rationality" and "fairness" constraints, which govern cost allocation decisions, are especially relevant in addressing issues arising from trans-regional air transport of pollution. Our interest here is to see how these political constraints affect the allocation of *emissions controls* across sources.

The models presented here will ultimately be used as the basis for an empirical analysis of cost-effective policies to reduce nutrient loadings to the Bay. The analysis will extend Pechan's earlier work (1996) to look at a broader set of policy alternatives, and to include ancillary (air) benefits in the analysis. Based on Pechan's cost estimates, and our theoretical models, optimal policies can be estimated empirically and compared to more traditional command and control policies. In addition, the "shadow prices" of the environmental standards for NOx loadings from air sources can be estimated and compared to shadow prices of nutrient reduction due to water-based controls. If they are out of balance, future reductions of NOx loadings should come first from the medium (air or water) which has the lower shadow price of control.

II. COST MINIMIZATION

The effect of accounting for so-called "ancillary benefits" will be to shift the control of NOx emissions toward sources generating greater ancillary benefits for a given amount of loadings reduction in the water. This outcome may differ from one where air quality is not considered an ancillary benefit, but must also meet a standard. Beyond investigating the effects of different combinations of environmental standards, we also consider the effects of various methods of allocating control costs. Interest groups organized by location or by emissions source may credibly threaten to limit their participation to match the benefits they receive in their region or at their source. Alternatively, if there is debate over willingness to pay for water- (or air-) quality improvements, individual preferences may need to be accounted for, with costs *within* individual sources allocated to the jointly-produced air and water benefits according to the relative levels produced at that source. We contrast the optimal allocation of emission *controls* across sources with what is implied by a base-case cost minimization model constrained only by a water quality target.

Adopting the notation used in Teitenberg (1985), in the benchmark model we seek to minimize total control costs over *J* sources of nitrogen oxides[1] given that we must reduce total Bay NOx loading to some pre-established limits $\overline{W_i}$ at each of *I* measurement locations. (If loadings are uniformly mixed, there will be only a single location and one limit $\overline{W}$, but for generality we will assume multiple locations.) Letting $c_j(r_j)$ represent the cost of reducing NOx emissions at source *j* by the amount r_j -- from some baseline emissions level $\overline{e}_j$ -- and letting the function $L_{ji}(\cdot)$ map NOx emissions at source *j* into Bay loadings at site *i*, the objective is simply to minimize the aggregate cost of those reductions across all sources subject to achieving the water quality targets. The objective is:

$$\min_{r_j} C(R) = \min_{r_j} \sum_{j=1}^{J} c_j\left(r_j\right), \tag{1}$$

subject to

$$-\overline{W_i} + \sum_{j=1}^{J} L_{ji}\left(\overline{e}_j - r_j\right) \leq 0 \tag{2}$$

That is, the regulator seeks to find the least expensive way of assuring that loadings L_{ji} of the emissions remaining after controls are installed, $\left(\overline{e}_j - r_j\right)$, are no greater than the

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[1] It is an open question how those *J* sources are selected. An extension of our work would be to derive the optimal extent of a regulatory region. This would involve trading off between regulator power, which presumably is greater the fewer sources that must be controlled, and costs of environmental control -- as extending the boundary could lower costs by creating increased gains from trading over a larger market, as well as possibly bringing large emissions sources under the control of the regulator.

imposed water quality standard $\overline{W}_i$. Total costs, summed over all emissions sources, are given by *C(R).* To achieve an optimum given that reductions r_j must be non-negative -- as must be the LaGrange multiplier λ_i on the environmental standard in (2) -- the Kuhn-Tucker conditions (see, *e.g.*, Varian, 1992) must be satisfied. The key first-order condition for cost minimization, which we explain below, is:

$$\frac{\partial c_j}{\partial r_j} - \sum_{i=1}^{I} \lambda_i L_{ji} \geq 0 \,. \qquad (3)$$

Cost minimization will not be achieved unless a complementary slackness condition is also satisfied, guaranteeing that for every source that optimally reduces its NOx emissions *(i.e.,* r_j>0), condition (3) is met with equality. In other words, at the optimum point, all sources are controlled to where their marginal control costs equal the sum of the "shadow prices" λ_i of the environmental standards, weighted by the loadings L_{ji} of their NOx emissions at each Bay receptor. For the single receptor (or uniform mixing) case, (3) implies that *sources are controlled to where the ratios of their marginal control costs, MC_j , to their Bay loading factors L_j are all equal:*

$$\frac{MC_j}{L_j} = \lambda = \frac{MC_{j'}}{L_{j'}}$$

for any sources j and j'. Sources with marginal costs too high to achieve this would not reduce their emissions.

This outcome can be achieved by regulatory fiat, but it has been shown elsewhere that a market-based, tradable permit approach, where permits for emissions producing total loadings of $\overline{W}_i$ at each receptor *i* can achieve the same outcome. (See Montgomery (1972) for initial development of a trading model in this context, and Krupnick *et al.* (1983) for refinements.) Equilibrium permit prices of $P_i = \lambda_i$ would arise at each receptor and, subject to the qualifications in Krupnick *et al.* (1983), would achieve the cost-minimizing outcome without regulatory intervention (beyond issuing the correct number of permits). Separate markets would exist for permits specific to each receptor. The initial allocation of the permits need have no effect on the outcome. Under this scheme, low-cost sources would reduce emissions beyond what they are permitted to emit, and would sell their excess permits at price P_i to high-cost sources.

III. ACCOUNTING FOR ANCILLARY AIR BENEFITS

The control of NOx sources to achieve water quality goals will inevitably also create benefits from improved air quality. These ancillary air benefits must be accounted for if emissions controls are to achieve the water quality standard in a socially optimal manner. Here the problem is one of social welfare maximization, rather than of cost minimization, given an imposed water quality target. That is, we seek to maximize ancillary air benefits B_a net of the costs of achieving the water standard:

$$\max_{r_j} B_a\left[\sum_{j=1}^{J}\sum_{k=1}^{K} d_{jk} \cdot r_j\right] - \sum_{j=1}^{J} c_j\left(r_j\right) \tag{4}$$

subject again to constraint (2). Here d_{jk} is a source-receptor matrix mapping emissions at source j to concentrations at (air) receptor k; c_j , and r_j are as before. (Note the substitution of "concentrations" for "loadings" when the context switches from water quality to air quality.) The first-order condition for maximization of (4) which is analogous to the first order condition (3) is:

$$\frac{\partial B_a}{\partial r_j}\sum_{k=1}^{K}\delta_{jk}-\frac{\partial c_j}{\partial r_j}+\sum_{i=1}^{I}\lambda_i L_{ji}\leq 0 \tag{5}$$

As before, complementary slackness implies that the optimal point of control occurs when marginal control costs *net of marginal ancillary benefits* are equal to the weighted shadow prices of the constraints. This can be seen by rearranging terms in (5):

$$MC_j - MB_{a_j} = \sum_{i=1}^{I}\lambda_i L_{ji}.$$

(MB_{aj} is the marginal ancillary benefits, $\partial B_a / \partial r_j$, from controlling source *j.)* Where uniform mixing is assumed, this condition simplifies to

$$\frac{MC_j - MB_{a_j}}{L_j} = \lambda = \frac{MC_{j'} - MB_{a_{j'}}}{L_{j'}} \tag{6}$$

for any two sources *j* and *j'*.

Three important results are implied by this equation. First, rather than controlling all sources to where their marginal control costs equal $L_j\lambda$, the shadow price of the constraint weighted by their individual loading factors, here sources which produce air benefits are controlled more than they otherwise would be, as an increasing function of those air benefits. Second, accounting for the air benefits implies a different shadow price λ than before, one that reflects the true social cost of the water-quality target. Finally, and perhaps most important, the air benefits are external to the Bay clean-up. A trading market for Bay nutrients would not achieve the optimal outcome unless a mechanism were designed to reflect each source's ancillary benefits in the price of its permits. The straightforward system for the benchmark, cost-minimization model would not work here.

As a generalization of the ancillary benefits model, consider the case where both air and water targets are imposed, and neither type of benefit is considered ancillary. With ancillary benefits out of the objective function, the problem once again becomes one of cost minimization. In the case where there is only one receptor for water quality, we can assert that only one set of constraints will be binding. Meeting the atmospheric NOx loading target for the water either requires such stringent air emissions controls that the air quality targets are also met, or it does not. In the former case, the water targets bind. In the latter case, it is the air standards.

This statement may need some refinement for the case where there are multiple water targets (or there is non-uniform mixing in the one target). However, for the simplifications adopted in (6) and in what follows, this assertion applies. It will be invoked in working out some of the less immediate implications in the analyses which follow.

IV. COST ALLOCATION ACROSS SOURCES

We next consider how political reality can require additional constraints on (5). These constraints concern how the *costs* of control are allocated across--or within--sources. As we show, cost allocation can alter the allocation of *controls* across emission sources.

There are two different cases to be considered. One concerns coalitions that are linked to individual sources and have some "hold-up" power. That is, sources cannot be compelled to install controls, but must be satisfied in some relation to the benefits they will receive from those controls. The other kind of cost allocation accounts for the different valuations people will have for air benefits *versus* water benefits. Allocating an individual source's control costs according to its relative levels of water and air benefits can affect the optimal amount of emissions control for each of the sources.[2]

Coalitions organized around emissions sources and possessing hold-up power require the addition to the model of constraints that assure the "participation" of these coalitions. Accounting for ancillary benefits, the objective function to be maximized remains expression (4). Two sets of constraints are added to the constraints on water quality, (2). Participation constraints assure that the amount of control at each source is individually rational for that coalition to undertake. In the extreme case that the regulators have no coercive power over the coalitions, each coalition's "threat point" will depend solely on the benefits it receives from its own actions, ignoring the benefits all others receive from its actions. If the regulators are indeed held up to this point, they will not necessarily be able to achieve a full allocation of all control costs. They may have to make a transfer from the public sector to the sources fully to cover costs in this case.

Such a transfer actually would have no real effect on the allocation of *emissions control*, so to make this model consistent with the others, we shall assume that the regulators do possesses power sufficient to impose control costs beyond individual threat points, but that they must accept some form of participation constraints.[3] Here the regulators balance the requirement of a full cost allocation against the political constraints by allocating *total* program

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[2] When this cost accounting, which is internal to each individual source, has real effects on the amount of control, it must also affect the allocation of controls across all sources. We do not explore the implications of this here.

[3] Since the implications for emissions reduction are the same, the requirement of a wealth transfer in the case of no coercive regulatory power is the only interesting difference between that case and the one analyzed here.

(control) costs over *all* sources in such a way that no source incurs costs greater than the share of total program benefits (in air and water) achieved by controls at that source. This scheme appeals to some notion of fairness in that the benefits of control at a source are related to the damages for which that source is responsible.[4] With full cost allocation, the regulators' participation constraints are:

$$f\left(B_{tot}\left(R;r_j\right)\right)-s_j\cdot C(R)\geq 0\,. \tag{7}$$

This says that the share s_j of total control costs $C(R)$ allocated to source j cannot exceed some function $f(\bullet)$ of the share of total benefits B_{tot} of control at source j. The function $f(\bullet)$ is completely arbitrary, in the sense that its shape will be something the rival coalitions can determine among themselves, according to their own notions of fairness, or that the regulator can impose.[5] The actual function chosen will have real effects on the allocation of controls across sources, but there is no *a priori* "best" function in a world where the coalitions cannot be coerced.

The requirement that a full cost allocation be achieved means that the cost shares s_j must all be non-negative, and must sum to one:

$$\sum_{j=1}^{J} s_j - 1 = 0\,, \quad s_j \geq 0 \text{ for all } j, \tag{8}$$

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[4] Benefits will also be related to the costs of available control technologies.

[5] Young, *et al.* (1982) show that the Shapley value approach (Shapley, 1953) is superior to other well-known cost allocation methods in regards to notions of fairness, rationality, monotonicity, and other properties desirable in a cost allocation.

The first-order (Kuhn-Tucker) conditions reveal that $g_j = g_{j'}$ for all sources *j* and *j'*, where g_j are the LaGrange multipliers associated with the participation constraints (7). This means that these political constraints are either *all* binding, or none of them are. Indicating their common value by g, and letting f stand for the LaGrange multiplier on the shares constraint (8), this means that $g = f\ /C(R)$.

This condition has a very important interpretation. Recall our remarks, above, that there is no real effect of failing to allocate fully the control costs--thus violating condition (8). In this event, a transfer must be made from the public sector to cover the unallocated control costs, but this transfer does not increase the *social* cost, which comprises public and private costs. Thus f, the shadow (or social) cost of the "full cost allocation" constraint (8), must be zero! The implication of this result is therefore that *side payments* (which in effect occur whenever a source pays an amount different from its own control costs) *have no effect on how much control is installed at any source.* In other words, it is immaterial, in this model, whether or not the regulator has any coercive power to compel sources to absorb costs beyond their threat points.[6]

This result also holds no matter the actual cost shares s_j. These shares are arbitrary for the purposes of this analysis (even to the point where they can even be negative). They will be

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[6] This is a different matter than the regulator's ability to impose controls independent of who pays. If the environmental target had been derived as part of an optimization, the environmental targets would be generating benefits in excess of costs, and the regulator would (in theory, and under the assumption people have uniform tastes for environmental quality) need no political power to institute controls. In the case of controls on loadings to the Chesapeake Bay, the water quality target is *imposed*, not derived, so the regulator's political power is relevant.

determined by whatever balance of power exists between sources and regulator. Of course, there is the separate issue of the regulators' ability to effect a transfer in the event they cannot fully allocate costs. The analysis of that situation is beyond the scope of this paper, although we note in passing that, were they to have insufficient power with respect to the coalitions and also the taxpayers, they would have to aim for a less stringent environmental target.

V. COST ALLOCATION WITHIN SOURCES

Finally, we consider allocating costs of control at individual sources to air and water benefits. This is somewhat akin to the problem a multi-product firm has in assigning joint production costs to its individual product lines. The firm's decision will affect the prices it charges for its individual products, and therefore the quantities demanded and its profits. Here, as we shall show, only under a particular circumstance does cost allocation between air and water benefits matter. Unlike in Section IV, there are no side payments being considered in this scheme.

This problem can be set up analogously to (4)-(7), but with the allocation constraints altered to reflect allocation within, rather than across, sources. Thus, each source can be thought of as an individual firm making cost allocations between its two products, air and water benefits. These allocations might depend, for example, upon the preferences of persons living in the vicinity for air quality improvements *versus* water quality improvements:

$$\max_{r_j} B_a\left[\sum_{j=1}^{J}\sum_{k=1}^{K} d_{jk} \cdot r_j\right] - \sum_{j=1}^{J} c_j\left(r_j\right) \qquad (4)$$

subject to (2) and:

$$f\left(B_a\left(r_j\right), B_w\left(r_j\right)\right) - s_e \cdot c_j(r_j) \geq 0\,, \tag{7'}$$

where $e \in \{air, water\}$ and B_w represents water quality benefits; *and:*

$$s_{air}+s_{water}=1,\ s_e \geq 0 \tag{8'}$$

By analogy with the previous analysis, it should be clear that, as long as cost allocations do not appear in the objective function (4), the way control costs are allocated to the air side and the water side at any particular source will have no effect on how much control is instituted at that source. This is because, with a single environmental target ((2) or its air equivalent), the allocation constraint (7') does not constrain the amount of control instituted at that source. The result is that controls will still be instituted using the net marginal costs rule (6). These marginal costs (and the marginal ancillary benefits) are unaffected by whatever internal cost accounting procedure that may be in force at a source.

However, allocations across benefit areas *do* matter when they enter the objective function directly. The allocation of some of a source's control costs to air benefits effectively makes the *water* benefits simultaneously achieved less expensive. Even if this is considered an accounting "sleight of hand," this apparent lowering of the costs of water benefits does matter when those allocated costs are what are being minimized in the objective function.

Allocating a share s_j of control costs to *j's* air benefits makes the effective cost of *water* benefits $\left(1-s_j\right)c_j\left(r_j\right)$. It is *this* cost function which enters into the objective function (4) in place of full costs. Thus the problem becomes:

$$\max_{r_j} B_a\left[\sum_{j=1}^{J}\sum_{k=1}^{K} d_{jk} \cdot r_j\right] - \sum_{j=1}^{J}\left(1-s_j\right)c_j\left(r_j\right), \tag{4'}$$

subject again to (2), (7'), (8').

The effect of this allocation of costs is to shift controls to sources which achieve more ancillary benefits -- a result similar to (6) but with the added element that it is not *full* marginal costs (net of marginal ancillary benefits) which are equalized, but rather the share of marginal costs allocated to *water* that are equalized (net of marginal ancillary benefits). Sources which achieve more air benefits per unit of water benefits will be more tightly controlled relative to their control under the net-marginal-cost rule (6).

It is one matter to assert, as we have done, that an objective function such as (4'), with cost allocations there rather than in the constraints, is the only way those cost allocations will affect the amount of control at each source. It still remains to consider what the rationale is for *putting* cost shares in the objective function. Here the answer is the same one we gave when considering how much a coalition can be coerced: it depends on the distribution of bargaining power in the actual situation.

The effect of equation (6), the marginal costs net of marginal benefits rule, is to shift emissions controls toward sources that create greater ancillary air benefits (on the margin) for each unit of water benefits achieved. Since the water quality target is imposed, and will be met with equality, this is an outcome that most favors those who value air benefits most highly. The same reasoning applies to (4'): the greater is the share s_j of costs at source j that is allocated to ancillary benefits, the less the water share of those costs will diminish the objective function, and the more that source will be controlled to achieve the water target.

It should be clear that this outcome favors the "air coalition" more than the net-marginal-cost rule (6) does. This answers the question of what the rationale is for including cost allocations in the objective function: its inclusion reflects the degree of bargaining power the air coalition has relative to the water coalition.[7] The whole of our analysis can now be seen as a description of how the outcome changes as the bargaining power of the air coalition increases continuously from zero (ancillary benefits are ignored; cost minimization implies $MC_j / L_j = \lambda$ for all sources) up to a point where ancillary air benefits are accounted for (thus shifting emissions control toward sources achieving greater ancillary benefits), to a greater point still, where preferences for air benefits relative to water benefits are strong enough that the cost shares s_j are inserted into the objective function.[8]

VI. CONCLUSIONS

This paper has identified conditions under which political economy considerations will affect the efficient allocation of controls on the air emissions of nitrogen oxides across multiple sources. By political economy, we mean the relative bargaining strengths and preferences of interest groups, coalitions, and regulators. We represent these, for the most part, by various kinds of cost allocations, both across emissions sources (as when, for instance, rate-payers in

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[7] There is, of course, considerable overlap between those two "coalitions." These artificial constructs are useful here for expository purposes, to represent differences in individual preferences for air and water benefits.

[8] The careful reader will have anticipated the *reductio ad absurdum* where the air coalition has "full" power. In this case, the share of costs allocated to water improvements will be zero! At that point the objective will simply be to maximize air benefits regardless of costs. This outcome, though, begs the question of why there would be an environmental constraint on water quality when nobody cares about that and everybody cares about air quality. (This is the implication of full political power for the air coalition.) The model *is* flexible, but setting s_j=1 would break it.

upwind states such as Ohio are reluctant to undertake emissions controls that will largely benefit persons in downwind states such as Maryland and Virginia), and within emissions sources. In the latter case, preferences over the air and water benefits achievable at individual sources govern the allocation of costs within those sources.

While we examine many levels of bargaining power, we show that only in fairly extreme circumstances, when interest groups succeed in changing the objective function rather than merely the constraints of the problem, cost allocations do not matter. We are most interested in the case where water quality standards from air emissions of NOx must be achieved, and we wish to account for what are therefore the ancillary benefits from concomitant air quality improvements. In this case the efficient level of control is to net out ancillary benefits, on the margin, from control costs and to equate the ratio of the net marginal costs to the Bay loading factors across all sources.

Diverse individual preferences for air and water quality are represented in this outcome. Only in the case where water quality improvements are valued very little relative to air will controls have to explicitly account for cost allocations over those media. In that case, however, it seems unlikely that the water quality standards would have had the political or popular support to be implemented in the first place, and the focus would shift to control for air benefits alone.

The political economy of instituting emissions controls in upwind regions where local benefits will be low is perhaps more relevant to the problem of water quality improvements in the Chesapeake Bay is. The implications of our model are that if it is economically efficient (in terms of costs and benefits) to control sources in, say, Ohio, it does not affect the optimal amount of control at those sources if they require side-payments to induce them to cooperate. In other words, such distributional issues have no affect on allocation of emissions *controls.*

There is further work to be done before this analysis will have addressed all of the outstanding issues in this area. We must reconsider the case of joint air and water standards in the case where there are multiple receptors for each medium. We must also consider the case where coalitions form simultaneously along both media and source lines. That is, cost allocations may be required both within and across sources. However, it appears from our analysis that these issues will not matter except in extreme cases which may call into question the environmental goals being pursued.

The most important extension of our work was noted in an early footnote. This is the issue of the optimal regulatory boundary. This is a larger project than those noted above. It involves an application of integer programming to solve for the optimal boundary when there are tradeoffs between size of regulatory domain and regulatory power. The nature of these tradeoffs will be determined by transactions costs, bargaining coalitions, and the gains from trade in large *versus* small markets.

Ultimately, all of this research is directed toward supporting future policy decisions affecting the allocation of emissions (or effluent) controls across both air and water sources. The empirical work we are performing in conjunction with this research will examine trading outcomes and will estimate cost-effective levels of controls across sources. Even then, however, we will not have estimated the shadow price of controlling air emissions of nitrogen oxides for water benefits. To achieve efficient levels of control, these prices must be brought to equality with the shadow price of water-based nutrient controls.

APPENDIX

E. H. Pechan's (1996) estimates of the costs of controlling NOx emissions to improve Chesapeake Bay water quality are the starting point of an empirical investigation by the authors, and Scott Atkinson of the University of Georgia, of the costs of control taking ancillary benefits into account (using equation (6) above), and of the gains from various emissions trading schemes. Pechan produced these estimates for utility and mobile source emissions in various Bay airshed states:

Table A1: Pechan-Estimated Costs of Controlling NOx Emissions for Bay Loading Reductions, by Selected Scenarios

Scenario/State	*NOx Reduction (000 tons)*	*Nitrogen (N) Load Reduction (000 lbs)*	*Total Annual Cost ($000,000)*	*Cost Effectiveness ($/ton NOx)*	*Cost Effectiveness ($/lb N)*	*Ratio: ($/ton)/($/lb)*
Utility—(reduce 0.15lbs/MMBtu)						
Maryland	47.0	1,610	$62.7	$1,300	$39	0.33
Pennsylvania	178.2	3,510	214.0	1,200	61	0.20
Virginia	52.8	1,990	57.9	1,100	59	0.19
West Virginia	155.5	2,240	157.5	1,000	70	0.14
Kentucky	169.1	760	192.3	1,100	254	0.04
Mobile Source (Introduce LEVs)						
Maryland	13.6	410	$39.0	$2,900	$95	0.30
Pennsylvania	24.1	470	76.5	3,200	164	0.20
Northern Virginia	4.4	90	11.9	2,700	130	0.21
Virginia (all)	10.4	220	58.4	5,600	270	0.21

The first column of Table A1 shows Pechan's estimates of the reduction in NOx emissions that would be realized by achievement of a 0.15lbs/MMBtu standard for utilities, and by the introduction of low-emission vehicles (LEVs) in each respective state. Gains on the utility side may differ because existing levels of control at individual sources may differ, as may current utility capacities in each state. The LEV estimates are based on Pechan's modeling of the adoption of California's LEV program in each of the states and Northern Virginia. According to Pechan, these estimates would change "somewhat" if instead they modeled a 49-State LEV program different from California's program (Pechan, 1996).

Based on these estimates, and a transport matrix mapping emissions to Chesapeake Bay loadings, Maryland and Virginia can achieve a disproportionate reduction in Bay loadings, relative to their potential NOx emissions reductions, because of their proximity to the Bay (second column). More of their NOx emissions end up in the Bay than do the emissions of more distant states.

The two cost-effectiveness columns take Pechan control-cost estimates (column 3) and divide them by, respectively, tons of NOx emissions reductions (column 4), and pounds of nitrogen loadings reduced (column 5). Notice that Maryland sources are the least cost-effective to control for NOx emissions, but for a goal of loadings reduction in the Bay, Maryland sources become the *most* cost-effective to control. Kentucky, being farthest away, has a smaller fraction of its NOx emissions transported to the Chesapeake Bay, and so controlling these sources for Bay water quality improvements is the least cost-effective of these options.

The last column of the table tells this story in a slightly different way. The ratio of NOx-reduction cost effectiveness to loading-reduction cost-effectiveness is greatest for Maryland, and least for Kentucky (for mobile sources, with Kentucky not represented, it is least for Pennsylvania--which is farther from the Bay than Maryland and Virginia). That is, in both collections of states the pounds of nitrogen loading reduction per ton of NOx reduction is greatest in Maryland, least in the state farthest from the Bay. Were NOx emissions uniformly "mixed" and transported in equal proportions to the Bay, the ratios would be equal across these states.

REFERENCES

Krupnick, Alan J., Wallace E. Oates, and Eric Van den Berg. 1983. "On Marketable Air-Pollution Permits: The Case for a System of Pollution Offsets," *Journal of Environmental Economics and Management,* vol. 10, no. 3 (September), pp. 233-247.

McConnell, Virginia D. 1990. "Costs and Benefits of Vehicle Inspection: A Case Study of the Maryland Region," *Journal of Environmental Management*, vol. 30, pp. 1-15.

Montgomery, David. 1972. "Markets in Licenses and Efficient Pollution Control Programs," *Journal of Economic Theory,* vol. 5, no. 3 (December), pp. 395-418.

Pechan, E.H. Associates, Inc. 1996. *Costs to Reduce Airborne Nitrogen Deposition Affecting the Chesapeake Bay: Project Briefing*, prepared for ES EPA, Springfield, Virginia.

Shapley, Lloyd S. 1953. "A Value for n-Person Games," in H. Kuhn and A. W. Tucker, eds., *Contributions to the Theory of Games,* vol. 2 (Princeton, N.J., Princeton University Press).

Teitenberg, Thomas H. 1985. *Emissions Trading, an Exercise in Reforming Pollution Policy* (Washington, D.C., Resources for the Future, Inc.).

Varian, Hal R. 1992. *Microeconomic Analysis* (New York, N.Y., W. W. Norton & Company, Inc.).

Young, H. P., N. Okada, and T. Hashimoto. 1982. "Cost Allocation in Water Resources Development," *Water Resources Research*, vol. 18, no. 3 (June), pp. 463-475