**Potential Cost Savings from Discharge Permit Trading to meet TMDLs for Phosphorus in the Passaic River Watershed**

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# Potential Cost Savings from Discharge Permit Trading to meet TMDLs for Phosphorus in the Passaic River Watershed

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## Abstract

We use the non-tidal Passaic River Watershed as a case study to investigate the size of potential cost savings associated with allowing phosphorus emissions trading amongst Waste Water Treatment Plants (WWTP) to achieve a significant reduction in ambient phosphorus levels. To measure the cost saving, we specify a trading-ratio system similar to that proposed recently by Hung and Shaw (*JEEM*, 2005) that minimizes the abatement cost of meeting environmental standards. Because there are relatively few potential traders and abatement costs are relatively homogeneous across firms, the cost savings to the 22 municipal waste water treatment plants relative to the base case will be on the order of 7%.

We believe that these results fail to support efforts to establish a permit exchange market structure in the Passaic Watershed such as the one celebrated with the success of the U.S. acid rain trading program. Rather, our results suggest quite a different strategy for water quality trading in small watersheds such as the Passaic, where there are relatively few potential traders and abatement costs are relatively homogeneous across firms. In these situations, trading programs should instead be designed to identify the subset of firms that will gain substantially from trade in pollution permits and to nurture trade amongst these firms. Furthermore, because markets in such watersheds are relatively thin and investments in pollution abatement capacity are costly and lumpy and must be framed within five-year permit cycles, it is likely that these "structured bilateral" opportunities for trade will need to take the form of multiyear contracts.

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## Potential Cost Savings from Discharge Permit Trading to meet TMDLs for Phosphorus in the Passaic River Watershed

### Background and Objectives

Fostered by the U.S. EPA endorsement of market initiatives, the United States is increasingly turning to water quality trading programs as a way to meet objectives of the Clean Water Act (U.S. EPA, 1996; 2003). This enthusiasm may be warranted in some settings, but the extent of cost saving in a "typical" Total Maximum Daily Load (TMDL)-governed watershed associated with market trading remains an open, empirical question. We use the non-tidal Passaic River Watershed as a case study to investigate the size of potential cost savings associated with allowing phosphorus emissions trading amongst Waste Water Treatment Plants (WWTP) to achieve a significant reduction in ambient phosphorus levels.

To measure the cost saving, we specify a trading-ratio system similar to that proposed recently by Hung and Shaw (*JEEM*, 2005) that minimizes the abatement cost of meeting environmental standards. Under trading, each plant's emissions must be less than or equal to the TMDL plus any emissions permits purchased (weighted by the trading ratios that account for the downstream attenuation of phosphorus) minus the emissions permits sold to others. By solving the model for no trade and trading scenarios, we determine the reduction in annual variable costs due to trading. By estimating both variable and capital abatement cost functions from a consistent set of actual treatment cost data in the nearby Chesapeake Bay watershed and adjusting for cost-differentials across biological and chemical treatment technologies based on engineering data, we are able to calculate *ex post* the change in the level of investment, and therefore the change in the annual capital cost due to trading.

Below, a description of the Passaic watershed is followed by discussions of the trading ratio system and how capital costs are accommodated. We then discuss TMDLs, trading ratios, and the estimation of capital and operating costs for phosphorus abatement. A discussion of empirical results is followed by a discussion of policy implications.

**The Essential Features of the Non-tidal Passaic Watershed**

The non-tidal Passaic watershed is located primarily in northeastern New Jersey; a portion extends into New York State. Consisting of the Passaic River and its tributaries, the 803 square mile watershed drains 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) lives there.

From its source, the Passaic River initially flows south, then turns and flows in a north-easterly direction (Map 1), and then turns east and finally south before reaching

Newark Bay. The Great Brook and Black Brook Rivers flow into the Passaic River near its source. 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 Pompton River begins in the northern part of the watershed. The Ramapo and Pequannock Rivers flow into the Pompton north of where the Pompton flows into the Passaic. Beyond this confluence, Preakness Brook, Goffle Brook, and the Saddle and Third Rivers flow into the Passaic.

The two major water supply reservoirs (among 21 others), the Monksvill and the Wanaque, are located upstream on the Pompton River. Together, they supply over 200 MGD of water to more than two million people in northern New Jersey. The Wanaque Reservoir takes water from the natural tributary system, the Pompton Lake, and the Two Bridges Pumping Station, at the confluence of the Pompton and the Passaic Rivers.

The NJDEP has targeted the 22 largest wastewater treatment plants (WWTPs) in the non-tidal portions of the Passaic River watershed for limiting discharges of effluents (Map 2 and Table 1). In particular, discharges of phosphorus along the Passaic pose a serious threat to the quality of the Wanaque Reservoir (NJDWSC, 2002; Najarian Associates, 2005). Although water from the Passaic accounts for only 6% of the total inflow into the reservoir, it accounts for 35% of the phosphorus load. Currently, six of the major WWTPs are treating for phosphorus (Table 1).

**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,…,n) can be specified as:

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

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

(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 $j$.[1] Defining $e_i^j$ as the amount measured at site $j$ after site $i$ discharges $e_i$, transfer coefficients that reflect decay or attenuation of effluent between discharge and the receptor points are:

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

When $t_{ij} = 1$, one unit of pollutant from discharger $i$ results in one unit of pollutant at zone $j$: there is no decay or attenuation between the source and receptor sites. If $t_{ij} = 0$, then any emissions from source $i$ do not affect water quality in zone $j$. This zero-effect

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[1] Although it is not necessary, it is convenient (e.g. Hung and Shaw, 2005) for exposition to assume that there is a one-to-one correspondence between the zones and the WWTP point sources of phosphorus. Sado (2006) discusses the implications of there being more that one WWTP per zone. Further, the basic model can be extended to accommodate natural background levels.

condition may occur if there is complete decay or attenuation between sites. More typically, $t_{ij} = 0$ represents a situation wherein zone *j* is located upstream from source *i* or on a separate tributary or branch not affected by emissions from zone *i*.

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 (Sado, 2006). If dischargers were charged similar emissions fees, the minimum cost solution would also obtain (Baumol and Oates, 1988).

*The Trading Ratio System*

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

(5) $\overline{T}_j = E_j - \sum_{k=1}^{j-1} t_{kj} \overline{T}_k$

where $\overline{T}_j$ are the aggregate tradable permits in a zone *j*, and *k* (< *j* ) indicates a zone upstream to the zone *j*. For the most upstream zone, an authority will set $\overline{T}_j = E_j$ because there is no inflow of pollutants from other zones. For downstream zones, the contributions from upstream sources $\sum_{k=1}^{j-1} t_{kj} \overline{T}_k$ must be accounted for in the initial allocation of permits.[2] Hung and Shaw prove that the TRS avoids free-riders, and makes the environmental constraint binding for every zone so that the market equilibrium coincides with the cost-effective solution.

The effluent emitted in zone *i* must be below the standard, $\overline{T}_i$, unless *i* purchases permits from *k*. Then *i* can discharge more effluent. By assuming that transfer coefficients defined in equation (4) are equal to trading ratios at which trade takes place and that all the $\overline{T}_i$ are initially binding, the effluent at *i* is:

$$(6)\quad e_i = \overline{T}_i + \sum_{k=1}^{i-1} t_{ki} T_{ki}$$

where $T_{ki}$ is the number of permits sold by *k* to *i*. The actual emissions allowed for each permit transferred to site *i* from site *k* is reduced by an attenuation rate between the sites. The effective trades from a buyer's point of view are proportional to trading ratios, $t_{ki}$.

When site *i* sells permits (i.e., sells its right to discharge effluent), unless it also buys some permits from upstream, it must meet a more stringent standard. The final

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[2] Equation (5) can be modified if zone *j* is determined to be a "critical zone", such as $t_{(j-1)j}E_{j-1} > E_j$; "*j* is a critical zone" means that *j* will violate the environmental standard no matter what it does because of inflow of pollutants from upstream. In the instance of a critical zone, Hung and Shaw (2005) modify the zonal standard so that zone *j* becomes the binding constraint for its immediate upstream zone, and thus, the environmental capacities become $\overline{T}_j = 0$, and $\overline{T}_{j-1} = E_j / t_{(j-1)j} - \sum_{k=1}^{j-2} t_{kj} \overline{T}_k$.

effluent must be reduced by the unweighted number of permits sold downstream,

$\sum_{k>i}^{n} \mathrm{T}_{ik}$ , since reductions in emissions occur at point of sale. The trading constraint is:

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

The general trading model is now specified as:

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

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

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

The corresponding Lagrangian for this model is:

(11) L($e_i$, $\mathrm{T}_{ik}$, $\mathrm{T}_{ki}$, $\lambda_i$) = $Z + \sum_{i=1}^{n} \lambda_i (e_i - \sum_{k=1}^{i-1} t_{ki}\mathrm{T}_{ki} + \sum_{k>i}^{n} \mathrm{T}_{ik} - \overline{\mathrm{T}}_i)$

Since the number of permits bought by *i* from *k*, must equal number of permits sold by *k* to *i*, we substitute $\mathrm{T}_{ik}$ for $\mathrm{T}_{ki}$ in equation (11). The resulting Kuhn-Tucker conditions are:

(12) $\partial L / \partial e_i = -Z_i' + \lambda_i \geq 0$ ; ($i$ = 1,…,n)

(13) $e_i * (-Z_i' + \lambda_i) = 0$ ; ($i$ = 1,…,n)

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

(15) $\mathrm{T}_{ki} * [-t_{ki}\lambda_i + \lambda_k] = 0$ ($k$ = 1,...,$i$-1; $i > k$,…,n)

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

(17) $\lambda_i * (e_i - \sum_{k=1}^{i-1} t_{ki}\mathrm{T}_{ki} + \sum_{k>i}^{n} \mathrm{T}_{ik} - \overline{\mathrm{T}}_i) = 0$ ($i$ = 1,…,n)

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

From (12) and (13), we know that for $e_i > 0$, $Z'_i = \lambda_i$. From equations (14) and (15), $-\lambda_i t_{ki} + \lambda_k$ cannot be positive when $T_{ki}$ is positive. For an interior solution, $\lambda_i t_{ki} = \lambda_k$.

Also, we have:

(19) $Z_i' = \lambda_i = \dfrac{\lambda_k}{t_{ki}}$

Since $Z'_i = C'(e_i^0 - e_i)$, $\lambda_i$ is the shadow price of a unit of effluent at site *i*, and it is equivalent to the marginal abatement cost at site *i*. Hung and Shaw show that these shadow prices are the prices of the permits at the respective points. More generally:

(20) $t_{ki} * \lambda_i \leq \lambda_k$.

From the complementary slackness conditions, we know that when trade takes place between discharger *k* and discharger *i* (e.g. $T_{ik}$ and $T_{ki}$ are strictly positive), equation (20) must hold as an equality for $k < i$; *i* is downstream of *k*. If equation (20) holds as a strict inequality, there is no trade between zones *k* and *i*. Since the price at which discharger *k* is willing to sell is larger than the value of a permit to discharger *i*, the value of the permit is the price at *i*, "discounted" by the trading ratio. Because trading ratios are always less than or equal to unity marginal costs from upstream, suppliers must be no greater than that for a downstream purchaser. The implication is that if there are no low-cost plants upstream, there will be no opportunities to trade.

*A Consideration of Capital Costs*

This TRS model minimizes only the annual variable costs of pollution abatement, as trades in a market setting are based on differences in marginal abatement costs across dischargers. However, most of the wastewater treatment plants must upgrade their facilities to remove phosphorus. The appropriate strategy to estimate long-run cost savings would be to incorporate integer variables into the model to minimize combined annual variable plus the annualized capital cost of the required upgrades. Since the variable cost functions in our case are non-linear, there is no way to solve such a model of this size that also includes a large number of integer variables.

As an alternative, we first solve the watershed programming model for the minimum annual O&M costs with no possibilities for permit trading. This requires each firm to treat to its TMDL-specified level $\overline{T}_i$. Second, we determine the associated level of capital investment needed for each firm to treat to the required level. This investment is a function of both the size of the plant and the required level of abatement. By annualizing these investment costs, we are able to determine *ex post* the combined O&M and annualized fixed cost of meeting the environmental standard. This forms a base case, and cost savings due to permit trading are measured relative to this base case.

For each trading scenario, we then solve the model to minimize the annual O&M

costs of abatement. Because permit trading allows some plants to avoid some portion of its abatement, the implicit level of investment may be lower. Alternatively, those plants that sell permits may require upgrades beyond what would be needed under the base case. These changes in investments, and the changes in annualized capital costs are determined *ex post* on the basis of optimal abatement levels under trading. While there is no guarantee that this procedure will yield the solution that minimizes long-run costs of abatement, it does provide important information about realistic changes in investment made possible by a trading program since these changes are all measured relative to the investment required in the absence of the trading program.

**The Data and the Empirical Specification**

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

*The Environmental Capacity and the TMDLs*

For the Passaic Watershed, effluent load capacities are defined in terms of the total maximum daily loads (TMDL's), which account for background and natural levels of pollutant, and the inflows from upstream sources are adjusted for transfer coefficients.

The corresponding allowable firm (or zonal) discharges are specified under each discharger's National or State Pollution Discharge Elimination System (NPDES) permits. These policy tools are consistent with Hung and Shaw's (2005) zonal load caps. The current total phosphorus (TP) effluent levels vary substantially among plants (Table 1). The average TP concentration is 2.33mg/L for plants which currently do not remove any phosphorus, well above the Phase I TMDLs implied by target effluent level is 0.2mg/L.

*The Trading Ratios*

The transfer coefficients or trading ratios (Table 2) 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 attenuations 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).

*Estimating the Costs of Phosphorus Abatement*

Since most WWTPs in the watershed currently have little or no capacity to remove phosphorus, we estimate consistent cost functions for both yearly operating costs and capital costs from data on actual costs of 104 treatment plants located in the

Chesapeake Bay watershed (NRTCTF, 2006). Given geographic proximity and other similarities between the Chesapeake Bay and Passaic watersheds, the data are nearly ideal for our purposes.

Estimating the Annual O&M Cost Functions. 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). We estimate:

(21) $\ln OM = \ln\alpha + \beta\ln C + \gamma\ln F + \delta\ln C\ln F + \ln u$

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 $\alpha$, $\beta$, $\gamma$, and $\delta$ are parameters to be estimated, and ln *u* is an error term assumed to be normally distributed. For this flexible cost function (Boisvert, 1982; Vinod, 1972), the elasticity of cost of phosphorus removal w.r.t. to one characteristic depends on the level of the other:

(22) $\partial\ln OM/\partial\ln C = \beta + \delta\ln F$ ;

(23) $\partial\ln OM/\partial\ln F = \gamma + \delta\ln C$ .

One would expect that $\beta < 0$, because as the final concentration (*C*) goes down, costs should rise. Similarly, it is expected that $\gamma > 0$, since the cost of achieving a specified environmental standard should be lower for larger plants. The regression corresponding to equation (21) explains about 88% of the variation in the logarithm of the cost of removing phosphorus (Table 3). Since the estimated value of $\beta$ is negative, while the estimated value of $\gamma$ is positive, the results conform to *a priori* expectations. The effect of the positive coefficient, $\delta$, on the cross product term on ln *OM* cost is negative at concentrations below 1mg/L (e.g. where ln $C < 0$). Thus, larger plants can treat to low levels of concentration more efficiently than smaller plants.

Estimating Capital Costs for Upgrading Facilities to Remove Phosphorus. Using a similar method, the capital investment cost function is specified as:

(24) $\ln CC = \ln \eta + \kappa \ln C + \varsigma \ln F + \omega \ln C \ln F + \ln v$

where *CC* is capital investment cost; ln $v$ is error term assumed to be normally distributed; and $\eta$, $\kappa$, $\varsigma$, and $\omega$ are parameters to be estimated. Similar to the annual O&M cost function, the expectation is that $\kappa < 0$, as targeting the lower final concentration (i.e. ln $C < 0$) requires greater investments, and $\varsigma > 0$, as a large plant needs more capital to retrofit its facility. Estimated parameters (Table 3) conform to these *a priori* expectations.

Costs of Alternative Technologies. 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 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 (Sado, 2006).

***The Phosphorus Emissions Trading Model for the Passaic Watershed***

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 limit (TMDL) on the amount each plant can discharge without trade. After transforming the functions in Table 3 to convert concentrations in mg/L into pounds of phosphorus, the model is:

(25) $Min\ Z = \sum_i OM_i(e_i) = \sum_i \exp(\phi_i) * e_i^{\psi_i}$ , $i$ = 1, ..., n ; subject to:

(26) $e_i - \sum_{k=1}^{i-1} t_{ki} \mathrm{T}_{ki} + \sum_{k>i}^{n} \mathrm{T}_{ik} \le TMDL_i$ , $i$ = 1, ..., n ;

(27) $e_i \le e_i^0$ ;

(28) $e_i, T_{ki}, T_{ik} \ge 0$ .;

The coefficients (Table 4) 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 equations (26) 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 permits bought, less the number of permits 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 (Sado, 2006). The estimated capital cost functions are continuous in both concentration and maximum flow, but plants would likely make investments to accommodate treating to one of a small number of final concentration levels. These upgrades would be "lumpy", and in the second step of the analysis in which investment levels, and annualized capital costs are determined, we allow for only five discrete concentrations: a) current level > target concentration ≥ 1.0mg/L; b) 1mg/L > target concentration ≥ 0.5mg/L; c) 0.5mg/L > target concentration ≥ 0.25mg/L, d) 0.2 mg/L > target concentration ≥ 0.10mg/L, and e) 0.10mg/L > target concentration (e.g. Figure 1).

**The Empirical Results**

The appropriate base situation against which the trading program is to be evaluated is where there is no trade allowed and each WWTP must treat to meet its own TMDL. Two alternative trading scenarios are developed, and each WWTP is allocated initial pollution rights equal to its TMDL:

- Scenario 1. There are 22 zones, one for each WWTP. Permit sales can occur only from upstream to downstream plants, at unity trading ratios.
- Scenario 2. There are 22 zones, one for each WWTP. Permit sales can occur only from upstream to downstream plants. Trading ratios between all plants that can trade are equal to the annual ratios (Table 2), being bounded between zero and one.

Scenario 1 is where potential cost saving would, all else equal, be a maximum, since there is no attenuation in the effluent as it moves downstream. Comparisons between Scenarios 1 and 2 isolate the effects of phosphorus attenuation throughout the watershed.

***The Base Case Results: Treatment Costs When no Trade is Allowed***

We assume phosphorus is removed by chemical treatment, except for the three plants that already use biological treatment. In treating to a 0.2mg/L concentration (e.g. Table 1), total annual costs of phosphorus removal are 9.4 million (Table 5). It is no surprise that annual capital costs account for 72% of total phosphorus removal costs, particularly since upgrades to the facilities take place in discrete amounts (Figure 1).

***The Trading Scenarios***

The cost savings due to trading for the two scenarios are also reported in Table 5. Because of the unit trading ratios, Scenario 1 places an upper bound on potential cost savings. Under these ideal conditions, the cost savings due to trading represent only 3% of the costs of phosphorus removal when no trade is allowed. Since Scenario 2 accounts for the phosphorus attenuation between upstream and downstream plants through the actual trading ratios, it is somewhat surprising that cost savings under this scenario are the same as for Scenario 1 (Table 5). This is primarily because there is very little attenuation of phosphorus throughout this watershed-- trading ratios are in the range of 1 - 0.98. In general, one cannot rely on the trading ratios being so close to unity. For this reason, the remainder of our discussion can focus on the Base Case and Scenario 2.

The total annual cost of removing phosphorus in a trading program under Scenario 2 is about \$8.7 million. This is a reduction of about 7% from the estimated \$9.4 million in annual costs of phosphorus removal in the base case, where no trades are allowed.

*The Sources of the Cost Savings*

The trading program under Scenario 2 leads to a reduction in the annual O&M costs by only 3%, while the annual capital costs are reduced by 9%. These cost savings are distributed only to several plants across the watershed. For six plants in the watershed, O&M cost savings are greater than 10% (P1, P2, P4, P6, P8, and T1), and for seven plants, their O&M costs rise by more than 10% (D1, D2, D3, P3, P7, W2, and W3).

These changes in O&M costs were possible in part because of adjustment in the new treatment levels. Thus, four plants (P1, P4, P8, and T1) were able to reduce the substantial amount of the capital costs to upgrade their facility by purchasing permits, more than offsetting any increase in O&M costs. Because of the assumed "lumpy" nature of upgrades to facilities, no plants needed to make investments beyond the level of the base case.

*Patterns of Permit Trading*

Under Scenario 2, there are 12 plants that sell permits, and 14 plants purchase them (Table 6). Nearly 3,800 permits are traded in the watershed, which represents over 6% of the total allowable emissions in the watershed. The average price of a permit is about $50 per pound of phosphorus, and the range in the prices is between $31.70 and $87.10. Also, all trades take place among adjacent plants in the watershed.

*Assessment of the Potential Market for Phosphorus Permits*

It is difficult to know exactly how to take the information generated above and make some assessment of the market potential, but certainly one needs to examine the size of the potential savings throughout the watershed, as well as the volume and value of permits traded. From an individual plant's perspective, the value of the permits traded relative to O&M costs also provides some perspective on the importance of the trading program relative to other costs or sources of revenue.

The cost savings from Scenario 2 relative to the base case with the 0.2mg/L environmental standard total about $666,000 or about 7% of total costs in the base case. Importantly, these costs savings are concentrated: with trading, four firms experience a cost savings exceeding 49% of their total base case costs, while the other 18 firms each save less than 6 percent of their total costs relative to the base case.

These savings are realized through a volume of trade of nearly 3,800 units. With an average price of nearly $50 per unit, the value of the trades total is about $189,000. As seen in Table 6, six plants spend more than $10,000 to purchase permits and the value of sales exceeds $10,000 for seven plants. Perhaps more notable from a market perspective is the importance of these transactions relative to the O&M costs of phosphorus abatement. Simply stated, the realized gains from trade have to exceed transactions costs for trade to be viable. While it is impossible to assess these transactions costs *a priori*, some insight may be gained by arbitrarily selecting a threshold transactions cost figure and examining if gains from trade are still possible. Using an arbitrary figure of 20% of the annual O&M costs of phosphorus abatement, there are five WWTPs in which the net positive trade position exceeds this threshold.(Figure 2), whereas, there are two plants in which the negative trade position (e.g. cost of permits purchased exceeds revenue from permit sales exceeds 20% of annual O&M costs of phosphorus abatement).

The relatively small overall percentage cost savings across the 22 WWTPs in the watershed juxtaposed against these substantial trading activities and gains for a subset of firms have important policy significance. Looking at the overall gains from trade, it seems unlikely that a vibrant, exchange-market trading program would emerge in this watershed. On this basis, it is possible to argue against investing in a marketable pollution trading program in the Upper Passaic Watershed. However, these small aggregate gains from trade are concentrated among a small group of firms. When combined, these results suggest that in watersheds such as the Upper Passaic River, it may be more effective to create a tradable permit program where efforts are directed to facilitate bilateral transactions amongst a few entities rather than pursue the establishment of an exchange market of the form typically envisioned for a pollution permit trading program. We develop the policy implications of this idea further in the following section.

**Summary and Policy Implications**

Efforts to extend the success of the U.S. acid rain program to other media have had mixed results (Tietenberg, 2006). With respect to water quality trading, there have been more than 70 trading programs established throughout the country since the implementation of the initial water quality trading program on the Fox River in

Wisconsin in the early 1980's (Breetz *et al.*, no date). Despite this substantial policy and financial investment, very few trades have actually occurred (King and Kuch, 2003; Faeth, 2006). The nitrogen trading program in Long Island Sound may be an exception; recent preliminary assessments indicate that substantial gains from trade can be obtained (Stacey, 2006).

Our research provides some insight into these divergent results. Using a trading ratio model that exploits the special characteristics of water pollution, we estimate the potential demand for effluent permits and document the magnitude of the potential cost savings associated with a phosphorus trading program in the Upper Passaic Watershed. The cost savings due to the trading program are calculated relative to a base case that minimizes the annual variable cost of meeting the environmental standard when each plant must limit emissions to its TMDL without the possibility of trading. The results of our analysis suggest that across the entire watershed, the cost savings to the 22 municipal waste water treatment plants relative to the base case will be on the order of 7%. These cost savings are concentrated, amongst several firms: four firms each save over 49% of their total costs relative to the base case.

We believe that these results fail to support efforts to establish a permit exchange market structure in the Passaic Watershed such as the one celebrated with the success of the U.S. acid rain trading program. Rather, our results suggest quite a different strategy for water quality trading in small watersheds such as the Passaic, where there are relatively few potential traders and abatement costs are relatively homogeneous across firms. In these situations, trading programs should instead be designed to identify the subset of firms that will gain substantially from trade in pollution permits and to nurture trade amongst these firms. Furthermore, because markets in such watersheds are relatively thin (e.g., only 22 possible participants) and investments in pollution abatement capacity are costly and lumpy and must be framed within five-year permit cycles, it is likely that these opportunities for trade will need to take the form of multiyear contracts. The negotiations involved in that needed to realize these opportunities for water quality trading in watersheds such as the Upper Passaic might well be referred to as "structured bilateral trades". If, as we suspect, many "typical" watersheds across the United States have similar characteristics to those of the Upper Passaic River Watershed, there may be widespread opportunities in which this "structured bilaterial" approach is an effective strategy to realize the potential benefits from watershed-based water quality trading.

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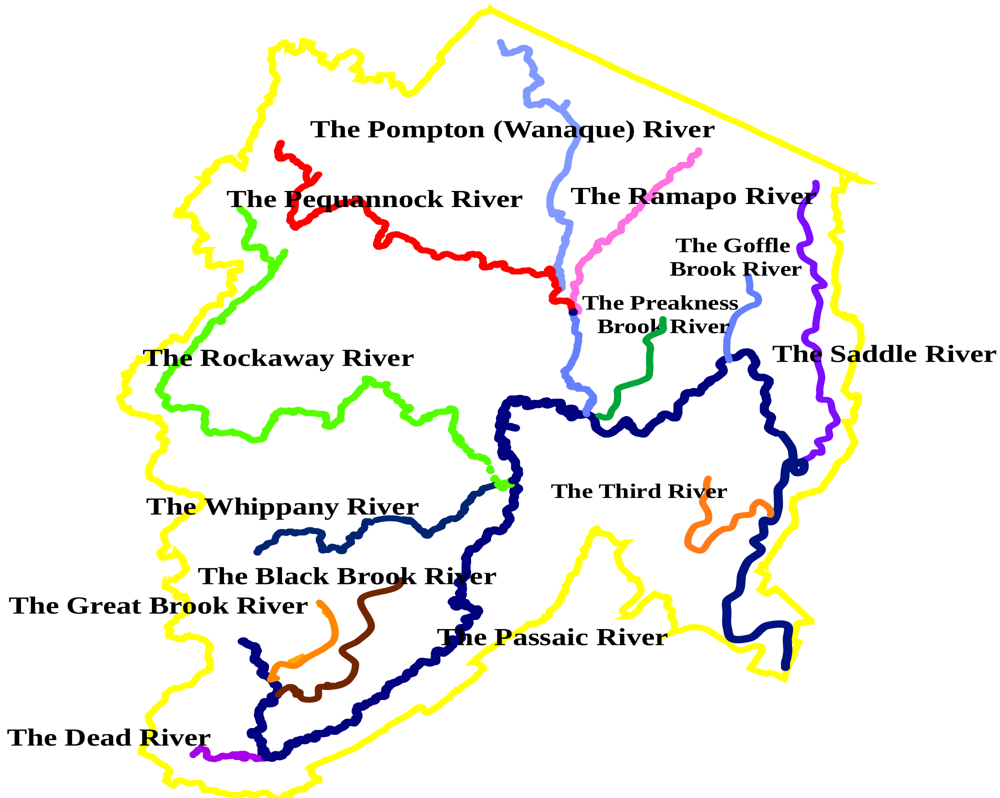
Map 1. Non-tidal Rivers in the Passaic Watershed



Map 2. Municipal Waste Water Treatment Plants in the Passaic Watershed

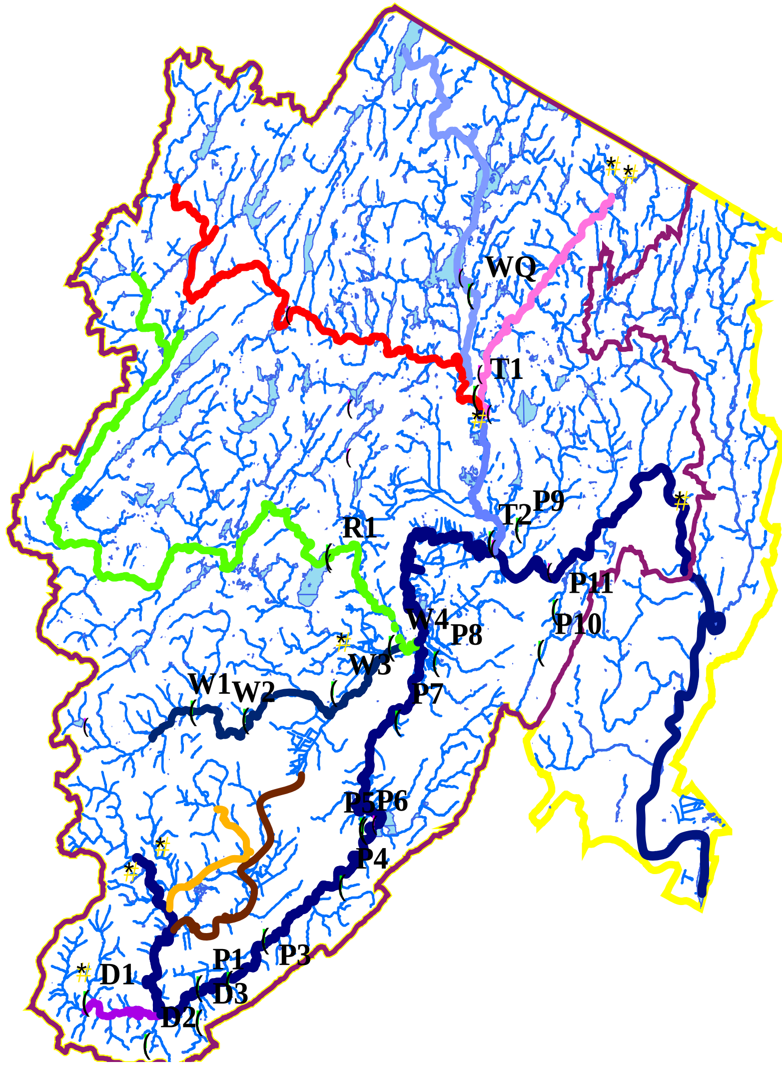


Table 1. Data for Municipal Waste Water Treatment Plants (WWTP)

| Map Code for WWTP | River | Flow (MGD) | Phosphorus Load (lbs/Y) | Phosphorus Concentration (mg/L) | Phosphorus TMDL 0.2mg/L (lbs/year)# |
|---|---|---|---|---|---|
| D1 | Dead | 1.78 | 16,971 | 3.13 | 1,522 |
| D2 | Dead | 0.15 | 845 | 1.85 | 231 |
| D3 | Dead | 0.31 | 1,804 | 1.91 | 487 |
| P1 | Passaic | 1.09 | 8,732 | 2.63 | 548 |
| P2 | Passaic | 0.38 | 1,933 | 1.67 | 286 |
| P3* | Passaic | 1.59 | 2,906 | 0.60 | 1,887 |
| P4 | Passaic | 0.12 | 559 | 1.53 | 94 |
| P5 | Passaic | 2.52 | 25,178 | 3.28 | 2,131 |
| P6 | Passaic | 0.92 | 4,148 | 1.48 | 852 |
| P7 | Passaic | 2.36 | 18,906 | 2.63 | 2,801 |
| P8 | Passaic | 4.13 | 20,380 | 1.62 | 2,740 |
| W1* | Whippany | 2.15 | 5,501 | 0.84 | 2,009 |
| W2* | Whippany | 3.17 | 5,407 | 0.56 | 3,836 |
| W3 | Whippany | 2.10 | 18,103 | 2.83 | 2,807 |
| W4 | Whippany | 12.64 | 114,737 | 2.98 | 9,741 |
| R1* | Rockaway | 8.32 | 37,001 | 1.46 | 7,306 |
| WQ* | Wanaque | 1.07 | 521 | 0.16 | 761 |
| T1* | Pompton | 0.98 | 955 | 0.32 | 731 |
| T2 | Pompton | 5.90 | 38,460 | 2.14 | 6,088 |
| P9 | Preakness Brook | 8.43 | 58,290 | 2.27 | 8,224 |
| P10 | Passaic | 2.53 | 23,659 | 3.07 | 3,046 |
| P11 | Passaic | 1.31 | 8,978 | 2.25 | 1,523 |

* Plants that currently have some capacity to remove phosphorus.

#This is the Phase I TMDL released on July 19, 2005.

Table 2. Annual Trading Ratios, no Diversion

| | 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 | 1 | 1 | 1 | 0.99 | 0.99 | 0.98 | 0.98 | 0.98 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D2 | 0 | 1 | 1 | 1 | 1 | 1 | 0.99 | 0.99 | 0.98 | 0.98 | 0.98 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D3 | 0 | 0 | 1 | 1 | 1 | 1 | 0.99 | 0.99 | 0.98 | 0.98 | 0.98 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0.99 | 0.99 | 0.99 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P2 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0.99 | 0.99 | 0.99 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0.99 | 0.99 | 0.99 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P4 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0.99 | 0.99 | 0.99 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| W1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| W2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| W3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| R1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| W4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| WQ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| T1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| T2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| P9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| P10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| P11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

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

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

| | O&M Costs | | | | |
|---|---|---|---|---|---|
| | Coefficients | S.E. | t Stat | P-value | Alternative Technology* |
| Intercept | 9.870 | 0.052 | 190.467 | 0.000 | 9.468 |
| ln C | -0.997 | 0.032 | -31.312 | 0.000 | -1.175 |
| ln F | 0.785 | 0.048 | 16.394 | 0.000 | 0.785 |
| T | -- | -- | -- | -- | 0.604 |
| ln C*ln F | 0.043 | 0.029 | 1.448 | 0.149 | 0.043 |
| T*ln C | -- | -- | -- | -- | 0.268 |
| | | | | | |
| R Square | 0.879 | | | | |
| Adjusted R Square | 0.877 | | | | |
| Observations** | 208 | | | | |
| | Capital Costs | | | | |
| | Coefficients | S.E. | t Stat | P-value | Alternative Technology* |
| Intercept | 11.878 | 0.006 | 1915.770 | 0.000 | 11.050 |
| ln C | -0.995 | 0.004 | -261.313 | 0.000 | -1.424 |
| ln F | 0.302 | 0.006 | 52.668 | 0.000 | 0.195 |
| T | -- | -- | -- | -- | 1.242 |
| ln C*ln F | -0.164 | 0.004 | -46.484 | 0.000 | -0.164 |
| T*ln C | -- | -- | -- | -- | 0.644 |
| T*ln F | -- | -- | -- | -- | 0.160 |
| | | | | | |
| R Square | 0.998 | | | | |
| Adjusted R Square | 0.998 | | | | |
| Observations** | 208 | | | | |

* These coefficients are determined from the analysis in Appendix A of Sado (2006).

**There are 208 observations because there were cost data for two levels of concentration, C, for each of the plants, and the data were stacked for the regression.

Table 4. The Parameters for the Transformed O&M Cost Functions for the 22 Plants

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

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

**Figure 1. Example of Step Capital Cost Function for Largest Plant**

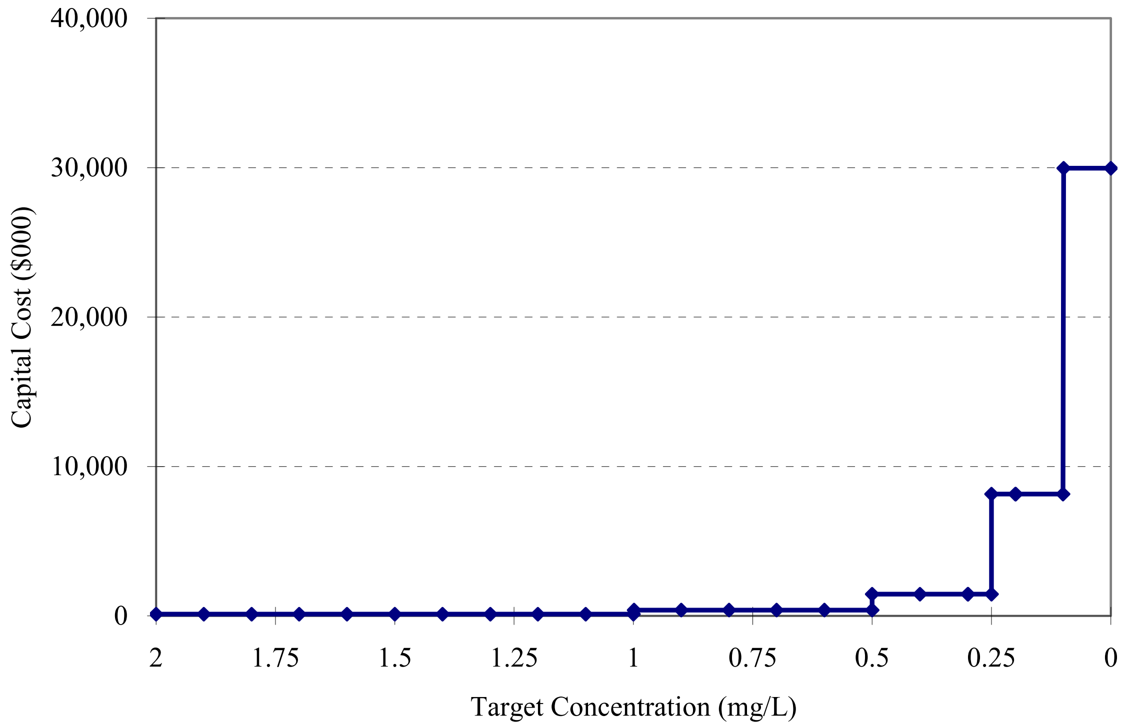


Table 5. Costs of Phosphorus Removal for Scenarios: TMDL 0.2mg/L

| | Base Case | | | | Scenarios 1 and 2 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Annual Cost | | | | Annual Cost | | | | | | |
| WWTP | O&M | Capital* | Total | | O&M | Capital* | TR** | Total | Change in Cost*** | | |
| | | | Amount | | | | | | Total | O&M | Capital |
| | --------1,000 Dollars-------- | | | % Capital | --------1,000 Dollars-------- | | | | ---------%--------- | | |
| D1 | 90 | 272 | 362 | 75 | 103 | 272 | 14 | 361 | 0 | 14 | 0 |
| D2 | 7 | 93 | 100 | 93 | 11 | 93 | 6 | 98 | -2 | 58 | 0 |
| D3 | 12 | 142 | 154 | 92 | 21 | 142 | 16 | 147 | -4 | 80 | 0 |
| P1 | 118 | 152 | 269 | 56 | 66 | 42 | -30 | 138 | -49 | -44 | -72 |
| P2 | 34 | 105 | 139 | 75 | 26 | 105 | -6 | 137 | -1 | -24 | 0 |
| P3 | 57 | 284 | 341 | 83 | 73 | 284 | 20 | 337 | -1 | 28 | 0 |
| P4 | 14 | 55 | 69 | 80 | 7 | 20 | -4 | 31 | -56 | -50 | -64 |
| P5 | 118 | 330 | 448 | 74 | 110 | 330 | -7 | 447 | 0 | -7 | 0 |
| P6 | 51 | 195 | 246 | 79 | 45 | 195 | -5 | 245 | 0 | -12 | 0 |
| P7 | 76 | 385 | 462 | 83 | 104 | 385 | 36 | 453 | -2 | 36 | 0 |
| P8 | 222 | 380 | 602 | 63 | 171 | 82 | -40 | 293 | -51 | -23 | -78 |
| W1 | 125 | 224 | 349 | 64 | 125 | 224 | 0 | 349 | 0 | 0 | 0 |
| W2 | 133 | 334 | 467 | 71 | 149 | 334 | 18 | 464 | 0 | 12 | 0 |
| W3 | 61 | 386 | 447 | 86 | 77 | 386 | 19 | 443 | -1 | 25 | 0 |
| R1 | 355 | 493 | 848 | 58 | 355 | 493 | 0 | 848 | 0 | 0 | 0 |
| W4 | 423 | 786 | 1,208 | 65 | 382 | 786 | -37 | 1,205 | 0 | -10 | 0 |
| WQ | 121 | 0 | 121 | 0 | 121 | 0 | 8 | 113 | -6 | 0 | |
| T1 | 69 | 132 | 200 | 66 | 50 | 0 | -7 | 57 | -71 | -27 | -100 |
| T2 | 176 | 601 | 777 | 77 | 176 | 601 | -1 | 777 | 0 | 0 | 0 |
| P9 | 244 | 713 | 957 | 74 | 244 | 713 | 0 | 957 | 0 | 0 | 0 |
| P10 | 79 | 404 | 483 | 84 | 83 | 404 | 4 | 483 | 0 | 5 | 0 |
| P11 | 51 | 272 | 322 | 84 | 46 | 272 | -4 | 322 | 0 | -9 | 0 |
| **Total** | **2,635** | **6,736** | **9,371** | **72** | **2,544** | **6,161** | **0** | **8,705** | **-7** | **-3** | **-9** |

*Capital costs are amortized over 15 years at 5%.

** If this net trade amount is positive (negative) permit sales are larger (smaller) than purchases.

*** This is a change from the base case in percentage terms.

**Figure 2: Net Trade: Revenue from Permits Sold minus Cost of Permits Purchased as a % of O&M Costs, Base Case**

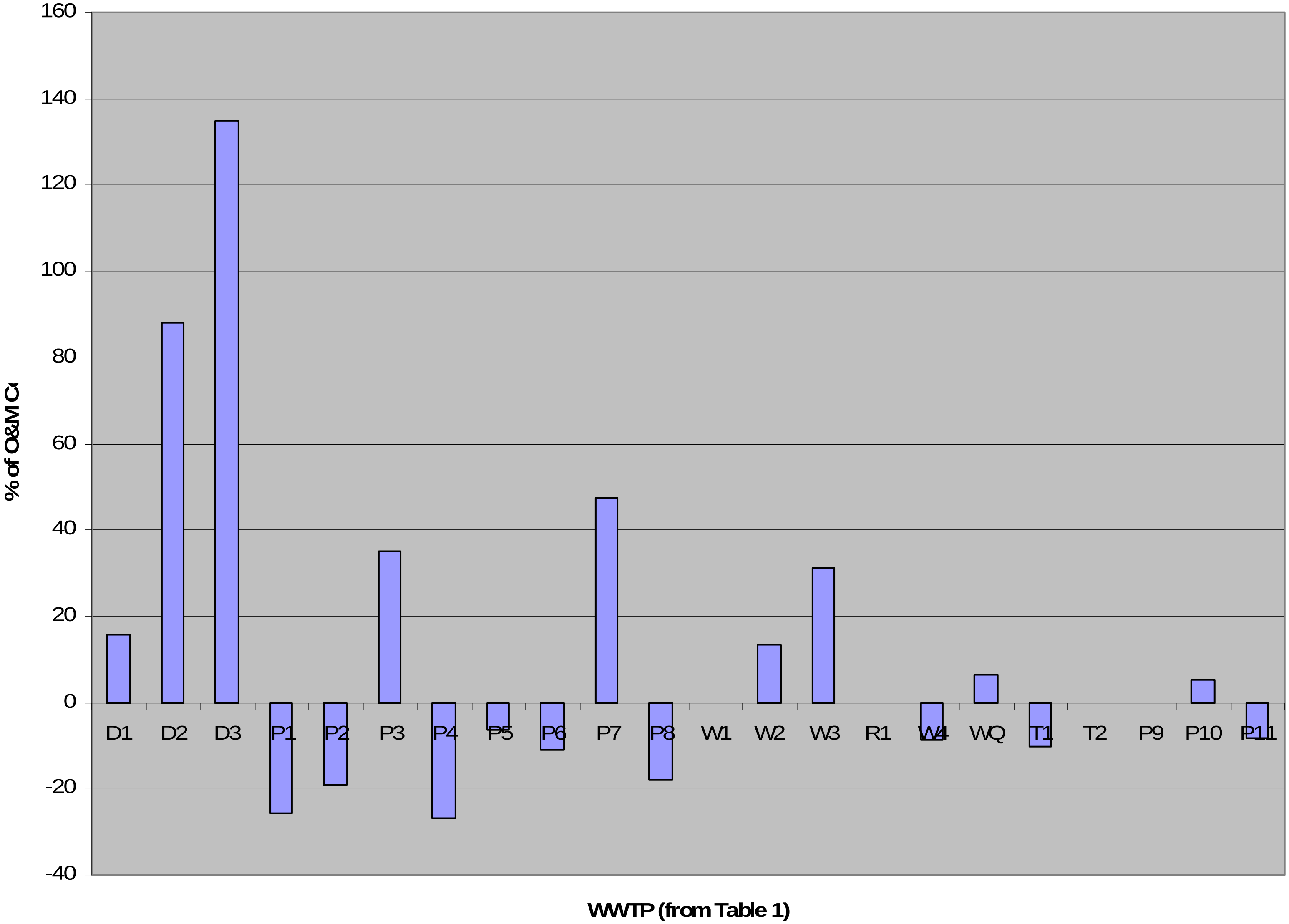


Table 6. Numbers of Permit Traded (lbs) and the Price of Permit Scenario 2: TMDL 0.2mg/L

| | D1 | D2 | D3 | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | W1 | W2 | W3 | R1 | W4 | WQ | T1 | T2 | P9 | P10 | P11 | $/lb | $ Sales |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D1 | | 2 | | 161 | | | | | | | | | | | | | | | | | | | 87 | 14207 |
| D2 | | | 1 | | 72 | | | | | | | | | | | | | | | | | | 87 | 6384 |
| D3 | | | | 187 | | | | | | | | | | | | | | | | | | | 87 | 16264 |
| P1 | | | | | 3 | | | | | | | | | | | | | | | | | | 87 | 260 |
| P2 | | | | | | | | | | | | | | | | | | | | | | | 87 | 0 |
| P3 | | | | | | | 362 | 0 | | | | | | | | | | | | | | | 55 | 19958 |
| P4 | | | | | | | | 294 | | | | | | | | | | | | | | | 55 | 16219 |
| P5 | | | | | | | | | 100 | 60 | | | | | | | | | | | | | 55 | 8780 |
| P6 | | | | | | | | | | | | | | | | | | | | | | | 55 | 0 |
| P7 | | | | | | | | | | | 719 | | | | | | | | | | | | 55 | 39618 |
| P8 | | | | | | | | | | | | | | | | | | | | | | | 55 | 0 |
| W1 | | | | | | | | | | | | | | | | | | | | | | | 54 | 0 |
| W2 | | | | | | | | | | | | | | 474 | | | | | | | | | 38 | 18025 |
| W3 | | | | | | | | | | | | | | | | 977 | | | | | | | 38 | 37113 |
| R1 | | | | | | | | | | | | | | | | | | | | | | | 40 | 0 |
| W4 | | | | | | | | | | | | | | | | | | | | | | | 38 | 0 |
| WQ | | | | | | | | | | | | | | | | | | 224 | 17 | | | | 32 | 7612 |
| T1 | | | | | | | | | | | | | | | | | | | | | | | 32 | 0 |
| T2 | | | | | | | | | | | | | | | | | | | | | | | 32 | 0 |
| P9 | | | | | | | | | | | | | | | | | | | | | | | 32 | 0 |
| P10 | | | | | | | | | | | | | | | | | | | | | | 129 | 32 | 4169 |
| P11 | | | | | | | | | | | | | | | | | | | | | | | 32 | 0 |
| $/lb | 87 | 87 | 87 | 87 | 87 | 55 | 55 | 55 | 55 | 55 | 55 | 54 | 38 | 38 | 40 | 38 | 32 | 32 | 32 | 32 | 32 | 32 | | |
| $ Purchases | - | 172 | 130 | 30299 | 6513 | 0 | 19951 | 16226 | 5497 | 3284 | 39618 | 0 | 0 | 18025 | 0 | 37113 | 0 | 7088 | 524 | 0 | 0 | 4169 | | 188609 |

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