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Potential cost savings from discharge allowance trading: A case study and implications for water quality trading

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[1] Applying a trading ratio system similar to that proposed by Hung and Shaw (2005), we estimate the potential cost savings of a phosphorus emissions trading program that meets overall total maximum daily load allocations among 22 wastewater treatment plants (WWTPs) in the Passaic River watershed (United States) to be a modest 2–3% relative to a no-trade baseline. These results may be typical of those in relatively small watersheds such as the Passaic, where there are limited numbers of potential traders and relatively homogeneous abatement technologies across WWTPs. More substantial gains from trade may accrue to a concentrated group of WWTPs, suggesting that watershed managers should focus on a targeted set of traders within a watershed. Under certain conditions, additional gains may be achieved by aggregating WWTPs into zones within which there can be one-to-one allowance trading.

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1. Background and Objectives

[2] Water quality trading has been met with mixed success in the United States. Despite the theoretical promise of water quality markets, substantial financial and technological support by the United States Environmental Protection Agency (EPA), and more than 70 established and pilot programs, "only 100 facilities have participated in trading" [*EPA*, 2008] (E-S 1). Moreover, 80 of these 100 trades have occurred in a single market, the Long Island Sound Nitrogen Credit Exchange program, which operates more like an exceedence tax abatement subsidy than a market with endogenously determined prices. For the more "typical" watershed trading programs without such a generous credit exchange to absorb imbalances between supply and demand, reallocation of abatement levels across firms through the buying and selling of pollution allowances or credits has been much more limited (see *King and Kuch* [2003], *Breetz et al.* [2004], and *EPA* [2008] for discussions). Thus the extent of cost savings in a "typical" total maximum daily load (TMDL)-governed watershed associated with market trading remains an open, empirical question.

[3] In this paper, the nontidal Passaic River watershed in the state of New Jersey is used as a case study to investigate the size of potential cost savings associated with allowing phosphorus emissions trading among wastewater treatment plants (WWTPs) to achieve a significant reduction in ambient phosphorus levels. On 24 April 2008, a final TMDL rule was promulgated, calling for a more than 80% reduction in the total phosphorus concentration emissions from 22 WWTPs in the watershed. It is estimated that the average (flow weighted) total phosphorus emissions are 2.13 mg/l (402,000 lbs (1 lb = 0.4536 kg)). The TMDL document calls for a long-term average year-round effluent concentration of 0.40 mg/l of total phosphorus, equivalent to 75,650 lbs of phosphorus at existing flow.

[4] To measure cost savings, we specify a trading-ratio system similar to one proposed by *Hung and Shaw* [2005] that minimizes the abatement cost of meeting environmental standards throughout the watershed. Under trading, each plant's emissions must be less than or equal to the initial allocations under the WWTP's National Pollution Discharge Elimination System (NPDES) permits, plus any emissions allowances purchased (weighted by the trading ratios that account for the downstream attenuation of phosphorus) minus the emissions allowances sold to others. By solving the model for no trade and trading scenarios, we determine the reduction in annual operating and management (OM) costs due to trading and the patterns of trade.

[5] To foreshadow our findings, our analysis suggests that the watershed-wide gains from trade under a market exchange system to regulate water quality are likely to be nominal, on the order of 2 to 3% of baseline, no-trade costs of meeting the same objectives. For a subset of 10 firms in the watershed, gains from trade are about 6%, suggesting that watershed managers should focus on a targeted set of traders within a watershed, rather than simply establishing a broad watershed-wide exchange market. Under certain conditions, additional gains may be achieved by aggregating WWTPs into zones within which there can be one-to-one allowance trading. Below, a description of the Passaic watershed is followed by discussions of the trading ratio system and how capital costs are also accommodated. We then discuss the TMDL established on the upper Passaic River Basin, corresponding biophysical trading ratios, and the estimation of capital and OM costs for phosphorus abatement. A discussion of empirical results is followed

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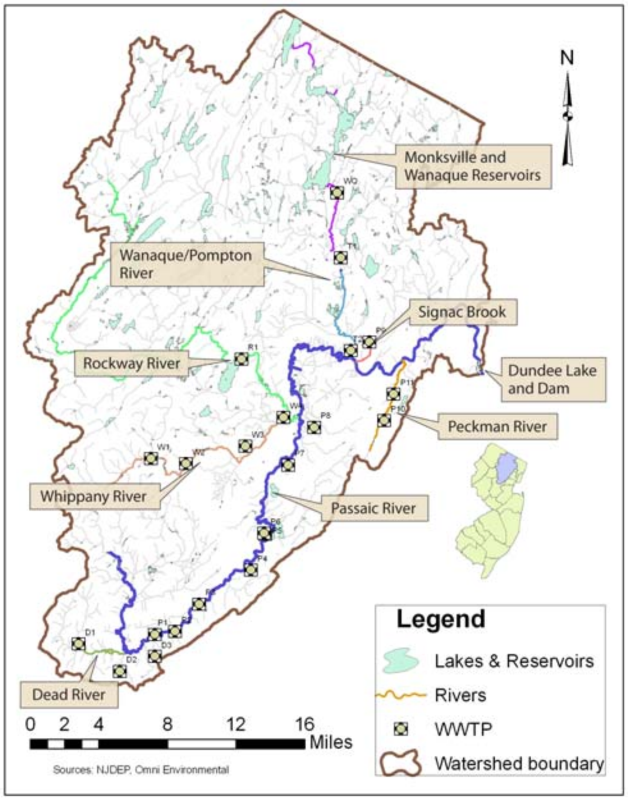

Figure 1. Upper Passaic River basin and the location of major wastewater treatment plants.

by a discussion of the implications for policy and for modeling.

2. Essential Features of the Nontidal Passaic Watershed

[6] The nontidal Passaic watershed is located primarily in northeastern New Jersey; a portion extends into New York State. As depicted in Figure 1, this 803 square mile watershed consists of the Passaic River and its tributaries, and it drains five densely populated counties in New Jersey near the New York City metropolitan area. About one quarter of New Jersey's population (2 million people) lives there.

[7] From its source, the Passaic River initially flows south, then turns and flows in a northeasterly direction, and then turns east and finally south before reaching Newark Bay. The terminus of the upper Passaic River is at Dundee Dam, which separates the upper, nontidal part from the tidal part of the river. The Dead River joins the Passaic at the point where it first changes direction. At the watershed's center, the Rockaway River flows into the Whippany River, and in turn, the Whippany River flows into the Passaic. The Wanaque River begins in the northern part of the watershed, flowing into the Pompton River, which subsequently joins the Passaic. Below this confluence, but above the Dundee Dam, the Singac Brook and the Peckman River enter the Passaic.

[8] The two major water supply reservoirs, the Monksville and the Wanaque, are located upstream on the Pompton River. Together, they supply over 200 million gallons per day (mgd) of water to more than two million people in northern New Jersey. The Wanaque Reservoir takes water from the natural tributary system upstream and the Two Bridges Pumping Station, at the confluence of the Pompton and the Passaic Rivers.

[9] The New Jersey Department of Environmental Protection (NJDEP) has targeted the 22 largest wastewater treatment plants (WWTPs) in the nontidal portions of the Passaic River watershed for limiting discharges of effluents (Figure 1 and Table 1). Under the recently promulgated TMDL, acceptable long-term averages of total phosphorus emissions have been established at 0.40 mg/l for each of the 22 WWTPs. Below we evaluate the possible cost savings that could be achieved by meeting water quality targets associated with this baseline through an allowance trading program.

3. Cost Minimization and Tradable Discharge Allowance Programs

[10] We describe a general model to minimize abatement costs to achieve an environmental standard and show that the trading ratio model assures the same result.

3.1. A Model to Minimize Abatement Costs

[11] A general model to minimize the aggregate abatement costs to achieve a specified environmental standard E_j for j zones (j = 1, . . ., n) can be specified as minimize

$$Z = \sum_{i=1}^{n} C_i\left(e_i^0 - e_i\right), \qquad (1)$$

Table 1. Data for Municipal Wastewater Treatment Plants

Code for WWTP	River	Flow (mgd)	Phosphorus Load (lbs/year)	Phosphorus Concentration (mg/l)	Phosphorus TMDL 0.4 mg/l (lbs/year)[a]
D1	Dead	1.76	16,780	3.13	2144
D2	Dead	0.15	845	1.85	183
D3	Dead	0.31	1804	1.91	378
P1	Passaic	1.00	8011	2.63	1218
P2	Passaic	0.36	1831	1.67	439
P3[b]	Passaic	1.57	2869	0.60	1913
P4	Passaic	0.12	559	1.53	146
P5	Passaic	2.41	24,079	3.28	2936
P6	Passaic	0.90	4057	1.48	1097
P7	Passaic	2.61	20,909	2.63	3180
P8	Passaic	3.75	18,505	1.62	4569
W1[b]	Whippany	1.90	4862	0.84	2315
W2[b]	Whippany	3.03	5186	0.56	3704
W3	Whippany	2.03	18,505	2.83	2473
W4	Whippany	12.58	114,192	2.98	15,327
R1[b]	Rockaway	8.81	39,180	1.46	10,734
WQ[b]	Wanaque	1.07	487	0.16	1218
T1[b]	Pompton	0.86	838	0.32	1048
T2	Pompton	5.33	34,744	2.14	6494
P9	Preakness Brook	7.47	51,652	2.27	9602
P10	Passaic	2.46	23,004	3.07	2997
P11	Passaic	1.26	8636	2.25	1535
Total			401,535	2.13[c]	75,650

[a]This is the TMDL adopted on 24 April 2008.
[b]Plants that currently have some capacity to remove phosphorus.
[c]Average is weighted by flows.

subject to

$$\sum_{i=1}^{n} t_{ij} e_i \leq E_j \quad (j = 1, \cdots, \mathrm{n}) \tag{2}$$

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

C_i is an abatement cost function at source i; e_i^0 is initial effluent at i; e_i is effluent after treatment at i; and t_{ij} is a transfer coefficient from source i to source or receptor zone j. It is convenient [e.g., *Hung and Shaw*, 2005] to assume a one-to-one correspondence between the zones and the WWTP point sources of phosphorus, a point to which we return to below. The model can be extended to accommodate natural background levels [e.g., *Tietenberg*, 2006].

[12] Defining e_i^j as the amount measured at site j after source i discharges e_i, transfer coefficients reflecting attenuation of effluent between discharge and receptor points are

$$t_{ij} = e_i^j / e_i, \quad 0 \leq t_{ij} \leq 1. \tag{4}$$

When $t_{ij} = 1$, one unit of pollutant from discharger i results in one unit of pollutant at zone j; there is no decay or attenuation between the source and receptor sites. If $t_{ij} = 0$, then any emissions from source i do not affect water quality in zone j. This zero-effect condition may occur if there is complete decay or attenuation between sites. More typically, $t_{ij} = 0$ represents a situation wherein zone j is located upstream from source i or on a separate tributary or branch not affected by emissions from zone i.

[13] The model's Kuhn-Tucker conditions imply that a discharger's marginal abatement cost equals the sum of the shadow prices of total load constraints at affected zones weighted by transfer coefficients [*Sado*, 2006]. If dischargers were charged similar emissions fees, the minimum cost solution would also obtain [*Baumol and Oates*, 1988].

3.2. Trading Ratio System

[14] *Hung and Shaw* [2005] achieve this same result with allowance trading under a trading ratio system (TRS) wherein the relative prices of emissions allowances are equated to the transfer coefficients. Because water flows downhill, upstream allowance allocations affect allocable emissions downstream. Thus

$$\overline{\mathrm{T}}_j = E_j - \sum_{k=1}^{j-1} t_{kj} \overline{\mathrm{T}}_k. \tag{5}$$

$\overline{\mathrm{T}}_j$ are the aggregate tradable allowances in zone j, E_j is the allowable aggregate emissions in zone j, and k ($<j$) indicates a zone upstream to the zone j. For the most upstream zone, an authority sets $\overline{\mathrm{T}} = \mathrm{E}_j$; there is no inflow of pollutants from elsewhere. For downstream zones, the contributions from upstream sources $\sum_{k=1}^{j-1} t_{kj} \overline{\mathrm{T}}_k$ must be accounted for in the initial allocation of allowances. If the environmental constraints are binding in every zone, the TRS avoids free-riders and the market equilibrium is also the cost-effective solution [*Hung and Shaw*, 2005].

[15] The effluent emitted in zone i must be below the standard, $\overline{\mathrm{T}}_i$, unless i purchases allowances from upstream sources $k < i$. Then i can discharge more effluent. If transfer coefficients defined in equation (4) are set equal to trading ratios at which trade takes place and that all the $\overline{\mathrm{T}}_i$ are initially binding, the allowable effluent at i increases

$$e_i = \overline{\mathrm{T}}_i + \sum_{k=1}^{i-1} t_{ki} \mathrm{T}_{ki}, \tag{6}$$

where T_{ki} is the number of allowances sold by k to i. The actual emissions allowed for each allowance transferred to site i from site k are reduced by attenuation rates between sites. Effective trades from a buyer's point of view are proportional to trading ratios, t_{ki}.

[16] If site i sells allowances (i.e., sells its right to discharge effluent), then it must meet a more stringent standard than specified by equations (5) and (6). The final effluent must be reduced by the number of allowances sold downstream, $\sum_{k>i}^{n} \mathrm{T}_{ik}$, since reductions in emissions occur at point of sale. Allowing for buying (from upstream sources, k < i) and selling (to downstream sources, k > i) the trading constraint is

$$e_i = \overline{\mathrm{T}}_i + \sum_{k=1}^{k<i} t_{ki} \mathrm{T}_{ki} - \sum_{k>i}^{n} \mathrm{T}_{ik}. \tag{7}$$

[17] Allowable emissions are determined by initial allocation of allowances, plus allowances purchased from upstream sources weighted by the trading ratio, minus any allowances sold downstream. Equation (7) ensures that for every unit allowance sold, the buyer can emit only a portion of a unit, equal to the trading ratio. The general trading model is minimize

$$\mathrm{Z} = \sum_{i=1}^{n} C_i\left(e_i^0 - e_i\right), \tag{8}$$

subject to

$$e_i - \sum_{k=1}^{i-1} t_{ki} \mathrm{T}_{ki} + \sum_{k>i}^{n} \mathrm{T}_{ik} \leq \overline{\mathrm{T}}_i \quad (i = 1, \ldots, n) \tag{9}$$

$$\mathrm{T}_{ik}, \mathrm{T}_{ki} \geq 0; \quad e_i \in \left[0,\ e_i^0\right]. \tag{10}$$

[18] In Appendix A, it is shown that when trade takes place between discharger k and discharger i (e.g., T_{ik} and T_{ki} are strictly positive in the minimum cost solution to this model), the allowance price at k (equal to the marginal abatement cost at k) must be equal to the allowance price at i (equal to the marginal abatement cost at i), multiplied (i.e., discounted) by the trading ratio between dischargers k and i. Moreover, if the price at which discharger k is willing to sell is larger than the value of an allowance to discharger i, "discounted" by the trading ratio, there is no trade between zones k and i. Because trading ratios are always less than or equal to unity, marginal costs from upstream suppliers must be no greater than that for a downstream purchaser. If there are no low-cost plants upstream, there are no opportunities to trade. *Hung and Shaw* [2005] provide a simple example of such a trading ratio system in their article.

[19] On the basis of this discussion, it is evident that this TRS model minimizes only the annual variable, or operation and maintenance, costs of pollution abatement, as trades in a market setting are based on differences in marginal abatement costs, $\mathrm{Z}_{\mathrm{i}}' = C_i'\,(e_i^o)$, across dischargers.

Table 2. Trading Ratios[a]

	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1	1	1	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98											
D2		1	1	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98											
D3			1	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98											
P1				1	1	1	1	1	1	1	1											
P2					1	1	1	1	1	1	1											
P3						1	1	1	1	1	1											
P4							1	1	1	1	1											
P5								1	1	1	1											
P6									1	1	1											
P7										1	1											
P8											1											
W1												1	1	1		1						
W2													1	1		1						
W3														1		1						
R1															1							
W4																1						
WQ																	1	1	1			
T1																		1	1			
T2																			1			
P9																				1		
P10																					1	1
P11																						1

[a]The WWTP in the row represents the seller and the WWTP in the column represents the buyer of allowances.

Thus through the application of this model, we can estimate the volume of allowance trading and isolate the magnitude of the variable cost savings due solely to allowance trading. This information is critical to any assessment of the economic feasibility of a fully functioning market exchange system. These cost savings are based on the assumption that the wastewater treatment plants currently have capacity to remove phosphorus.

[20] However, in our study watershed, most of the wastewater treatment plants must upgrade their facilities to remove phosphorus. There are mixed integer programming methods [*Liao et al.*, 2009] and iterative algorithms [e.g., *Bennett et al.*, 2000] which, at least conceptually, can be used to minimize the combined capital and operating costs of meeting an environmental standard. Yet there is currently no market trading mechanism for sharing the potential capital cost savings among dischargers. In this paper we address the issue of capital costs savings ex post, a strategy which would seem appropriate in the evaluation of the potential for an open market or open exchange trading program. That is, we first solve the watershed programming model for the minimum annual OM costs with no possibilities for allowance trading. This requires each firm to treat to its TMDL-specified level $\overline{T}_i$. Second, we determine the associated level of capital investment needed for each firm to treat to the required level. This investment is a function of the size of the plant and the required level of abatement. By annualizing these investment costs, we determine ex post the combined OM and annualized capital cost of meeting the environmental standard. This is a base case against which cost savings due to allowance trading are measured.

[21] For each trading scenario, we then solve the model to minimize the annual OM costs of abatement. Because allowance trading allows some plants to avoid some portion of their abatements, the implicit levels of investment may be lower. Alternatively, those plants that sell allowances may require upgrades beyond what would be needed under the base case. These changes in investments and the changes in annualized capital costs are determined ex post on the basis of optimal abatement levels under OM-based trading. While there is no guarantee that this procedure will yield the solution that minimizes long-run costs of abatement, it does provide important information about realistic changes in investment made possible by a market-based trading program, in which WWTPs trade allowances based on comparing marginal abatement costs with prevailing allowance prices, since these changes are all measured relative to the investment required in the absence of the trading program.

4. Data and Empirical Specification

[22] There are three essential components to the data: (1) data for the allowable effluent for each plant; (2) the transfer coefficients or trading ratios between each plant and all downstream plants between which trading is possible; and (3) operating and capital cost data for phosphorus abatement for each of the wastewater treatment plants.

4.1. Environmental Capacity and the TMDLs

[23] For the Passaic watershed, effluent load capacities are defined in terms of the total maximum daily loads (TMDLs), which account for background and natural levels of pollutant, and the inflows from upstream sources are adjusted for transfer coefficients. The corresponding allowable firm (or zonal) discharges are specified under each discharger's National or State Pollution Discharge Elimination System (NPDES) permits, with the TMDL specifying that the long-term average emissions from each WWTP not exceed 0.40 mg/l total phosphorus [*NJDEP*, 2008]. These policy tools are consistent with *Hung and Shaw*'s [2005] zonal load caps. The current total phosphorus (TP) effluent levels differ substantially among plants (Table 1). The average TP concentration is 2.13 mg/l, well above the TMDLs target effluent level of 0.40mg/l.

4.2. Trading Ratios

[24] The transfer coefficients or trading ratios (Table 2) are based on several scientific factors such as the rate of

Table 3. Estimated Cost Function for Phosphorous Removal, Chesapeake Bay Data

	Coefficients	Standard Error	t Stat	P Value	Alternative Technology[a]
			OM Costs		
Intercept	9.870	0.052	190.467	0.000	9.468
ln C	−0.997	0.032	−31.312	0.000	−1.175
ln F	0.785	0.048	16.394	0.000	0.785
T	–	–	–	–	0.604
ln C*ln F	0.043	0.029	1.448	0.149	0.043
T*ln C	–	–	–	–	0.268
R Square	0.879				
Adjusted R Square	0.877				
Observations[b]	208				
			Capital Costs		
Intercept	11.878	0.006	1915.770	0.000	11.050
ln C	−0.995	0.004	−261.313	0.000	−1.424
ln F	0.302	0.006	52.668	0.000	0.195
T	–	–	–	–	1.242
ln C*ln F	−0.164	0.004	−46.484	0.000	−0.164
T*ln C	–	–	–	–	0.644
T*ln F	–	–	–	–	0.160
R Square	0.998				
Adjusted R Square	0.998				
Observations[b]	208				

[a]These coefficients are determined from the analysis in Appendix A of *Sado* [2006].
[b]There are 208 observations because there were cost data for two levels of concentration, C, for each of the plants and the data were stacked for the regression.

inflow-outflow of pollutants, biophysical conditions, and the geography of the designated areas. The attenuations were derived by distances between outlets of the point sources and target location, settling and uptake rates of orthophosphate and organic phosphorus in the flow path, and ratios of orthophosphate and organic phosphorus discharged from the source [*Najarian Associates*, 2005].

4.3. Estimating the Costs of Phosphorus Abatement

[25] Since most WWTPs in the watershed have no present capacity to remove phosphorus, it is necessary to estimate phosphorus abatement costs for these WWTPs using data from other sources. Data from these sources are used to econometrically estimate the coefficients for continuous phosphorus removal cost functions for both yearly OM and capital costs. In so doing, it is possible to derive continuous marginal abatement cost functions for each WWTP as required for the programming model.

[26] Estimated abatement costs for 104 treatment plants in the Chesapeake Bay watershed are used in these regression analyses, primarily because of geographic proximity and other similarities between the Chesapeake Bay and Passaic watersheds. These cost estimates for the existing WWTPs in the Chesapeake Bay watershed were derived using a combination of actual cost data and engineering methods. These, and additional data, are for specific use "...by the Chesapeake Bay Program to estimate costs of nutrient removal programs for all point-source categories across the Bay watershed during the nutrient and sediment water quality criteria and use development process" [*Nutrient Reduction Technology Cost Task Force*, 2002, p. i]. One limitation is that these data are not rich enough to estimate separate OM functions for distinct levels of fixed investment.

4.3.1. Estimating the Annual OM Abatement Cost Functions

[27] For the wastewater treatment plants in the Chesapeake Bay study, we have data on daily flow and annual OM cost for two effluent concentrations (e.g., 1mg/l and 0.1mg/l). Similar to the flexible cost function estimated by *Boisvert and Schmit* [1997] for drinking water treatment and delivery systems and its much more generalized form used by *Feigenbaum and Teeples* [1983], we estimate the following cost function:

$$\ln OM = \ln\alpha + \beta\ln C + \gamma\ln F + \delta\ln C\ln F + \ln u, \qquad (11)$$

where OM is the annual operation and maintenance costs; C is final phosphorus concentration, in mg/l; F is daily flow in million gallons per day; α, β, γ, and δ are parameters to be estimated; and ln u is an error term assumed to be normally distributed. For this cost function, the marginal cost of phosphorus removal with respect to one characteristic depends on the level of the other

$$\partial OM/\partial C = [\beta + \delta\ln F]\left[\frac{OM}{C}\right] \qquad (12)$$

$$\partial OM/\partial F = [\gamma + \delta\ln C]\left[\frac{OM}{F}\right]. \qquad (13)$$

[28] One would expect that $\beta < 0$, because as the final concentration (C) goes down, costs should rise. Similarly, it is expected that $\gamma > 0$, since the cost of achieving a specified environmental standard should be lower for larger plants.

[29] The regression corresponding to equation (11) explains about 88% of the variation in the logarithm of the cost of removing phosphorus (Table 3). This high R^2 is in part due to the fact that many of the cost estimates are based primarily on engineering relationships. The coefficients are all statistically significant after correcting the standard errors for hetertoscedasticity [*White*, 1980] due to the multiple observations per WWTP. Since the estimated value of β is negative, while the estimated value of γ is

positive, the results conform to a priori expectations. The effect of a positive coefficient, δ, on the cross product term on ln *OM* cost is negative at concentrations below 1mg/l (e.g., where ln $C < 0$); larger plants treat to low concentrations more efficiently than smaller plants.

4.3.2. Estimating Capital Costs for Upgrading Facilities to Remove Phosphorus

[30] Using a similar method, the capital investment cost function is specified as

$$\ln CC = \ln \eta + \kappa \ln C + \varsigma \ln F + \omega \ln C \ln F + \ln v, \qquad (14)$$

where *CC* is capital investment cost; ln v is error term assumed to be normally distributed; and η, κ, ς, and ω are parameters to be estimated. Similar to the OM cost function, the expectation is that $\kappa < 0$, as targeting the lower final concentration (i.e., ln $C < 0$) requires greater investments, and $\varsigma > 0$, as a large plant needs more capital to retrofit.

[31] The regression corresponding to equation (14) is presented in Table 3. This R^2 approaching unity is explained by the lack of variation in capital cost estimates for specific flow levels in the Chesapeake Bay. Again, after correcting the standard errors for hetertoskedasticity, the coefficients are all statistically significant and conform to a priori expectations.

4.3.3. Costs of Alternative Technologies

[32] The data from the Chesapeake Bay study are for inexpensive chemical removal of phosphorus, and we assume this technology is adopted by the Passaic WWTPs with no current capacity to treat phosphorus. For the three plants (W2, WQ, and T1) that operate biological phosphorus removal processes, we adjust the coefficients to reflect this difference in technology. These adjustments are based on 75 cost estimates generated from simulation analyses by the University of Georgia for eight designs of wastewater treatment facilities, some based on an activated sludge removal technology and others based on biological removal [*Jiang et al.*, 2005]. Since similar procedures were used to make adjustments to both the OM and the capital cost functions, it is sufficient to focus the discussion on the OM cost functions.

[33] To make the adjustments to the OM cost function, we first estimated two cost functions from the University of Georgia data, one using the same specification as in equation (11) and one including a zero-one variable (T) that takes on a value of one in those observations for biological removal, along with an interaction term between T and ln C. The coefficients of these two additional regression equations (reported by *Sado* [2006]) are used to develop the cost functions for the alternative technology in Table 3. The coefficients on T and T(ln C) are taken directly from the new regression based on the data from the Georgia study. In making this adjustment, we essentially account for the shifts in the cost function for the alternative technology as reflected through the zero-one variable. However, the coefficients on the other terms also differ from those in column two of Table 3. The differences are equal to the differences in the coefficients on these terms between the two regressions based on the Georgia data. In making these latter adjustments, we effectively benchmark the OM cost function for the alternative technology to the one for chemical treatment from Table 3, but we also ensure that the differences in marginal effects of concentration and flow on costs between the two technologies in Table 3 are the same as for the functions estimated using the Georgia data. Because the variables are in logarithms, it is the proportional differences in the marginal effects that remain the same. On the basis of these adjustments, it is evident from Table 3 that there is a shift in the OM cost function upward to reflect generally higher costs of biological removal and the cost elasticity with respect to concentration declines.

5. Phosphorus Emissions Trading Model for the Passaic Watershed

[34] Hung and Shaw's objective function is based on the costs of removing specific amounts of phosphorus. This is equivalent to minimizing the combined costs across all plants of discharging phosphorus where there is an upper TMDL-specified limit on the amount each plant can discharge without trade. We use average flow from the prior 3 years as the flow factor and, consistent with the TMDL, the maximum permitted concentration from each WWTP is 0.40mg/l [*NJDEP*, 2008]. After the concentrations for the functions in Table 3 are converted from mg/l into lbs of phosphorus, the model is

$$Min\ Z = \sum\nolimits_i OM_i(e_i) = \sum\nolimits_i \exp(\phi_i) * e_i^{\psi_i}, i = 1, \ldots, \text{n}, \qquad (15)$$

subject to

$$e_i - \sum\nolimits_{k=1}^{k<i} t_{ki} \mathrm{T}_{ki} + \sum\nolimits_{k>i}^{n} \mathrm{T}_{ik} \leq \bar{T}_i, i = 1, \ldots, \text{n}, \qquad (16)$$

$$e_i \leq e_i^0, \qquad (17)$$

$$e_i, T_{ki}, T_{ik} \geq 0. \qquad (18)$$

[35] The coefficients (Table 4) for these transformed cost functions, $OM_i(e_i)$, also embody the differences in daily flows across the WWTPs, and OM costs decline as the lbs of phosphorus emissions increase and flow decreases. Thus if the constraint on phosphorus emissions embodied in equations (16) were not in the model, the minimum cost solution would be zero, and no phosphorus would be removed. With this constraint, costs are minimized, subject to emissions by each plant being less than the TMDL, plus the trade ratio weighted number of allowances bought, less the number of allowances sold. The model is formulated and solved within GAMS [*Brooke et al.*, 1988].

[36] The starting point for the empirical analysis assumes current treatment capacities [*Sado*, 2006]. The estimated capital cost functions are continuous in both concentration and maximum flow, but plants would likely make investments to accommodate treating to one of a small number of final concentration levels. These upgrades would be "lumpy"; in the second step of the analysis in which investment levels, and annualized capital costs are determined, we allow for five discrete concentrations: (1) current level > target concentration $\geq$ 1.0 mg/l; (2) 1.0 mg/l > target concentration $\geq$ 0.50 mg/l; (3) 0.50 mg/l > target concen-

Table 4. Parameters for the Transformed OM Cost Functions for the 22 Plants[a]

WWTP	ϕ	ψ
D1	19.844	−1.151
D2	15.701	−1.256
D3	16.971	−1.225
P1	19.064	−1.172
P2	17.319	−1.216
P3	19.667	−1.156
P4	15.302	−1.266
P5	20.385	−1.136
P6	18.790	−1.179
P7	20.284	−1.139
P8	21.135	−1.115
W1	18.387	−0.875
W2	18.880	−0.858
W3	20.103	−1.144
W4	22.757	−1.067
R1	20.049	−0.817
WQ	19.035	−1.172
T1	18.893	−1.176
T2	21.664	−1.100
P9	22.182	−1.085
P10	20.391	−1.136
P11	19.359	−1.164

[a]Note that the cost functions are specified in equation (25).

tration $\geq$ 0.25 mg/l; (4) 0.25 mg/l > target concentration $\geq$ 0.10 mg/l; and (5) 0.10 mg/l > target concentration (e.g., Figure 2). Although informed by engineers, these discrete capital cost thresholds are arbitrary. To assess the impact of our specification, we adopt a simple robustness test, as is discussed below.

6. Empirical Results

[37] The base situation against which the trading program is evaluated is where there is no trade allowed, and each WWTP must treat to meet its own 0.40 mg/l flow standard. We use these cost estimates as a baseline to identify cost savings associated with trading.

6.1. Base Case Results: Treatment Costs When No Trade is Allowed

[38] We assume phosphorus is removed by chemical treatment, except for the three plants that already use biological treatment. In treating to a 0.40 mg/l concentration (e.g., Table 1), total annual costs of phosphorus removal are \$3.10 million (Table 5). Annualized capital costs account for 38% of total phosphorus removal costs.

6.2. Trading Scenario

[39] As indicated in Table 5, the total annual cost of removing phosphorus under a trading program falls to \$3.05 million, a savings of about 2% relative to the base case. The corresponding purchases and sales of allowances are presented in the trade revenue (TR) column of Table 5, rounded to the nearest \$1000. Final concentrations for each WWTP after trading are presented in Table 6, along with the actual purchases (\$ Buy) and the sales (\$ Sales), which reflect the volume traded multiplied by the appropriate allowance price (\$/lbs). All sales are downstream.

[40] Recognizing that our estimated cost savings are likely to rest to some extent on our choice of capital cost increments indicated in Figure 2, we examined the consequence of moving the 0.50 mg/l capital cost step to 0.45 mg/l, a 10% shift (shifting other thresholds by 10% does not change the estimated costs of meeting the TMDL). By altering this assumption, there are an additional combined annual capital cost savings of \$38 thousand by WWTPs D3 and P2. Overall total cost savings across the entire watershed would increase to 3% if this alternative threshold were adopted.

[41] Compared to potential gains from trade observed in other settings [see *Tietenberg*, 2006] these aggregate cost savings are rather meager. If one accounts for transactions costs, it is unlikely that gains of 2 to 3% would motivate a trading program.

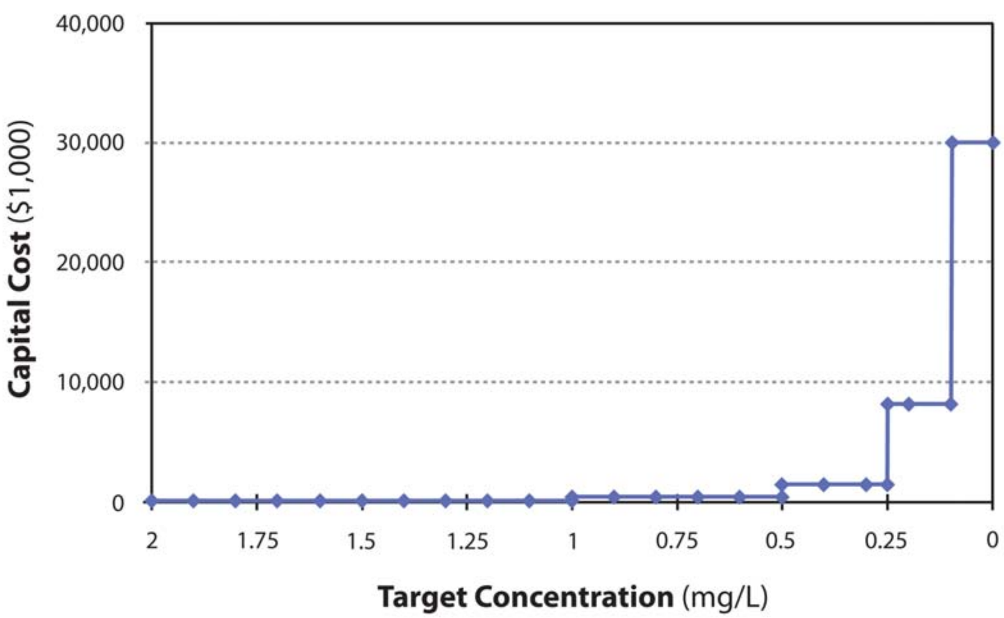

Figure 2. Example of the step capital cost function for largest plant.

Table 5. Annualized Costs of Phosphorus Removal for Scenarios: TMDL 0.40mg/l Concentration

	Base Case				Trade Scenario ($1000)				Change in Cost[a] (%)		
WWTP	OM ($1000)	Capital[b] ($1000)	Total ($1000)	Total Percent Capital	OM	Capital[b]	TR[c]	Total	OM	Capital	Total
D1	60	55	115	48	59	55	6	115	−1	0	0
D2	10	20	29	67	9	6	−2	15	−6	−67	−47
D3	16	27	43	62	16	27	−2	43	−3	0	−1
P1	39	44	83	53	39	44	1	83	0	0	0
P2	18	28	47	61	18	28	−2	46	−2	0	−1
P3	55	34	89	38	55	34	2	89	0	0	0
P4	8	18	26	69	7	6	−2	13	−9	−67	−49
P5	75	63	139	46	75	63	3	139	0	0	0
P6	36	42	78	54	36	42	−3	78	−1	0	0
P7	80	65	145	45	80	65	0	145	0	0	0
P8	105	76	181	42	105	76	0	181	0	0	0
W1	90	41	132	31	90	41	0	132	0	0	0
W2	128	58	186	31	128	58	1	186	0	0	0
W3	66	59	125	47	66	59	−1	125	0	0	0
R1	284	174	458	38	284	174	0	458	0	0	0
W4	259	127	386	33	259	127	0	386	0	0	0
WQ	115	0	115	0	102	0	13	102	−11	0	−11
T1	46	0	46	0	42	0	4	42	−8	0	−8
T2	136	88	225	39	134	88	−16	222	−2	0	−1
P9	175	102	277	37	175	102	0	277	0	0	0
P10	77	64	140	45	76	64	3	140	0	0	0
P11	47	48	95	51	46	48	−3	94	−1	0	−1
Total	1925	1170	3094	38	1902	1145	0	3046	−1	−2	−2

[a]This is a change from the base case in percentage terms.
[b]Capital costs are amortized over 15 years at 5%.
[c]If this net trade amount is positive (negative), allowance sales are larger (smaller) than purchases.

6.3. Sources of the Cost Savings and Patterns of Trade

[42] As indicated in Tables 5 and 6, trades and cost savings occur only among a subset of WWTP identified in the TMDL. In addition to trades on the Dead, Passaic, and Wanaque/Pompton Rivers above, the two WWTPs on the Peckman River are also predicted to trade allowances. While all trades follow the pattern of downstream trading associated with Hung and Shaw's TRS, three types of trading opportunities are identified.

[43] 1. OM savings only; trades between P5 and P6 and between P10 and P11. Both of these trades involve adjacent trading partners in which the larger of the two WWTPs is located upstream. Because of this size differential, OM

Table 6. Number of Allowances Traded and the Prices of Allowances Sold[a]

	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11	mg/l	$/lbs	$ Sales
D1		50	62		45																		0.371	38	5947
D2																							0.510	38	0
D3																							0.466	38	0
P1					13																		0.396	39	514
P2																							0.452	39	0
P3							52																0.389	35	1813
P4																							0.541	35	0
P5									109														0.385	32	3442
P6																							0.440	32	0
P7																							0.400	29	0
P8																							0.400	26	0
W1																							0.400	34	0
W2														23									0.398	30	689
W3																							0.404	30	0
R1																							0.400	22	0
W4																							0.400	18	0
WQ																			731				0.160	17	12,747
T1																			210				0.320	17	3657
T2																							0.458	17	0
P9																							0.400	21	0
P10																						93	0.388	31	2891
P11																							0.424	31	0
$/lbs	38	38	38	39	39	35	35	32	32	29	26	34	30	30	22	18	17	17	17	21	31	31		23	
$ Buy	0	1900	2349	0	2200	0	1813	0	3442	0	0	0	0	689	0	0	0	0	16,404	0	0	2891			31,687

[a]The WWTP in the row represents the seller and the WWTP in the column represents the buyer of permits. Allowances traded are in lbs.

marginal costs for P5 and P10 are lower than their trading partners. In combination with its upstream location, this makes P5 (P10) a natural seller to P6 (P11) under the trading ratio system. However, the differences in flow are not of sufficient magnitude to create substantial shifts in treatment levels: under the trading scenario, P5 (P10) treats to 0.385 mg/l (0.388 mg/l) and P6 (P11) treats to 0.440 mg/l (0.424) mg/l, instead of the no-trade restriction of 0.40 mg/l or below. Neither of these buyer/seller treatment ranges bracket the 0.50 mg/l or the 0.45 mg/l capital investment thresholds; thus the gains from trade are limited to OM cost savings. Overall gains from trade are only a nominal part of OM costs.

[44] 2. OM and capital cost savings; trading among D1, D2, D3, P1, P2, P3, and P4. This set of trades results in capital cost savings associated with not having to upgrade to the 0.40 mg/l level needed to meet the TMDL in the absence of trading. These capital cost savings are in excess of 67% for buyers D2 and P4 associated with buying allowances instead of investing in costly capital upgrades. In contrast, the sellers of allowances at best receive only nominal savings. This difference is due to the fact that sellers only experience trade gains associated with the allowance prices relative to their OM costs, while buyers also save substantially by not having to invest capital to treat beyond the 0.50mg/l (Figure 2).

[45] 3. Benefits to early adopters; WQ and T1. Prior to the TMDL these WWTPs, which are strategically located upstream on the Wanaque/Pompton River, upgraded their facilities to enable phosphorus abatement below 0.40 mg/l. Hence with trading, these WWTPs would be allocated an excess of allowances relative to their no-trade abatement levels. This, combined with the fact that T2 has not upgraded and is large enough to absorb these excess allowances, in effect acts to compensate these firms for their previous abatement decisions. In this case, OM cost savings for WQ and T1 are 11% and 8%, respectively. The costs savings to T2 are less consequential, estimated to be 2% (1%) of baseline OM (total) costs. These trades do not result in capital costs savings for T2 because this downstream firm is five to six times larger than the upstream firms, and hence the number of allowances available for purchase is not sufficient to preclude the need to upgrade to the 0.50 to 0.25mg/l treatment level.

6.4. Alternative Perspectives on Trading Potential

[46] While the modest cost savings from this trading program are largely explained by the relatively homogeneous treatment technologies, they are also based on a relatively strict interpretation of the TRS developed by *Hung and Shaw* [2005]. In this section, our discussion focuses on the potential cost savings of a program targeted to a subset of WWTPs and another program design that groups WWTP into trading zones.

6.4.1. A More Targeted Program

[47] Examination of Tables 5 and 6 indicates that only a subset of firms trade and that gains from trade are concentrated in the Dead (D1–D3), upper Passaic (P1–P4), and Pompton (WQ,T1,T2) Rivers. Therefore by targeting a program to these three areas, regulators could garner a majority of the cost savings presented above for the entire watershed. Total costs for this subset of 10 firms fall by about 6% relative to the no trade scenario. Corresponding capital and OM cost savings are 8% and 4%, respectively. The details of these cost savings for this subset of WWTPs are in Appendix B, Table B1. The allowances traded are the same as in Table 6.

6.4.2. Grouping WWTPs Into Trading Zones

[48] In the analysis above, each firm is a distinct zone. However, due to biophysical parameters and the proximity of the WWTPs, many of the trading ratios in Table 2 are equal to or approach unity. By assuming all these ratios are in effect unity, the individual WWTPs can be grouped into zones, within which trading can occur both upstream and downstream. In so doing, it may be possible for a low-cost downstream WWTP to sell allowances to a high-cost WWTP located upstream within the same zone, thus creating the potential for greater cost savings. To explore this possibility, the watershed is divided into six zones. Within each zone one-to-one trading ratios were specified. The six zones are (1) D1–D3, P1–P8; (2) W1–W4; (3) R1; (4) WQ, T1, T2; (5) P9; and (6) P10, P11.

[49] The results for this zonal scenario are in Appendix B, Tables B2 and B3. With the zonal configuration, there is now bidirectional trade within zones. For example, P8 now sells allowances to D1, D2, D3, P1, P3, P4, and P6. Similarly, W4 sells allowances upstream to W1, W2, and W3. Despite these changes in patterns of trade between firms, the overall cost savings remain rather modest. Total cost savings rise to about 4% across the watershed. Capital cost savings rise to about 7%, and OM savings rise to about 2%.

7. Summary and Policy Implications

[50] Efforts to extend the success of the United States acid rain program to other media have had mixed results [*Tietenberg*, 2006]. With respect to water quality trading, very few trades have actually occurred [*King and Kuch*, 2003; *Breetz et al.*, 2004; *EPA*, 2008; P. Faeth, Point-nonpointillism: The challenges that water quality trading faces and what we might do about it, paper presented at the Second National Water Quality Trading Conference, Environmental Protection Agency, Pittsburgh, Pa., 23–25 May 2006] despite substantial policy and financial investment in such programs.

[51] Using a trading ratio model that exploits the special characteristics of water pollution, we estimate the potential demand for effluent allowances and document the magnitude of the potential cost savings associated with a phosphorus trading program in the upper, nontidal Passaic River Basin. The cost savings due to the trading program are calculated relative to a base case that minimizes the annual variable cost of meeting the environmental standard when each plant must limit emissions to its TMDL without the possibility of trading. The results of our analysis suggest that across the 22 municipal wastewater treatment plants in the entire watershed, the cost savings associated with a market-based program in which trades are based on comparisons of marginal abatement costs relative to the prevailing allowance prices will be modest, on the order of 2–3% relative to the no-trade base case.

[52] These results appear consistent with the limited number of actual trades that have been completed in the United States. The results lend little support to efforts to establish an open market allowance exchange structure in the upper, nontidal Passaic Watershed as along the lines of

Table B1. Annualized Costs of Phosphorus Removal for a Targeted Program: TMDL 0.40mg/l Concentration

	Base Case				Trade Scenario ($1000)				Change in Cost[a] (%)		
WWTP	OM ($1000)	Capital[b] ($1000)	Total ($1000)	Total Percent Capital	OM	Capital[b]	TR[c]	Total	OM	Capital	Total
D1	60	55	115	48	59	55	6	115	−1	0	0
D2	10	20	29	67	9	6	−2	15	−6	−67	−47
D3	16	27	43	62	16	27	−2	43	−3	0	−1
P1	39	44	83	53	39	44	1	83	0	0	0
P2	18	28	47	61	18	28	−2	46	−2	0	−1
P3	55	34	89	38	55	34	2	89	0	0	0
P4	8	18	26	69	7	6	−2	13	−9	−67	−49
WQ	115	0	115	0	102	0	13	102	−11	0	−11
T1	46	0	46	0	42	0	4	42	−8	0	−8
T2	136	88	225	39	134	88	−16	222	−2	0	−1
P11	47	48	95	51	46	48	−3	94	−1	0	−1
Total	502	314	817	38	481	289	0	770	−4	−8	−6

[a]This is a change from the base case in percentage terms.
[b]Capital costs are amortized over 15 years at 5%.
[c]If this net trade amount is positive (negative), allowance sales are larger (smaller) than purchases.

the much celebrated United States acid rain trading program. Rather, our results suggest that different strategies for water quality trading should be pursued in small watersheds such as the Passaic, where there are relatively few potential traders and abatement costs are relatively homogeneous across firms. In these situations, trading programs should instead be designed to identify the subset of firms that will gain substantially from trade in pollution allowances and to nurture trade among these firms. Additional gains may also be achieved by aggregating firms into zones within which the biological and hydrological conditions imply no attenuation of effluent (e.g., trading ratios of unity) and thus allow for bidirectional trades. Furthermore, markets in such watersheds are relatively thin (e.g., only 22 possible participants), intertemporal banking is prohibited under the Clean Water Act, and investments in pollution abatement capacity are costly and lumpy and must be framed within 5-year allowance cycles.

[53] Thus it is likely that these opportunities for trade will need to take the form of multiyear contracts, in essence allowing WWTPs to move beyond comparisons of marginal cost and allowance prices and to share the costs of investing in discrete capital upgrades. If, as we suspect, many "typical" watersheds across the United States have similar characteristics to those of the upper Passaic River watershed, there may be widespread opportunities in which a combination of these design features will offer an effective, preferred strategy to realize the potential benefits from watershed-based water quality trading. Because such negotiations may involve capital cost savings, a form of sharing of these savings across WWTPs and perhaps communities will have to be orchestrated.

[54] While these conclusions might appear to conflict with the notion of actively pursuing water quality trading markets, they do not. We maintain that allowance trading can result in substantial cost savings in water quality settings. However, to achieve these gains, the trading institution needs to be tailored to the opportunities at hand, simply opening an exchange market intended to mimic the success of the United States acid rain allowance trading program is not likely to be appropriate for typical watersheds. We can achieve, perhaps substantial, gains from trade. The gains may just not arise naturally from an open market discharge allowance trading system.

Appendix A

[55] The purpose of this appendix is to demonstrate how prices for allowances between any two sources are related to marginal costs of abatement at the sources and the trading ratio between them. For this demonstration, one must formulate the Lagrangian corresponding to the trading model in equations (8) through (10) above

$$\mathrm{L}(\mathrm{e}_i, \mathrm{T}_{ik}, \mathrm{T}_{ki}, \lambda_i) = Z + \sum\nolimits_{i=1}^{n} \lambda_i \cdot \left(e_i - \sum\nolimits_{k=1}^{i-1} t_{ki}\mathrm{T}_{ki} + \sum\nolimits_{k>i}^{n} \mathrm{T}_{ik} - \overline{\mathrm{T}}_i\right). \tag{A1}$$

[56] Since the allowances bought by i from k, must equal the allowances sold by k to i, we substitute T_{ik} for T_{ki} in equation (A1). The Kuhn-Tucker necessary and sufficient conditions for a minimum are

$$\partial L/\partial e_i = -Z_i' + \lambda_i \geq 0; (i = 1, \ldots, \mathrm{n}), \tag{A2}$$

$$e_i * \left(-Z_i' + \lambda_i\right) = 0; (i = 1, \ldots, \mathrm{n}), \tag{A3}$$

$$\partial L/\partial \mathrm{T}_{ki} = -t_{ki}\lambda_i + \lambda_k \geq 0 \quad (k = 1, \ldots, i-1; i > k, \ldots, \mathrm{n}), \tag{A4}$$

$$\mathrm{T}_{ki} * [-t_{ki}\lambda_i + \lambda_k] = 0 \quad (k = 1, \ldots, i-1; i > k, \ldots, \mathrm{n}), \tag{A5}$$

$$\partial L/\partial \lambda_i = e_i - \sum\nolimits_{k=1}^{i-1} t_{ki}\mathrm{T}_{ki} + \sum\nolimits_{k>i}^{n} \mathrm{T}_{ik} \leq \overline{\mathrm{T}}_i \quad (i = 1, \ldots, \mathrm{n}), \tag{A6}$$

$$\lambda_i^* \left(e_i - \sum\nolimits_{k=1}^{i-1} t_{ki}\mathrm{T}_{ki} + \sum\nolimits_{k>i}^{n} \mathrm{T}_{ik} - \overline{\mathrm{T}}_i\right) = 0 \quad (i = 1, \ldots, \mathrm{n}), \tag{A7}$$

$$e_i \geq 0,\ T_{ki} \geq 0,\ \lambda_i \geq 0. \tag{A8}$$

Table B2. Annualized Costs of Phosphorus Removal for Six Zone Trading Model: TMDL 0.40mg/l Concentration

	Base Case				Trade Scenario ($1000)				Change in Cost[a] (%)		
WWTP	OM ($1000)	Capital[b] ($1000)	Total ($1000)	Total Percent Capital	OM	Capital[b]	TR[c]	Total	OM	Capital	Total
D1	60	55	115	48	59	55	−1	114	1	0	1
D2	10	20	29	67	6	6	−2	13	34	67	56
D3	16	27	43	62	12	11	−3	24	25	57	45
P1	39	44	83	53	35	44	−3	79	10	0	5
P2	18	28	47	61	14	28	−3	42	23	0	9
P3	55	34	89	38	53	34	−2	87	3	0	2
P4	8	18	26	69	5	6	−4	11	36	67	57
P5	75	63	139	46	78	63	3	142	−4	0	−2
P6	36	42	78	54	32	42	−4	74	11	0	5
P7	80	65	145	45	84	65	4	150	−5	0	−3
P8	105	76	181	42	116	76	15	193	−11	0	−6
W1	90	41	132	31	74	0	−13	74	18	100	42
W2	128	58	186	31	113	48	−14	161	12	0	9
W3	66	59	125	47	56	59	−9	115	15	0	8
R1	284	174	458	38	284	124	0	407	0	0	0
W4	259	127	386	33	290	127	35	417	−12	0	−8
WQ	115	0	115	0	115	0	13	115	0	0	0
T1	46	0	46	0	46	0	4	46	0	0	0
T2	136	88	225	39	117	88	−16	206	14	0	8
P9	175	102	277	37	175	102	0	277	0	0	0
P10	77	64	140	45	79	64	3	143	−4	0	−2
P11	47	48	95	51	43	48	−3	92	7	0	4
Total	1925	1170	3094	38	1889	1092	0	2981	2	7	4

[a]This is a change from the base case in percentage terms.
[b]Capital costs are amortized over 15 years at 5%.
[c]If this net trade amount is positive (negative), allowance sales are larger (smaller) than purchases.

[57] From (A2) and (A3), we know that for $e_i > 0$, $Z_i' = \lambda_i$. From (14) and (15), $-\lambda_i t_{ki} + \lambda_k$ cannot be positive when T_{ki} is positive. For interior solutions, $\lambda_i t_{ki} = \lambda_k$, and

$$Z_i' = \lambda_i = \frac{\lambda_k}{t_{ki}}. \tag{A9}$$

Since $Z_i' = C'(e_i^0 - e_i)$, λ_i is the shadow price of a unit of effluent at site i; it is equivalent to the marginal abatement cost at site i. Hung and Shaw show that these shadow prices are the prices of the allowances at the respective points, but more generally:

$$t_{ki}^{*}\lambda_i \leq \lambda_k. \tag{A10}$$

[58] From the complementary slackness conditions, we know that when trade takes place between discharger

Table B3. Number of Allowances Traded and the Price of Allowances Sold, Six Zone Trading Model: TMDL 0.40mg/l[a]

	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11	mg/l	$/lbs	$ Sales
D1																							0.404	31	0
D2																							0.554	31	0
D3																							0.507	31	0
P1																							0.436	31	0
P2																							0.497	31	0
P3																							0.410	31	0
P4																							0.569	31	0
P5							62		32														0.387	31	2928
P6																							0.442	31	0
P7					107	28																	0.383	31	4220
P8	22	70	101	109		22	62		83														0.364	31	14,717
W1																							0.501	23	0
W2																							0.465	23	0
W3																							0.462	23	0
R1																							0.400	22	0
W4												583	601	386									0.359	23	35,310
WQ																			731				0.160	17	12,747
T1																			210				0.320	17	3657
T2																							0.458	17	0
P9																							0.400	21	0
P10																						93	0.388	31	2891
P11																							0.424	31	0
$/lbs	31	31	31	31	31	31	31	31	31	31	31	23	23	23	22	23	17	17	17	21	31	31		23	
$ Buy	703	2206	3154	3421	3339	1566	3876	0	3601	0	0	13,113	13,518	8679	0	0	0	0	16,404	0	0	2891			76,470

[a]The WWTP in the row represents the seller and the WWTP in the column represents the buyer of permits. Allowances traded are in lbs.

k and discharger i (e.g., T_{ik} and T_{ki} are strictly positive), equation (A10) must hold as an equality for $k < i$; i is downstream of k. If equation (A10) holds as a strict inequality, there is no trade between zones k and i. The price at which discharger k is willing to sell is larger than the value of an allowance to discharger i, the value of the allowance is the price at i, "discounted" by the trading ratio.

Appendix B

[59] This appendix includes Table B1, which contains the results for a program targeted specifically to a subset of firms in which the gains from trade are concentrated. This program is discussed in section 6.4.1. Tables B2 and B3 contain results on the gains from trade and the patterns of trade for a program where some portions of the watershed are defined as single zones. As explained in section 6.4.2, this zonal configuration allows for one-to-one trading both upstream and downstream within a zone.

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