Linking the Theory and Actuality of Water Quality Trading Opportunities: Management Areas and Fixed Costs

by

Tianli Zhao

Yukako Sado

Richard N. Boisvert

Gregory L. Poe

Dyson School of Applied Economics and Management
Cornell University

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Funding for this research was provided by the US-EPA Targeted Watershed Grant Program (WS972841) and USDA Hatch Project funds provided through Cornell University (121-6415). Without implication, we appreciate helpful inputs into this and related research from Josef Kardos and Chris Obrupta, Rutgers University. Neither the US EPA nor the USDA has reviewed nor endorsed this publication, and the views expressed herein may not reflect the views of these agencies.

Linking the Theory and Actuality of Water Quality Trading Opportunities: Management Areas and Fixed Costs

Whereas in their review of the United States sulfur dioxide emissions trading program, Schmalensee et al. (1998) concluded that "tradable permit programs can work roughly as the textbooks describe; that is, they can both guarantee emissions reductions and allow profit-seeking emitters to reduce total compliance cost" (p. 66), this does not appear to be the case for water quality trading. Despite the theoretical promise of water quality markets, substantial financial and technological support by the US EPA, and more than 48 established and pilot programs:

> "Only 100 facilities have participated in trading… Moreover, relatively few trading programs have been scaled up from pilot projects to permanent programs, and even fewer can claim to have had a significant impact on improving water quality or reducing pollution control costs" (U.S. EPA 2008, 1-2).

The lack of widespread success in existing water quality trading programs may be attributed, in part, to a limited correspondence between the institutional and hydrologic circumstances in "typical" watersheds and the open-market trading system envisioned in standard economics presentations of pollution trading. As Hoag and Hughes-Popp (1997) suggested some time ago; translating theory into practice may necessitate a reexamination of "the main principles associated with water pollution credit trading theory…to identify factors that influence program feasibility" (p. 253).

Heeding this admonition, we explore two particular aspects of the disparity between the theory and practice of water quality trading programs using empirical modeling results from a case study of the Non-Tidal Passaic River Basin phosphorus emissions trading program. First, recognizing that hydrological systems and Total Maximum Daily Load (TMDL) objectives for a particular watershed may be quite complex, we broadly interpret the Hung and Shaw (2005) Trading Ratio System (TRS) to enable firms to trade allowances upstream and across tributaries within a specified multi-zone management area. Hung and Shaw show that the TRS can cost effectively meet water quality requirements at all points in a watershed through trades that reallocate permits from upstream to downstream sources. However, as we demonstrated in Sado, Boisvert and

Poe (2010), and reiterate here, the gains from such a TRS system are likely to be minimal.

Whereas in a pure TRS-based zonal system the exchange rate between firms within a zone is one (i.e., a unit of emissions from one source has the same effect on downstream water quality as other sources within the zone), “other ratios potentially could provide policy makers with an additional degree of freedom” (Tietenberg, 2006). We investigate this possibility by modeling a “Management Area” (MA) policy proposed for the Upper-Passaic River Basin TMDL (Obrupta, Niazi and Kardos, 2008). The MA approach is motivated by the fact that TMDL regulations are often oriented toward avoiding critical “hot spots” (i.e., localized areas with unacceptably high degraded water quality due to high concentrations of a pollutant) rather than maintaining fixed concentration standards throughout the watershed. MAs group pollution sources with a common endpoint at one of these potential hot spots, and may or may not have trading ratios equal to unity between sources. Within an MA bidirectional trades are allowed. Trading between MAs is consistent with TRS-type trading rules wherein only downstream sales of allowances are allowed.

Second we raise the practical concern that the canonical theoretical presentation of tradable pollution allowances, in which firms buy and sell pollution allowances based on marginal abatement costs relative to the market determined price, is inappropriate for cost-effectively meeting a TMDL in a typical watershed. Such open-market exchange programs have been effective in settings, such as the U.S. Acid Rain Trading program that are characterized by large numbers of potential traders with heterogeneous abatement technologies across firms, and heterogeneous present capacity to meet standards. However this type of a trading mechanism is less amenable to point-to-point source water quality trading programs characterized by a small number of potential traders in a watershed, with discrete and homogeneous abatement technologies across firms, and most, if not all, firms not having the present capacity to meet the specified standard. In such settings, managers may be reluctant to not upgrade (and buy permits) or to develop excess treatment capacity (and sell permits) because of the relative lack of buyers and sellers in a thin market. This potential, in conjunction with our subsequent demonstration of cost savings associated with trades that account for discrete fixed costs, leads us to argue that a structured bilateral trade system in which profitable trading opportunities are identified and implemented with multiyear contracts between firms, would more likely approximate cost-effective outcomes than an open-market, price directed system.

In addressing these issues, we recognize that neither zonal aggregation nor capital cost considerations are novel issues in the pollution control literature. For example, Tietenberg (2006) provides a comprehensive review of studies with various zonal configurations, mostly in the context of air quality, while Bennett, Thorpe, and Guse (2000) examine the consequences of broadening trading areas with respect to the Long Island Sound Nitrogen Credit Exchange program. Rose-Ackerman (1974), amongst others raised concerns about market incentives vis-à-vis substantial, discrete fixed costs likely to arise in water quality treatment. More recently, Hanley et al. (1998), the US EPA (2004), Boisvert, Poe and Sado (2007), Caplan (2008) and Rowles (2008) have discussed the importance of the discontinuous or stepwise nature of capital costs in the design and implementation of water quality trading programs. Further, a series of least cost abatement studies for sewage treatment, have included fixed costs in their identification of optimal watershed investment plans, inferring substantial opportunites for gains from trade in water quality markets (Eheart, 1980; Eheart, Joeres, and David, 1980; Bennett, Thorpe and Guse, 2000). However, such studies have failed to identify trading patterns and have largely been constructed within a single receptor framework. Our contribution is to bring these issues to the forefront, in an empirical exploration of factors that could improve the cost-effectiveness of trading programs with fixed costs and multiple receptors and thus, by adding these realistic features, enhance the viability of water quality trading.

The remainder of the paper is organized as follows. The next section provides background information on the TMDL and essential attributes of the Upper-Passaic River Basin. We then introduce our conceptual framework in two separate sections, each building off of the TRS model. Given this framework we employ programming models to explore the effects of zonal aggregation and the cost-savings associated with considering fixed costs in a trading regime. The final section concludes with a discussion of the need to further explore long term contracting in a structured bilateral trade system or to adopt other incentives to encourage trading in the face of fixed capital investments.

Essential Features of the Non-tidal Passaic Watershed

The Non-Tidal Passaic watershed is located primarily in northeastern New Jersey, with the uppermost portion extending into New York State. As depicted in Map 1, this 803 square mile watershed consists of the Passaic River and its tributaries, draining five densely populated counties in New Jersey near the New York City Metropolitan area.

Approximately one-quarter of New Jersey's population (i.e., two million people) resides within the watershed boundaries. It is a major source of drinking water both inside and out of the basin.

As shown in Map 1 the Passaic River initially flows south, then turns and flows in a north-easterly direction, and then turns east and finally south before reaching Newark Bay. The formal terminus of the Upper Passaic River is Dundee Dam, which separates the Upper, Non-Tidal Passaic River from the tidal part of the Passaic 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 join the Passaic River.

In April 2008, a final TMDL rule was promulgated for this river basin (NJDEP, 2008), calling for a more than 80% reduction in the total phosphorus concentration emissions from 22 Waste Water Treatment Plants (WWTPs) in the watershed.

> "Except as necessary to satisfy the more stringent criteria…or where watershed or site-specific criteria are developed…phosphorus as total P shall not exceed 0.1 [mg/l] in any stream, unless it can be demonstrated that total P is not a limiting nutrient and will not otherwise render the waters unsuitable for the designated uses." (NJDEP, p. 15)

These WWTPs are depicted in Map 1 and described in Table 1. At present the average (flow weighted) total phosphorus emissions is estimated to be 2.13 mg/l.

A Trading-Ratio System (TRS)

A critical feature of the TRS developed in Hung and Shaw, and indeed in all trading systems involving non-uniformly mixed pollutants, is the spatial issue of the transport and degradation of the pollutant. Following Montgomery (1972) this can be incorporated into basic trading models by defining a *diffusion (or transfer) coefficient*, d_{ik} that measures the contribution of one unit of emissions from the i*th* discharger or source to the total load of effluent at the k*th* receptor. Formally, let e_i indicate an amount of emissions from source i, and let e_i^k indicate the corresponding amount measured at the k*th* receptor after discharger i emits e_i. Then,

$$d_{ik} = \frac{e_i^k}{e_i} \tag{1}$$

where “zero” indicates that the i*th* discharger has no effect on the *jth* receptor (as in the case of being upstream or on a separate tributary) and “one” indicates that the unit of pollution from the i*th* source does not diminish in any way by the time it reaches the *jth* receptor. (For this reason, d_{ii} should always equal to one). An intermediate coefficient of, say, $d_{ik} = 0.5$ would indicate that one additional unit of pollution for discharger i results in one-half a unit of pollution at receptor k. For a region or watershed with i sources of pollutants and k receptor points, the dispersion of water emissions for the i sources can be specified by an i by k matrix of diffusion coefficients (Montgomery 1972):

$$D = \begin{bmatrix} & \vdots & \\ \cdots & d_{ik} & \cdots \\ & \vdots & \end{bmatrix} \tag{2}$$

Taking advantage of the fact that water flows downstream, and hence restricting the realm of possible buyers (k) to include only those that have a direct physical linkage to source i (i.e. d_{ik}=0), Hung and Shaw (2005) prove that the following TRS model can achieve a cost-effective solution in a multi-zone stetting:

(3) Minimize Z = $\sum_{i=1}^{n} C_i(e_i^0 - e_i)$, subject to:

(4) $e_i - \sum_{k=1}^{i-1} t_{ki} \mathrm{T}_{ki} + \sum_{k>i}^{n} \mathrm{T}_{ik} \le \overline{\mathrm{T}}_i$ (i = 1,…,n)

(5) $\mathrm{T}_{ik}, \mathrm{T}_{ki} \ge 0$; and $e_i \in [0, e_i^0]$.

where, zones (i=1,….n) are indexed from upstream to downstream, with, in the Hung and Shaw presentation, each zone corresponding to a single pollution source. The parameters are defined as follows;

$C_i(.)$ = costs of abatement for source i,

e_i^o = unregulated emissions from source i,

e_i = emissions under abatement program from source i

t_{ik} = the diffusion or transfer coefficient between source i and receptor k (that is t_{ik} is set to d_{ik} as defined in equation 1)

$\overline{T}_j$ = aggregate tradable allowances allocated to a zone j,

T_{ki} (T_{ik}) = the number of allowances sold by *i* to *k (k* to *i)*

The Kuhn-Tucker conditions associated with Equations 3-5 imply that a discharger's marginal abatement cost equals the sum of the shadow prices of the total load constraints at affected zones weighted by transfer coefficients (Hung and Shaw, 2005; Sado, Boisvert and Poe, 2010) and that least-cost trading between individual sources i and j with respect to the closest common downstream receptor (k) will achieve the spatially adjusted equimarginal relationship

$$MC_i(e_i^j) = \frac{1}{d_{ij}}\frac{\partial C_i(e_i)}{\partial e_i} = \frac{1}{d_{kj}}\frac{\partial C_k(e_k)}{\partial e_k} = MC_k(e_k^j)\,. \tag{6}$$

where e_i^j indicates the contribution of one unit of emissions from the i*th* discharger or source to the total load of effluent at the j*th* receptor.

As such, Hung and Shaw comports with the standard marginal cost trading necessary condition for non-uniformly mixing pollutants.

> "..it is not the marginal costs of emission reduction that are equalized across sources in a cost-effective allocation… it is the marginal costs of pollution reduction at each receptor location that are equalized" (Tietenberg, 2006 p. 34).

Hung and Shaw further demonstrate that, using an open-market approach in which firms compare their marginal costs of abatement with the going permit price to determine whether they will buy or sell permits, this approach will provide the minimum cost of meeting water quality objectives at all points of the watershed – in essence stipulating a no degradation outcome relative to the original TMDL specified allocation – and prevent free-riding. This framework can be readily incorporated into a programming model.

Some intuition can be gained about this mathematical equimarginal condition using simple geometry. Figure 1 depicts two spatially-adjusted marginal abatement cost curves[1] (relative to receptor site *j*) where total spatially-adjusted abatement (in terms of pollution at receptor site *j*) required is 400 units. Although not typically stated, the implicit assumption underlying this type of presentation, is that the timeframe is the short run, where capital investment is fixed. Diminishing returns are expected: given a fixed level of capital investment, marginal abatement costs tend to rise with successive levels of abatement. With chemical treatment processes, for example, the effectiveness of each small addition of chemicals beyond a certain point is expected to diminish, raising the marginal abatement cost of each successive pound of pollutant abated.

Assume further that firm *i* and *k* are the only two sources of emissions in the watershed and *j* is the only receptor of concern. For simplicity, we make the additional assumption that two source have the same level of spatially-adjusted initial pollutant (400 units), and that, absent reallocation opportunities across sources, the environmental constraint requires each reduce its effluent by half, i.e. (200, 200). The spatially adjusted equimarginal condition implies that, the cost-effective equilibrium e_1* is at (100, 300) where two spatially adjusted marginal cost curves cross, corresponding to emissions reductions by source *i* of 300 units and source *k* of 100 units. At this point, the total abatement costs for the two firms to meet the emissions reduction of 400 units at receptor j, represented by the area under $MC_i(e_i^j)$ from $e_i^j = 400$ to $e_i^j = 100$ plus the area under $MC_i(e_i^j)$ from $e_k^j = 400$ to $e_k^j = 300$, is minimized. Any other allocation of final emissions across the two firms would lead to greater total costs. Following basic market principles and assuming zero transactions costs, the two firms would trade to achieve this least cost outcome in this simple model, with the cost savings associated with reallocating pollution responsibility being represented by the shaded area in Figure 1.

Management Areas: The Non-Tidal Passaic River Basin TMDL

We extend the TRS model to more closely reflect the Management Area approach being applied to phosphorus trading in the Non-Tidal Passaic River Basin. As a reference point the typical conceptualization of a multi-zone system treats emissions form various source within a zone as having equal effects on water quality (Tietenberg, 2006).

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[1] All the effluent units in Figure 1, 2 and 3 are spatially-adjusted relative to receptor *j*.

Hung and Shaw adopt this formulation, defining a trading zone “as an area in which the environmental effects of the effluent of a particular pollutant are the same” (p. 99). Following this framework, the trading ratios between sources within a zone would be set to unity (Sado, Boisvert and Poe, 2010).

With respect to the Non-Tidal Passaic River Basin TMDL it was found that the 0.1 mg/l restriction on total phosphorus was overly restrictive at many points in the watershed. An extensive water quality simulation study (Omni Environmental, 2007) indicates that any possible range of water quality trading outcomes that meet the water quality objective at the two designated endpoints will also lead to no excessive loading in other areas of the watershed because of other factors that mitigate the impact of phosphorus (viz. flow, shad cover and turbidity). That is, meeting the water quality constraints at these critical junctures would not create any hotspots at other points in the watershed. Based on these modeling results, a Management Area approach has been adopted for the TMDL implementation: a Management Area (M.A.)

> “is delineated so that its outlet represents the *only* hot spot concern in that management area. Because there are no hot-spot concerns in addition to the management area outlet, bidirectional trades (i.e., seller can be upstream or downstream of the buyer) are allowed within the same management area. Trades are subject to a trading ratio in order to equalize the load treated and account for difference in attenuation for the load from each WWTP relative to the management area outlet” (Obrupta, Niazi and Kardos, p. 952)

Three M.A.s are identified in the Upper Passaic River Basin TMDL: the Upper Passaic MA consisting of WWTPs D1-D3, P1-P8, W1-W4, and R1 with associated endpoint at the confluence of the Passaic and Pompton rivers; the Pompton MA, WQ, T1 and T2, with endpoint at the confluence of the Passaic and Pompton Rivers; and the Lower Passaic M.A., P9-P11, with endpoint at the Dundee Lake and Dam. Accounting for a number of factors, including seasonal variations in flows, the set of allowable trades is depicted in the table below.

Buyer / Seller	Upper Passaic MA (D1-D3, P1-P8, W1-W4, R1)	Pompton MA (WQ,T1,T2)	Lower Passaic MA (P9-P11)
Upper Passaic MA	Yes	No	Yes
Pompton MA	Yes	Yes	Yes
Lower Passaic MA	No	No	Yes

That is, the following trades are allowed: 1) within MA – upstream and downstream trades within a MA; 2) downstream trades from the Upper Passaic and Pompton MAs to the Lower Passaic MA; and 3) cross tributary trades from the Pompton MA to the Upper Passaic MA but not *vice versa*. While we refer to opportunity three as a cross tributary trade, such transactions are only possible in the M.A. approach we outline below because the endpoint of the Upper Passaic M.A. lies hydrologically below the endpoint of the Pompton M.A.

The specific rules of M.A demarcation yield an important result that all water flowing out from an upstream M.A into the downstream M.A necessarily passes through the critical location at the end-point of the upstream M.A. (In this sense one can think the end-point as Customs that export all effluent from upstream M.A to downstream M.A.) Therefore, the amount of discharge exported from a M.A can always be measured equivalently by the "effective discharge" at its end-point.

To formulate this problem mathematically, think of a management area as a set of dischargers with $\{ j_1 , j_2 \cdots j_{n_j} \}$ being a source in the upstream management area *J* and [*J*] denoting the end-point of *J*. Similarly let $\{ k_1 , k_2 \ldots k_{n_k} \}$ be a source in the downstream management area *K*. Note that an M.A. is considered upstream to another M.A if the endpoint of the former is upstream to the latter.[2] Further, in order to facilitate the discussion, the point sources are ordered alphabetically from upstream to

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[2] For the very rare case in which one endpoint is neither upstream nor downstream of the other , one cannot clearly order the M.A. This special case is rule out in this study.

downstream. For instance, management area *J* is always upstream to management area K without additional specification.

Then there exists a following multiplicative relation of diffusion rates between a source in J and a source in K[3]:

$$d_{jk} = d_{j[J]} \cdot d_{[J]k} \quad , \tag{7}$$

That is, the diffusion rate from *j* to *k* is equal to the diffusion rate from *j* to its end-point [*J*] multiplied by the diffusion rate from [*J*] to *k*. Then, multiplying both sides of the equation by the effluent e_k, Equation (7) becomes:

$$e_j \cdot d_{jk} = e_j \cdot d_{j[J]} \cdot d_{[J]k} \tag{8}$$

Equation (8) can be further reduced by utilizing the following notation. $e_j^{[J]}$, which denotes the relative impact on end-point [J] as a source *j* in J emits e_j. Formally, $\forall j \in J \ , e_j^{[J]} = e_j \cdot d_{j[J]}$ (hereafter referred to $e_j^{[J]}$ as "Effective discharge at [J] contributed by *j*"):

$$e_j \cdot d_{jk} = e_j^{[J]} \cdot d_{[J]k} \tag{9}$$

Equation (9) states that e_j units of discharge at source *j* in upstream M.A has the same impact on the downstream M.A as $e_j^{[J]}$ units of "effective discharge" at the end-point [J]. By the same token, the total discharge exported from management area J can be measured by $e_{[J]}$, which equal to the sum of the effective discharge contributed by all sources in J, that is:

$$e_{[J]} = \sum_{j \in J} e_j^{[J]} \tag{10}$$

This equivalent measure of discharge plays a vital role in designing the proper trading ratios.

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[3] Note that this multiplicative relation is guaranteed because $[J]$ is the sole-outlet of J.

As discussed above, the way each M.A is delineated guarantees that each M.A end-point is the sole outlet of its M.A. This makes it possible to hydrologically separate each M.A. In other words, as long as the water quality at the critical location is ensured, the allowances trading within its M.A would not jeopardize the water quality in other M.As. For this reason, the trading ratios for intra-M.A trading are designed to adequately protect the water quality at its end-point. In particular, let k_1 and k_2 be two sources within the management area K, (i.e. $k_1, k_2 \in K$) Suppose k_1 sells allowance to k_2, then k_1 has to discharge Δe_{k_1} units less, while k can discharge Δe_{k_2} units more. Equation (11) guarantees that this trade has zero net effect at their end-point [*K*] :

$$\Delta e_{[K]} = \Delta e_{k_1} \cdot d_{k_1[K]} + \Delta e_{k_2} \cdot d_{k_2[K]} = 0 \tag{11}$$

Finally, rearranging equation (11), the intra-M.A trading ratio $\tau_{k_1k_2}$ is set equal to the diffusion rates from seller k_1 to the end-point [*K*] divided by the diffusion rate from k_2 to [*K*]

$$\tau_{k_1k_2} = -\frac{\Delta e_{k_2}}{\Delta e_{k_1}} = \frac{d_{k_1[K]}}{d_{k_2[K]}} \tag{12}$$

The design of trading ratio $\tau_{k_1k_2}$ ensures that allowing trade to be both upstream and downstream within a M.A will not affect the water quality at its end-point; however, other areas within the same M.A might have elevate concentrations as a result of trading. Yet, the very definition of the M.A> precludes the possibility that these elevated concentrations will engender a “hot spot”. As such, one can think the trading system within each M.A as a bare-bones version of the ambient permit system, whereas the problem of transaction complexity is avoided since there is only one market for emission allowances.

Formally, the idea of allowing intra-M.A trades relative to a single end-point is essential for the proof of the following Proposition: (The proof is provided in Zhao, 2010)

Proposition 1:

Intra-M.A trading constraints support the cost-effective allocation of allowances subject to the water quality at the M.A end-point.

Proposition 1 ensures that the water quality at the endpoint of the M.A is strictly protected by Intra-M.A trading constraints, so when the water flows out of each M.A and enter the downstream M.A, the water quality is met with the predetermined standard. Moreover, it claims that the cost-effective benchmark in which the environmental authority minimizes the aggregate abatement costs subject to environmental constraints is the same as the model in which the environmental authority minimizes aggregate abatement costs subject to the Intra-M.A. trading constraints

Similarly, the trading ratios for inter-M.A trades are also designed to preserve the water quality at each zonal endpoint. And since only the buyer's endpoint is subject to the negative impact by the trades, ensuring the endpoint of the buyer's M.A is adequate. Formally, let j be the seller and *k* be the buyer from different management areas J and K respectively ($j \in J, k \in K$) and so [*K*] is buyer's M.A end-point; Δe_j is the change of effluent from *j*, Δe_k is the change of effluent from *k*, Equation (2.3.3-1) guarantees that the trade has zero net effects at the buyer's end-point [*K*].

$$\Delta e_j \cdot d_{j[K]} + \Delta e_k \cdot d_{k[K]} = 0 \qquad (13)$$

Solving the above equation, the inter-M.A trading ratio γ_{ik} is given as:

$$\gamma_{jk} = -\frac{\Delta e_k}{\Delta e_j} = \frac{d_{j[K]}}{d_{k[K]}} \qquad (14)$$

Comparing Equation (14) with Equation (12) shows that the trading ratio for both intra-M.A trades and inter-M.A trades are described by the same simple relation------*the trading ratio is equal to the relative diffusion rates to the end-point of buyer's M.A.*

$$\gamma_{jk} \equiv \frac{d_{j[K]}}{d_{k[K]}} \qquad \tau_{jk} \equiv \frac{d_{j[K]}}{d_{k[K]}} \tag{15}$$

To see a more interesting result associated with inter-M.A trades, recall that using the upstream end-point [*I*] as intermediary, one can apply a multiplicative effect over diffusion from *j* to [*K*], that is:

$$d_{j[K]} = d_{j[J]} \cdot d_{[J][K]} \tag{16}$$

Substituting Equation (15) into (13) yields:

$$\Delta e_j \cdot d_{j[J]} \cdot d_{[J][K]} + \Delta e_k \cdot d_{k[K]} = 0 \tag{17}$$

And since $\Delta e_{[K]} = \Delta e_k \cdot d_{k[K]}$, and $\Delta e_{[J]} = \Delta e_j \cdot d_{j[J]}$, the above equation can be further reduced to:

$$\Delta e_{[J]} \cdot d_{[J][K]} + \Delta e_{[K]} = 0 \tag{18}$$

Finally, the equivalent trading ratio $t_{[J][K]}$ between the two end-points [*J*], [*K*] can be solved from equation (18):

$$t_{[J][K]} = -\frac{\Delta e_{[K]}}{\Delta e_{[J]}} = d_{[J][K]} \tag{19}$$

Equation (19) demonstrates that the inter-M.A trading between two sources *j* and *k* is as if the two M.A end-points [*J*] and [*K*] were trading the "effective allowances" under the Trading Ratio System-----the trading ratio equal to the natural diffusion rate between the two end-points. This result can be further interpreted as there were an imaginary broker at each M.A end-point who buys (sells) allowances from (to) other brokers following the TRS and sells (buys) them to (from) the sources within its M.A. In other words, one can think the inter-M.A trading as being carried out into two steps: allowances are traded across M.As by "brokers" at each M.A end-point under Trading Ratio System, and then localized to each sources through intra-M.A trading.

Hung and Shaw's TRS guarantees that, in the first step, effective allowances can be traded between M.A end-points cost-effectively, while meeting the environmental quality at all end-points. Since the cost-effectiveness of the second step can also be ensured by *proposition 1* discussed earlier, the whole inter-M.A trading process is consummated cost-effectively subject to the environmental standard at all M.A end-points. The above is formally expressed in the proposition 2.

Proposition 2:

Under Management Area approach, there exists an imaginary broker at each M.A endpoint, the inter-M.A trading can be seen as having imaginary brokers trade with each other under TRS, and then redistribute the allowances to local sources based on Intra-M.A. trading constraints. The whole system support the cost-effective allocation of allowance among the whole watershed subject to the water quality at all M.A endpoints.

A formal proof of this proposition is provided in Zhao (2010)>

After incorporating the Management Area Approach, Hung and Shaw's trading model shall be re-written into the following set up:

(3') Minimize $Z = \sum_{i=1}^{n} C_i(e_i^0 - e_i)$, subject to:

(4') $e_i - \sum_{k=1}^{n} \frac{d_{k[I]}}{d_{i[I]}} \mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} \le \overline{\mathrm{T}}_i$ (i = 1,…,n)

(5') $\mathrm{T}_{ik}, \mathrm{T}_{ki} \ge 0$; and $e_i \in [0, e_i^0]$.

Note that the trading equation 4' now allows some trades to take place in both directions. The actual rule of trading is explicit given, by the exogenously determined natural diffusion rates.

To sum up, in this section, the Hung and Shaw (2005) Trading Ratio System (TRS) is broadly interpreted to enable firms to trade allowances upstream and across tributaries within a specified multi-discharger Management Area. Aggregating firms with non-unitary exchange rates into "Management Areas" focusing on meeting environmental objectives at specific endpoints and adopting a TRS system between management areas can achieve cost-effectiveness given predetermined environmental standard at those end-points (which are equivalent to the critical locations). The biggest merit of this Management Area approach is that, the environmental authority can have the flexibility to choose exactly which locations are to be protected while the cost-effectiveness always holds. In comparison, in a typical zonal approach with a one-to-one trading ratio within a zone, control authorities would have to increase the amount of required emissions reduction for the whole watershed to create a margin of safety for the critical locations, which defeats one of the central purposes of a zonal permit approach--the prevention of over-control. (Tietenberg, 2006) Moreover, the M.A approach has also proven to be very convenient instrument in the assessment of potential cost savings. In simulating various hydrological configurations, one only needs to re-group the M.As based on different critical locations.

Accounting For Discrete Capital Costs

Our second modification to the Hung and Shaw TRS model is to account for discrete fixed costs associated with upgrading to enable treating effluent to a lower concentration level. In setting up their model, Hung and Shaw assume that the abatement cost function $C_i(e_i^o - e)$ is "increasing and strictly convex", consistent with the marginal cost approach utilized by Montgomery (1972, "convex and twice differentiable), Tietenberg (2006,"continuous cost function") and others. While marginal abatement cost is a useful theoretical construct, actual pollution abatement decisions often do not occur at the margin. Adding additional chemicals or other small changes allow additional abatement control in some instances, but, given initial capital configurations, there can be limits to such opportunities.

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

The optimal allocation of capital investments can be described by considering the adjusted capital investment cost curves for emission abatement for two firms presented in Figure 2. For comparison purposes, we use the same two firms, *i* and k, as in the previous discussion, assuming again that the initial TMDL allocation corresponds to each source abating the equivalent of 200 units at receptor *j*. Suppose that with current capital levels neither waste water treatment plant can independently achieve the effective 400 unit reduction. Each firm has two capital investment options: firm *i* can choose a low level of capital spending on its abatement facility, which can only achieve emission levels as low as 300 units. If *i* wants to abate beyond this level, it would have to incur high level capital spending to upgrade its facility. Similarly, firm *j* can choose a low level capital spending and high emission levels (more than 310 units), or high level capital spending and emission levels below 310 units. Again assuming that the initial TMDL allocation stipulates that each WWTP reduce effective emissions to 200 units at point *j*, there are incentives for trade up to the point where source *j* achieves an effluent level higher than 310 units by buying allowances from firm *i*, and discharger *k's* effluent level of less than 90 units allows k to supply allowances to *i*. As such, firm *k* avoids a high level of capital spending. In other words, only one firm needs to upgrade and the other can avoid upgrading through trade. If no trade had been possible, each discharger would have abated 200 units; they both would have to incur high level capital costs to upgrade each of their abatement facilities.

To this point, we have illustrated the potential cost-savings from operation and management (OM) and capital costs separately. However, the optimal abatement allocation should minimize the firms' total abatement cost, namely, the combination of both "continuous" OM costs and the discrete capital investment cost. Given appropriate numerical assumptions, the savings from capital costs can more than offset the additional OM costs of moving beyond the equimarginal position of (300,100) to a total-cost-minimizing outcome (310, 90). This result is depicted in Figure 3, which suggests that there may be a range of possible allowance prices due to the gap between adjusted marginal abatement costs. The shaded area represents the increase in OM costs relative to the equimarginal optimum.[4]

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[4] Related discussions of trading in the face of discrete capital costs are provided in US EPA (2006) and Caplan (2008) These studies treat marginal costs as constant, however.

While our results depict a setting in which one firm abates to the maximum level of abatement possible for a fixed level of investment, the relationship between fixed and OM costs may be such that the there is an interior sollution corresponding to the aforementioned trading-ratio-adjusted equimarginal principle. Further, the depictions in Figures 1 and 3 rely on a single marginal abatement cost curve, independent of the level of fixed investment, which also may not hold.

More generally, the the minimization problem of allocating fixed capital investment we have the following cost minimization problem, which consider explicitly the allocation of fixed capital investment, as well as the optimal abatement decisions among dischargers:

(3’’) min $Z = \sum_{i=1}^{n} C_i(e_i, x_i) = \sum_{i=1}^{n} [OM_i^{xi}(e_i) + CC_i(x_i)]$ subject to:

(4’’) $e_i - \sum_{k=1}^{n} \frac{d_{k[I]}}{d_{i[I]}} \mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} \le \overline{\mathrm{T}}_i$ (i = 1, ..., n)

(5’’) $\phi_i(x_i) \le e_i \le e_i^0$; $x_i \in Z_i$; and T_{ki}, $\mathrm{T}_{ik} \ge 0$ (i = 1, ..., n)

where $C_i(e_i, x_i)$, the total annual abatement cost is determined by continuous variable e_i and discrete integer variable x_i. In the right hand side of Equation 4’’, $OM_i^{x_i}(\cdot)$ denotes the annual OM costs of firm *i* with investment level x_i, at final effluent level e_i; $CC_i(x_i)$ denotes the annualized capital cost of firm *i* when it upgrades the capacity to the level x_i. Note that x_i is used as a superscript on the annual OM cost function. This is because the facility upgrade of a firm may have impact on the variable cost function of that firm. Although, how exactly the OM cost functional form evolves with different upgrade levels remains an open empirical question.

It is further assumed that the maximal abatement capacity of each firm is determined by its own facility upgrade level x_i. Hence, each firm's maximal achievable level of abatement is bounded by a function of its upgrade level $x_i : e_i \ge \phi_i(x_i)$. In Equation 5’’ the first inequality gives the constraint of maximal abatement capacity, (equivalent to the lower bound of effluent level). In the second inequality of Equation 5’’, each level of upgrade x_i belongs to a subset of integers Z_i. Note that each integer set Z_i may be different, meaning each firm faces different spectrum of upgrade choices. In addition, since the capital investment is irreversible, each firm can only upgrade but never downgrade their facility level. Consequently, if firm *i* has certain level of existing capacity to remove pollutant, then "0" must not be in its choice set Z_i

In all, the results from Kuhn-Tucker condition can be summarized into six facts:

i. *For a discharger operating at an interior point, her willingness to pay (WTP) and willingness to sell (WTS) is unique and equal to the marginal cost of abatement.*

ii. *For a discharger who is constrained by the non-degradation rule, it is willing to sell the excess allowances at any positive price. In other words, his WTS is NOT unique. On the other hand, its WTP is trivial as he is not allowed to increase its effluent any further.*

iii. *For a discharger who has already hit her physical capacity to abate, she is willing to pay additional permits at whatever high price*[5]*. Her marginal abatement cost is lower than her WTP, simply because her abatement facility is physically incapable of removing any more pollutant.*

iv. *Trade between any pair of the "interior" dischargers has a unique price ratio which follows* $t_{ki} = \frac{\lambda_k}{\lambda_i}$

v. *Trade between an "interior" discharger and a "corner" discharger does not have a unique price ratio, while it is bound above (below) by on the "interior" discharger's WTP (Or WTS).*

vi. *Trade between any pair of the "corner" dischargers does NOT have a unique price ratio, the actual trading price of permits depends on the bargaining.*

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[5] This results from the mathematical assumption that the penalty of non-compliance is infinite, and that it cannot upgrade its treatment capacity in the short term. In practice willingness to pay will be bound by the level of the penalty.

The Data and the Empirical Specification

There are three essential components of the data for estimating total abatement costs and trade patterns: 1) data on the initial effluent allowed for each WWTP under the TMDL; 2) the transfer coefficients or trading ratios between each plant for which trading is possible; and 3) data on OM and capital costs of phosphorus abatement for each WWTP.

The Environmental Capacity and the TMDLs

For the Passaic Watershed, effluent load capacities are defined in terms of TMDLs which account for background and natural levels of pollutant and the transfer adjusted inflows from upstream sources. 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 set so that the long term average emissions from each WWTP not exceed 0.40 mg/l total phosphorus (NJDEP). These policy tools are consistent with Hung and Shaw's zonal load caps. As depicted in Table 1, the current total phosphorus (TP) effluent levels vary substantially among plants, with only three WWTPs presently capable of meeting the 0.40 mg/l standard. The average existing TP concentration is 2.13 mg/l, well above the TMDL's target effluent level of 0.40 mg/l.

The Trading Ratios

The transfer coefficients and trading ratios are based on several scientific factors such as the rate of inflow-outflow of pollutants, bio-physical conditions, and the geography of the designated areas. The transfer coefficients were derived by the distance between the outlet of the point source and the target location, the settling and uptake rates of orthophosphate and organic phosphorus occurring in the flow path, and the ratio of orthophosphate and organic phosphorus discharged from the source (Najarian Associates 2005). Table 2 presents the trading ratio matrix corresponding to Hung and Shaw's TRS model. Note that each of non-zero ratios is close to unity, reflecting the relatively close proximity of WWTPs in the watershed and limited attenuation. Later we manipulate this data to accommodate the management area approach.

Estimating the Costs of Phosphorus Abatement

Since most WWTPs in the watershed currently have little or no present capacity to remove phosphorus, we estimate consistent phosphorus removal cost functions for both yearly OM and capital costs from data on actual costs of 104 treatment plants located in the Chesapeake Bay watershed (NRTCTF 2002) and an engineering study conducted in

Georgia (Jiang *et al.* 2005). Given geographic proximity and other similarities between the Chesapeake Bay and Passaic watersheds, the data are nearly ideal for our purposes. For the 104 waste water treatment plants in the Chesapeake Bay study, we have data on daily flow and annual O&M cost for several effluent concentrations (e.g. 2mg/l; 1mg/l; 0.5mg/l; and 0.1mg/l). Adopting a flexible functional form, similar to the one adopted by Boisvert and Schmidt (1997) for drinking water treatment and delivery systems and its much more generalized form used by Fiegenbaum and Teeples (1983) the following cost function was estimated using OLS, with Huber-White corrections to account for clustering:

$$\begin{aligned} \ln O\,\&\,M &= \underset{(0.057)}{9.870} - \underset{(0.018)}{0.995}\ln C + \underset{(0.034)}{0.781}\ln F + \underset{(0.015)}{0.023}\ln C \ln F + \underset{(0.082)}{0.581}t \\ &+ \underset{(0.14)}{0.358}t\ln C - \underset{(0.014)}{0.041}t\ln C\ln F \end{aligned} \qquad (20)$$

where *C* is final phosphorus concentration, in mg/l; *F* is daily flow in million gallons per day; t is a binary variable equaling 1 (0) if biological (chemical) treatment is used; and the numbers in parentheses are estimated standard errors. All coefficients have expected signs. Importantly, treatment costs are inversely related to concentration levels and treatment costs rise with flow levels.

Using a similar method, the capital investment cost function is specified as:

$$\begin{aligned} \ln CC &= \underset{(0.0132)}{11.889} - \underset{(0.009)}{0.985}\ln C + \underset{(0.005)}{0.347}\ln F - \underset{(0.031)}{0.128}\ln C\ln F + \underset{(0.197)}{0.996}t \\ &+ \underset{(0.045)}{0.442}t\ln C + \underset{(0.031)}{0.114}t\ln C\ln F \end{aligned} \qquad (21)$$

where *CC* is capital investment cost.

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 (W1, W2 and R1) that operate biological phosphorus removal processes, we adjust the coefficients by setting t=1 to reflect this difference in technology.

Implementation and Empirical Results

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 three years as the flow factor in the model. Consistent with the TMDL, the maximum permitted concentration from each WWTP is 0.40 mg/l (NJDEP). For the three WWTPs that already exceed this standard, their TMDL allocations correspond to their current levels of treatment. Since the OM cost function specified in the programming models has argument e_i measured in lbs/year, the estimated OM cost functions is transformed to equation 10, where the firm specific parameters, ϕ and ψ are listed in Table 2.

$$OM_i(e_i) = \exp(\phi_i) \cdot e_i^{\varphi_i} \tag{22}$$

The starting point for the programming analysis also assumes current treatment capacities. While Equation 21 suggests that the estimated capital cost functions are continuous in both concentration and flow capacity, plants would likely have to make discrete investments to accommodate treating to one of a small number of final concentration levels. These upgrades would be “lumpy”, and in the portion of the analysis in which investment levels and annualized capital costs are accounted for, we allow for only five discrete concentrations: a) current level > target concentration ≥ 1.0mg/l; b) 1mg/l > target concentration ≥ 0.5mg/l; c) 0.5mg/l > target concentration ≥ 0.25mg/l, d) 0.2 mg/l > target concentration ≥ 0.10mg/l, and e) 0.10mg/l > target concentration (e.g. Figure 4). These are designated integer values 1 to 6 in the programming model. The six WWTPS (T1, WQ, PS, W1, W2, and R1) that currently have existing capacity to remove are assumed to only incur incremental upgrading costs, defined as the targeted capital cost minus the initial (existing) capital value.

While these capital costs rise in discrete steps associated with increasingly stringent concentration levels, the average costs of treatment falls with flow for a given concentration level. *Ceteris paribus* this suggests that total capital costs could be saved by shifting abatement responsibilities from small to large WWTPs. Although informed by engineers, these discrete capital cost thresholds are arbitrary. Ideally, we would have estimated distinct O&M cost curves for each level of capital investment, but our data was not rich enough for such an analysis.

Given the above cost functions and the Hung and Shaw and management area trading ratios detailed below, the programming models corresponding to equations 3” to 5” were solved using non-linear and mixed integer programming solvers in GAMS (see Zhao, 2010 for details). In our discussion of comparative results across treatments we will focus on the watershed cost savings and the direction of trades under different circumstances. While cost savings for individual firms, relative OM versus capital costs and other metrics are of interest, they divert from the major focus of this paper.

The Baseline Case: Treatment Costs When No Trade is Allowed

The appropriate base situation for evaluating cost-savings associated with allowance trading is the no-trade situation in which each WWTP independently meets its NPDES defined concentration standard associated with the TMDL. We assume phosphorus is removed by chemical treatment, except for the three plants that already use biological treatment. In treating to the minimum of 0.40 mg/l or current concentration, the total annual costs of phosphorus removal are $3.16 million/year. Annualized capital costs account for 39% of total phosphorus removal costs.

Trading Case 1: Hung and Shaw TRS System, OM Cost Only

This scenario corresponds to the Hung and Shaw TRS: the only trades allowed are those with non-zero trading ratios and the corresponding trading matrix, τ, in Table 3; no degradation is allowed at any point in the watershed relative to the original TMDL; and only O&M costs are accounted for in determining whether individual WWTPs buy, sell, or do not trade allowances. We assume that each WWTP invests in the capacity to independently meet its NPDES permit requirements. Empty cells in Table 3 indicate that trades are not allowed between that seller and buyer (i.e., $t_{ik} = 0$).

Because $t_{ik} = 0$ for $k < i$, allowances can only be sold downstream in the TRS. The realization of such trades will thus only occur if upstream WWTPs have lower abatement costs than downstream WWTPs after appropriate adjustments for the transfer coefficient. That is trades will only occur with respect to ambient water quality at receptor k if $MC(e_i^k) < MC(e_k)$ for $k < i$. As would be expected with downstream trading all trades between the eight buyers and eight sellers are above the main diagonal in Table 4. Most of these trades are between immediately adjacent WWTPs. Total costs under this program fall a nominal 0.69% relative to the baseline case, with savings being attributed to reduced O&M costs. This low level of savings can be attributed to the relative homogeneity of waste water treatment costs. Moreover, there are no capital cost savings because each firm is assumed to invest in the capacity to independently meet the no-trade NPDES standard.

Trading Case 2: Three Management Areas, Two Endpoints, OM Cost Only

The modeling of the three management areas, three endpoints approach requires a restructuring of the trading matrix. The matrix used up to this point accounts for direct physical linkages between sources and receptors. The present scenario instead requires a trading-ratio matrix to be developed that defines the trading ratios in terms of the relative effects of emissions from each source on the nearest common endpoint. For WWTPs in the same MA, the ratio of the source to endpoint transfer coefficients serves as the appropriate trading ratio. In the Pompton MA, for example, all trading ratios are defined relative to the source emission impacts on water quality at the confluence of the Pompton and Passaic Rivers. Between MAs the closest common endpoint is used: for the Pompton and Upper Passaic MAs the relevant endpoint is the confluence of the Pompton and Passaic Rivers; for Upstream (Pompton and Upper Passaic) and Downstream (Lower Passaic) MAs the common endpoint is the Dundee Lake and Dam. The resultant trading ratio matrix is provided in Table 4, which we shall designate as τ^{MA}. Note that trading ratios no longer have the upper bound of one, indicating that sources are allowed to sell allowances to firms hydrologically more distant from the relevant endpoint.

The trading patterns for this scenario are depicted in Table 6. As in Trading Case 1, all firms are assumed to have the capacity to treat to the 0.40 mg/l level, and hence the only cost savings are though O&M cost reductions. As demonstrated, the pattern of trades changes dramatically. Now only four WWTPs (P8, W4, WQ and P9) act as sellers, and 17 WWTPs buy permits. Interestingly, most of these trades occur with sellers located hydrologically downstream as indicated by the predominance of trading entries below the main diagonal. Despite this additional trading activity, the cost savings remain a relatively meager 1.33% relative to the baseline no-trade scenario.

Trading Case 3: Hung and Shaw TRS System, O&M and Capital Cost

In this scenario, τ once again serves as the relevant trading ratio. In contrast with Case 1 trades are based on total cost savings resulting from a mixed integer programming model to account for the discrete capital costs as well as the possibility of an interior solution for the continuous O&M costs. In all, overall O&M and capital cost savings estimated to be 6.79% relative to the no-trade baseline.

Trading Case 4: Three Management Areas, Two Endpoints, O&M and Capital Costs

Case 2 was adapted to the discrete cost model. Trading patterns are presented in Table 8. The following pattern of trade is observed: large firms (taking advantage of economies of scale in capital treatment costs) that are well positioned (in terms of trading ratios relative to ambient measurement points) become sellers, avoiding the need for higher average cost capital investments of smaller, typically upstream WWTPs. Overall savings are

18.26% relative to the no-trade baseline. As depicted in Table 9 the number of sellers is limited to six firms, four of which upgrade their treatment facilities.

Concluding Remarks

The above results suggest that moderate cost savings from trading phosphorus allowances can be achieved through a Management Area approach and that substantial gains are possible if trades can effectuate the efficient allocation of fixed cost investments across WWTPs. The former issue is primarily driven by the hydrology of a particular watershed and whether managing water quality to avoid a selected number of hot spots is deemed appropriate. We focus on the later issue, asking the critical question of how to organize a cost-effective market exchange in a typical watershed characterized by a small number of potential traders, with discrete and homogeneous abatement technologies across firms, and most, if not all, firms not having the present capacity to meet the specified standard.

In large, fluid pollution permit markets with many traders, such as the nation-wide U.S. acid rain program, the issue of fixed costs is expected to have little practical significance. This is because a discharger's decision to upgrade its facility is likely to have no noticeable effect on the market supply or demand for permits. In smaller markets with few trading partners, however, firms that opt not to upgrade their systems fully are not guaranteed that a supply of permits will be available as a substitute at any price. In a similar manner, firms that choose to upgrade, base their decision, in part, on the presupposition that demand exists for their unused allowances. In such settings a likely outcome, consistent with Cases 1 and 3 explored here, is that all WWTPs will upgrade so as to have the capacity to independently meet their NPDES permit requirement. Having made this capital investment WWTPs will trade allowances based on comparing their marginal O&M costs to the prevailing market price. Our case study suggests that the gains from such trading are nominal, ranging from 0.69% to 1.33% of total costs in the no-trade baseline. Given positive transactions costs, it is unlikely that a vibrant trading market would result in such circumstances. These results and conjectures are consistent the disappointing level of water quality trading observed to date.

However, if firms are able to account for discrete fixed costs, our results suggest that the costs savings can increase dramatically. In our case study cost savings exceed 18% of the total costs in the no-trade baseline. The policy issue is, how can this cost-effective allocation be achieved?

One approach would be to develop a *structured bilateral trading program*. The gains from bilateral trading opportunities have long been recognized in settings where transactions costs associated with open-market trading are high relative to the gains from trade (Woodward, Kaiser and Wicks, 2002). A simple example of the potential of bilateral transactions in the face of discrete fixed investments is found in is found in Breetz et al.'s discussion of the trading program in Bear Creek, CO in which each year a large discharger (Evergreen Metro) reduces phosphorus release in a trade of 40-80 pounds per year so that a smaller discharger (Forest Hills) does not have to undergo a costly upgrade to its facilities:

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

Our results suggest that approaching a cost-effective reallocation of abatement responsibilities may require a more structured approach than one-on-one negotiations. This is because large, well-located WWTPs can engender substantial watershed-wide costs savings by upgrading and accepting treatment responsibilities for several smaller WWTPs simultaneously. For example, in our case study a limited number of larger firms upgrade, allowing smaller firms to avoid such investments: W4 is able to treat for D1-D3, P1, P2, P4, P7, W1-W3 and R1, allowing each of these WWTPs to avoid having to invest in costly capital. Moreover, given that these savings are likely to persist over a number of years, multi-year contracting may be a necessity. Facilitating such contracts, in which capital cost savings by one firm trading with another is dependent upon the concurrent contracting decisions by a number of other firms, may necessitate an organized structure of contracting between one WWTP, say W4, and a number of buyers.

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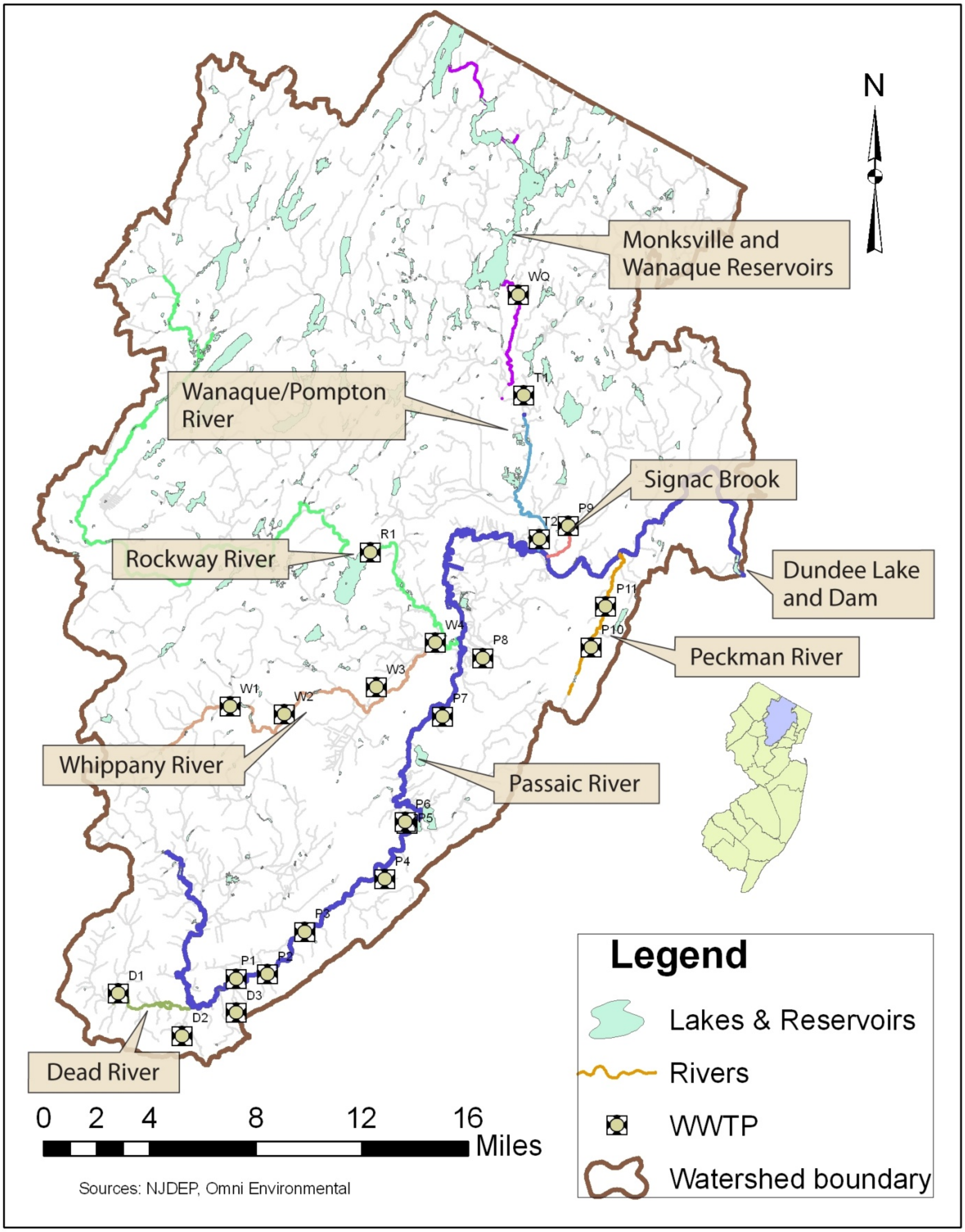
Map 1: Upper Passaic River Basin and WWTPs.



Sources: NJDEP, Omni Environmental

Figure 1. Simple Geometry of Marginal Cost Trading

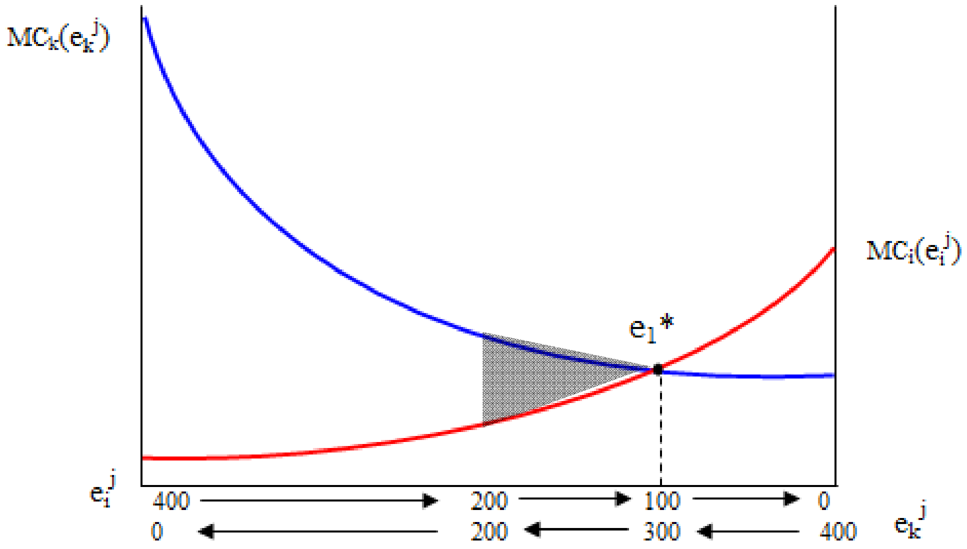


Figure 2. Simple Geometry of Fixed Costs Trading

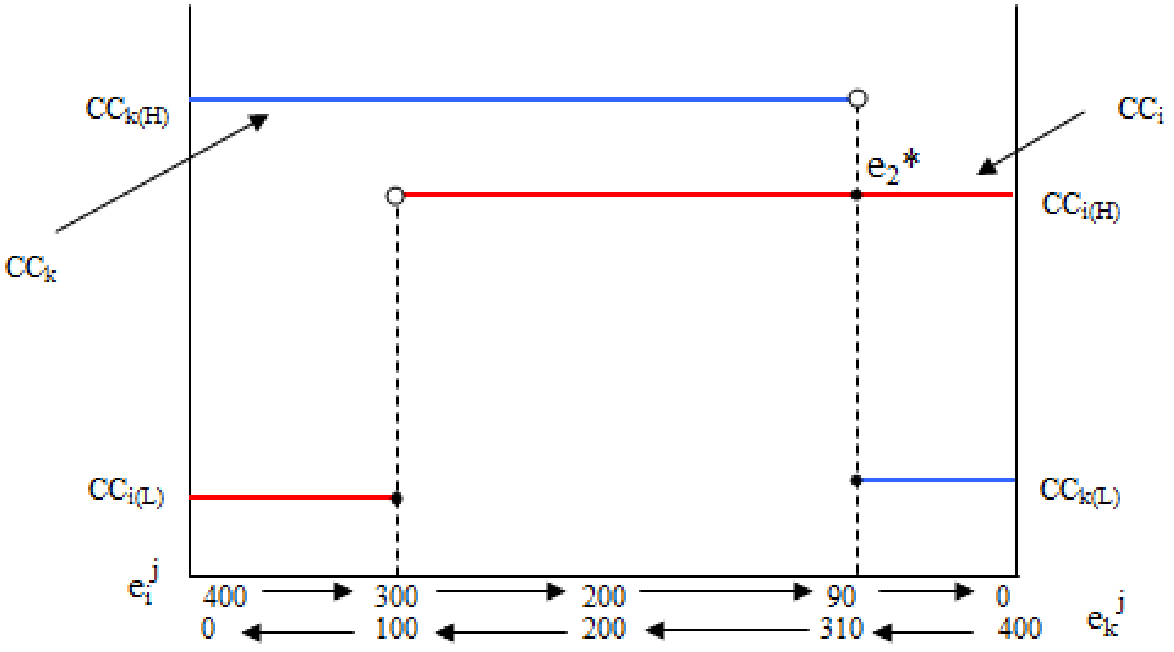


Figure 3. Simple Geometry of Total Cost Trading

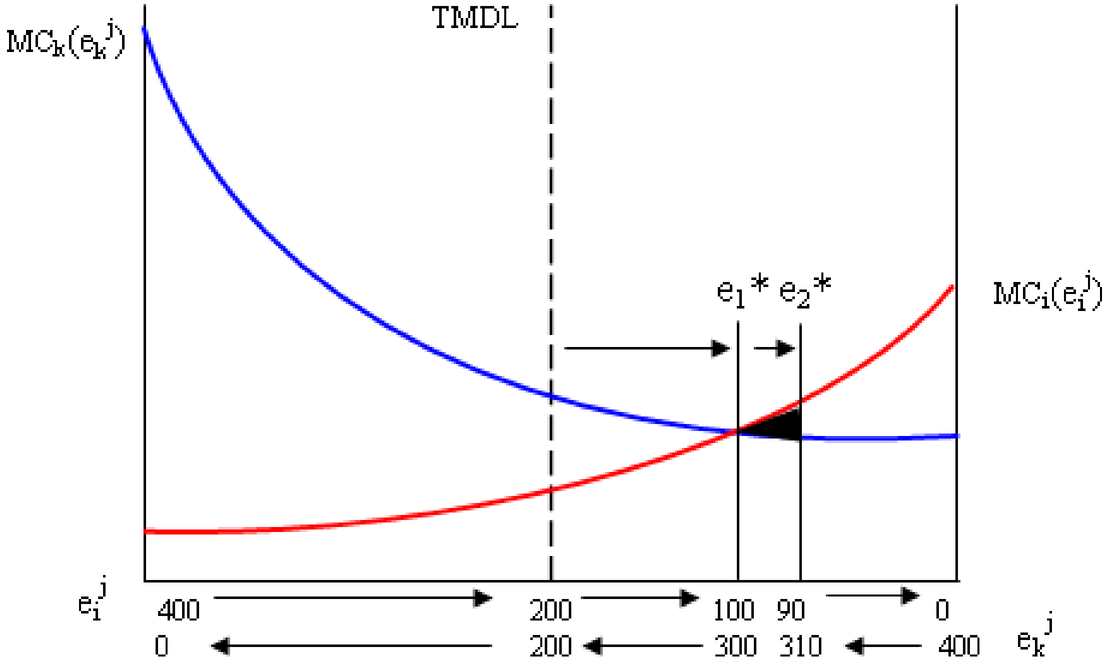
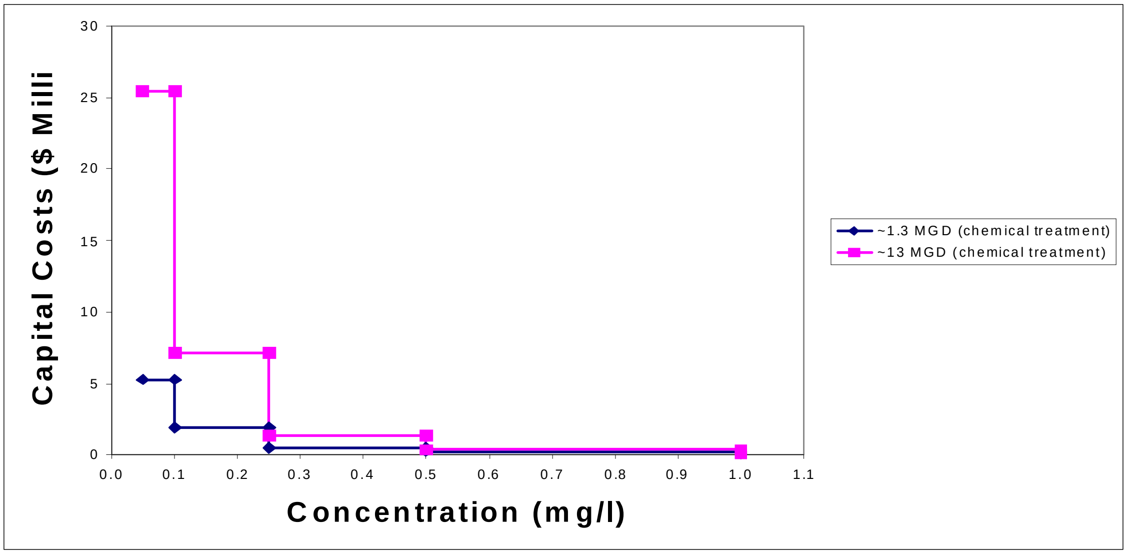


Figure 4. Stepwise Discrete Captial Costs



The figure above provides two examples of the capital cost functions used in our simulations of Phosphorus emissions trading between WWTPs in the Upper Passaic River Basin. The upper curve represents the fixed costs associated with a fairly large WWTP (13 million gallons per day). The lower curve presents similar information for a smaller WWTP (1.3 million gallons per day). The discrete investment points at 1 mg/l, 0.5 mg/l, 0.25 mg/l and 0.1 mg/l effluent concentrations were arbitrarily determined (recall that the emissions standard for the Upper Passaic River Basin TMDL is 0.4 mg/l). Note that while capital costs rise with size, the average costs of treatment fall because with size because of the substantial difference in flow handled across the firms depicted.

Table 1. Data for Municipal Waste Water Treatment Plants (WWTP)

			Phosphorus		
Map Code for WWTP	River	Flow (MGD)	Load (lbs/Y)	Concentration (mg/l)	TMDL 0.4mg/l (lbs/year)[#]
D1	Dead	1.76	16,780	3.13	2,144
D2	Dead	0.15	845	1.85	183
D3	Dead	0.31	1,804	1.91	378
P1	Passaic	1.00	8,011	2.63	1,218
P2	Passaic	0.36	1,831	1.67	439
P3[*]	Passaic	1.57	2,869	0.60	1,913
P4	Passaic	0.12	559	1.53	146
P5	Passaic	2.41	24,079	3.28	2,936
P6	Passaic	0.90	4,057	1.48	1,097
P7	Passaic	2.61	20,909	2.63	3,180
P8	Passaic	3.75	18,505	1.62	4,569
W1[*]	Whippany	1.90	4,862	0.84	2,315
W2[*]	Whippany	3.03	5,186	0.56	3,704
W3	Whippany	2.03	18,505	2.83	2,473
W4	Whippany	12.58	114,192	2.98	15,327
R1[*]	Rockaway	8.81	39,180	1.46	10,734
WQ[*]	Wanaque	1.00	487	0.16	1,218
T1[*]	Pompton	0.86	838	0.32	1,048
T2	Pompton	5.33	34,744	2.14	6,494
P9	Preakness Brook	7.47	51,652	2.27	9,602
P10	Passaic	2.46	23,004	3.07	2,997
P11	Passaic	1.26	8,636	2.25	1,535
Total			401,535	2.13[**]	75,650

Notes: [#]This is the TMDL adopted on April 24, 2008; [*] Plants that currently have some capacity to remove phosphorus; [**]Average weighted by flow.

Table 2. The Parameters for the Transformed O&M Cost Functions for the 22 Plants

WWTP	ϕ	ψ	WWTP	ϕ	ψ
D1	19.793	-1.151	W1	18.195	-0.879
D2	15.675	-1.257	W2	18.788	-0.859
D3	16.943	-1.225	W3	20.015	-1.145
P1	18.893	-1.175	W4	22.707	-1.066
P2	17.198	-1.219	R1	20.075	-0.813
P3	19.613	-1.156	WQ	19.002	-1.172
P4	15.276	-1.266	T1	18.649	-1.181
P5	20.281	-1.137	T2	21.476	-1.103
P6	18.723	-1.180	P9	21.967	-1.089
P7	20.403	-1.134	P10	20.312	-1.136
P8	20.953	-1.118	P11	19.264	-1.165

Note: The cost functions are specified in equation (25).

Table 3: Trading Ratios (t) for TRS models

	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	0.97	0.97	0.97	0.97	0.93	0.93	0.93	0.93											
D2		1	1	0.97	0.97	0.97	0.97	0.93	0.93	0.93	0.93											
D3			1	0.97	0.97	0.97	0.97	0.93	0.93	0.93	0.93											
P1				1	1	1	1	0.96	0.96	0.96	0.96											
P2					1	1	1	0.96	0.96	0.96	0.96											
P3						1	1	0.96	0.96	0.96	0.96											
P4							1	0.96	0.96	0.96	0.96											
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	0.99			
T1																		1	0.99			
T2																			1			
P9																				1		
P10																					1	1
P11																						1

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

Table 4: Trading Ratios (τ^{MA}) for Three MA models

	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.00	1.00	1.00	0.97	0.97	0.97	0.97	0.93	0.93	0.93	0.93	1.04	1.04	1.04	1.20	1.04				0.63	0.64	0.64
D2	1.00	1.00	1.00	0.97	0.97	0.97	0.97	0.93	0.93	0.93	0.93	1.04	1.04	1.04	1.20	1.04				0.63	0.64	0.64
D3	1.00	1.00	1.00	0.97	0.97	0.97	0.97	0.93	0.93	0.93	0.93	1.04	1.04	1.04	1.20	1.04				0.63	0.64	0.64
P1	1.04	1.04	1.04	1.00	1.00	1.00	1.00	0.96	0.96	0.96	0.96	1.08	1.08	1.08	1.24	1.08				0.65	0.66	0.66
P2	1.04	1.04	1.04	1.00	1.00	1.00	1.00	0.96	0.96	0.96	0.96	1.08	1.08	1.08	1.24	1.08				0.65	0.66	0.66
P3	1.04	1.04	1.04	1.00	1.00	1.00	1.00	0.96	0.96	0.96	0.96	1.08	1.08	1.08	1.24	1.08				0.65	0.66	0.66
P4	1.04	1.04	1.04	1.00	1.00	1.00	1.00	0.96	0.96	0.96	0.96	1.08	1.08	1.08	1.24	1.08				0.65	0.66	0.66
P5	1.08	1.08	1.08	1.04	1.04	1.04	1.04	1.00	1.00	1.00	1.00	1.13	1.13	1.13	1.29	1.13				0.68	0.69	0.69
P6	1.08	1.08	1.08	1.04	1.04	1.04	1.04	1.00	1.00	1.00	1.00	1.13	1.13	1.13	1.29	1.13				0.68	0.69	0.69
P7	1.08	1.08	1.08	1.04	1.04	1.04	1.04	1.00	1.00	1.00	1.00	1.13	1.13	1.13	1.29	1.13				0.68	0.69	0.69
P8	1.08	1.08	1.08	1.04	1.04	1.04	1.04	1.00	1.00	1.00	1.00	1.13	1.13	1.13	1.29	1.13				0.68	0.69	0.69
W1	0.96	0.96	0.96	0.92	0.92	0.92	0.92	0.89	0.89	0.89	0.89	1.00	1.00	1.00	1.14	1.00				0.60	0.61	0.61
W2	0.96	0.96	0.96	0.92	0.92	0.92	0.92	0.89	0.89	0.89	0.89	1.00	1.00	1.00	1.14	1.00				0.60	0.61	0.61
W3	0.96	0.96	0.96	0.92	0.92	0.92	0.92	0.89	0.89	0.89	0.89	1.00	1.00	1.00	1.14	1.00				0.60	0.61	0.61
R1	0.84	0.84	0.84	0.81	0.81	0.81	0.81	0.78	0.78	0.78	0.78	0.87	0.87	0.87	1.00	0.87				0.52	0.54	0.54
W4	0.96	0.96	0.96	0.92	0.92	0.92	0.92	0.89	0.89	0.89	0.89	1.00	1.00	1.00	1.14	1.00				0.60	0.61	0.61
WQ	0.70	0.70	0.70	0.73	0.73	0.73	0.73	0.76	0.76	0.76	0.76	0.67	0.67	0.67	0.59	0.67	1.00	1.00	0.99	0.51	0.52	0.52
T1	0.70	0.70	0.70	0.73	0.73	0.73	0.73	0.76	0.76	0.76	0.76	0.67	0.67	0.67	0.59	0.67	1.00	1.00	0.99	0.51	0.52	0.52
T2	0.70	0.70	0.70	0.73	0.73	0.73	0.73	0.76	0.76	0.76	0.76	0.67	0.67	0.67	0.59	0.67	1.01	1.01	1.00	0.52	0.53	0.52
P9																				1.00	0.90	0.90
P10																				1.11	1.00	1.00
P11																				1.11	1.00	1.00

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

Table 5: Lbs of Allowances Traded ,Trading Case 1 - Hung and Shaw TRS System, Operating and Maintenance Cost Only

	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1		50.9	63.2		39.9																	
D2																						
D3																						
P1					17.3																	
P2																						
P3							51.7															
P4																						
P5									108.9													
P6																						
P7																						
P8																						
W1																						
W2														22.7								
W3																						
R1																						
W4																						
WQ																			731.4			
T1																			209.8			
T2																						
P9																						
P10																						93.3
P11																						

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

Table 6: Lbs of Allowances Traded ,Trading Case 2 - Three Management Areas, Two Endpoints, Operating and Maintenance Cost Only

	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1																						
D2																						
D3																						
P1																						
P2																						
P3																						
P4																						
P5																						
P6																						
P7																						
P8			71.3		78.5										7.8							
W1																						
W2																						
W3																						
R1																						
W4	242.5	98.1	71.9	230.4	72.4	221.2	84.0					451.7	403.4	271.4								
WQ								156.8	269.8	122.6									182.2			
T1																			209.8			
T2																						
P9																					182.7	262.2
P10																						
P11																						

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

Table 7: Lbs of Allowances Traded, TRS (downstream trades only), Trades Based on O&M and Capital Costs.

	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
Order in restrictions $e_i \le e_i(0.50\, mg/l)$		6	7	8	9		3		4		5			1								2
D1		45.7	94.5	315.9	113.7																	
D2																						
D3																						
P1																						
P2																						
P3							36.6		209.9													
P4																						
P5									72.4		497.5											
P6																						
P7											645.9											
P8																						
W1														138.2								
W2														480.8								
W3																						
R1																						
W4																						
WQ																			731.4			
T1																			209.8			
T2																						
P9																						
P10																						384.2
P11																						

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

Table 8: Lbs of Allowances Traded, Three Management Areas, Trades Based on O&M and Capital Costs.

	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
Order in restrictions $e_i \leq e_i(0.50\, mg/l)$	6	13	14	3	10	8	12	9	4	2		1	7	5	11						16	15
D1																						
D2																						
D3																						
P1																						
P2																						
P3																						
P4																						
P5																						
P6																						
P7																						
P8	491.4					460.6				181.5												
W1																						
W2																						
W3																						
R1																						
W4	7.8	47.8	98.8	330.1	118.8		39.6			11.8		579.3	926.9	619.0	2347.2							
WQ								249.1	296.8	185.5												
T1								65.4	66.3	78.1												
T2								657.8		535.4												
P9																					834.7	427.5
P10																						
P11																						

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

Table 9: Trading Patterns in Trading Case 4

Seller	Buyer
W4*	W1, W2, W3 R1 P1, P2, P3, P4, P6
P8*	D1, P5, P7
T2*	D1, D2, D3
P9*	P10, P11
WQ	R1
T1	R1

* Indicates firms that upgrade.

The trading patterns from the mixed-integer, management area simulation for the Upper Passaic River Basin are reported in the table below. The first column indicates the WWTPs selling permits while the second indentifies buyers. Sellers and buyer are matched by rows. Linking these entries to the information provided in previous boxes, particularly Boxes 1 and 2, the following pattern of trade is observed: large firms (taking advantage of economies of scale in capital treatment costs) that are well positioned (in terms of trading ratios relative to ambient measurement points) become sellers, avoiding the need for higher average cost capital investments of smaller, typically upstream WWTPs. In addition, there are benefits to early adopters of technology, specifically WQ and T1.