

**“Open Markets” v. “Structured Bilateral Trades”:  
Results of Economic Modeling of Point-to-Point Source Water Quality Trading  
in the Non-Tidal Passaic River Basin**

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## **“Open Markets” v. “Structured Bilateral Trades”: Results of Economic Modeling of Point-to-Point Source Water Quality Trading in the Upper Passaic Watershed**

Water quality trading has had mixed success in the United States. 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” (US EPA 2008, E-S 1). Moreover, 80 of these 100 trades have occurred in a single market, the Long Island Sound Nitrogen Credit Exchange program, which operates more like an exceedance tax-abatement subsidy than a market with endogenously determined prices. In the Long Island Sound program annual allowance prices are exogenously established by a Nitrogen Credit Exchange (NCE) which buys and sells credits at this price and absorbs imbalances between supply and demand: over the first six years of the program, annual purchases of credits by NCE ranged from a deficit of -\$3,087,018 to a surplus \$1,440,100 (Nitrogen Credit Advisory Board, 2008). For the more “typical” watershed trading programs without such a generous credit exchange to absorb imbalances between supply and demand, reallocation of abatement levels across firms by buying and selling pollution allowances or credits has been much more limited (see King and Kuch, 2003; Breetz et al. (no date); and US EPA, 2008 for discussions).

In this paper we argue that 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. Heeding the admonition made by Hoag and Hughes-Popp (1997), translating theory into practice may necessitate a reexamination of “the main principles associated with water pollution credit trading theory...to identify factors that influence program feasibility” (p. 253). If such efforts are undertaken, King (2005) maintains that, “the potential for [water quality] trading might be realized. If not [water quality] trading will probably end up in the overflowing dustbin of well-intentioned economic policies that attracted attention for a while but never delivered.” (p. 75)

We explore two 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. 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). MAs group 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 a MA bidirectional trades are allowed. Trading between MAs is consistent with the TRS wherein only downstream sales of allowances are permitted.

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-source-to-point-source 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 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, 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, the US EPA (2003), 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. 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 and 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, 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.

### **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. 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. Under the TMDL, acceptable long term averages of total phosphorus emissions have been established at 0.40 mg/l for each of the 22 WWTPs. The primary objective is to meet water quality objectives at the two locations with the greatest vulnerability to phosphorus contamination. One of these potential hot spots occurs at the confluence of the Pompton and the Passaic, where, depending on demand, a water intake diverts water through a pumping station, to the Wanaque Reservoir, and subsequently to consumers in Newark, a major city outside the watershed. This fundamentally alters the hydrology of the watershed (Obrupta, Niazi and Kardos). The second potential hot spot is at Dundee Lake and Dam, where the water slows. The 0.40 mg/L TMDL concentration limits were established to meet state water quality requirements on an equitable basis, and any water quality trading program must meet these water quality objectives at the two endpoints.

### **Cost Minimization and Tradable Discharge Permit (TDP) Programs**

A general model to minimize the aggregate abatement costs to achieve a specified environmental standard  $E_j$  for  $j$  zones ( $j = 1, \dots, n$ ) can be specified as:

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

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

(3)  $e_i \in [0, e_i^0]$ ,

where  $C_i$  is abatement cost function at source  $i$ ,  $e_i^0$  is initial effluent at  $i$ ,  $e_i$  is effluent after treatment at  $i$ , and  $t_{ij}$  is a transfer coefficient from source  $i$  to source or receptor zone  $j$

that accounts for fate and transport. Defining  $e_i^j$  as the amount measured at site  $j$  after source  $i$  discharges  $e_i$ , transfer coefficients that reflect decay or attenuation of effluent between discharge and the receptor points are:

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

This coefficient is necessarily bounded between zero and one, where “zero” indicates that the  $i$ th source has no effect on the  $j$ th receptor (as in the case of being upstream) and “one” indicates that the unit of pollution from the  $i$ th source does not diminish in any way by the time it reaches the  $j$ th receptor. An intermediate coefficient of, say,  $t_{ij} = 0.5$  would indicate that one additional unit of pollution for source  $i$  results in one-half a unit of pollution at receptor  $j$ . For a region or watershed with  $I$  stationary sources of pollutants and  $J$  receptor points, the fate and transport of water emissions for the  $I$  sources can be specified by an  $I$  by  $J$  matrix of (linear) unit transfer coefficients (Montgomery, 1972):

$$(5) \quad \tau = \begin{bmatrix} & & & \cdot & & & \\ & & & \cdot & & & \\ & & & \cdot & & & \\ \cdot & \cdot & \cdot & t_{ij} & \cdot & \cdot & \cdot \\ & & & \cdot & & & \\ & & & \cdot & & & \\ & & & \cdot & & & \end{bmatrix}$$

Expressing this minimization problem as a Lagrangian Function and solving the Kuhn-Tucker conditions yields a spatially differentiated equimarginal condition for two emission sources ( $i$  and  $k$ ) relative to a single receptor ( $j$ ):

$$(6) \quad MC(e_i^j) = t_{ij} \frac{\partial C_i(e_i^o - e)}{\partial e_i} = t_{kj} \frac{\partial C_k(e_k^o - e)}{\partial e_k} = MC(e_k^j)$$

This equimarginal condition is depicted in Figure 1, where total abatement required is 400 units (the concentration level is converted to the equivalent weight accounting for the flow level of the firm) and two transfer adjusted marginal abatement costs are presented. Assume that WWTPs  $i$  and  $k$  are the only two sources of emissions in the watershed and  $j$  is the only receptor of concern. For simplicity, we further assume that two WWTPs are of similar size and have the same initial level of pollutant (400 units) measured at receptor  $j$ . Thus the same TMDLs allocations are assigned to each. In this case, the cost-effective equilibrium occurs where the effective emissions of sources  $i$  and  $k$  are reduced

by 300 units and 100 units respectively (300, 100). Following basic market principles and assuming zero transactions costs, the two WWTPs would trade to achieve this least cost outcome. As per Montgomery, any initial allocation of permits that meets the water quality objectives would also obtain the cost-effective abatement strategy.

More generally for a setting with multiple sources and receptors, the Kuhn-Tucker conditions for this model 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. If dischargers were charged similar emissions fees, the minimum cost solution would also obtain (Baumol and Oates, 1988).

Hung and Shaw achieve this cost minimization result with allowance trading under a TRS wherein the relative prices of emissions allowances are equated to the transfer coefficients. Because water flows downhill, upstream allowance allocations affect allocable emissions to downstream sources. Letting  $\bar{T}_j$  represent the aggregate tradable allowances in a zone,  $i$  and  $k$  indicate different sources, and  $T_{ki}$  ( $T_{ik}$ ) identify the number of allowances sold by  $i$  to  $k$  ( $k$  to  $i$ ) the trading constraint can be represented as:

$$(7) e_i = \bar{T}_i + \sum_{k=1}^{k<i} t_{ki} T_{ki} - \sum_{k>i}^n T_{ik} .$$

Thus allowable emissions are determined by the initial allocation or allowances, plus allowances purchased from upstream sources weighted by the relevant trading ratio, minus any allowances sold downstream. Equation 7 reflects the fact that while the seller always sells a unit allowance, the buyer receives rights to emit only a portion of a unit, equated to the trading ratio defined in Equation 4. Indexing the most upstream zone as 1 and the most downstream zone by  $n$ , the TRS model is specified as:

$$(8) \text{Minimize } Z = \sum_{i=1}^n C_i (e_i^0 - e_i), \text{ subject to:}$$

$$(9) e_i - \sum_{k=1}^{i-1} t_{ki} T_{ki} + \sum_{k>i}^n T_{ik} \leq \bar{T}_i \quad (i = 1, \dots, n)$$

$$(10) T_{ik}, T_{ki} \geq 0; \text{ and } e_i \in [0, e_i^0].$$

As with the previous cost minimization model, The Kuhn-Tucker conditions associated with Equations 8 through 10 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, 2006). Hung and Shaw

demonstrate that 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. As will be discussed below, this framework can be readily incorporated into a programming model.

### **Adapting the TRS Model to the Non-Tidal Passaic River Basin TMDL**

We extend the TRS model to more closely reflect the reality of phosphorus trading in the Non-Tidal Passaic River Basin. First, Hung and Shaw’s presentation equates sources with zones, adopting a one-discharger-one-zone principle. They note that this concept can be generalized to address the range of circumstances between the one-discharger-one-zone and the other extreme of only one zone within a basin. The typical conceptualization of a multi-zone system treats emissions from various sources within a zone as having equal effects on water quality (Tietenberg). Following this framework, the trading ratios between sources within a zone would be set to unity. To the extent that such ratios comport with the underlying hydrological model, firms can trade emissions in a TRS with no degradation relative to the initial TMDL allocation at all points in the watershed and obtain this result at least cost.

With respect to the Non-Tidal Passaic River Basin TMDL, a no-degradation requirement at all points in the watershed is overly restrictive. 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, shade cover and turbidity). Based on these modeling results, a Management Area approach has been adopted for the TMDL implementation: a Management Area (MA)

“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 MAs are identified in the 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 MA, 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) internal – upstream and downstream trades within a management area; 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 Passaic MA but not *vice versa*. As is discussed below, this management area approach can be accommodated in the Hung and Shaw TRS model by manipulating a matrix of trading ratios. The development of these MAs is fully detailed in Obrupta et al.

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 (“convex and twice differentiable), Tietenberg (“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  $j$ , 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 WWTP 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  $j$ 's effluent level of less than 90 units allows  $j$  to supply allowances to  $i$ . As such, firm  $j$  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 O&M and capital costs separately. However, the optimal abatement allocation should minimize the firms' total abatement cost, namely, the combination of both “continuous” variable cost (O&M costs) and the discrete capital investment cost. Given appropriate numerical assumptions, the savings from capital costs can more than offset the additional O&M 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 O&M costs relative to the equimarginal optimum.

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

O&M costs may be such that there is an interior solution corresponding to the aforementioned trading-ratio-adjusted equimarginal principle in Equation 6. 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.

### **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 O&M 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 2008). 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 for plants which currently do not remove any phosphorus, 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 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 O&M and capital costs from data on actual costs of 104 treatment plants located in the Chesapeake Bay watershed (NRTCTF 2002). 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 (Boisvert 1982; Vinod 1972) the following cost function was estimated using OLS:

$$(11) \ln OM = \ln 9.870 - \underset{(0.052)}{0.997} \ln C + \underset{(0.032)}{0.785} \ln F + \underset{(0.048)}{0.043} \ln C \ln F$$

where  $OM$  is the annual operation and maintenance costs;  $C$  is final phosphorus concentration, in mg/l;  $F$  is daily flow in million gallons per day; and the numbers in parentheses are estimated standard errors. As discussed in Sado and Sado, Boisvert and Poe (2009) 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:

$$(12) \ln CC = \ln 11.878 - \underset{(0.006)}{0.995} \ln C + \underset{(0.004)}{0.302} \ln F - \underset{(0.006)}{0.164} \ln C \ln F$$

where  $CC$  is capital investment cost and the numbers in parentheses are estimated standard errors. Again, the estimated parameters conform to *a priori* expectations

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 to reflect this difference in technology. These modifications, based on simulation analyses by the University of Georgia for eight designs of wastewater treatment facilities (Jiang, *et al.* 2005), shift the O&M cost function upward to reflect the generally higher cost of the biological removal process; the cost elasticity with respect to concentration declines (see Sado and Sado, Boisvert and Poe).

### **The Phosphorus Emissions Trading Model for the Non-Tidal Passaic River Basin**

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 2008). For the three WWTPs that already exceed this standard, their TMDL allocations correspond to their current levels of treatment. After transforming the estimated functions presented in Equations 11 and 12 to convert concentrations in mg/l into pounds of phosphorus, the model is:

$$(13) \text{ Min } Z = \sum_i OM_i(e_i) = \sum_i \exp(\phi_i) * e_i^{y_i}, i = 1, \dots, n; \text{ subject to:}$$

$$(14) e_i - \sum_{k=1}^{k<i} t_{ki} T_{ki} + \sum_{k>i}^n T_{ik} \leq \bar{T}_i, i = 1, \dots, n;$$

$$(15) e_i \leq e_i^0;$$

$$(16) e_i, T_{ki}, T_{ik} \geq 0.;$$

The coefficients (Table 7) for these transformed cost functions,  $OM_i(e_i)$ , also embody the differences in daily flows across the WWTPs, and O&M costs decline as the pounds of phosphorus emissions increase and flow decreases. Thus, if the constraint on phosphorus emissions embodied in Equation 14 were not in the model, the minimum cost solution would be zero, and no phosphorus would be removed. With this constraint, costs are minimized, subject to emissions by each plant being less than the TMDL, plus the trade-ratio weighted number of allowances bought, less the number of allowances sold. The model is formulated empirically and solved within GAMS (Brooke, *et al.* 1988).

The starting point for the empirical analysis also assumes current treatment capacities. While Equation 12 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  $\geq 1.0\text{mg/l}$ ; b)  $1\text{mg/l} >$  target concentration  $\geq 0.5\text{mg/l}$ ; c)  $0.5\text{mg/l} >$  target concentration  $\geq 0.25\text{mg/l}$ , d)  $0.2 \text{ mg/l} >$  target concentration  $\geq 0.10\text{mg/l}$ , and e)  $0.10\text{mg/l} >$  target concentration (e.g. Figure 4). 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.

## **Implementation and Empirical Results**

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 O&M 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. This provides the baseline of comparison for evaluating subsequent trading regimes.

### *Trading Case 1: Hung and Shaw TRS System, O&M Cost Only*

This scenario corresponds to the Hung and Shaw TRS: the only trades allowed are those with non-zero trading ratios as defined in Equation 4 and the corresponding  $\tau$  matrix 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, adapting Equation 6, trades will only occur 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 TMDL standard.

*Trading Case 2: Three Management Areas, Two Endpoints, O&M Cost Only*

The modeling of the three management areas, two endpoints approach requires a restructuring of the matrix  $\tau$ . The  $\tau$  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  $\tau^{MA}$ . 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 through 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,  $\tau$  once again serves as the relevant trading ratio. In contrast with Case 1 trades are based on total cost savings. Conceptually, such savings could be modeled two ways. One option would be to employ 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. An alternative is to use a sequential decision heuristic that restricts capital investments for individual firms based on flow level, location, and concentration levels relative to a discrete, capital-cost threshold. We have pursued both approaches, and they provide the exact same trade patterns and costs savings. Here we describe the method of implementing the sequential decision heuristic.

Our starting point for this analysis is Case 1. Recall, that in our previous analysis WWTPs were assumed to invest in enough capacity to meet their specified 0.40 mg/l concentration (i.e. they incur capital costs associated with the 0.50 mg/l to 0.25 mg/l capital cost step). The exception is WQ, which already is treating to 0.16 mg/l. We allow O&M marginal-cost trading from this initial allocation. One outcome is that a few selected firms purchase enough allowances to be able to emit more than 0.50 mg/l. If, *a priori*, these firms could be assured access to permits, monies could have been saved by not requiring these WWTPs to upgrade to the 0.50 mg/l to 0.25 mg/l capital step. In our modeling framework this was achieved by adding the following additional restriction to the model described by Equations 13-16.

$$(17) e_i \leq e_i(0.50 \text{ mg/l})$$

In the above equation  $e_i(0.50 \text{ mg/l})$  is the emissions level for firm  $i$  associated with achieving a 0.50 mg/l concentration. Given these restrictions, the capital costs savings associated with not upgrading to the 0.50 mg/l to 0.25 mg/l treatment range are imputed.

Moving beyond these selected firms, we sequentially restrict the concentration levels of other WWTPs based on the level of concentration emerging from O&M trading, the WWTP's flow level, and the location of the WWTP relative to larger (presumably lower cost) trading partners. WWTPs with Case1-O&M-based concentrations nearing 0.50 mg/l, WWTPs more distant from a relevant endpoint, and smaller WWTPs were selected for sequentially implementing the Equation 17 restrictions. The second row of Table 7 indicates the order that the restrictions were placed. For example, W3 was the first WWTP for which emissions were restricted. In all, nine concentration restrictions were imposed, with 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 using the same methods used in Case 3. Trading patterns are presented in Table 8 and the savings associated with the sequential restrictions on concentration levels depicted in Figure 5. 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.

### **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 of how to organize a cost-effective market exchange and further narrow our attention to the previously described typical watershed: one 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 of 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.

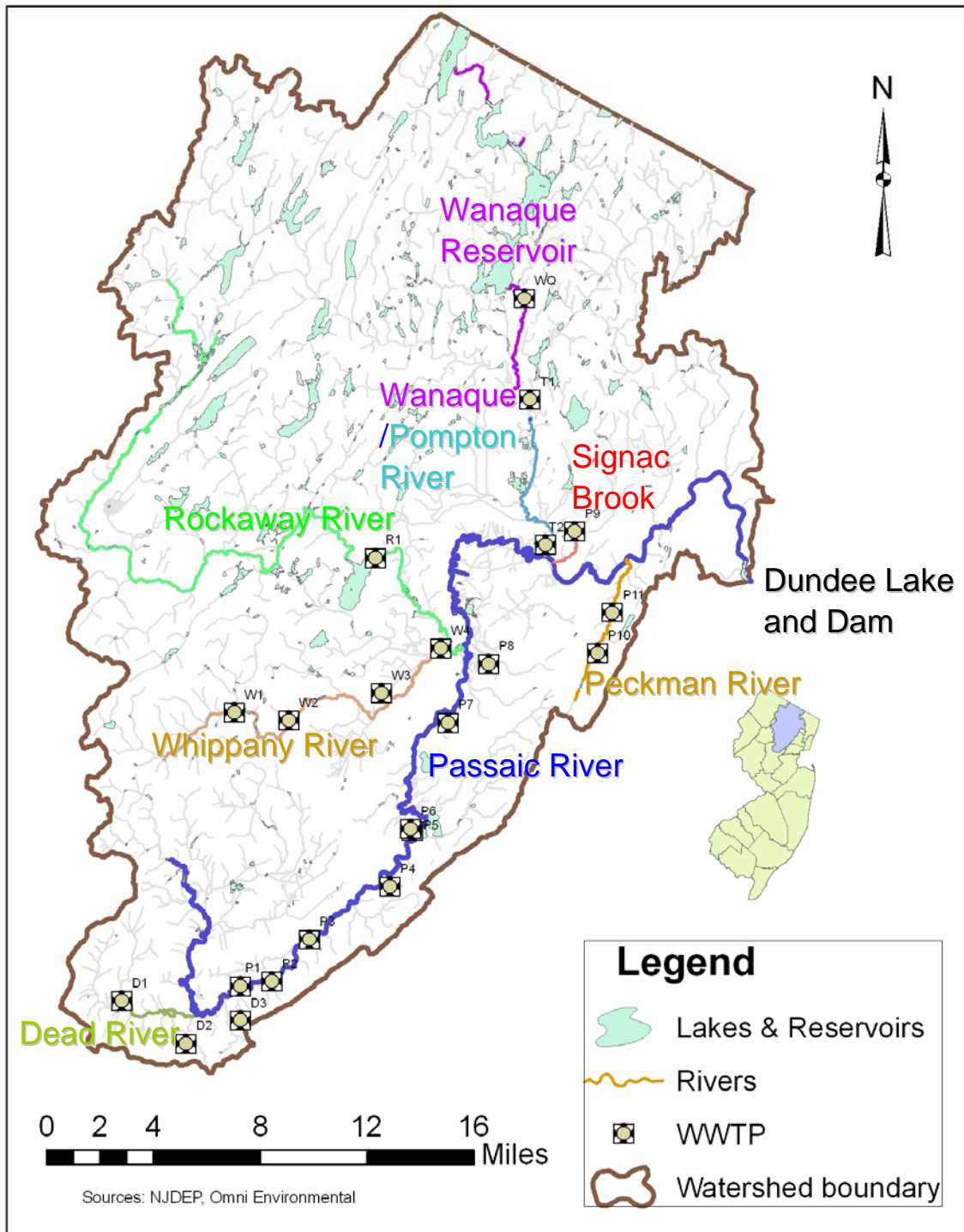
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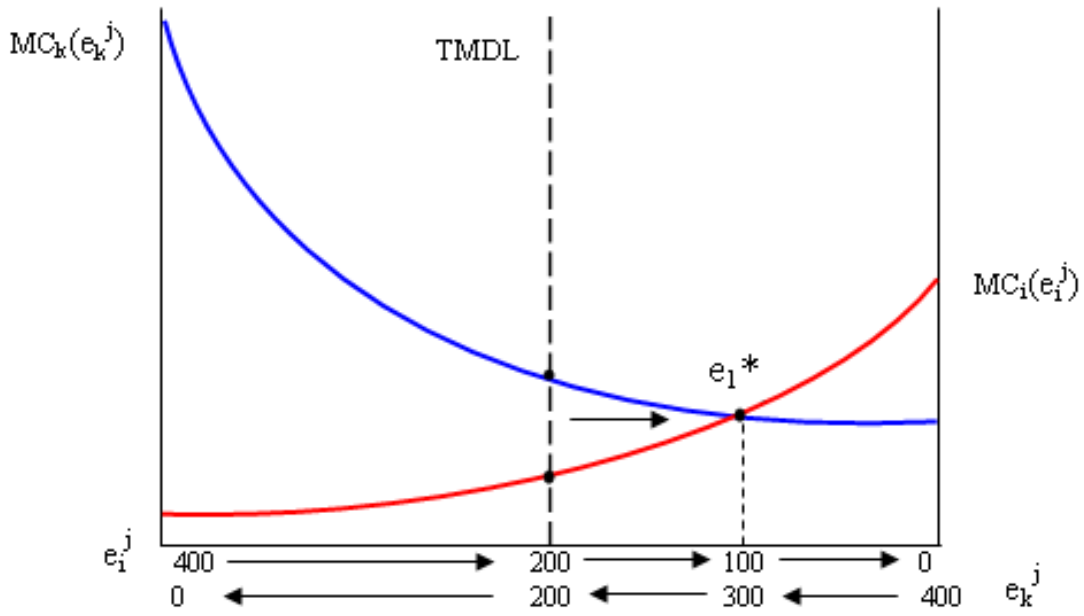
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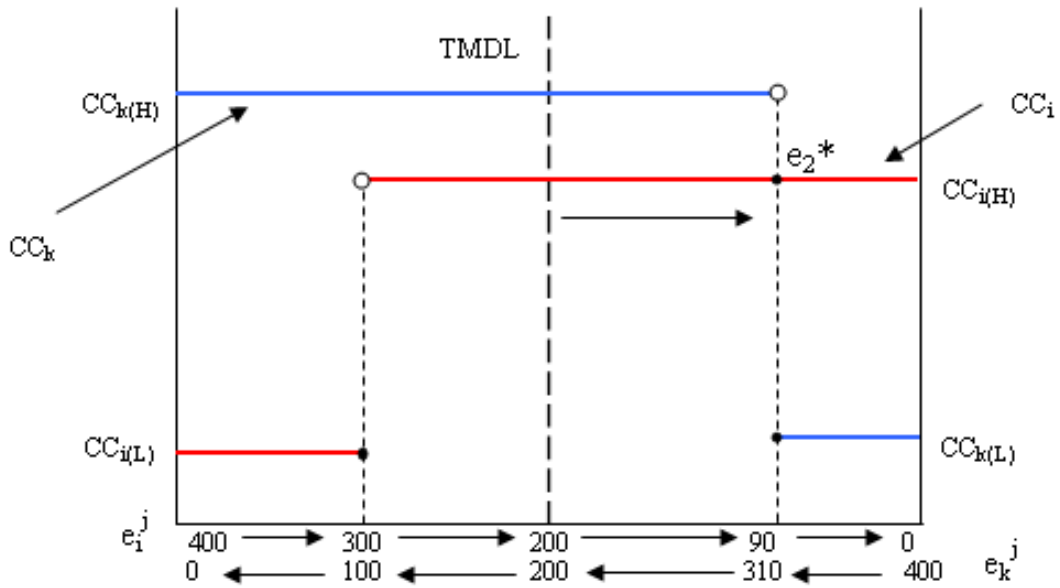
Map 1: Upper Passaic River Basin and WWTPs.



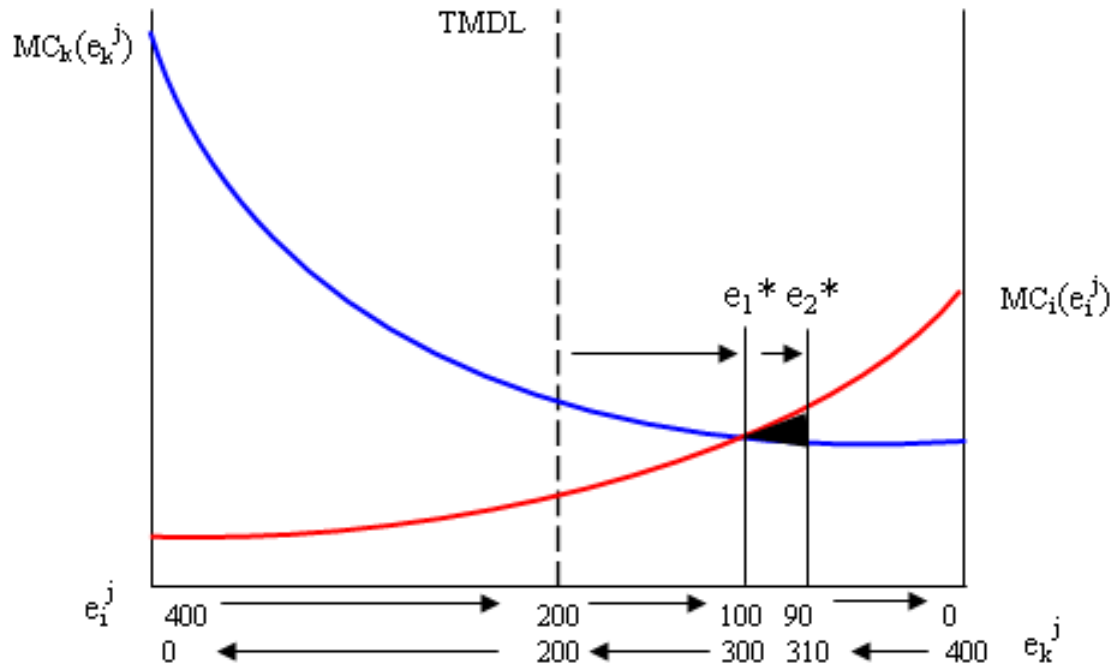
**Figure 1. Simple Geometry of Marginal Cost Trading**



**Figure 2. Simple Geometry of Fixed Costs Trading**



**Figure 2. Simple Geometry of Total Cost Trading**



**Figure 4. Example of Step Capital Cost Function for Largest Plant**

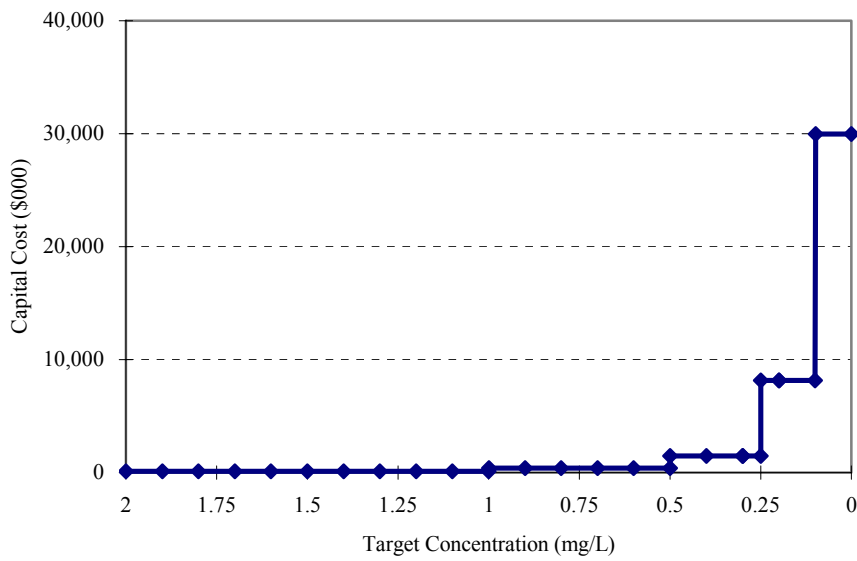
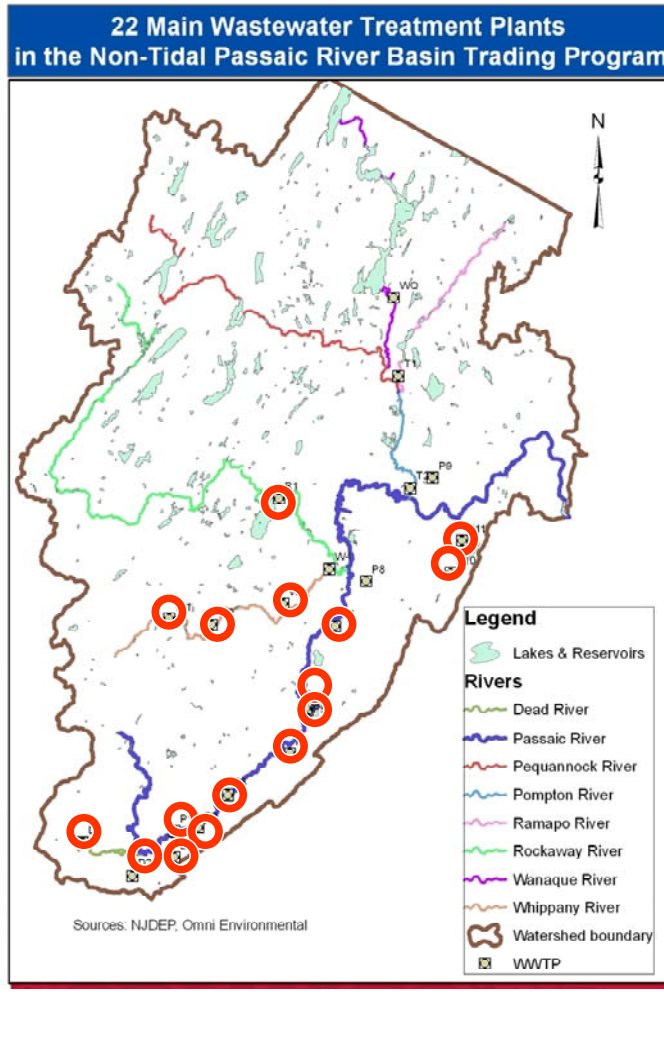




Figure 5: Example of Sequential Savings



WWTP	Restriction	% Total Cost Saving
O&M Trading		1.33
W1	> 0.50 mg/L	4.33
P7	> 0.50 mg/L	5.60
P1	> 0.50 mg/L	6.48
P6	> 0.50 mg/L	7.31
W3	> 0.50 mg/L	8.51
D1	> 0.50 mg/L	9.62
W2	> 0.50 mg/L	11.39
P3	> 0.50 mg/L	12.43
P5	> 0.50 mg/L	13.02
P2	> 0.50 mg/L	13.55
R1	> 0.50 mg/L	14.93
P4	> 0.50 mg/L	15.24
D2	> 0.50 mg/L	15.58
D3	> 0.50 mg/L	16.06
P11	> 0.50 mg/L	17.04
P10	> 0.50 mg/L	18.26

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

Map Code for WWTP	River	Phosphorus			
		Flow (MGD)	Load (lbs/Y)	Concentration (mg/l)	TMDL 0.4mg/l (lbs/year) <sup>#</sup>
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: <sup>#</sup>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	$\phi$	$\psi$	WWTP	$\phi$	$\psi$
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 ( $\tau$ ) 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 ( $\tau^{MA}$ ) 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 $e_i \leq e_i(0.50 \text{ mg/l})$		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 7: 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 $e_i \leq e_i(0.50 \text{ mg/l})$	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.

