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By

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Abstract: Hung and Shaw's (2005) trading-ratio system is modified to accommodate a management area approach wherein emissions sources are organized by impacts on identified "hot spots" and trading accounts for fixed as well as variable costs. An empirical example of phosphorus trading in a watershed with 22 potential traders demonstrates that marginal cost trading using a trading-ratio system yield nominal cost savings of less than 1% at the watershed level relative to the no-trade situation. A management area approach that accounts for fixed costs achieves over 13% in costs savings. The pattern of cost-effective trades is modeled using a mixed-integer approach.

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Management Areas and Fixed Costs in the Economics of Water Quality Trading

An expanding body of evidence has demonstrated that, despite substantial federal, state and local investments, nearly all active water quality trading programs are characterized by low trading volumes and nominal cost savings at best (King and Kuch, 2003; King, 2005; Morgan and Wolverton, 2005; Faeth, 2006; US EPA 2008; Selman et al. 2009; Fisher-Vanden and Olmstead, 2013). While there are undoubtedly a number of institutional or behavioral factors that inhibit water quality trading[i], we are motivated in this study by Hoag and Hughes-Popp's (1997) arguments that translating economic theory into practice may necessitate a reexamination of the "…[m]ain principles associated with water pollution credit trading… to identify factors that influence program feasibility" (p. 253). Using the empirical modeling results from a case study of the Non-Tidal Passaic River Basin phosphorus emissions trading program, we focus in this paper on two fundamental economic aspects of the disparity between the theory and the practice of water quality trading programs.

First, recognizing that hydrological systems and Total Maximum Daily Load (TMDL) objectives for a particular watershed may be quite complex, we broadly interpret Hung and Shaw's (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, each operating in a distinct zone.[ii,iii] One can logically extend this structure to multiple dischargers in a zone by assuming that dischargers have a one-to-one trading ratio within a zone. However, as Tietenberg (2006, p. 94) notes, "…other ratios potentially could provide policy makers with an additional degree of freedom." We investigate this possibility by modeling a "Management Area" (MA) policy proposed for the Upper-Passaic River Basin TMDL (Obrupta et al., 2008).[iv] Rather than restricting effluent concentration levels at all points within a watershed, the MA approach is motivated by the actuality 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). The MA approach groups pollution sources with a common endpoint at one of these hot spots, and may or may not have trading ratios equal to unity between sources. Within an MA both upstream and downstream trades are permitted. 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 watershed in the long run. 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 (Schmalensee and Stavins, 2013). However, as suggested by Sado et al. (2010), 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 lacking the present capacity to meet the specified standard. In such settings, managers may be reluctant to not upgrade (and buy permits instead) or to develop excess treatment capacity (and sell permits) because of the relative lack of buyers and sellers in a thin market. Suter et al. (2013) support this conjecture empirically in an experimental economics context.

We recognize that neither zonal aggregation nor capital cost considerations are novel issues in the pollution trading literature. For example, Tietenberg (2006) provides a comprehensive review of studies with various zonal configurations, mostly in the context of air quality, while Bennett et al. (2000) examine the consequences of broadening trading areas with respect to the Long Island Sound Nitrogen Credit Exchange program. Decades ago, Rose-Ackerman (1973) and Kneese and Bower (1968) raised concerns about market incentives vis-à-vis substantial, discrete fixed costs likely to arise in water quality treatment. Hanley et al. (1998), the US EPA (2004), Caplan (2008), Sado et al. (2010), and Suter et al. (2013) 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 opportunities for gains from trade in water quality markets (David et al., 1980; Eheart, 1980; Eheart et al., 1980; Bennett et al., 2000).

These empirical studies, however, have failed to identify optimal trading patterns between firms that explicitly take advantage of fixed cost savings. Rather, they typically assert that firms with above (below) average incremental costs will be buyers (sellers), and they have been constructed largely within a single receptor framework. For example, David et al. (1980, p. 268) trace out an aggregate least-cost phosphorus removal curve, identify the industry marginal cost of removing the unit of effluent that just meets the prescribed standard, and infer that firms with unit costs above this value will be demanders for allowances while dischargers with removal costs below this value will be suppliers. More recently Bennett et al. (2000) similarly trace out the least-cost abatement curve including fixed costs and identify total potential cost savings from firms; but they do not model the pattern of trades that will occur between firms. Our contribution in this paper is to directly model the trades across firms to explore empirically those factors that could improve the cost-effectiveness of trading programs and enhance the economic viability of water quality trading. In a case study, we demonstrate empirically that potential watershed-wide costs savings can increase dramatically by relaxing zonal trading constraints and incorporating fixed as well as variable costs into the determination of trading patterns.

The remainder of the paper begins with a section that provides background information on the TMDL and the Upper-Passaic River Basin. We then introduce our conceptual framework, using Hung and Shaw's TRS model as a starting point. Applying this framework, we employ a mixed-integer programming method to explore the effects of zonal aggregation and the cost-savings associated with considering fixed and variable costs in the determination of a trading regime. The final section concludes with a discussion of the need to explore long term contracts in greater depth and/or to examine other incentives to encourage trading in the face of fixed capital investments.

Essential Features of the Non-tidal Passaic River Watershed

The Non-Tidal or Upper Passaic River watershed is located primarily in northeastern New Jersey, with the uppermost portion extending into New York State. 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 Figure 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 (P) from the tidal part of the Passaic River. The Dead River (D) joins the Passaic at the point where it first changes direction. At the watershed's center, the Rockaway River (R) flows into the Whippany River (W), and in turn, the Whippany River flows into the Passaic. The Wanaque River (WQ) begins in the northern part of the watershed, flowing into the Pompton River (T), 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 more than an 80% reduction in the total phosphorus concentration emissions from 22 Waste Water Treatment Plants (WWTPs) in the watershed. The TMDL specifies the following:

> "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)

The 22 WWTPs are depicted in Figure 1 and the corresponding pre-TMDL flow and concentration levels are provided in the first five columns of Table 1. The 0.1 mg/l concentration level indicated in the TMDL language above translates into a long-term (i.e. annual) average 0.4 mg/l effluent from each of the 22 dischargers. Prior to the TMDL rule, the average (flow weighted) total phosphorus emissions across WWTPs were estimated to be 2.13 mg/l.

The Modeling Framework

We begin this section with the development of the Hung and Shaw (2005) trading ratio system for water quality trading in which permits can only be sold from upstream sellers to downstream buyers and prices are based on differential marginal costs of treatment. We then develop a second model where, because of the specific hydrology of the watershed, it is appropriate to define management areas that group pollution sources with a common endpoint at a discrete hot spot. Finally, we develop a third model that accommodates the cost of investing in new abatement technology as well as the variable costs of treatment.

Problem A: The Hung and Shaw Trading-Ratio System (TRS)

By recognizing that water flows downstream, and by restricting the realm of possible buyers (k) to include only those that have a direct physical linkage to source i, Hung and Shaw (2005) prove that the following TRS model, which we refer to as Problem A, can be used to find a cost-effective solution in a setting in which each discharger comprises a separate zone:

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

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

(3) $\mathrm{T}_{ik}, \mathrm{T}_{ki} \ge 0$; $e_i \in [0, e_i^0]$; and $0 \le t_{ki} \le 1$

where, zones (i=1,…,n) are indexed from upstream to downstream, and each zone corresponding to a single pollution source. The parameters are defined as:

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

e_i^o = unregulated (i.e. pre-TMDL) emissions from source i,

e_i = emissions under abatement program from source i

t_{ki} = the trading ratio, which is set equal to the hydrological pollution diffusion coefficient. That is $t_{ki} = d_{ki} = \frac{e_i^k}{e_i}$, where e_i^k indicates 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 and d_{ki} is referred to as the diffusion or transfer coefficient.

$\bar{\mathrm{T}}_j$ = aggregate tradable allowances allocated to 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 1-3 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) and that least-cost trading between individual sources i and k with respect to a common downstream receptor achieves the spatially adjusted equimarginal relationship associated with the least-cost abatement,

$$MC_i(e_i^j) = \frac{1}{d_{ij}} \frac{\partial C_i(e_i)}{\partial e_i} = \frac{1}{d_{kj}} \frac{\partial C_k(e_k)}{\partial e_k} = MC_k(e_k^j)\,. \qquad (4)$$

In the special case when k=j, then $d_{kj} = 1$. When k and j are not directly connected hydrologically, then $d_{kj} = 0$.

Management Areas (MA) Approach: We extend Hung and Shaw's TRS model to more closely represent the MA 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 from various sources within a zone as having equal effects on water quality (Tietenberg, 2006). 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). Within this framework, the trading ratios between sources within a zone would be set to unity.

With respect to the Non-Tidal Passaic River Basin TMDL, the 0.1 mg/l restriction on total phosphorus was found to be overly restrictive for most of the watershed (Obropta et al., 2008). In accordance with the TMDL language quoted above, the maximum ambient concentration level of 0.1 mg/L could be relaxed at all but two locations in the watershed: the area near the confluence of the Passaic and Pompton Rivers, and at Dundee Dam. Put differently, by meeting the water quality constraints at these critical junctures, one could avoid any hotspots at other points in the watershed.

Based on this hydrological modeling, three MAs are identified in the Upper Passaic River Basin TMDL (Obrupta et al., 2008): the Upper Passaic MA consisting of WWTPs D1-D3, P1-P8, W1-W4, and R1 with associated downstream endpoint on the Passaic River immediately below the confluence of the Passaic and Pompton rivers; the Pompton MA (WQ, T1 and T2) with a downstream outlet at the endpoint of the Pompton River where it feeds into the Passaic River; and the Lower Passaic MA, P9-P11, with endpoint at the Dundee Lake and Dam. Accounting for a number of factors, including seasonal variations in flows, the MAs and the patterns of allowable inter-MA trades are depicted schematically in the Figure 2. Allowable trades between MAs include: 1) downstream trades from the Upper Passaic and Pompton MAs to the Lower Passaic MA; and 2) cross-tributary trades from the Pompton MA to the Upper Passaic MA, but not *vice versa.* While we refer to option two as a cross-tributary trade, such transactions are only possible in the MA approach we outline below because the endpoint of the Upper Passaic MA lies hydrologically below the endpoint of the Pompton MA as depicted schematically in Figure 2. Within each MA, upstream and downstream trades are permitted subject to the constraint that emissions within the MA do not exceed the water quality constraint at the MA endpoint.

A series of trade scenarios were simulated to investigate if the proposed management area framework would protect water quality and ensure the avoidance of hot-spots at the TMDL end points. (Omni Environmental Coroporation, 2007). As discussed in Obrupta et al. (2008), "…intramanagement and intermanagement area trade scenarios that would most stress the system and simulate critical conditions were developed to test the proposed framework…. These simulation results verify that the trading framework is robust and can be expected to protect water quality" (p. 954).

Problem B: A Trading-Ratio-System for Management Areas

As discussed above, the way each MA is delineated guarantees that the endpoint for each MA is the sole outlet of its MA, making it possible to separate each MA hydrologically. In other words, as long as the water quality at the critical location is ensured, any allowance trading within any MA would not jeopardize the water quality in other MAs. For this reason, the trading ratios for intra-MA trading are designed to adequately protect the water quality at its end-point. Specifically, 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 an allowance to k_2, then k_1 has to discharge Δe_{k_1} units less, while k_2 can discharge Δe_{k_2} units more. The following relationship determines the magnitude of Δe_{k_2} needed to ensure that this trade has zero net effect at the MA end-point [*K*] :

$$(5) \qquad \Delta e_{[K]} = \Delta e_{k_1} \cdot d_{k_1[K]} + \Delta e_{k_2} \cdot d_{k_2[K]} = 0$$

Rearranging, we have the following trading ratio:

$$(6) \qquad t_{k_1 k_2} = -\frac{\Delta e_{k_2}}{\Delta e_{k_1}} = \frac{d_{k_1[K]}}{d_{k_2[K]}} \quad ,$$

which ensures that allowing both upstream and downstream trades within an MA will not affect the water quality at its outlet [K]; however, other areas within the same MA might have elevated concentrations as a result of trading. Because we have placed no restrictions on the relative location of k_1 and k_2 in K , the trading ratio need not have an upper bound of unity. Moreover, the definition of the MA precludes the possibility that these elevated concentrations will engender a hot spot. One can thus regard the trading system within each MA as a bare-bones version of the ambient permit system in which the problem of transaction complexity is avoided. Appendix 1 provides a proof that setting intra-MA trading-ratios in this manner supports the cost-effective allocation of allowances subject to water quality constraints at the MA end-points.

In a similar fashion, the trading ratios for inter-MA trades are designed to preserve the water quality at each MA endpoint. Since only the buyer's endpoint is subject to the negative impact of the trades, it is adequate simply to ensure the water quality endpoint of the buyer's MA. Formally, let j be the seller and *k* be the buyer from different management areas J and K respectively ($j \in J$, $k \in K$), where the outlet of J ([J]) is hydrologically upstream from the outlet of K. Using the above notation for changes in emissions, the following equation guarantees that the trade has zero net effects at the buyer's end-point [*K*]:

$$\Delta e_j \cdot d_{j[K]} + \Delta e_k \cdot d_{k[K]} = 0 \quad (7)$$

By rearranging, we have:

$$t_{jk} = -\frac{\Delta e_k}{\Delta e_j} = \frac{d_{j[K]}}{d_{k[K]}} \quad (8)$$

By comparing equation (8) with equation (6), we see that the trading ratio for both intra-M.A trades and inter-MA trades are described by the same simple relation------*the trading ratio is equal to the relative diffusion rate to the end-point of the buyer's MA.* One difference between the two ratios is that equation (8) is bounded between zero and unity, while the trading ratio in equation (6) is only restricted to be non-negative.

To gain further insight into the process of trades between upstream and downstream MAs, the upstream end-point [*J*] can serve as an intermediary to which one can then apply a multiplicative effect over diffusion from *j* to [*K*]. That is:

$$d_{j[K]} = d_{j[J]} \cdot d_{[J][K]} \quad (9)$$

Substituting equation (9) into equation (7) yields:

$$\Delta e_j \cdot d_{j[J]} \cdot d_{[J][K]} + \Delta e_k \cdot d_{k[K]} = 0 \quad (10)$$

Since $\Delta e_{[J]} = \Delta e_j \cdot d_{j[J]}$ and $\Delta e_{[K]} = \Delta e_k \cdot d_{k[K]}$, equation (10) can be reduced to:

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

Finally, the equivalent trading ratio $t_{[J][K]}$ between the two end-points [*J*], [*K*] can be determined by combining equations (8) and (11):

$$t_{[J][K]} = -\frac{\Delta e_{[K]}}{\Delta e_{[J]}} = d_{[J][K]} \tag{12}$$

,

which is essentially the Hung and Shaw (2005) TRS result. Equation (12) demonstrates that the inter-MA trading between two sources *j* and *k* is as if the two MA end-points [*J*] and [*K*] were trading the "effective allowances" under the TRS-----the trading ratio equals the natural diffusion rate between the two end-points. This result can be further interpreted as if there were an imaginary broker at each MA end-point who buys (sells) allowances from (to) other brokers following the TRS and sells (buys) them to (from) the sources within its MA. In other words, one can think of the inter-MA trading as being carried out in two steps: allowances are traded across MAs by "brokers" at each MA end-point under TRS, and then they are localized to each source through intra-MA trading.

Hung and Shaw's (2005) TRS guarantees that, in the first step, effective allowances can be traded between MA end-points in a cost-effective manner, while also meeting the environmental quality at all end-points. Since the cost-effectiveness of the second step--trading within an MA--has been demonstrated, the entire MA trading process is consummated in a cost-effective manner subject to the environmental standard at all MA end-points.[v]

By incorporating the MA approach, the trading model is now re-written as Problem B:

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

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

(3’) $\mathrm{T}_{ik}, \mathrm{T}_{ki} \geq 0$; and $e_i \in [0, e_i^0]$.

While not explicit in the above equations, the definition of d_{ki} implies that $d_{i[I]} > 0$ and $d_{k[I]} \geq 0$, restricting the ratio in equation (2’) to be non-negative. Because there is no upper bound restriction on the ratio $d_{k[I]}/d_{i[I]}$ when k and i both lie in management area I, the trading equation (2’) now allows intra-management area trades to take place in both directions.

To sum up, we have interpreted the Hung and Shaw (2005) TRS broadly to enable firms to trade allowances upstream and across tributaries within a specified multi-discharger MA. By aggregating firms with non-unitary exchange rates into MAs that focus on meeting environmental objectives at specific endpoints and adopting a TRS system between MAs, we can achieve cost-effective solutions for predetermined environmental standards at those end points. Put somewhat differently, this aggregation of dischargers into an MA is analogous to the “representative agent” alluded to by Hung and Shaw (see footnote 1). This MA approach has particular merit in that the environmental authority can have the flexibility to choose exactly which locations are to be protected while at the same time ensuring the cost-effectiveness of the strategy. By way of comparison, control authorities in a typical zonal approach with a one-to-one trading ratio within a zone would have to increase the amount of required reductions in emissions for the entire watershed to create a margin of safety for the critical locations. This requirement would defeat a central purpose of zonal permit approaches--the prevention of over-control (Tietenberg, 2006).

Problem C: Discrete Capital Costs

Our second extension of the TRS model is to account for discrete, fixed capital costs associated with upgrading abatement capacity to enable plants to treat effluent to a lower concentration level. While the addition of chemicals or other small changes can facilitate additional abatement control in some instances, there are likely to be limits to such opportunities for any initial capital configurations at the plants.

> “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” (US EPA, 1996, p. 3-2).

The following cost minimization problem (Problem C) explicitly considers the allocation of fixed capital investment as well as variable costs in identifying the optimal abatement decisions among dischargers. The model is given by:

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

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

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

where the total annual abatement cost $C_i(e_i^o - e_i, x_i)$ is determined by continuous variable e_i and discrete integer variable x_i. On the right hand side of equation (3’’), $OM_i^{x_i}(e_i)$ denotes the annual operating and management costs of firm *i* with investment level x_i, at final effluent level e_i, and $CC_i(x_i)$ denotes the annualized capital cost of firm *i* when it upgrades the capacity to the level x_i. We use x_i as a superscript on the annual OM cost function because the facility upgrade for a firm may also affect its variable cost function.

We also assume that the maximal abatement capacity of each firm is determined by its own facility upgrade level, $x_i \in Z_i$. Hence, each firm's maximal achievable level of abatement is bounded by a function of its upgrade level $x_i : e_i \ge \phi_i(x_i)$. Since each integer set Z_i may be different, each firm may face a different spectrum of upgrade choices. In addition, since the capital investments are assumed irreversible, each firm can only upgrade but never downgrade its capacity to abate. Consequently, if firm *i* has a certain level of existing capacity to remove the pollutant, then "0" must not be in its choice set Z_i

The nature of the solutions to this model are evident from the Kuhn-Tucker conditions of the standard convex programming model that are associated with a specific branch of the integer model in which each firm's upgrade level is fixed (Zhao, 2013). Based on these conditions (see Appendix 2) the characteristics of these solutions are summarized into the following six facts:

i. *For a discharger operating at an interior point, willingness to pay (WTP) and willingness to sell (WTS) are unique, both equaling the marginal cost of abatement.*
ii. *For a discharger constrained by* e_i^o, *excess allowances will be sold at any positive price. In other words, this discharger's WTS is NOT unique. On the other hand, this discharger's WTP is trivial because it is not allowed to increase its effluent any further.*
iii. *For a discharger operating at the maximum physical capacity to abate,* $\phi_i(x_i)$, *WTP is bounded by a lower bound of marginal abatement cost and an arbitrarily determined high price as the upper bound determined by the level of the penalty for non-compliance.*
iv. *Trade between any pair of the "interior" dischargers has a unique price ratio which follows* $t_{ki} = \frac{\lambda_k}{\lambda_i}$ *, where* λ *is the shadow price.*
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 bargaining.*

Altogether these six results suggest that a unique price between dischargers will emerge only when both dischargers are operating at an interior solution. When either of the dischargers is operating at a corner solution, the permit price is not unique, and hence will require a bargaining outcome. We return to this practical issue below.

The Data and the Empirical Specification

There are three essential components of the data needed to estimate total abatement costs and trade patterns: 1) data for 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 for OM and capital costs of phosphorus abatement for each WWTP.

The Environmental Capacity and the TMDLs

Under the baseline, no-trade policy, the allowable firm (or zonal) discharges are specified under each discharger's National Pollution Discharge Elimination System (NPDES) permits to not exceed 0.40 mg/l total phosphorus (P), calculated as a long-term (i.e. annual) average (NJDEP, 2008). As depicted in the first five columns of Table 1, the current phosphorus effluent levels differ substantially among plants, with only two WWTPs presently capable of meeting the 0.40 mg/l standard (also see the 13th column). The average pre-TMDL phosphorus concentration was 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, the 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). Because trading ratios varied across probabilistic water level scenarios, each trading ratio represents the worst-case scenario--the most vulnerable condition for a each buyer-seller pair across three distinct water level scenarios.

Table 2 contains the resulting trading-ratio matrix corresponding to the One-Discharger-

Per-Zone TRS model (Problem A). Empty cells indicate that emissions from potential sellers do not have a direct effect on water quality at the buyer's location. Consistent with the downstream trading structure of the Hung and Shaw TRS system, trading ratios are bounded by zero and one and all feasible trades lie above the main diagonal.

Trading ratios corresponding to the management area approach characterized in Problems B and C and Figure 2 are provided in Table 3. In contrast to Table 2, trading opportunities appear both above and below the main diagonal, indicating the possibility for both downstream and upstream trades for some buyer/seller combinations. The elements of the matrix are not symmetrical in the sense that the trading ratio for the transfer of a permit between a buyer and a seller is not necessarily the inverse of the trading ratio if the direction of trade were reversed. For example, P8 would be allowed to increase its phosphorus emissions by 0.714 lbs. for each pound of allowances purchased from R1. However, R1 could only increase phosphorus emissions by 1.235 lbs., which is less than $\frac{1}{0.714} = 1.401$, for each pound of allowance purchased from P8. In this case, the product of the two ratios equals 0.88 (1.235 * 0.714) < 1, thus preluding the possibility of profitable circular trading. This relationship generalizes to the entire matrix such that $t_{ik} * t_{ki} \leq 1 \; \forall \; i,k$. because the worst-case trading ratios, as discussed above, are utilized.

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 for the actual costs of 104 treatment plants located in the Chesapeake Bay watershed (NRTCTF 2002) and from an engineering study conducted in Georgia (Jiang *et al.* 2005). For the 104 Chesapeake Bay waste water treatment plants, we have data on daily flow and annual Operating and Management (O&M) and cost for several effluent concentrations (e.g.

2mg/l; 1mg/l; 0.5mg/l; and 0.1mg/l). The following specification is estimated for O&M costs.

$$\begin{aligned}\ln O\,\&\,M &= \alpha_1 + \alpha_2 \ln C + \alpha_3 \ln F + \alpha_4 \ln C \cdot \ln F + \alpha_5 T + \alpha_6 T \cdot \ln C + \alpha_7 T \cdot \ln F \\ &+ \alpha_8 T \cdot \ln C \cdot \ln F + \alpha_9 R + \alpha_{10} R \cdot \ln C + \alpha_{11} R \cdot \ln F + \alpha_{12} R \cdot \ln C \cdot \ln F + u_0\end{aligned}$$

where C is final phosphorus concentration in mg/l; F is daily flow in million gallons per day; T is a binary technology variable equaling 1 (0) if biological (chemical) treatment is used; and R is a regional indicator of whether the observations was drawn from the Georgia (R=1) or Chesapeake (R=0) studies. Given this specification, the following cost function is estimated using OLS, with Huber-White corrections to the covariance matrix to account for the clustering of multiple observations per WWTP:

$$\begin{aligned}\ln O\,\&\,M &= \underset{(0.058)^{**}}{9.876} - \underset{(0.020)^{**}}{0.990} \ln C + \underset{(0.030)^{**}}{0.796} \ln F + \underset{(0.014)^{**}}{0.046} \ln C \cdot \ln F + \underset{(0.083)^{**}}{0.650} T \\ &+ \underset{(0.022)^{**}}{0.314} T \cdot \ln C + \underset{(0.179)^{**}}{1.180} G - \underset{(0.020)^{*}}{0.050} G \cdot \ln C \cdot \ln F \qquad R^2 = 0.95\end{aligned} \tag{13}$$

The numbers in parentheses are estimated standard errors with "*", and "**" indicating significance at the 5% and 1% levels, respectively. Variables were retained in the final estimated equation only if the estimated p values for the coefficients were less than 0.20.

Using a similar regression strategy, the following capital investment cost (CC) function is estimated:

$$\begin{aligned}\ln CC &= \underset{(0.011)^{**}}{11.889} - \underset{(0.010)^{**}}{0.985} \ln C + \underset{(0.041)^{**}}{0.347} \ln F - \underset{(0.031)^{**}}{0.128} \ln C \cdot \ln F + \underset{(0.230)^{**}}{0.996} T \\ &+ \underset{(0.044)^{**}}{0.442} T \cdot \ln C + \underset{(0.038)^{**}}{0.290} T \cdot \ln F + \underset{(0.031)^{**}}{0.114} T \cdot \ln C \cdot \ln F + \underset{(0.368)}{0.680} R \quad R^2 = 0.97\end{aligned} \tag{14}$$

Given geographic proximity and other similarities between the Chesapeake Bay and Passaic watersheds, the Chesapeake data are thought to provide the preferred baseline for our analyses. To accomplish this, the regional dummy R is set equal to "0" for the 22 firms in the Passaic watershed. Further, 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.

The elasticities of both O&M cost and Capital cost can be derived by taking the logarithmic partial derivatives of above equations with respect to concentration level (see Zhao, 2013). The results can be summarized as: 1) For the range of flows in this study the elasticities for both O&M cost and Capital costs are negative, indicating that as the final concentration goes down, both costs rise; (2) O&M costs are more elastic for smaller plants (with lower discharge flow) than for larger plants; and (3) The capital costs required to retrofit facilities are more elastic for larger plants. These properties conform to the basic economic intuition as well as common sense. In addition, the coefficients for the biological plants shift the cost functions upward but, at the same time, the cost elasticities with respect to concentration decline. These differences are consistent with the results from the Georgia study. Relative to chemical abatement, biological removal processes generally involve higher operating costs and are more investment intensive; they are, however, more efficient in phosphorus abatement to low concentration levels.

Following Sado et al. (2010), we generate a discrete capital cost function by allowing 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 concentration $\geq$ 0.25 mg/l; (4) 0.25 mg/l > target concentration $\geq$ 0.10 mg/l; and (5) 0.10 mg/l > target concentration. The corresponding capital costs for each WWTP and treatment level are provided in Table 1, columns 7-12. Although informed by engineers, these discrete capital cost thresholds are arbitrary.

General Trading Patterns and Cost Savings under Alternative Trading Scenarios

This section identifies the cost-effective abatement levels for each WWTP, the resulting patterns of trade between WWTPs, and the cost savings associated with the following four scenarios: Marginal Cost Trading, One-Discharger-Per-Zone; Optimal Trading, One-Discharger-Per-Zone; Marginal Cost Trading, Management area Approach**;** Optimal Trading, Management Area Approach. The term "optimal" signifies that total costs, including fixed capital costs, are minimized as in Problem C. Each of these is compared to a baseline No-Trade scenario.[vi]

No-Trade Scenario: The appropriate baseline situation from which to estimate potential cost-savings associated with allowance trading is a no-trade situation in which each WWTP independently meets the 0.4 mg/l concentration standard associated with the NPDES-TMDL. In the two cases (WQ and T1) for which the WWTPs already treat effluents to concentration levels below the 0.4 mg/l standard, we assume that the concentration levels for the firms correspond to the pre-TMDL treatment level and the firms incur no additional capital upgrade costs as a result of the TMDL. The last three columns of Table 1 provide the effluent concentration level and the level of capital upgrade, the total annual abatement costs for the firm, and the marginal treatment costs at the specified concentration level.

Annualized total abatement costs differ widely across firms, but they vary systematically by flow level, level of upgrade required, and treatment type. The estimated total annualized treatment costs across all 22 WTPs is $3,995,368, of which about 40% is associated with capital expenses. This high level of capital costs relative to total costs suggests that reallocation of treatment responsibilities to account for capital investments would likely have a non-negligible impact on total costs.

The marginal treatment costs also differ by treatment type, flow level, and firm size. WWTPs with smaller average flow levels have substantially higher marginal treatment costs—thus exhibiting economies of size. For example, the smallest flow WWTP is P4 with an average flow level of 0.12 million gallons per day (MGD) and a marginal costs of treatment at the 0.4 mg/l standard of $72.48 per pound. At the other extreme, R1, with an average flow level of 12.58 MGD achieves the 0.4 mg/l standard with a marginal cost of $19.13 per pound. The marginal treatment costs are even lower for WWTPs using biological treatment.

Marginal Cost Trading, One-Discharger-Per-Zone: This approach is consistent with Hung and Shaw's (2005) TRS presentation in the sense that each WWTP is a separate MA or zone and only downstream trades in the same tributary are allowed. WWTPs are further assumed to trade based only on differences in marginal costs. The corresponding patterns of trades are reported in the bracketed numbers, '[ ]', in Table 4. There are eight WWTPs (D1, P1, P3, P5, W2, WQ, T1 and P10) that act as sellers, and eight WWTPs (D2, D3, P2, P4, P6, W3, T2 and P11) buy permits. Overall trade volume is very low, due to the limited trading opportunities as a result of prohibiting upstream or cross-tributary trading and the reliance on marginal, O&M cost-based trading. In total, only 1,549 units are traded, just over 2% of the total allowable emissions in the watershed. As expected with downstream trading, all trades between the buyers and sellers are indicated above the main diagonal in the trading pattern matrices. Most of these trades are between immediately adjacent WWTPs.

Under Marginal Cost Trading, only O&M costs are considered in the cost minimization problem and no changes in capital investments relative to the baseline are available. As such, while the concentration level after trading does change from the no-trade levels (see Table 6, column 3), the capital investment in abatement technology remains at the no-trade level reported in Table 1, column 13. Under this trading system, total costs fall a nominal $23,489, or 0.57% relative to the no-trade case, with savings being attributed solely to reduced O&M costs. This small level of savings is attributed to the limitations placed on trading opportunities. Moreover, there are no capital cost savings because each firm is assumed to invest in the capacity to independently meet the no-trade TMDL standard.

Marginal Cost Trading, Management Area Approach: Under this trading structure, inter-MA trading is allowed from the Upper Passaic MA to the Lower Passaic MA, and from the Pompton MA to the Lower Passaic MA. Moreover, trades are allowed from the Pompton MA to the Upper Passaic MA, but not the reverse. The trading ratios under this configuration are specified in Table 3. Recall that these trading ratios are no longer bounded by one, indicating that sources can sell allowances to firms hydrologically more distant from the relevant critical location.

The trading pattern that results from this trading rule is depicted by the numbers in '[ ]'s in Table 5. Seven WWTPs (W4, WQ, T1, R1, P8, P9 and P10) act as sellers, and 14 WWTPs (D1-D3, P1-P4, P6, P7, W1-W3, T2 and P11) buy allowances. Interestingly, most of these trades occur with sellers located hydrologically downstream from buyers, as indicated by the predominance of trading entries below the main diagonal of the trading matrices. This is largely due to the geographical/hydrological organization of firm sizes, namely, large efficient firms with lower marginal abatement costs happen to be located downstream. Another factor is that most trading ratios for upstream trading are greater than or equal to one, as the discharges from upstream firms have less impact at the end-point. The volume of trade increases notably compared with the One-Discharger-Per-Zone TRS approach. There are 3,663 units of allowances traded, representing nearly 5% of the total allowable emissions in the watershed.

Despite the additional trading activity, the cost savings remain nominal. The total cost savings are $41,385 or 1.02% relative to the baseline. Hence, the added flexibility associated with the MA approach does not engender cost-savings under marginal cost trading in which each firm is assumed to invest in the capacity to independently meet the NPDES TMDL standard.

Optimal Trading, One-Discharger-One-Zone: In this scenario, incentives for allowance trading are embodied not only in the differential marginal O&M costs, but also in avoiding costly capital upgrades. It is expected that some WWTPs would buy enough allowances to avoid facility upgrades and maintain a lower level of capital cost. Trading ratios are again defined in Table 2. The resulting pattern of trades is reported in '{ }'s in Table 4. Nine WWTPs (D1, P1, P5, P7, W1, W2, WQ, T1 and P10) act as sellers, and 10 WWTPs (D2, D3, P2 - P4, P6, P8, W3, T2 and P11) buy permits.

Compared with marginal cost trading under the same trading ratio conditions, the optimal trading system has much larger trading volumes as the incentive to avoid capital upgrade stimulates more trades. There are 4,150 units of allowances traded, about 2.6 times as many as in the marginal cost trading. This represents about 5% of the total allowable watershed emissions.

The optimal trading scenario assumes optimal capital upgrades, that is, the aggregate watershed costs of abatements consisting of both aggregate O&M costs and aggregate Capital upgrade costs are jointly minimized through allowance trading. Under these conditions, the watershed annualized capital costs fall a considerable $237,787, amounting to a 14.8% reduction relative to the baseline capital costs. Interestingly, the watershed OM costs after the trades is slightly higher than the no-trade baseline as many allowances are sold from high marginal cost WWTPs to low marginal cost WWTPs, driven by the incentive to avoid capital upgrade cost. The resulted total cost-savings is $221,927 (or over 5.5% relative to the no trade baseline), with all savings being attributed to the reduced capital costs. This level of total savings is about 10 times of those attained under the marginal cost trading under the same conditions.

Optimal Trading, Management Area Approach: The trading ratios under this configuration of the MAs are specified in '{ }' Table 5 according to the relative effects of each transaction on the buyer's endpoints. All 22 WWTPS participate in trading: six (R1, W4, WQ, T1, T2 and P9) act as sellers, and 16 (D1 - D3, P1 - P8, W1 - W3, P10 and P11) buy permits. Among the five sellers, WQ and T1 are currently abating to less than 0.4mg/L, over-complying with the prospective NDPES requirements. Therefore, they can simply dump their excess allowances into the market.[vii] The other three sellers, W4, R1, P9, do not have present capacity to meet the NDPES. It is expected that they will upgrade their abatement capacities fully and then sell the leftover allowances to the buyers. On the other hand, the sixteen buyers can avoid upgrading their facilities fully (e.g. to level 3) by acquiring allowances from the sellers. This pattern of trade, which conforms to *a priori* expectations, can be summarized as follows: 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, allowing the higher than average cost, capital intensive smaller WWTPs to avoid full upgrades. Specifically, among the three WWTPs that upgrade fully and become sellers: W4 is the largest (and most efficient) WWTP in the watershed; R1 is the second largest WWTP in the watershed, and, due to external factors it has already adopted a biological treatment technology which has relatively lower cost elasticity of abatement than the chemical technology (i.e. more efficient when treating to a low concentration level); and P9 has the highest flow in the Lower Passaic MA.

Compared with the marginal cost trading, the optimal trading results in much larger trading volumes as the incentive to avoid capital upgrade stimulates more trades. There are 9,618 units of allowances traded, nearly three times as many as in the marginal cost trading. The volume of trade represents nearly 13% of the total allowable emissions in the watershed

Under optimal trading, MA system, trading generates substantial capital cost savings, to the order of $538,415 (or 33.4% relative to the baseline capital costs). However, this benefit of avoiding capital upgrade costs for some firms is offset somewhat through an increase in variable abatement costs. As a result, the watershed OM costs after the optimal trading are slightly higher than those in the no-trade baseline for both Multiple Source MA approaches. In total, the cost savings for Optimal Trading MA $523,417 (13.1% relative to the baseline total costs), nearly eight times that of the Marginal Cost Trading.

On Prices and Willingness to Pay for Permits

For any interior equilibrium of the Marginal Cost Trading, the competitive price of pollution allowances at each WWTP is equal to its marginal abatement cost. Pollution allowances are traded to the point where the spatially adjusted equi-marginal condition holds. There is a unique price at each location: that is, the price of allowances at the seller's location must be equal to the price at the buyer's location adjusted by the trading ratio.

For example, as indicated in Table 3, under the Marginal Cost – MA System the trading ratio between R1 and D1 is 0.809, and R1 sells 339 allowances to D1 (see Table 5). Table 6, Column 8 indicates that the allowances price at R1 is equal to 21.2 $/lbs, and the price at D1 is 26.2 $/lbs. These numbers verify the spatially adjusted equi-marginal condition at the internal equilibrium, as $26.2 multiplied by 0.809 is equal to $21.2. Note that the allowances prices at WQ and T1 cannot be determined because their non-degradation constraints are binding at the equilibrium. Comparing the prices in the fifth and eighth columns of Table 6, allowance prices are more equalized under the MA System. This is because the MA System provides more trading opportunities than the One-Discharger-Per-Zone TRS.

The optimal trading scenarios differ from marginal cost trading in that the prices for allowances may not be uniquely determined for some trades. This is because many WWTPs operate at their maximum abatement capacity in equilibrium so as avoid upgrading to the higher level. Under these "corner" conditions, although ranges for willingness to pay (WTP) and willingness to sell (WTS) can be determined for potential trading partners, the price associated with a transaction is not unique, varying with the bargaining power of the traders.

To this point, we have not specified numerical values for maximum WTP for additional permits when firms are operating at the uppermost limit of their present capital investment. We have only indicated that it will be bounded from above by the penalty for emitting without an allowance. In the following discussion we assume that the penalty for non-compliance is set at a sufficiently high level that all potential buyers will prefer to buy allowances in the market. Given this assumption, if a firm has the option to upgrade then its maximum WTP is the difference in total costs between the baseline no trading scenario and the optimal trading outcome of the firm, divided by the change in allowances needed between the two settings (i..e. It is the permit price at which the buyer is indifferent between participating in optimal trading and the baseline no trade case.). This of course assumes that the buyer is guaranteed the supply of permits to avoid the upgrade.

In this manner, WTP can be viewed as an incremental cost (US EPA, 2004; Caplan, 2008), computed as the average cost saving per unit of abatement by not having to meet the standard without trading. For instance, the WTP of D1 is $62.60 per unit allowance which is equal to D1's total cost savings from the trade, $52,708, divided by the number of allowances bought, 842. Drawing from the previous tables, Table 7 presents the amount and source of allowances purchased in the optimal setting, and the derived maximum WTP of all buyers in the Optimal Trade MA System.

In a similar fashion, sellers' WTS can be defined as the lowest average price per allowance the seller is willing to sell its allowances based on comparisons between the optimal and no trade scenarios. Since for sellers operating at an interior optimum, the minimum WTS is equal to the average marginal cost of treatment based over the range between the no-trade and optimal trade scenarios. These values are as follows: R1 = $23.80, W4 = $25.64, P9 = $25.89 and T2=$24.00. The minimum WTS for WQ and T1 is zero, due to the fact that the current unregulated abatements by WQ and T1 already over-comply with the required target. Thus, they can simply dump all their unused allowances without any additional cost.

A comparison between paired WTS and WTP values indicates a wide range for bargaining. For example, if we assume that all firms pay the lowest WTP in the group of buyers associated with the seller R1 (i.e. there is not price discrimination amongst the buyers), then the range of possible prices is $23.80 to $52.79, and even wider if price discrimination across buyers does occur. The determination of this possible range is based on a set of simplifying assumptions, whereas the actual market mechanism may be more complex. For example, it is assumed that if a firm cannot reach the deal with its designated trading partners, it will be excluded from the market, and so it has to independently abate to the required environmental standard. Yet, in practice, the firm may be able to form an alternative coalition where it can generate a higher cost savings. In this sense, the above example provides only a very rough estimate of the range of possible price to demonstrate the complications associated with capital cost edges in price negotiation. A refined price range could be derived using the concept of

"Core" in the cooperative game theory. This refined price range should be contained in the price range provided above and is not explored further in this study.

Summary and Discussion

The principal findings from this research can be organized into three main results.

Result 1: The maximum total costs savings from the various MA approaches are nominal under the marginal cost trading, ranging from 0.57% to 1.02% relative to the no trade scenario. This low level of savings follows *a priori* expectations. Recall that there are only two treatment technologies currently existing in the Passaic Watershed, so the differences in marginal abatement costs arise primarily from differences in the economies of scale based on flow levels. Hence, it should not be surprising that the volumes of trade account for only 2% to 6% of the total allowable emissions in the watershed. These small trading volumes and disappointing saving results are consistent with the experience from extant water quality trading programs.

Result 2: In sharp contrast with the marginal cost trading, the Optimal Trading, MA approach yields relatively optimistic saving results, generating about 10 times of the savings as the marginal cost trading under the same MA approach. With optimal allocation of the capacity upgrade, the maximum percentage cost savings from the various trading regimes range from to 13.1% relative to the no-trade scenario. The trading volume rises considerably. Specifically, the volume of trade accounts for between 5% to 14% of the total allowable emissions in the watershed. As the result, almost all buyers end up being able to acquire enough allowances to stay within the maximum capacity of capital level 2 (i.e. emissions related to higher than 0.5mg/L concentration). They can take advantage of economies of scale associated with a few large, hydrologically well-situated firms and do not need to upgrade their abatement capital to the level 3 as in the no-trade baseline scenario. It is also important to note that, as the trading equilibrium deviates from the equi-marginal point, the variable OM costs are not necessarily minimized. However, the savings on the discrete capital costs outweigh the increase in O&M costs, and thus greater total savings are realized.

Result 3: The percentage savings increase as different alternatives of the MA Approach become less restrictive. The One-Discharger-Per-Zone TRS Approach does not allow increased phosphorous load at any point in the watershed relative to the original NDPES. Permitting upstream trade within MAs generates twice as much savings as in the One-Discharger-Per-Zone TRS Approach. These additional cost savings are due in large measure to an ability to trade in any direction within an MA. As a result, some low-cost downstream plants can now sell permits to high abatement cost plants located upstream. When capital planning is feasible, these expanded trading opportunities allow some high-cost upstream plants to avoid additional capital investments while still avoiding increased concentrations in potential hot spots.

The above results suggest that moderate cost savings from trading phosphorus allowances can be achieved through the MA approach (Result 3) and that substantial gains are possible if trades can facilitate the efficient allocation of fixed cost investments across WWTPs (Result 2). The former issue is primarily driven by the hydrology of a particular watershed and whether managing water quality in a flexible way to protect a selected number of locations is deemed appropriate. The later issue points to the need to consider a broader concept of trading pollution abatement responsibilities beyond simple, single-period spot markets or auctions envisioned in canonical treatments of water quality trading.

Our work shows that with the optimal allocation of fixed-cost upgrades, the market can be cleared at the minimum overall abatement cost for the whole watershed through trading of emissions allowances. 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. In practice, however, it would be very difficult for firms to achieve the optimal fixed-cost upgrade allocation under spot market conditions. Due to the discrete nature of the capital upgrades, firms cannot instantaneously adjust their abatement capacities according to the actual trading outcomes in the market. Instead, firms need to make *ex ante* capacity choices before entering the spot market. In some cases where too few WWTPs choose to upgrade, the market cannot be cleared at any price. Moreover, since the capital investment is irreversible, even if the market is cleared at some price, it is unlikely to be optimal (For example, the Marginal Cost Trading scenarios give the savings estimates in the case of a precautionary over-investment). Hence, to accomplish this objective in practice, risk averse buyers will likely need assurances that adequate allowances will be available if they choose not to upgrade to a capacity that would allow them to independently meet TMDL standards. Sellers too would benefit from knowing that they will have a market for any excess allowances.

To an extent, contemporary policy experiments offer possible approaches to addressing the capital investment problem. For example, the clearing house approach used in the Pennsylvania water quality trading program allows forward-contract auctions, and has thus far demonstrated the capacity to meet these contracts (O'Hara et al., 2012). Moreover, anecdotal evidence suggest that these trades have largely involved buyers seeking to avoid costly capital investments (Shortle, Personal Communication) Likewise, the success of the Long Island Sound Nitrogen Credit Exchange program can be linked to the smoothing of investments by establishing a fixed annual price for nitrogen credits and having the State of Connecticut absorb or cover any market imbalances. As such the program acts more like an exceedance tax/abatement subsidy approach in which the annual establishment of a reasonable credit price guarantees the availability of available credits to buyers and a market for sellers.

While these programs may be effective, it is incumbent upon economists and policy makers to more broadly conceptualize what least cost trading would involve. We note in closing that while the cost savings demonstrated herein are not large in absolute terms, the relative savings of 13% identified in the Optimal Trading, Management Area approach are likely worth pursuing when aggregated across states and the entire nation. As an example, New York State alone anticipates $36 billion in waste water treatment infrastructure over the next 20 years. (NYS DEC).

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Table 1: Descriptive Statistics for Passaic Waste Water Treatment Plants (WTPS) for Phosphorus (P)

Descriptive Statistics						Annualized Capital Costs by Investment Level ($)						No Trade Scenario		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Management Area	River	WWTP Map Code	Avg. Flow (MGD)	Initial Phosp. Conc. (mg/l)	Treatment Tech.	$X_i = 0$	$X_i = 1$	$X_i = 2$	$X_i = 3$	$X_i = 4$	$X_i = 5$	Concentration (mg/l) / Capital Level (X_i)	Total Annual Cost ($)	Marginal Cost ($)
						$P \geq$ 1.50 mg/l	$P \geq$ 1.00 mg/l	$P \geq$ 0.50 mg/l	$P \geq$ 0.25 mg/l	$P \geq$ 0.10 mg/l	$P \geq$ 0.05 mg/l			
Upper Passaic	Dead	D1	1.76	3.13	Chemical	11,121	17,074	35,533	73,949	194,849	405,503	0.4 / 3	147,733	33.17
	Dead	D2	0.15	1.85	Chemical	5,377	7,265	12,152	20,327	40,125	67,116	0.4 / 3	31,856	67.96
	Dead	D3	0.31	1.91	Chemical	6,662	9,346	16,674	29,745	63,934	114,057	0.4 / 3	49,672	55.07
	Passaic	P1	1.00	2.63	Chemical	9,412	14,033	27,775	54,976	135,564	268,323	0.4 / 3	103,158	39.15
	Passaic	P2	0.36	1.67	Chemical	6,962	9,844	17,796	32,172	70,374	127,221	0.4 / 3	54,477	52.73
	Passaic	P3	1.57	0.60	Chemical	n/a	n/a/	33,808	69,649	181,075	373,039	0.4 / 3	103,537	34.30
	Passaic	P4	0.12	1.53	Chemical	5,035	6,724	11,026	18,082	34,771	57,022	0.4 / 3	27,826	72.48
	Passaic	P5	2.41	3.28	Chemical	12,202	19,042	40,749	87,201	238,394	510,158	0.4 / 3	180,712	30.24
	Passaic	P6	0.90	1.48	Chemical	9,124	13,529	26,529	52,021	126,701	248,448	0.4 / 3	96,524	40.37
	Passaic	P7	2.61	2.63	Chemical	12,492	19,576	42,189	90,924	250,908	540,748	0.4 / 3	190,228	29.54
	Passaic	P8	3.75	1.62	Chemical	13,902	22,199	49,406	109,657	316,605	704,631	0.4 / 3	240,458	26.54
	Whippany	W1	1.90	0.84	Biological	n/a	n/a	83,836	122,913	203,823	298,826	0.4 / 3	151,234	31.21
	Whippany	W2	3.03	0.56	Biological	n/a	n/a	113,615	167,333	279,163	411,153	0.4 / 3	212,841	26.99
	Whippany	W3	2.03	2.83	Chemical	11,599	17,941	37,813	79,696	213,537	450,060	0.4 / 3	161,862	31.80
	Rockaway	R1	12.58	2.98	Chemical	n/a	151,933	226,089	336,442	569,002	846,726	0.4 / 3	532,433	19.13
	Whippany	W4	8.81	1.46	Biological	19,871	33,786	83,717	207,442	688,404	1,705,786	0.4 / 3	541,009	18.52
Pompton	Wanaque	WQ	1.00	0.16	Biological	n/a	n/a	n/a	n/a	135,564	268,323	0.16 / 4	133,993	38.31
	Pompton	T1	0.86	0.32	Chemical	n/a	n/a	n/a	50,795	123,058	240,333	0.32 / 3	53,736	40.91
	Pompton	T2	5.33	2.14	Chemical	15,422	25,079	57,585	133,222	396,741	910,960	0.4 / 3	302,329	23.92
Lower Passaic	Signac Brook	P9	7.47	2.27	Chemical	17,038	28,196	66,709	157,827	492,698	1,165,679	0.4 / 3	377,225	21.63
	Peckman	P10	2.46	3.07	Chemical	12,276	19,178	41,115	88,145	241,557	517,867	0.4 / 3	183,115	30.06
	Peckman	P11	1.26	2.25	Chemical	10,077	15,205	30,718	62,060	157,237	317,669	0.4 / 3	119,411	36.59

Table 2: Trading Ratios: One-Discharger-Per-Zone Models

B S	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883											
D2		1	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883											
D3			1	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883											
P1				1	1.000	1.000	1.000	0.935	0.935	0.935	0.935											
P2					1	1.000	1.000	0.935	0.935	0.935	0.935											
P3						1	1.000	0.935	0.935	0.935	0.935											
P4							1	0.935	0.935	0.935	0.935											
P5								1	1.000	1.000	1.000											
P6									1	1.000	1.000											
P7										1	1.000											
P8											1											
W1												1	1.000	1.000		1.000						
W2													1	1.000		1.000						
W3														1		1.000						
R1															1							
W4																1						
WQ																	1	1.000	0.970			
T1																		1	0.970			
T2																			1			
P9																				1		
P10																					1	1.000
P11																						1

Notes: The numbers in each cell are trading ratios between the potential seller and the potential buyer.

Table 3: Trading Ratios – Management Area Models

B S	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	**1.026**	**1.026**	**1.026**	**1.147**	**1.026**				**0.599**	**0.440**	**0.440**
D2	**1.000**	1	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	**1.026**	**1.026**	**1.026**	**1.147**	**1.026**				**0.599**	**0.440**	**0.440**
D3	**1.000**	**1.000**	1	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	**1.026**	**1.026**	**1.026**	**1.147**	**1.026**				**0.599**	**0.440**	**0.440**
P1	**1.024**	**1.024**	**1.024**	1	1.000	1.000	1.000	0.935	0.935	0.935	0.935	**1.053**	**1.053**	**1.053**	**1.176**	**1.053**				**0.634**	**0.466**	**0.466**
P2	**1.024**	**1.024**	**1.024**	**1.000**	1	1.000	1.000	0.935	0.935	0.935	0.935	**1.053**	**1.053**	**1.053**	**1.176**	**1.053**				**0.634**	**0.466**	**0.466**
P3	**1.024**	**1.024**	**1.024**	**1.000**	**1.000**	1	1.000	0.935	0.935	0.935	0.935	**1.053**	**1.053**	**1.053**	**1.176**	**1.053**				**0.634**	**0.466**	**0.466**
P4	**1.024**	**1.024**	**1.024**	**1.000**	**1.000**	**1.000**	1	0.935	0.935	0.935	0.935	**1.053**	**1.053**	**1.053**	**1.176**	**1.053**				**0.634**	**0.466**	**0.466**
P5	**1.024**	**1.024**	**1.024**	**1.000**	**1.000**	**1.000**	**1.000**	1	1.000	1.000	1.000	**1.105**	**1.105**	**1.105**	**1.235**	**1.105**				**0.678**	**0.499**	**0.499**
P6	**1.024**	**1.024**	**1.024**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	1	1.000	1.000	**1.105**	**1.105**	**1.105**	**1.235**	**1.105**				**0.678**	**0.499**	**0.499**
P7	**1.024**	**1.024**	**1.024**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	1	1.000	**1.105**	**1.105**	**1.105**	**1.235**	**1.105**				**0.678**	**0.499**	**0.499**
P8	**1.024**	**1.024**	**1.024**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	1	**1.105**	**1.105**	**1.105**	**1.235**	**1.105**				**0.678**	**0.499**	**0.499**
W1	**0.927**	**0.927**	**0.927**	**0.905**	**0.905**	**0.905**	**0.905**	**0.857**	**0.857**	**0.857**	**0.857**	1	1.000	1.000	**1.115**	1.000				**0.582**	**0.427**	**0.427**
W2	**0.927**	**0.927**	**0.927**	**0.905**	**0.905**	**0.905**	**0.905**	**0.857**	**0.857**	**0.857**	**0.857**	**1.000**	1	1.000	**1.115**	1.000				**0.582**	**0.427**	**0.427**
W3	**0.927**	**0.927**	**0.927**	**0.905**	**0.905**	**0.905**	**0.905**	**0.857**	**0.857**	**0.857**	**0.857**	**1.000**	**1.000**	1	**1.115**	1.000				**0.582**	**0.427**	**0.427**
R1	**0.809**	**0.809**	**0.809**	**0.764**	**0.764**	**0.764**	**0.714**	**0.714**	**0.714**	**0.714**	**0.714**	**0.833**	**0.833**	**0.833**	1	**0.833**				**0.485**	**0.356**	**0.356**
W4	**0.927**	**0.927**	**0.927**	**0.905**	**0.905**	**0.905**	**0.905**	**0.905**	**0.857**	**0.857**	**0.857**	**1.000**	**1.000**	**1.000**	**1.118**	1				**0.582**	**0.427**	**0.427**
WQ	**0.637**	**0.637**	**0.637**	**0.602**	**0.602**	**0.602**	**0.602**	**0.563**	**0.563**	**0.563**	**0.563**	**0.656**	**0.656**	**0.656**	**0.788**	**0.656**	1	1.000	1.000	**0.382**	**0.280**	**0.280**
T1	**0.637**	**0.637**	**0.637**	**0.602**	**0.602**	**0.602**	**0.602**	**0.563**	**0.563**	**0.563**	**0.563**	**0.656**	**0.656**	**0.656**	**0.788**	**0.656**	**1.000**	1	1.000	**0.382**	**0.280**	**0.280**
T2	**0.657**	**0.657**	**0.657**	**0.620**	**0.620**	**0.620**	**0.620**	**0.580**	**0.580**	**0.58**	**0.580**	**0.677**	**0.677**	**0.677**	**0.812**	**0.677**	**1.000**	**1.000**	1	**0.393**	**0.289**	**0.289**
P9																				1	**0.735**	**0.735**
P10																				**0.978**	1	1.000
P11																				**0.978**	**1.000**	1

Notes: The numbers in each cell are trading ratios between the potential seller and the potential buyer. Bolded numbers indicate cell entries that differ from those in Table 2.

Table 4: Allowances Traded between Sellers (S) and Buyers (B) --- One-Discharger-Per-Zone System

B S	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1		[57] {46}	[71] {95}		[33] {35}	{351}	{11}															
D2																						
D3																						
P1					[27] {77}	{147}	{26}															
P2																						
P3							[57]															
P4																						
P5									[120] {274}		{392}											
P6																						
P7											{752}											
P8																						
W1														{115}								
W2														[139] {504}								
W3																						
R1																						
W4																						
WQ																			[731] {731}			
T1																			[210] {210}			
T2																						
P9																						
P10																						[103] {384}
P11																						

Notes: Numbers in [ ] are the pounds of phosphorus traded between firms under the marginal cost trading scheme. The numbers in { } are the pounds of phosphorus traded between two firms under the optimal trading scheme that accounts for both marginal and fixed costs.

Table 5: Allowances Traded between Sellers (S) and Buyers (B) --- Management Area System

B S	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								[97]		[66]												
W1																						
W2																						
W3																						
R1	[339]	[132] {78}	[205] {117}	{304}	{144}	{627}	{67}				{1268}											
W4				[280]	[190]	[278]	[98]	{857}	[247] {320}	[7] {928}	{277}	[384] {579}	[231] {927}	[363] {619}								
WQ	{732}																		[731]			
T1	{110}			{99}															[210]			
T2				{21}																		
P9																					{1021}	[170] {523}
P10																						[23]
P11																						

Notes: Numbers in [ ] are the pounds of phosphorus traded between firms under the marginal cost trading scheme. The numbers in { } are the pounds of phosphorus traded between two firms under the optimal trading scheme that accounts for both marginal and fixed costs.

Table 6: Descriptive Statistics for Passaic Waste Water Treatment Plants (WTPS) for Phosphorus (P)

Management Area	WWTP Map Code	Marginal Cost Trading						Optimal Trading			
		One-Discharger-One-Zone			Management Area			One-Discharger-One-Zone		Management Area	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
		Concentration after Trading (mg/L) / Capital Level.	Total Annual Treatment Cost ($)	Price of Allowance at Each WWTP ($)	Concentration after Trading (mg/L) / Capital Level.	Total Annual Treatment Cost ($)	Price of Allowance at Each WWTP ($)	Concentration after Trading (mg/L) / Capital Level.	Total Annual Treatment Cost ($)	Concentration after Trading (mg/L) / Capital Level.	Total Annual Treatment Cost ($)
Upper Passaic	D1	0.37	153502	38.7	0.45	139662	26.2	0.30	171371	0.50	95025
	D2	0.53	28933	38.7	0.63	27359	26.2	0.50	21216	0.54	20522
	D3	0.48	46379	38.7	0.58	43379	26.2	0.50	32457	0.50	32457
	P1	0.39	104243	40.9	0.48	94948	26.9	0.32	115475	0.50	66399
	P2	0.45	51781	40.9	0.56	48004	26.9	0.50	35490	0.50	35490
	P3	0.39	105555	36.4	0.45	95897	26.9	0.50	54519	0.50	54519
	P4	0.56	24889	36.4	0.64	23895	26.9	0.50	18669	0.54	18063
	P5	0.38	184500	32.8	0.41	177878	28.4	0.31	206580	0.50	116391
	P6	0.44	92148	32.8	0.48	89354	28.4	0.50	62165	0.50	62165
	P7	0.40	190228	29.5	0.41	188330	28.4	0.31	219092	0.50	122582
	P8	0.40	240158	29.5	0.39	244457	28.4	0.50	155449	0.50	155449
	W1	0.40	151235	31.3	0.47	140649	24.3	0.38	154984	0.50	97079
	W2	0.39	216695	28.6	0.43	206926	24.3	0.35	228078	0.50	138391
	W3	0.42	157666	28.6	0.46	151772	24.3	0.50	104160	0.50	104160
	R1	0.40	541008	19.1	0.38	554593	21.2	0.40	541009	0.30	602900
	W4	0.40	532434	18.5	0.35	576525	24.3	0.40	532433	0.28	648000
Pompton	WQ	0.16	133993	n/a	0.16	133993	n/a	0.16	133993	0.16	133993
	T1	0.32	53736	n/a	0.32	53736	n/a	0.32	53736	0.32	53736
	T2	0.46	284078	18.6	0.46	284078	18.6	0.46	283077	0.40	302834
Lower Passaic	P9	0.40	377225	21.6	0.39	380963	22.4	0.40	377225	0.33	417040
	P10	0.39	186318	32.2	0.40	183807	30.5	0.35	196313	0.50	117953
	P11	0.43	115879	32.2	0.44	114481	30.5	0.50	76802	0.50	76802
Aggregate Cost			3972581 (0.57%)			3954684 (1.02%)			3774292 (5.53%)		3471951 (13.10%)

Numbers in paranthesis are percentage cost savings relative to No Trading scenario

Table 7: Price Range for Optimal Trading Management Area System

Seller	Units of allowances sold	WTS per unit of allowance	Buyer	Units of allowances bought	WTP per effective allowance	WTP per unit of allowance (adj for trading ratios)	Possible price range
R1	2604	23.80	D2	78	179.1	145.10	$23.80-$52.79
			D3	117	182.1	147.53	
			P1**	304	120.6	91.62	
			P2	144	173.0	131.46	
			P3	627	102.4	77.82	
			P4	67	191.4	145.45	
			P8*	1268	74.3	52.79	
W4	4508	25.64	P5	857	87.5	75.28	$25.64-$63.94
			P6	320	125.2	107.68	
			P7	928	85.0	73.10	
			P8*	277	74.3	63.94	
			W1	579	93.5	93.48	
			W2	927	80.3	80.32	
			W3	619	93.2	93.22	
P9	1543	25.80	P10	1021	86.9	63.42	$25.80-$63.42
			P11	523	110.9	80.96	
T2	21	24.00	P1**	21	120.6	74.74	$24.00-$74.74
WQ&T1	941	0.00	D1	842	98.2	62.60	$0.00-$62.60
			P1**	99	120.6	72.33	

* WWTPs which buy from two sellers

** WWTPs which buy from three sellers

Appendix 1:

Suppose without loss of generality that, there exist *n* sources in the Management Area K, denoted by $\{k_1, k_2, \ldots. k_n\}$ and let [K] denote the end-point of K. Further, let $\overline{T}_{k_i}$ denote the initial allocation of allowances at source k_i, thus, the implied environmental target at the endpoint [*K*] is
$E_{[K]} = \sum_{i=1}^{n} d_{k_i[K]} \overline{T}_{k_i}$

The cost-effective benchmark for Intra-Management Area trading is given by the following problem.

(A-1) $\min_{e_{k_i}} \sum_{i=1}^{n} C_{k_i}(e_k^o - e_{k_i})$ subject to:

(A-2) $\sum_{i=1}^{n} d_{k_i[K]} e_{k_i} \le E_{[K]} = \sum_{i=1}^{n} d_{k_i[K]} \overline{T}_{k_i}$;

(A-3) $e_{k_i} \in [0, e_{k_i}^0]$ $\quad \forall i \in \{1,2,\ldots.n\}$

On the other hand, the Intra-Management Area trading based on the trading ratio specified in Problem B of the text can be described by the following cost minimization problem.

(A-4) $\min_{e_{k_i}} \sum_{i=1}^{n} C_{k_i}(e_k^o - e_{k_i})$ subject to:

(A-5) $e_{k_i} - \sum_{j=1}^{n} \frac{d_{k_j[K]}}{d_{k_i[K]}} \mathrm{T}_{k_j k_i} + \sum_{j=1}^{n} \mathrm{T}_{k_i k_j} \le \overline{\mathrm{T}}_{k_i}$; $\quad \forall i \in \{1,2,\ldots.n\}$

(A-6) $e_{k_i} \in [0, e_{k_i}^0]$ $\quad \forall i \in \{1,2,\ldots.n\}$

(A-7) $\mathrm{T}_{k_j k_i} \ge 0$ $\quad \forall i, j \in \{1,2,\ldots.n\}$

To prove the cost-effectiveness of intra-M.A. trading, it is sufficient to show the equivalence of problem contained in equations A-1 to A-3 with the problem contained in equations A-4 to A-7. Let Ω_B denote the constrained choice set for problem A-1, i.e. the set of all possible vector $(e_{k_1} e_{k_2} \ldots.. e_{k_n})$ that satisfies the constraints A-2 to A-3. Similarly, let Ω_E denote the set of vector $(e_{k_1} e_{k_2} \ldots.. e_{k_n})$ that satisfies the constraints A-5, A-6 and A-7. For any element $(e_{k_1} e_{k_2} \ldots. e_{k_n}) \in \Omega_E$, it must satisfy:

$e_{k_i} \in [0, e_{k_i}^0]$ $\quad \forall i \in \{1,2,\ldots.n\}$ and

$e_{k_i} - \sum_{j=1}^{n} \frac{d_{k_j[K]}}{d_{k_i[K]}} \mathrm{T}_{k_j k_i} + \sum_{j=1}^{n} \mathrm{T}_{k_i k_j} \le \overline{\mathrm{T}}_{k_i}$; $\quad \forall i \in \{1,2,\ldots.n\}$

Multiplying each term by $d_{k_i[k]}$ gives:

$$d_{k_i[K]}e_{k_i} - d_{k_i[K]}\sum\nolimits_{j=1}^{n}\frac{d_{k_j[K]}}{d_{k_i[K]}}\mathrm{T}_{k_jk_i} + d_{k_i[K]}\sum\nolimits_{j=1}^{n}\mathrm{T}_{k_ik_j} \le d_{k_i[K]}\overline{\mathrm{T}}_{k_i}$$

$\forall i \in \{1,2,....n\}$

Summing the inequalities from 1 to n yields:

$$\Rightarrow \sum_{i=1}^{n} d_{k_i[K]}e_{k_i} - \sum_{i=1}^{n} d_{k_i[K]}\sum\nolimits_{j=1}^{n}\frac{d_{k_j[K]}}{d_{k_i[K]}}\mathrm{T}_{k_jk_i} + \sum_{i=1}^{n} d_{k_i[K]}\sum\nolimits_{j=1}^{n}\mathrm{T}_{k_ik_j} \le \sum_{i=1}^{n} d_{k_i[K]}\overline{\mathrm{T}}_{k_i}$$

$$\Rightarrow \sum_{i=1}^{n} d_{k_i[K]}e_{k_i} - \sum_{i=1}^{n}\sum_{j=1}^{n} d_{k_j[K]}\mathrm{T}_{k_jk_i} + \sum_{i=1}^{n}\sum_{j=1}^{n} d_{k_i[K]}\mathrm{T}_{k_ik_j} \le \sum_{i=1}^{n} d_{k_i[K]}\overline{\mathrm{T}}_{k_i}$$

Also, since:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} d_{k_j[K]}\mathrm{T}_{k_jk_i} = \sum_{i=1}^{n}\sum_{j=1}^{n} d_{k_i[K]}\mathrm{T}_{k_ik_j}$$

Therefore, the above weak inequality becomes:

$$\sum_{i=1}^{n} d_{k_i[K]}e_{k_i} \le \sum_{i=1}^{n} d_{k_i[K]}\overline{\mathrm{T}}_{k_i} = E_{[K]}$$

Hence, $(e_{k_1}e_{k_2}.....e_{k_n}) \in \Omega_B$.

On the other hand, for any element $(e_{k_1}e_{k_2}.....e_{k_n}) \in \Omega_B$, it must satisfy:

$e_{k_i} \in [0, e^0_{k_i}] \qquad \forall i \in \{1,2,.....n\}$

and

$$\sum\nolimits_{i=1}^{n} d_{k_i[K]}e_{k_i} \le E_{[K]} \le \sum\nolimits_{i=1}^{n} d_{k_i[K]}\overline{T}_{k_i}$$

Define:

$$\omega_{k_i} = d_{k_j[K]}\overline{T}_{k_i} - d_{k_i[K]}e_{k_i} + \sum\nolimits_{j=1}^{n} d_{k_j[K]}\mathrm{T}_{k_jk_i} - d_{k_j[K]}\sum\nolimits_{j=1}^{n}\mathrm{T}_{k_ik_j}$$

We know:

$$\sum_{i=1}^{n} \omega_{k_i} \geq 0$$

To help the demonstration, the set K is divided into three subset K^+, K^- and K^0, where K^+ is the set of firms which have positive ω, K^- is the set of firms which have negative ω; finally, K^0 is the set of firms which have $\omega = 0$.

(i) If $K^- = \phi$,that is, if all firms have nonnegative ω, then, it is easy to verify that there exists a null matrix $\{\mathrm{T}_{k_j k_i} = 0\}$ s.t. (E-1), (E-2) and (E-3) are satisfied. $\Rightarrow$ $(e_{k_1} e_{k_2} \ldots\ldots e_{k_n}) \in \Omega_E$

(ii) $K^- \neq \phi$, that is, if not all firms have nonnegative ω, let S^+ define the sum of all positive ω_{k_i}, that is: $S^+ = \sum_{i=1}^{n} \max\{\omega_{k_i}, 0\}$. Then there exists a nonnegative matrix $\{\mathrm{T}_{k_j k_i}\}$ with

$\mathrm{T}_{k_j^+ k_i^-} = \dfrac{\omega_{k_i^-} \cdot \omega_{k_j^+} / d_{k_j^+[K]}}{S^+} > 0$ for all $k_i^- \in K^-$, $k_i^+ \in K^+$; and all other elements are equal to zero. I claim that with $\{\mathrm{T}_{k_j k_i} = 0\}$, and constraints (E-1), (E-2) and (E-3) are satisfied and so are

$(e_{k_1} e_{k_2} \ldots. e_{k_n}) \in \Omega_E$

Now verify the claim:

For $k_i^0 \in K^0$ constraints (E-1), (E-2) and (E-3) are trivially satisfied.

For $k_j^+ \in K^+$

$$-\sum\nolimits_{j=1}^{n} \frac{d_{k_j[K]}}{d_{k_i[K]}} \mathrm{T}_{k_j k_i} + \sum\nolimits_{j=1}^{n} \mathrm{T}_{k_i k_j} = \sum_{K^-} \mathrm{T}_{k_j^+ k_i^-}$$

$$= \frac{(\omega_{k_j^+} / d_{k_j^+[K]}) \sum_{K^-} \omega_{k_i^-}}{S^+} = \omega_{k_j^+} / d_{k_j^+[K]}$$

Therefore, constraints (A-5), (A--6) and (A-7) are satisfied.

For $k_i^- \in K^-$

$$-\sum_{j=1}^{n} d_{k_j[K]} \mathrm{T}_{k_j k_i} + d_{k_i[K]} \sum_{j=1}^{n} \mathrm{T}_{k_i k_j} = \sum_{K^+} d_{k_j^+[K]} \mathrm{T}_{k_j^+ k_i^-}$$

$$= \omega_{k_i^-} \frac{\sum_{K^+} \omega_{k_j^+}}{S^+} = \omega_{k_i^-}$$

Therefore, constraints (E-1), (E-2) and (E-3) are satisfied.
Combining (i) and (ii), we know

$$(e_{k_1} e_{k_2} \ldots. e_{k_n}) \in \Omega_B \Rightarrow (e_{k_1} e_{k_2} \ldots.. e_{k_n}) \in \Omega_E$$

Since we have already shown

$$(e_{k_1} e_{k_2} \ldots.. e_{k_n}) \in \Omega_E \Rightarrow (e_{k_1} e_{k_2} \ldots.. e_{k_n}) \in \Omega_B$$

Therefore, we have shown that: $\Omega_B = \Omega_E$
Since the two minimization problems have the same objective function over the same choice set, I claim that the result of problem (B) must be the result of problem (E) and vice versa. This completes the proof that Intra-M.A. trading constraints support the cost-effective allocation of allowances subject to the environmental standard at the M.A. endpoint. QED

Appendix 2:

The corresponding Kuhn-Tucker equation for one branch of Problem C (given a set of upgrade choices) is:

$K(e_i, \mathrm{T}_{ki}, \lambda_i, \alpha_i, \beta_i) =$

$$Z + \sum_{i=1}^{n} \lambda_i \left(e_i - \sum_{k=1}^{n} t_{ki} \mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} - \overline{T}_i\right) + \sum_{i=1}^{n} \alpha_i (e_i - e_0) - \sum_{i=1}^{n} \beta_i \left(e_i - \overline{\phi_i(x_i))}\right.$$

By solving for the Kuhn-Tucker conditions (written in type II K-T representation),

$\partial K / \partial e_i = Z_i' + \lambda_i + \alpha_i - \beta_i = 0$; ($i = 1, \ldots, n$)

$\partial K / \partial \mathrm{T}_{ki} = -t_{ki} \lambda_i + \lambda_k \leq 0$ ($k = 1, \ldots, n$; $i = 1, \ldots, n$)

$\mathrm{T}_{ki} \cdot (-t_{ki} \lambda_i + \lambda_k) = 0$ ($k = 1, \ldots n$; $i = 1, \ldots, n$)

$\partial K / \partial \lambda_i = e_i - \sum_{k=1}^{n} t_{ki} \mathrm{T}_{ki} + \sum_{k=i}^{n} \mathrm{T}_{ik} - \overline{T}_i \leq 0$ ($i = 1, \ldots, n$)

$\lambda_i \cdot \left(e_i - \sum_{k=1}^{n} t_{ki} \mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} - \overline{T}_i\right) = 0$ ($i = 1, \ldots, n$)

$\partial K / \partial \alpha_i = e_i - e_0 \leq 0$ ($i = 1, \ldots, n$)

$\alpha_i \cdot (e_i - e_0) = 0$ (k = 1,...n; i =1,…,n)

$\partial K / \partial \beta_i = \overline{\phi_i(x_i)} - e_i \leq 0$ (i = 1,…,n)

$\beta_i \cdot (\overline{\phi_i(x_i)} - e_i) = 0$ (k = 1,...n; i =1,…,n)

Suppose that the cost functions are strongly monotonically decreasing with final effluent (e_i). It must be the case that every firm utilizes all of its tradable permits so the trading equation is binding (i.e. $e_i - \sum_{k=1}^{n} t_{ki}\mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} = \overline{T}_i$). Then, each firm at an interior solution (i.e. $\alpha_i = \beta_i = 0$) has a positive shadow price λ_i. Hung and Shaw show that these shadow prices are the prices of the permits at the respective points. Moreover, when trade takes place between k and i (e.g. T_{ki} is strictly positive), the following equality results: $t_{ki} == \frac{d_{k[i]}}{d_{i[i]}} = \frac{\lambda_k}{\lambda_i}$ which states that the ratio of shadow prices (as well as the ratio of prices of permits) between k and i, is just equal to the transfer coefficient between these two plants at the interior. In the interior, the complementary slackness conditions ensure that multipliers α_i, β_i are all equal to zero, and hence, the shadow price of a unit of effluent at site i, is equivalent to the marginal abatement cost at site i. (i.e. $MC_i = -Z_i' = \lambda_i + \alpha_i - \beta_i = \lambda_i$).

There are two corner situations that would make the permit price deviate from the marginal abatement cost: If the final effluent of plant i is bounded by the initial untreated effluent level (i.e. $e_i - e_0 = 0$), multipliers α_i would be nonnegative. Then $MC_i = -Z_i' = \lambda_i + \alpha_i \geq \lambda_i$, showing that the permit price at firm i could be less than its marginal cost. On the other hand, if the final effluent of plant i is bounded by its physical removal capacity (i.e. $\overline{\phi_i(x_i)} - e_i = 0$), multipliers β_i would be nonnegative. Then $MC_i = -Z_i' = \lambda_i - \beta_i \leq \lambda_i$, showing that the permit price at i could be higher than its marginal abatement cost.

Endnotes:

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[i] The limited trading in water quality markets has been attributed to a number of institutional and program design factors, including: the lack of regulatory coverage (Faeth, 2006; Stephenson and Shabman, 2011); the lack of a binding cap on emissions (Selman et al., 2009); the limited numbers of trading opportunities (Obrupta et al., 2008); the imposed market structures (Woodward and co-authors 2002a, b; 2003); and the high transactions costs associated with complex administrative requirements (Devlin and Grafton, 1998; O'Hara et al., 2012). From a behavioral perspective, managers of individual water treatment plants may choose to over-comply and not trade in response to local demographic pressures (Earnhart 2004a, b); to account for a margin of safety or to otherwise minimize regulatory risk (Bandyopadhyay and Horowitz 2006; Selman et al., 2009); or to protect opportunities for future growth (Hamstead and BenDor, 2010).

[ii] In their article Hung and Shaw (2005) do not explicitly address the issue of multiple dischargers within a zone. For example, they note: " in general, the number of dischargers in a zone would be greater than or equal to one, although we assume that there is only one representative discharger in each zone." (p. 88). Elsewhere, the authors state: "A zone can be defined as an area in which the dispersion characteristics of effluents and the environmental effects of any unit of effluent are very close." (p. 86)

[iii] A recent paper by Konishi et al. (2013) raises concerns about the Hung and Shaw TRS approach in cases where the trading ratios are non-associative or there exists a critical zone at the confluence of upstream branches.

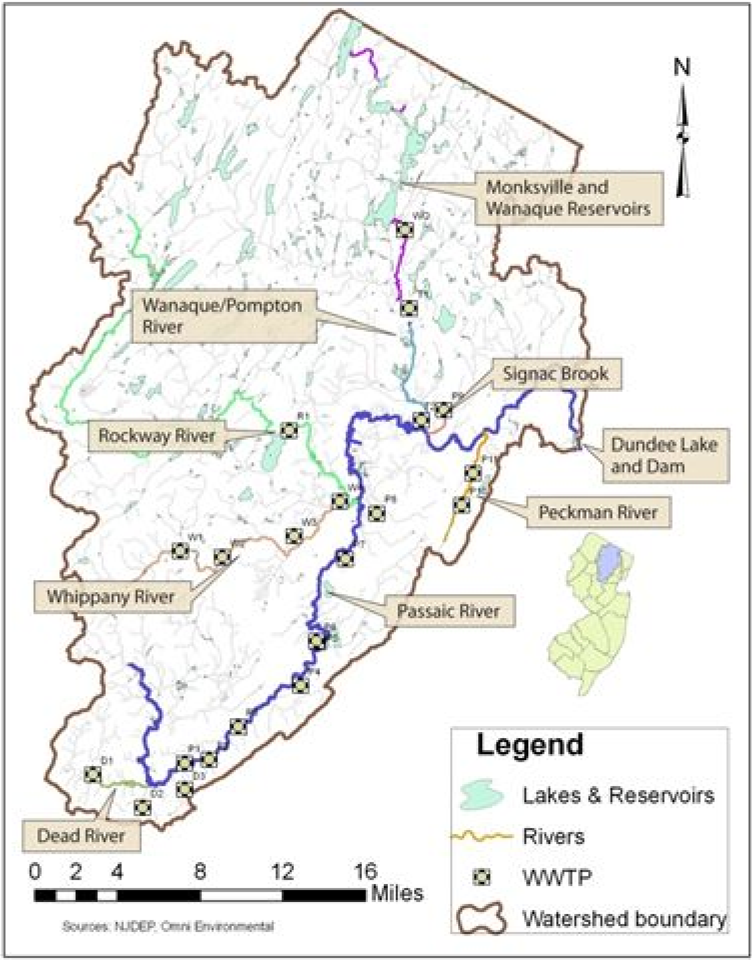
[iv] Two of the authors of the referenced article, Chris Obrupta and Josef Kardos, were collaborators with us on the US EPA-funded project "Development, Implementation, and Evaluation of a Water Quality Trading Program for the Non-Tidal Passaic River Watershed" underlying the present paper.

[v] Zhao (2013) provides a formal proof of this proposition.

[vi] The cost minimization problem C is formulated based on a mixed-integer nonlinear programming model. In this case study, the optimal allocation of allowances is solved on the **General Algebraic Modeling System** (**GAMS**) which provides an algorithm "DICOPT" designed for solving mixed-integer nonlinear programming problems that involve linear binary and linear and nonlinear continuous variables. The OM cost function being convex satisfies one of the necessary conditions for this algorithm to work effectively. One of the necessary conditions for DICOPT to work effectively is that the upper contour set of OM cost function must be pseudo-convex. The concavity of OM cost function guarantees the upper contour set is convex, which is a special case of pseudo-convex.

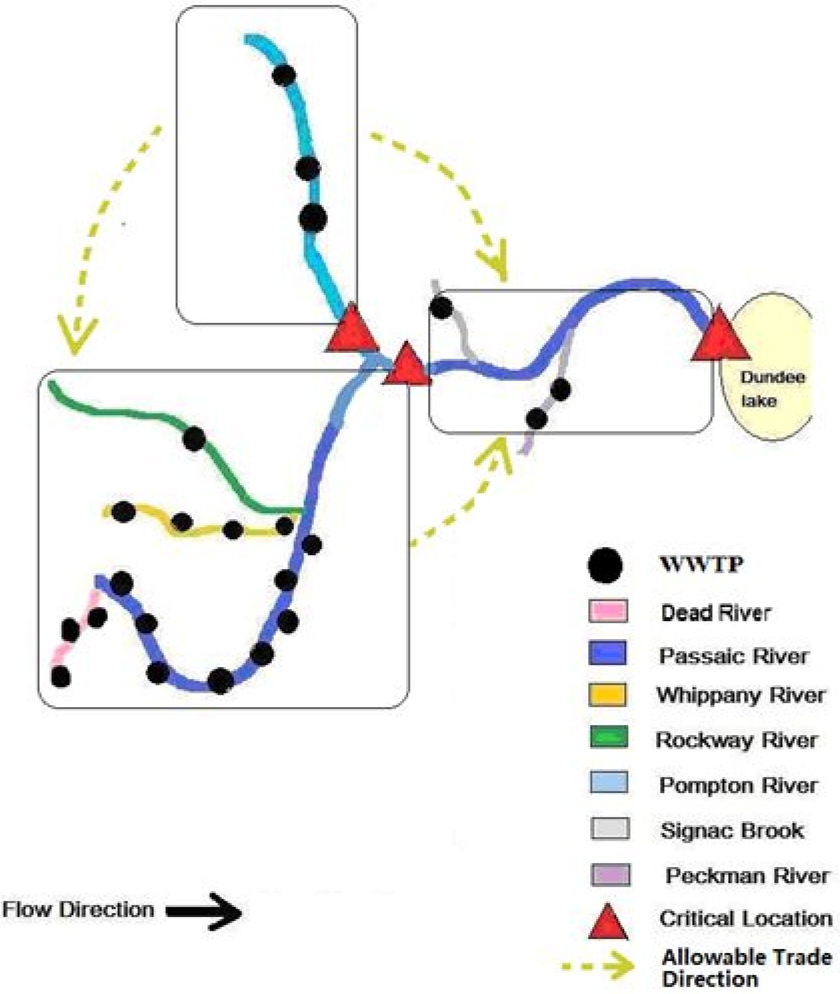
[vii] WQ and T1 cannot abate less because they are bounded by the non-degradation principle. However, they can sell their excess allowances through market trading.

Figure 1: The Upper Passaic River Basin.



Sources: NJDEP, Omni Environmental

Figure 2: Simplified Schematic of the Upper Passaic River Basin – Demarcation of Management Areas and Permissible Trade Flows



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