Economic Modeling of Point-to-Point Source Water Quality Trading in the Upper Passaic Watershed Accounting for Fixed and Variable Costs

A Thesis

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ABSTRACT

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. This thesis explores two aspects of the disparity between the theory and practice of water quality trading programs using 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, the Hung and Shaw (2005) Trading Ratio System (TRS) is broadly interpreted to enable firms to trade allowances upstream and across tributaries within a specified multi-zone management area. Specifically, the possibility of upstream and cross-tributary trading is investigated by modeling a “Management Area” (MA) policy proposed for the Upper-Passaic River Basin TMDL (Obrupta, Niazi, and Kardos, 2008).

Second this study raises 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.

Using the Non-Tidal Passaic River Basin phosphorus emissions trading program as a case study, I simulate trading scenarios under different market mechanisms. Based on the simulations of Marginal Cost Trading, cost savings accomplished under an open market mechanism range from 0.59% to 1.04% of total costs relative to the no-trade baseline. Given positive transactions costs, it is unlikely that a vibrant trading market would result in such circumstances, consistent with the disappointing level of water quality trading observed to date. On the other hand, the simulation results of Optimal Trading results suggest that if WWTPs are able to jointly optimize their capital investment levels, the costs savings can increase dramatically (up to 13.10% of the baseline total cost).

This cost-saving potential leads to the argument 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.

BIOGRAPHICAL SKETCH

After obtaining a bachelor degree in the University of Hong Kong, Tianli Zhao came to the United States to continue his education right away. He enrolled in Cornell University Dyson School of Applied Economics and Management in the fall of 2007 and became a research assistant for Professor Gregory Poe and Professor Richard Boisvert working on a research project for the Passaic River water discharge permit trading program. During this wonderful research experience, Tianli cultivated his strong interest in numerical algorithms and discovered his talent in programming. After the Passaic research project was completed, he decided to transfer to the department of economics where he could concentrate on computational macroeconomics. While he was pursuing his Ph.D in the field of macroeconomics, he also would like to receive a master degree in the field of Environmental Economics. In the spring of 2013, he submitted a thesis associated with the Passiac research project and completed the requirements for a Master of Science in the field of Environmental Economics.

To my family

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Upon completion of a graduate thesis, I would like to thank the people who have supported me to accomplish this. I would like to begin with my chairperson, Professor Gregory L. Poe. I was extremely fortunate to take his environmental economics class and became his research assistant on the Passaic Project in the first semester at Cornell. At that time, I was not really sure what academic research was all about, and I was even pondering whether I should continue my education to pursue a Ph.D degree. It is him who opened my eyes for doing research. His kindness and mentorship were far beyond the call of duty. I am also very grateful to Professor Richard N. Boisvert, who guided me through my first ever programming experience - constructing a mixed-integer-nonlinear-programming model and solving it in the General Algebraic Modeling System. Since then, numerical computation has become my favorite sledgehammer in my research toolkit. In term of this thesis, contributions from Professor Poe and Professor Boisvert were absolutely crucial, and I cannot imagine accomplishing this without their support. I am also thankful to people in Passaic Project.

My appreciation extends to my classmates and friends whom I met in Ithaca. Although I could not mention everyone, there are many people who supported me throughout the years. I would like to express my sincerest appreciation to all these people.

Finally, I am especially indebted to my family in China for their kindness, unconditional love and support. Another Dyson School graduate, Yan Qu, who then became my wife, continuously supported me all ways and all the time. Without her accompany, I would never have managed this venture.

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CHAPTER ONE

INTRODUCTION

Current Development in Water Quality Trading

Encouraged by the success of the United States acid rain program in accelerating reductions of sulfur dioxide pollution, as well as in providing substantial savings relative to command-and-control measures, environmental policymakers have been promoting market-based "cap and trade" approaches that allow flexibility across firms in meeting aggregate pollution levels. In particular, much attention has been given to the topic of water quality trading (WQT) in the United States following the issuance of the U.S. EPA's policy guidance documents for water quality trading in 1996 and 2003.[1] A comprehensive 2004 survey of existing water quality trading programs within the United States provides an overview of the breadth of initiatives. According to the survey, there were more than 70 WQT initiatives in the United States during 2004 (Breetz et al., 2004), which is up from around 25 just a few years earlier (King and Kuch, 2003). Fostered by these market initiatives, many "pilot" discharge permit trading programs have been launched in an effort to meet the objectives of the Clean Water Act (U.S. EPA, 2004). In 2006, the EPA reported that at least ten states had a trading framework in place or in development (U.S. EPA, 2006). Additionally, the agency reported 24 examples of trading that has occurred in the United States in programs or individual trades.[2] Beyond these trades, many additional WQT initiatives exist, including many that have not yet recorded

[1] The EPA Water Quality Trading Policy is available at http://www.epa.gov/owow/watershed/trading/tradingpolicy.html (accessed Febrary2009).
[2] A geographical allocation of these trading programs is available at: http://www.epa.gov/owow/watershed/trading/tradingmap.html (accessed March 2011).

trades or that have recorded trades subsequent to the EPA's 2006 assessment (Rowles, 2008).

While water quality trading (WQT) can be applied to manage various types of pollutants, the primary efforts to date have concentrated on nutrient trading. Such trades involve traditional National Pollutant Discharge Elimination System (NPDES) point sources (e.g. municipal wastewater treatment plants) and, in many cases, nonpoint sources such as agriculture. In addition, existing programs are also trying to address other pollutants, including sediment and toxics, and some programs are allowing trading among related pollutants (e.g., oxygen reducing pollutants, including nutrients and BOD) (Breetz et al., 2004; Kibler and Kasturi, 2007).

The canonical trading model rests on the ideal of open markets, in which firms buy and sell pollution allowances based on continuous marginal abatement costs through a price mechanism. If there is substantial diversity in marginal abatement cost functions across firms, gains from trade are expected. For example, there might be some dischargers for whom it is costly to reduce pollutant levels, while for others, their present technology may be such that additional reductions in pollutant levels could be achieved at relatively low cost. In such instances, discharge permit trading would allow one discharger to "over control" for a pollutant at a low cost, selling excess pollution equivalents via allowances to another discharger that is not able to reduce pollutants as cost-effectively. Through the trade, the buyer can achieve their share of pollution control responsibility at a lower cost, while the seller of allowances can recoup part of their abatement costs.[3]

Despite the theoretical promise of water quality trading and enthusiasm for this market-based approach, WQT to date has met with very limited practical success. Most of the WQT programs have stagnated at a pre-trading stage of development. While plenty of new guidelines, regional trading institutions, and computer simulations of trading, and even some WQT software and websites have been developed, very little actual trading has taken place (King, 2005). According to the U.S. EPA Water Quality Trading Evaluation Report in 2008, only 100 facilities have participated in trading nationally, and 80 percent of trades have occurred within a single trading program (the Long Island Sound Program). Moreover, relatively few trading programs have been scaled up from pilot projects to permanent programs, and even fewer can claim to have had a significant impact in improving water quality or reducing pollutant control costs (U.S. EPA, 2008). Hence, in the eyes of the many critics, the enthusiasm for WQT is supported only in concept by its potential to generate cost savings and by ideological arguments about the superiority of market-based solutions.

Why is WQT not working well in the reality?

There could be various reasons behind the limited success in the development of WQT. It may simply be the case that the potential cost savings for allowance trading programs are too low to cover the cost of establishing a trading program (Zhao et al,

[3] The term allowance, instead of credit or permit, is used so as to avoid confusion with the use of these terms in other contexts of water quality regulation. The term permits plays a central role in Clean Water Act regulations through respective National (NPDES) and State (SPDES) Pollution Discharge Elimination System permitting authority. In the water quality literature (Boisvert et.al, 2009), some discussions of credits restricts this term to end-of-year trading of firms' unused emissions.

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

While there are undoubtedly a number of institutional or behavioral factors that inhibit water quality trading, this thesis focuses on two fundamental modeling issues that arise when extending economic-theoretic constructs of pollution trading to the actual hydrological conditions of a water quality trading program. Although these issues prove to be intertwined in the empirical analysis of this thesis, for clarity I address these points separately here.

First, an (often implicit) assumption in economic theoretical presentations is that there are enough potential trading partners to allow the establishment of a competitive market, in which firms buy and sell pollution allowances based on marginal abatement costs relative to the market-determined price. However, as is evident in the case study used in this thesis – a point-source to point-source phosphorus trading program in the Upper Passaic River Basin in New Jersey (United States) – this assumption is questionable. In the Upper-Passaic River Basin, there are only 22 Waste Water Treatment Plants (WWTPs) subject to a Total Maximum Daily Load (TMDL) determination for phosphorus. Further, because water flows downstream and there are multiple branches of rivers within the Upper-Passaic River Basin, the application of the prevailing Trading-Ratio-System for water quality trading (Hung and Shaw, 2005) results in only one to 10 potential trading partners for each WWTP.

Recognizing the potential cost-saving gains associated with expanding the number of trading opportunities, I 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). I investigate this possibility by modeling a "Management Area" (M.A.) policy that has been proposed for the Upper-Passaic River Basin TMDL (Obrupta, Niazi and Kardos, 2008). The M.A. 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). M.A.s 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 M.A. bidirectional trades are allowed. Trading between MAs is consistent with TRS-type trading rules wherein only downstream sales of allowances are allowed.

A second concern related to thin markets is the discrete nature of capital investments. Water quality trading models typically presented in economic-theoretic presentations conventionally assume that marginal abatement costs are continuous and smooth. For example Hung and Shaw assume that abatement cost is “increasing and strictly convex”, consistent with the marginal cost approach utilized by Montgomery (1972, “convex and twice differentiable), Tietenberg (2006,“continuous cost function”) and others. While marginal abatement cost is a useful theoretical construct, actual pollution abatement decisions often do not occur at the margin. Adding additional chemicals or other small changes allow additional abatement control in some instances, but, given initial capital configurations, there can be limits to such opportunities.

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

This discrete nature of capacity makes is unrealistic to assume a continuous cost function. In other words, by assuming continuous abatement costs, each discharger is necessarily modeled as if he/she operates based on one particular fixed upgrade level and without need to consider the long run allocation of capital investment.

Recognizing the discrete nature of capital upgrade cost, it is necessary to decompose the total abatement cost into two major categories: (1) Operation and

Maintenance (OM) Cost, considered as the variable cost of abatement, including the cost of chemicals, electricity, payroll and all other administrative costs; (2) Capital Investment Cost, considered as the fixed (sunk) cost of abatement, including the cost of design and installation of fixed abatement facilities, as well as all other costs related to the physical expansion of treatment plant. It is because these two types of costs have disparate properties that the distinction of which is essential for the cost saving analysis.

For any fixed level of abatement facility, the Operation & Maintenance Cost is assumed to be at least first order continuously differentiable — it changes smoothly within the physical capacity, corresponding to continuous changing abatements. For example, an extra pound of reduction by a point source could be achieved by increasing the amount of chemicals used in its treatment process (U.S. EPA, 1996). The differentiability of the OM cost makes it valid to use the Marginal Cost which refers to the cost of implementing one more unit of emissions reduction, where the unit can be any small measure, such as a pound of nutrient.

While marginal cost is a useful theoretical construct, it is not a particularly useful concept in the characterization of fixed capital investment. As with most fixed capital investments, the cost of facility upgrades would be occur in several discrete jumps rather than continuously varying to accommodate all specific abatement levels.

Hence, the capital investment cost, or the fixed (sunk) cost of abatement should appear in a step-wise pattern where the functions are not differentiable at the jumps (kinks)[4].

[4] The concept of incremental abatement cost introduced by the EPA is analogous to the marginal cost in dealing with discrete capital investments. Incremental abatement costs are similar to marginal abatement costs, the only difference being the units of change being considered. As

In addition, this more comprehensive approach to deal with abatement cost would naturally identify the two sources of cost savings: (1) *Savings in the Operation and Maintenance Cost (variable cost savings)*—is achievable when trades occur in the direction of high marginal-variable-cost firms paying lower marginal-variable-cost firms to undertake abatement in the short run. (2) *Savings in the Capital Cost (fixed cost savings)*—is achievable when efficient firms upgrade and sell permits to less efficient firms so that they can avoid expensive abatement investments by buying permits.

In the case of Non-Tidal Passaic River Basin phosphorus emissions trading program, and probably other watershed based programs, there exist complex issues related to how the market structure can support the two types of cost savings through the trading subject to the limited number of trading opportunity. The savings in operation & maintenance cost are, at least conceptually, attainable under regular market conditions, especially when there is a noticeable difference in marginal variable costs across firms. Comparatively, the realization of capital costs savings under an open market framework is more challenging. In practice, firms that choose to upgrade, base their decision in part on the presupposition that demand exists for their unused permits. In a similar manner, firms that choose to postpone costly upgrades, rely on the projection that an ample supply of permits exists. Hence, for firms to be able to make the optimal investment decisions, the market must secure a stable demand of permits for those that should undertake upgrades, as well as an ample supply for others that should postpone upgrades.

above, marginal abatement cost refers to the additional cost associated with increasing abatement by one, usually small, unit. Incremental cost is defined as the average cost of incremental reductions. For example if additional abatement cannot be undertaken for small units, such as a pound at a time, but instead requires a discrete capital investment, marginal costs would be incalculable. However, incremental costs could be calculated by dividing the total costs of increasing abatement by the increment of abatement that occurs. If 100 pounds of abatement cost $2,000, the incremental cost would be $20 per unit.

This issue does not arise in large scale trading program such as the nation-wide acid rain program in the United States. Firms can receive the proper assurances under the open market mechanism with large number of potential traders. This is because the market is sufficiently large and fluid, such that any individual discharger's decision to upgrade its facility will not have a noticeable effect on the market's supply and demand for permits.

In comparison, the Passaic phosphorus trading program at watershed level involve a relatively few potential trading partners. Firms are not guaranteed that a supply of permits will be available at any price; those that opt not to upgrade will have to make the premature investment nonetheless. As a result, the actual upgrade decision made by each firm under open market conditions will likely deviate from the optimal portfolio of capital investments.

This potential, in conjunction with the subsequent demonstration of cost savings associated with trades that account for discrete fixed costs, leads me 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 for the Passaic phosphorus trading program than an open-market, price directed system.

Study Objective and Organization of the Thesis

The purpose of this study is to contribute to the assessment and design of typical water quality trading programs at watershed level. The non-tidal Passaic River Watershed is used 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. The new elements that this study is adding on are:

1. A Mixed Integer Nonlinear Programming Model (MINLP) is developed to minimize total abatement cost, accounting for the optimal allocation of dischargers' facility upgrades, and thus the potential total savings are measured from both "OM savings" and "Capital Cost savings". To the best of my knowledge, capital cost saving is not often considered explicitly in assessing the potential cost savings of water quality trading. By counting for capital cost sharing, this study extends the conventional framework for assessing the benefits of the effluent trading program.
2. To conduct computer simulations of various trading scenarios, a Management Area (M.A.) approach is specified in order to link emission permit trading to ambient water quality. The specification is a generalization of the one proposed by Hung and Shaw (Hung and Shaw, 2005), to increase the flexibility of trading by allowing multiple source Management Area.
3. This study hypothesizes some of the difficulties in achieving the optimal allocation of capital upgrades among dischargers, and proposes a trading structure which might outperform the traditional open-market-trading in terms of extracting savings on the long-term capital costs.

In all, this study argues that the failure to account for capital cost sharing might have been a source of the numerous failures in water quality trading. As such, I hope this study could convey a message that a reconsideration of trading structures are needed for typical watersheds.

The remainder of the thesis is organized as follows: Chapter 2 begins with a simple numerical example of emissions trading, as well as the mathematical treatment of the spatial effects using the Management Area Approach. For comparison purposes, two mathematical models are designed with each characterizing different trading frameworks. The first is a convex programming model adopted to formulate the standard marginal-cost trading framework where firms are assumed to operate based on their present facilities. The second is a mixed-integer nonlinear programming model developed to incorporate discrete capital investments so that optimal allocation of fixed-cost upgrades is explicitly considered. For each model we also discuss the relationships among marginal abatement costs, trading ratios, and the prices of permits.

Chapter 3 begins with some background information specific to the case study, including a brief description of the non-tidal Passaic Watershed and its major wastewater treatment plants. The remainder of Chapter 3 is devoted to identifying the data required for the empirical analysis. To begin, there is a discussion of the TMDLs and the trading ratios, including the discussion on how to identify appropriate Management Areas that account for some special characteristics of the Passaic watershed. This is followed by a discussion of the data and procedures used to estimate both capital and operating cost functions that can be used to calculate phosphorus abatement costs for each of the major wastewater treatment plants. Chapter 3 concludes with a description of some properties of plants' abatement costs.

Chapter 4 contains a discussion of the empirical modeling results including the patterns of trades, cost savings and possible price ranges, from several policy scenarios. I then briefly discuss the implication of comparative statics from these modeling results.

The final chapter, Chapter 5, contains a brief summary of the findings and provides a discussion of the policy implications of this research. I 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. Consequently I argue that a more structured multi-year contract is suggested to the policy makers.

CHAPTER TWO

A MATHEMATICAL FRAMEWORK FOR ASSESSING THE POTENTIAL COST SAVINGS FROM EFFLUENT TRADING PROGRAMS

Introduction

In Chapter One, it was suggested 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 setting in "typical" watersheds and the open market trading system envisioned in theoretical economics presentations of emission trading. As noted some time ago 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" (Hoag and Hughes-Popp, 1997, p,253). The intent of this chapter is to bridge the gaps between theory and practice of water quality trading by constructing a mathematical framework that is well suited to assess the potential cost savings of an actual "point-source to point-source" effluent trading program.

The discussion begins by reviewing the canonical benchmark of cost-effectiveness subject to a predetermined environmental objective, originally developed in Montgomery (1972). Subsequently, a theoretical model specified by Hung and Shaw (2005) is introduced as the foundation for the construction of the water quality trading framework to meet this cost-effective condition. Then, to accommodate two practical aspects in water quality trading, the Hung and Shaw Trading Ratio System (TRS) is modified as follows: (1) A mathematical model is developed that combines multiple "single-market ambient permit systems" with Hung and Shaw's TRS to formalize the

“Management Area” (M.A.) water quality trading approach recently suggested by Obrupta, et al. (2008) for the Upper Passaic River; and (2) the canonical equi-marginal abatement cost principle, which solves the short-run cost minimizing objective, is extended to explicitly address the optimal allocation of fixed capital investment as well as the optimal abatement and trading decisions among dischargers.

To accomplish the latter, total abatement costs are decomposed into continuous variable costs and discrete fixed costs by introducing a set of integer variables, which allow the optimal investment vector to be solved by the Mixed–Integer Nonlinear Programming. Proceeding with these two modifications, the corresponding relationships among marginal abatement costs, trading ratios, and the price of permits are discussed. Finally, this chapter is closed out by raising an empirical question: can individual firms and the entirety of firms within a watershed achieve notable additional cost savings from trading if they are allowed to make optimal investment (upgrades) plans above and beyond standard marginal cost trading opportunities?

Spatial Effects and the Cost-Effective Benchmark

The basic cost minimization objective of pollution abatement policy is to minimize the sum of pollution abatement costs C_i across i firms, subject to an environmental constraint. Evidence suggests that pollutants in a watershed are typically non-uniformly mixed, non-assimilative pollutants, with the resulting spatial distribution of water quality and environmental damages depending not only upon the level of emissions, but also upon the locations and biophysical and hydrologic diffusion and transfer characteristics of the emissions (Tietenberg, 1980; 1985).[5] Therefore, in the modeling framework, it is necessary to account for the spatial effects of the pollutant at the point of measurement *vis-à-vis* the source of the pollutant. For instance, due to dilution, dispersion, and other biophysical interactions, the impacts of a pollutant on ambient water quality at a given receptor are expected to decline as the hydrological distance between the discharger and the receptor increases. At the extreme, receptor sites upstream will be unaffected by the downstream discharger's emissions. Hence, for nutrient management at the watershed level, the spatial distribution of dischargers relative to receptor sites is critical to cost-effective program design because the fate and transport of the pollutants must be considered explicitly.

Fortunately, from a theoretical perspective, the issue of non-uniform mixing and spatial distribution of pollutants is readily accommodated. This can be achieved by defining a diffusion (or transfer) coefficient, d_{ij} that measures the contribution of one unit of emissions from the i*th* discharger or source to the total load of effluent at the j*th* receptor (Montgomery 1972; Hung and Shaw 2005). Formally, let e_i indicate an amount of emissions from source i, and let e_{ij} indicate the corresponding amount measured at the j*th* receptor after discharger i emits e_i. Then,

$$d_{ij} = \frac{e_{ij}}{e_i} \qquad \text{-------(2.2-1)}$$

If d_{ij} equals "zero", the i*th* discharger has no effect on the j*th* receptor (as in the case of being upstream or on a separate tributary). A d_{ij} of "one" indicates that the unit of

[5] Tietenberg (1985) categorizes the nature of pollutants into three classes: uniformly mixed assimilative pollutants, uniformly mixed accumulative pollutants, and non-uniformly mixed assimilative pollutants.

pollution from the i*th* source does not diminish in any way by the time it reaches the j*th* receptor (for this reason, d_{ii} should always equal to one). An intermediate coefficient of, say, d_{ij} = 0.5 would indicate that one additional unit of pollution for discharger *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 dispersion of water emissions for the *i* sources can be specified by an *i* by *j* matrix of diffusion coefficients (Montgomery 1972):

$$D = \begin{bmatrix} & & & . & & & \\ & & & . & & & \\ & & & . & & & \\ . & . & . & d_{ij} & . & . & . \\ & & & . & & & \\ & & & . & & & \\ & & & . & & & \end{bmatrix}$$

After properly accommodating the spatial effect of a pollutant, the cost-effective goal can be characterized by the following mathematical formulation, which minimizes the combined costs across all dischargers subject to predetermined environmental constraints *Ej* at each receptor site. This canonical minimization problem will be referred as Problem A-1.

$$\text{PROBLEM (A-1):} \quad \begin{cases} \min\limits_{r_i} \sum_{i=1}^{n} C_i(r_i) & \text{------(2.2-2)} \\ \text{subject to:} & \\ a_j + \sum_{i=1}^{n} d_{ij}(e_i^0 - r_i) \le E_j \qquad \forall j \in \{1,2,3...m\} & \text{------(2.2-3)} \\ r_i \ge 0; \qquad \forall i \in \{1,2,3...n\} & \text{------(2.2-4)} \end{cases}$$

Suppose there are n dischargers and m receptors, Equation (2.2-2) is the objective function of the cost minimization problem, where $C_i(.)$ is the abatement cost function for discharger *i* and the argument r_i is the amount of emission reduction achieved by discharger *i*. Equation (2.2-3) gives the environmental constraints where d_{ij} is a diffusion coefficient from discharger *i* to receptor *j*, E_j is a predetermined environmental standard at receptor *j*, and e_i^0 is referred to as the uncontrolled emission rate by source *i*. Note that r_i, E_j and e_i^0 are all measured in terms of load. Finally, the "a" parameter is used to represent background pollution (Tietenberg 2006).

To simplify the notation, the canonical minimization problem can be rewritten as Problem A-2 below in which the argument of cost function is converted to the final effluent e_i by the relation $e_i = e_i^0 - r_i$. Furthermore, for ease of presentation, the background pollution is assumed away in this study, hence "a=0 ":

PROBLEM (A-2):
$$\begin{cases} \min\limits_{e_i} Z = \sum_{i=1}^{n} C_i(e_i) \ , & \text{------(2.2-5)} \\ \text{subject to:} & \\ \sum_{i=1}^{n} d_{ij} e_i \le E_j \qquad \forall j \in \{1,2,3...m\} & \text{------(2.2-6)} \\ e_i \in [0, e_i^0]; \qquad \forall i \in \{1,2,3...n\} & \text{------(2.2-7)} \end{cases}$$

Note that the only choice variables in the objective function are the final effluent of each discharger. The discharge constraint is given in inequality (2.2-6), where E_j is a specified environmental standard at receptor *j*, also measured in terms of load. The inequality imposes the constraint that the diffused aggregate pollutants from all dischargers to each receptor site must meet the environmental standard at that receptor site. As previously e_i^0 is initial unregulated effluent at *i*. Hence equation (2.2-7) imposes the restriction that the equilibrium effluent level must lie in a closed interval between zero and e_i^0. The lower bound of zero indicates that a firm cannot do better than be emission-free while upper bound e_i^0 corresponds to the level of emissions that a profit maximizing firm would produce in the absence of regulations or other pollution abatement incentives. Hung and Shaw (2005) refer to this as the "primary" pollution level while Tietenberg (2006) describes this as the "uncontrolled emissions rate".

The Lagrangian for this cost-effective benchmark is[6]:

$$K(e_i, \lambda_i, \alpha_i, \beta_i) = Z + \sum_{j=1}^{m} \lambda_j (E_j - \sum_{i=1}^{n} d_{ij} e_i) + \sum_{i=1}^{n} \alpha_i (e_i - e_0) - \sum_{i=1}^{n} \beta_i (e_i - 0) \quad (2.2\text{-}8)$$

The corresponding Kuhn-Tucker conditions are:

$$\partial K / \partial e_i = Z_i' - \sum_{j=1}^{n} \lambda_j d_{ij} + \alpha_i - \beta_i \le 0 ; \quad \forall i \in \{1,2,3...n\} \quad \text{---(2.2-9)}$$

$$e_i \cdot (Z_i' - \sum_{j=1}^{n} \lambda_j d_{ij} + \alpha_i - \beta_i) = 0 ; \quad \forall i \in \{1,2,3...n\} \quad \text{---(2.2-10)}$$

$$\partial K / \partial \lambda_j = E_j - \sum_{i=1}^{n} d_{ij} e_i \le 0 ; \quad \forall j \in \{1,2,3...m\} \quad \text{---(2.2-11)}$$

$$\lambda_j \cdot (E_j - \sum_{i=1}^{n} d_{ij} e_i) = 0 ; \quad \forall j \in \{1,2,3...m\} \quad \text{---(2.2-12)}$$

$$\partial K / \partial \alpha_i = e_i - e_0 \le 0 ; \quad \forall i \in \{1,2,3...n\} \quad \text{---(2.2-13)}$$

$$\alpha_i \cdot (e_i - e_0) = 0 ; \quad \forall i \in \{1,2,3...n\} \quad \text{---(2.2-14)}$$

$$\partial K / \partial \beta_i = 0 - e_i \le 0 \quad \forall i \in \{1,2,3...n\} \quad \text{---(2.2-15)}$$

$$\beta_i \cdot (0 - e_i) = 0 \quad \forall i \in \{1,2,3...n\} \quad \text{---(2.2-16)}$$

[6] The Kuhn-Tucker conditions are written in type II K-T representation.

If the equilibrium occurs in the interior, the complementary slackness conditions for Problem A-2 imply that $\alpha_i = 0$ and $\beta_i = 0$ for all *i*, and so $Z_i' = \sum_{j=1}^{n} \lambda_j d_{ij}$, indicating that the least cost solution occurs when each discharger's marginal abatement cost is equal to the sum of its shadow prices of the total load constraints at all affected zones weighted by diffusion coefficients. [7]

To gain an intuitive grasp of his result, assume that *j* is the only receptor of concern. In this case, the interior solutions given by the first order necessary conditions, would yield a spatially-adjusted "equi-marginal" result:

$$MC_i(e_i^j) = \frac{1}{d_{ij}} \frac{\partial C_i(e_i)}{\partial e_i} = \frac{1}{d_{kj}} \frac{\partial C_k(e_k)}{\partial e_k} = MC_k(e_k^j) \qquad \text{---(2.2-17)}$$

which reduces to the standard least-cost equi-marginal conditions $MC_i(e_i) = MC_k(e_k)$ for the special case of $d_{ij} = d_{kj} = 1$ associated with pollutants characterized by uniform mixing. Equation (2.2-17) shows that the cost-effective allocation of the pollution abatement (if interior) for a non-uniformly mixed pollutant occurs at the point where spatially differentiated marginal abatement costs for two emission sources (i and k) relative to the binding receptor (j) are equal, corresponding to Tietenberg's observation that "..it is not the marginal costs of emission reduction that are equalized across sources in a cost-effective allocation… it is the marginal costs of pollution reduction at each receptor location that are equalized" (2006, p. 34).

[7] For generality, one can think that the shadow prices are zero at those affected zones for which total load constraints are not binding.

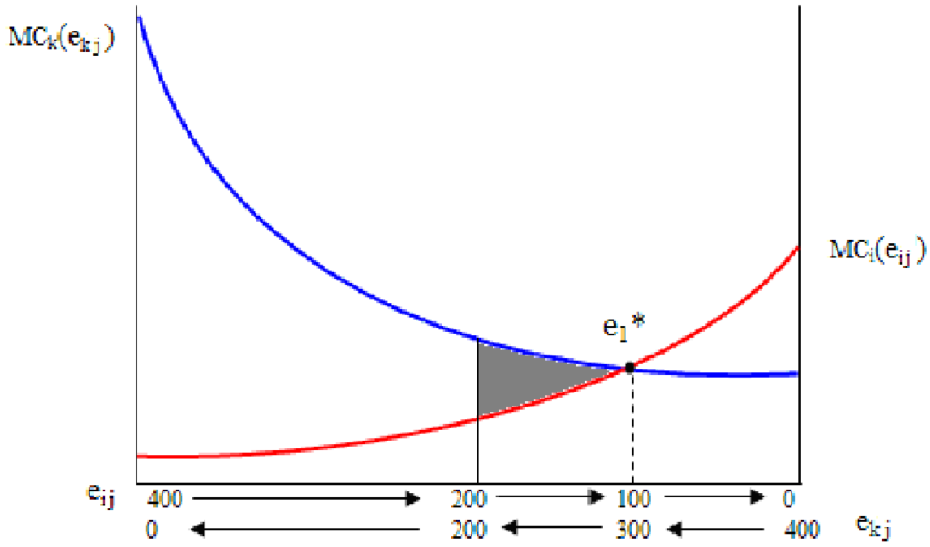

Figure 2.2-1 The Equi-marginal Condition

This spatially adjusted equi-marginal condition can be depicted using simple geometry. Figure 2.2-1 depicts two spatially-adjusted marginal abatement cost curves[8] (relative to receptor site *j*) where the total, spatially-adjusted abatement (relative to receptor site *j*) required is 400 units. Assume that firm *i* and *k* are the only two sources of emissions in the watershed and *j* is the only receptor of concern. For simplicity, we further assume that two firms have the same level of spatially-adjusted initial pollution level (400 units), and that the initial allocation of pollution abatement strategies is that each firm reduces its spatially-adjusted effluent by half (i.e. (200, 200)). In contrast to this restricted case, the spatially adjusted equi-marginal condition implies that, the cost-effective equilibrium is at (100, 300), where the two spatially adjusted marginal cost curves cross, corresponding to emissions reductions by source *i* of 300 units and source *k*

[8] All the effluent units in this chapter are spatially-adjusted relative to receptor j, unless otherwise noticed.

of 100 units. The cost savings associated with moving from the initial allocation (200, 200) to the cost-effective equilibrium (100, 300) is depicted by the shaded area in Figure 2.2-1.

Standard Trading Model and Trading Ratio System (TRS)

In Section 2.2, the fundamental characteristic of cost-effective pollution abatement -- equating spatially adjusted marginal abatement costs across firms after accounting for spatial effect and transport – was identified. The original suggestion that tradable pollution rights could achieve least-cost allocation of resources was provided independently by Crocker (1966) and Dales (1968a, b) [9] Drawing from Coase's seminal work on property rights (Coase, 1960), Dales proposed his concept for a market for fully transferable pollution rights within the context of water quality.

The early literature on trading pollution rights focuses on the comparison between two basic pollution control systems, namely, the *ambient permit system* (APS) and the *emission permit system* (EPS) (Montgomery, 1972). In the APS the commodity traded is the right to emit pollutants in terms of pollutant concentrations at a set of receptor points. Instead, under the EPS, firms can trade emission licenses, allowances, or permits which confer the rights to a discharger to emit pollutants up to a certain rate.

Neither of the two trading systems is "optimal from all points of view" (Atkinson and Tietenberg, 1982, p. 103). From a purely theoretical perspective, the ambient permit system can yield a cost-effective allocation of abatement for non-uniformly mixed

[9] Dales' application was for water quality and involved only trading amongst polluters. Crocker's vision of a market pricing system for emission rights was oriented to atmospheric pollution and involved trading between polluters and pollutees. Montgomery (1972) subsequent theoretical presentation of trading adopted Dales approach. This cost effectiveness focus has been followed since then in the pollution trading literature.

assimilative pollutants. In a result that Tietenberg (2003) calls "remarkable", Montgomery proved that this least-cost outcome is independent of how the initial permits are allocated across dischargers or sources. That is, theoretically at least, any initial permit allocation rule across dischargers still engenders the cost-effective allocation after trading.

> "[T]he logic behind this result is rather straight forward. Whatever the initial allocation the transferability of permits allows them ultimately to flow to their highest-valued uses. Since those uses do not depend on the initial allocation, all initial allocations result in the same outcome and that outcome is cost-effective" (Tietenberg 2003, p. 401).

The important implication of this invariance result from the perspective of economic theory is that such independence implies that there need not be a conflict between political feasibility, or equity, and cost-effectiveness. Further, ambient standards are always met. However, the implementation of the APS would be a challenging matter. In practice, both environmental authorities and sources would have to overcome some formidable administrative barriers due to the inherent complexity of an APS. In order for the ambient standards to be met everywhere, complete assurance that trade would not violate the ambient water quality requires a large number of separate markets, potentially up to one for each receptor.[10] The traded permits would have to be defined in terms of the reduction in concentration achieved at a specific receptor. Each of these receptor-specific permits could be traded independently of the others. Since an increase in

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[10] Fewer than j receptor-specific markets would leave some receptors unprotected; raising the possibility that trades would trigger violations at one or more of them.

emissions is not legitimized until all required offsetting credits are obtained, the expansion could be jeopardized by problems in any one of these markets. Problems could arise, for example, when few sellers exist in one or more of the markets. Markets with few sellers provide less assurance that competitive prices will prevail. When permit prices are not competitive, the transactions generally will not lead to a cost-effective allocation. (Tietenberg, 2006). The transactions cost of having to deal in several markets simultaneously could also pre-empt otherwise desirable trades. (Stavins, 1995).

Emissions permit systems ensure direct control over emissions and are administratively simple, with trades based on the amount of pollutants emitted at the source rather than the level of ambient water quality at one or many receptors downstream. By not having to operate in many receptor markets simultaneously, the EPS can avoid the main practical limitation of the APS. Nonetheless, the EPS has both theoretical problems in that its ability to achieve a cost-effective solution via market trading is dependent upon the initial allocation of permits:

> "[a]n extremely restrictive (and sometimes unattainable) condition is required to ensure that the market equilibrium is also the least-cost solution. This finding is particularly disturbing on two counts. First, the environmental authority may not be able to find an initial allocation of permits that ensures an efficient outcome. And second, should such an allocation exist, a substantial degree of flexibility in the choice of this initial allocation may be lost. Such flexibility can be extremely important in designing a system that is politically feasible (as well as efficient)" (Krupnick, Oates, and Van De Verg, 1983, p. 234).

That is the allocation invariance principle derived by Montgomery for the APS does not pertain to the EPS. Further, Hahn (1986) argues that, in practice, EPSs are also quite susceptible to market manipulation:

> "Whether EPS is viewed as one market in N differentiated products, N markets in different commodities, or some number of 'quasimarkets' related to air quality receptors the issue of market manipulation still remains" (Hahn, 1986, p 6).

In an effort to search for a more pragmatic alternative that will garner the benefits of both the emission permit systems and ambient permit systems while minimizing their respective shortcomings, a number of "trading rule" systems have been proposed in the literature. The unifying feature of these structured rules of trade is that emissions are traded under the constraint that ambient targets are not violated (Boisvert, et al., 2009). In general, all of these trading rules have pros and cons of their own. For instance, the Pollution-Offset System (POS) developed in full by Krupnick, et al. (1983) requires that exchange rates are endogenously determined in the environmental quality simulation model to ensure that the proposed transaction would not violate the predetermined environmental quality standard at any receptor point. Addressing a possible shortcoming of the POS, McGartland and Oates (1985) subsequently created the Modified Pollution Offset System (MPOS) which imposed an additional non-degradation constraint that prohibited the worsening of pre-trade environmental quality at any receptor. Yet with this condition, the MPOS still suffers from a free-rider problem (Hahn, 1986; McGartland and Oates, 1985; Hung and Shaw, 2005) in that one discharger can increase effluent at no cost as long as the ambient environmental standard is not violated. Another proposed trading rule is called the Exchange-Rate Emission Trading System (ERS), in which the environmental authority sets exchange rates *ex ante* equal to the ratios of the discharger's marginal abatement costs in the least-cost solution (Forsund and Naevdal, 1998; Klaassen and Forsund, 1994; Hung and Shaw, 2005). This places a huge burden on administrators in that they must have full information on dischargers' abatement cost functions to set exchange rates and to choose the initial distribution of permits that will lead to a cost-effective solution after trade. (Klaassen, 1996).

Noting the various shortcomings in each of these systems, Hung and Shaw (2005) instead proposed a trading-ratio system (TRS) for water quality trading that sets trading ratios between sources equal to the exogenous, hydrologically determined, diffusion coefficients among dischargers. Hence, trades of pollution rights are limited from upstream to downstream sales. Hung and Shaw argue that the TRS is particularly well-suited for water-related nutrient trading in that "problems with hot spots and free riding can be avoided, and the burdens on both dischargers and the environmental authority should be relatively light" (Hung and Shaw, 2005, p. 83).

By utilizing the property that water flows to the lowest level uni-directionally, Hung and Shaw effectively link emission permit trading to ambient water quality by setting the trading ratio equal to the exogenous diffusion coefficient among dischargers. Under their presentation of the TRS, the environmental standards must be met at all sources, (i.e. each discharger is also a receptor, so n=m) and the authorities sequentially issue discharge permits for each receptor area working from upstream to downstream based on the environmental standard. These modifications are captured in the constraint:

$$\overline{T}_i = E_i - \sum_{k=1}^{i-1} d_{ki} \overline{\mathrm{T}}_{ki} \qquad \text{------(2.3-1)}$$

where $\overline{T}_i$ are the aggregate tradable permits for a discharger *i*, and *k* (< *i*) indicates dischargers upstream to discharger *i*. For the most upstream discharger, authorities will set $\overline{T}_i = E_i$, because there is no possibility of buying permits from other dischargers. In the TRS, Hung and Shaw assume that the trading ratios at which trade takes place are equal to the diffusion coefficients defined in equation (2.2-1), and therefore, the notation d_{ki} can also be used to denote the trading ratio. The effluent from discharger *i* must be below the environmental standard, $\overline{T}_i$, but if *i* purchases permits from *k*, then *i* can discharge more effluent.

On the other hand, discharger *i* can also sell permits to downstream sites. In this situation, site *i* is selling its right to discharge units of effluent, and unless it also buys some permits from upstream, it must then meet a more stringent environmental standard. Thus, the amount of final effluent emitted by source *i* must be reduced by the number of permits sold to downstream sites, $\sum_{k>i}^{n} \mathrm{T}_{ik}$. Since the reduction in emissions due to the sale of a permit must occur at the point of sale, these sales need not be weighted by the trading ratios. After controlling for the effect of both sales and purchases of permits on the final allowable effluent and rearranging the trading constraint becomes:

$$e_i \leq \overline{\mathrm{T}}_i + \sum_{k=1}^{i-1} d_{ki}\mathrm{T}_{ki} - \sum_{k>i}^{n} \mathrm{T}_{ik} \qquad \text{-------(2.3-2)}$$

Where T_{ki} (T_{ik}) is the number of permits sold by *k* to *i* (*i to k*) following the aforementioned directional trading rule that sales can only occur downstream. The effective trades from the buyer's point of view are adjusted by the trading ratio, d_{ki}.

Finally, with equation (2.2-6) replaced by the new trading equation (2.3-2), the basic trading model under Hung and Shaw's trading ratio system can be specified as

$$\text{PROBLEM (B)} \quad \begin{cases} \min\limits_{e_i} Z = \sum_{i=1}^{n} C_i(e_i) & \text{------(2.3-3)} \\ \text{subject to} & \\ e_i - \sum_{k=1}^{i-1} d_{ki} \mathrm{T}_{ki} + \sum_{k>i}^{n} \mathrm{T}_{ik} \le \overline{\mathrm{T}}_i \quad (\, i = 1, \ldots, \mathrm{n}) & \text{------(2.3-4)} \\ e_i \in [0, e_i^0]; \quad (\, i = 1, \ldots, \mathrm{n}) & \text{------(2.3-5)} \\ \mathrm{T}_{ki},\ \mathrm{T}_{ik} \ge 0; \quad \forall i, k & \text{------(2.3-6)} \end{cases}$$

Hung and Shaw prove that the cost-effective model (Problem A-2) in which the environmental authority minimizes the aggregate costs subject to environmental constraints is the same as the model (Problem B) in which the environmental authority minimizes aggregate costs subject to the trading constraints under the TRS. They further prove that this least cost allocation of abatement responsibilities can be attained through competitive markets using the TRS.

Zonal and Management Area Approach

In the emissions trading literature, a trade-off is often perceived between the desire to protect the ambient quality and the desire to create as many as possible trading opportunities to maximize potential gains from trade (Tietenberg, 2006). A concern is that "overly restrictive" trading rules inevitably limit trading opportunities and narrow down the market, creating the potential for market imperfection and strategic behaviors, which may undermine the efficiency of water quality trading (Tietenberg, 2006). Hung and Shaw's TRS is a fairly restrictive trading rule which emphasizes only the one side of this trade-off: although 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, it greatly restricts trading opportunities as the TRS only allows trade to occur uni-directionally. For instance, if there are no relatively low-cost plants upstream on any reach in a watershed, there will be no opportunities to trade.

One appealing way to expand the trading opportunities under the TRS is the trading zone approach. The notion of "zone" is not novel in the pollution management literature. At least as early as 1973 in a discussion of tax policies, Tietenberg introduced a zonal approach to manage the air quality. He suggested:

> "...the area in which an air pollution control policy is to be implemented is divided up into zones. Within each zone the tax rate is the same for all emitters of a particular pollutant, but the tax rate varies across zones. Each zone has a predetermined air quality standard. Using existing air diffusion models, which express the ground level of steady state concentrations in a receptor zone as a linear function of emissions in all other zones, it is possible to compute uniquely the zonal pattern of emissions which is compatible with the air quality standards." (Tietenberg, 1973, p. 202)

In a 1978 article, Tietenberg similarly defines a tax zone as follows: "a tax zone will be defined as the geographic area within which all emitters pay the same tax rate" (Tietenberg, 1978, p. 267). As discharge allowance trading began to be widely studied as an alternative to managing the environmental quality, the zonal approach was transplanted from emission taxes to emission trading. Thereafter, "trading zones" have become a parallel concept to "tax zones", within which the trades take place on a "one-for-one basis" (e.g. Tietenberg, 1980).

Clearly, by grouping multiple dischargers into zones and allowing both upstream and downstream trades within each zone, environmental authorities can create more trading opportunities and likely increase the potential for cost-savings. However, since one-to-one bi-directional trading within the zone is typically inconsistent with hydrologically determined diffusion rates, it will likely compromise the water quality at some locations and potentially lead to “hot spots”, a point of concern that has been raised in previous evaluations of the zonal approach (Obrupta et al., 2008). The term "hot spots" describes localized areas with unacceptably degraded water quality due to high concentration of a pollutant.[11]

To some extent, Hung and Shaw's presentation eliminates hot spot concerns by assuming that each discharger/receptor constitutes a separate zone and placing a water quality constraint on each zone. Yet, they do argue that the TRS can be incorporated with cases where the watershed is divided into zones with more than one discharger,

> "in general, the number of dischargers in a zone should be greater than or equal to one, although we assume that there is only one representative discharger in each zone" (Hung and Shaw 2005, p. 88).

Beyond allowing the possibility of multiple dischargers per zone, they do not specify how exactly the multi-discharger zones are to be divided or the patterns of trade allowed within each zone.

Indeed, there has been a persistent ambiguity regarding what would be the proper way to trade within a zone. In the original definition of the "trading zones", Tietenberg

[11] The US EPA (2004) notes that one concern regarding water quality trading is the potential that trades will create hot spots immediately downstream of pollutant sources that purchase credits. Reflecting this concern, trading programs must be designed to avoid the creation of hot spots.

described trades to take place on a "one-for-one basis" within each zone. In the context of water quality management, using one-to-one trading ratio within a zone is equivalent to assuming that a unit of emissions from one source has the same effect on downstream water quality as each of the other sources within the same zone. Some previous studies such as such as Sado, et al. (2009) have followed Tietenberg's canonical conceptualization of trading zone. Hung and Shaw (2005) also treat emissions from various sources within a zone as having equal effects on water quality:

> "A zone can be defined as an area in which the dispersion characteristics of effluents and the environmental effects of any unit of effluent are very close. Then, by using a water quality model, the zonal water quality standards can be converted into the total load standards of effluents that cannot be violated within each zone." (Hung and Shaw, 2005, p.86)

While this approach is appropriate for the special case in which diffusion coefficients are indeed one-to–one, adopting unitary trading ratios for intra-zone trading cannot, however, guarantee ambient water quality at the least cost when such an assumption is not valid.

The adoption of the counterfactual assumption of unitary trading ratios then poses a challenge of how to divide a watershed into zones. It might seem natural to assume that the hot spot issue could be mitigated by using small zones---as long as all sources within each zone are closely clustered, all sources within each zone might be expected to have similar diffusion coefficients. In a crude way, this argument suggests an inverse relationship between hot spots and zone size. Yet, contrary to the possible expectation that small zone sizes would afford better control over concentration, Spofford (1984, p.

82) as well as Atkinson and Tietenberg (1982, p. 120) find empirical evidence that smaller zone sizes did not effectively alleviate the hot spot problem. In addition smaller zones without inter-zone trading significantly increase watershed-wide abatement cost as they restrict trading opportunities substantially. Given the shortcomings of the traditional approach, it is useful to explore a more flexible zonal system which does not have restrict intra-zone trading to be one-to-one. Along these lines, Tietenberg suggests that "allowing other ratios (non-unitary) potentially could provide policymakers with an additional degree of freedom" (Tietenberg, 2006 p. 94).

Obrupta, Niazi and Kardos (Obrupta, et al., 2008), who are collaborators on the Upper Passaic River Basin Trading project examined in this thesis, propose a hydrologically-based zonal approach, which they call the "Management Area (M.A.) approach", using the Upper Passaic River Basin Trading Program as a case study.   The M.A. approach is designed to ensure the avoidance of hot-spots. Yet, in comparison with the TRS which stipulates that the seller must always be upstream of the buyer, the M.A approach increases trading opportunities and potential market size by utilizing an important fact that, in practice, only some locations pose a hot-spot concern. Different locations in the watershed show varying sensitivity to water quality impacts from certain pollutant or pollutant concentration.

> "certain locations are more vulnerable to hot-spot effects than other locations in the watershed........... (Therefore) water quality is protected on the basis that high phosphorus at some, not all, locations is a hot-spot concern as determined from water quality studies conducted throughout the watershed." (Obrupta, et al. 2008 p.952)"

According to their proposed framework, each M.A. is delineated so that its outlet represents the only hot-spot concern in that M.A. Because, by design, there are no hot-spot concerns beyond the M.A. outlets, trades are allowed both upstream and downstream within the same management area. Such trades should be subject to a trading ratio in order to equalize the load traded and account for differences in attenuation of load from each waste water treatment plant (WWTP) relative to the management area outlet (Obrupta, et al.,2008). Trades across M.A.s would have to be conducted in correspondence with defined trading ratios between M.A.s.

This study incorporates the Management Area concept into the TRS by developing an explicit mathematical framework to investigate the economic aspects of various management area configurations. To do so, the M.A. approach needs to be generalized and consolidated systematically. Specifically, explicit answers to the following three questions must be given: 1) how is a watershed to be divided into M.A.s? ; 2) what are the trading ratios appropriate for intra-management area trading? ; and 3) What are the trading ratios to be used for inter-management area trading?

How to divide a watershed into M.A.s?

The demarcation of Management Areas can be broken into two steps, as follows:

<u>Step One. *Identifying the "critical locations" based on the hydrological conditions in the watershed.*</u>

Some locations such as reservoirs and highly populated areas, are of great importance from a water use perspective, and hence may involve more restrictive criteria to accommodate designated uses. The critical locations should also include those that are particularly vulnerable to hot-spot effects and so must be protected by a predetermined standard. In other words, the water quality at locations that are not identified as critical must not experience notable degradations in ecological well-being. As an example, an extensive water quality simulation study (Omni Environmental 2007a) based on the Non-Tidal Passaic River Basin identifies two critical locations in which excessive phosphorus concentrations are more likely to stimulate algal blooms. Other locations are not deemed to be critical as high concentrations of phosphorus in those areas are not expected stimulate algal growth due to other limiting factors such as light availability or high stream velocity. After identifying all the "critical locations", the second step is to delineate management areas based on those critical locations.

Step Two. *Management Areas are delineated in such a way that each critical location is the end-point of one M.A., which is also the "sole outlet" of that M.A..*[12]

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

To formulate this problem mathematically, think of a management area as a set of dischargers with $\{j_1, j_2 \dots j_{n_j}\}$ being a source in the upstream management area *J* and [*j*] denoting the end-point of *j*'s M.A. Similarly let $\{k_1, k_2 \dots k_{n_k}\}$ represent sources in the downstream management area *K*. Note that an M.A. is considered upstream

[12] By the M.A. delineation, each critical location is an end-point and each end-point is a critical location, hence, with the context of this and subsequent chapters the terms "end-point" and "critical location" can be used interchangeably.

to another M.A. if the endpoint of the former is upstream to the latter.[13] Further, in order to facilitate the discussion, the point sources are alphabetically ordered from upstream to downstream. For instance, in the remainder of this presentation, management area *J* is always upstream to management area *K* without additional specification.

Then there exists a following multiplicative relation of diffusion rates between a source in *J* and a source in *K*[14]:

$$d_{jk} = d_{j[j]} \cdot d_{[j]k} \qquad \text{------(2.4.1-1)}$$

Equation (2.4.1-1) says the diffusion rate from *j* to *k* is equal to the diffusion rate from *j* to its end-point [*j*] multiplied by the diffusion rate from [*j*] to *k*. Multiplying both sides of the equation by the effluent e_k, equation (2.4.1-1) becomes:

$$e_j \cdot d_{jk} = e_j \cdot d_{j[j]} \cdot d_{[j]k} \qquad \text{------(2.4.1-2)}$$

Equation (2.3.1-2) can be further reduced to equation (2.4.1-3) by defining a notation $e_{j[j]}$, which denotes the relative impact on end-point [*j*] as a source *j* in J emits e_j.

Formally, $\forall j \in J$, $e_{j[j]} = e_j \cdot d_{j[j]}$ (hereafter $e_{j[j]}$ is referred to as the "Effective discharge at [*j*] contributed by *j*"):

$$e_j \cdot d_{jk} = e_{j[j]} \cdot d_{[j]k} \qquad \text{------(2.4.1-3)}$$

Equation (2.4.1-3) states that e_j units of discharge at source *j* in upstream M.A. has the same impact on source k in the downstream M.A. as $e_{j[j]}$ units of "effective discharge"

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

[14] Note that this multiplicative relation is guaranteed because the endpoint is always the sole-outlet of the M.A.

by the end-point [*j*]. By the same token, the total discharge exported from management area J can be measured by e_J, which is equal to the sum of the effective discharge contributed by all sources in J relative to the endpoint, that is:

$$e_J = \sum_{j \in J} e_{j[j]} \qquad \text{------(2.4.1-4)}$$

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

What are the trading ratios for intra-M.A. trades?

As discussed above, the way each M.A. is delineated guarantees that each M.A. end-point is the sole outlet of its M.A. This makes it possible to hydrologically separate M.A.s In other words, as long as the water quality at the critical location is ensured, the allowances trading within its M.A. would not jeopardize the water quality in other M.A.s. For this reason, the trading ratios for intra-M.A. trading are designed to adequately protect the water quality at its end-point. In particular, let k_1 and k_2 be two sources within the management area K (i.e. $k_1, k_2 \in K$). Suppose k_1 sells one allowance to k_2, then k_1 has to discharge Δe_{k_1} units less, while k_2 can discharge Δe_{k_2} units more. Equation (2.4.2-1) guarantees that this trade has zero net effect at their common end-point (i.e. $[k_1]=[k_2]$):

$$\Delta e_K = \Delta e_{k_1} \cdot d_{k_1[k_2]} + \Delta e_{k_2} \cdot d_{k_2[k_2]} = 0 \qquad \text{-------(2.4.2-1)}$$

Finally, solving for equation (2.4.2-1), the intra-M.A. trading ratio $\tau_{k_1 k_2}$ is set equal to the diffusion rates from seller k_1 to buyer's end-point $[k_2]$ divided by the diffusion rate from buyer k_2 to its endpoint $[k_2]$.

$$\tau_{k_1 k_2} = -\frac{\Delta e_{k_2}}{\Delta e_{k_1}} = \frac{d_{k_1[k_2]}}{d_{k_2[k_2]}} \qquad \text{-------(2.4.2-2)}$$

The design of trading ratio $\tau_{k_1 k_2}$ ensures that allowing trade to be both upstream and downstream within an M.A. will not affect the water quality at its end-point; however, pollution concentration levels of other areas within the same M.A. might increase as a result. Nevertheless, these elevated concentrations do not result in "hot spot" by the explicit designs of the M.A.s. From this sense, one can think the trading system within each M.A. as a bare-bones version of the ambient permit system, whereas the problem of transaction complexity is avoided since there is only one market for emission allowances.

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

Proposition 1:

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

Proposition 1 ensures that, *ceteris paribus*, the water quality at the endpoint of the M.A. is strictly protected by Intra-M.A. trading constraints, so that when the water flows out of each M.A. and enters the downstream M.A., the water quality is within the predetermined standard set for effluents or concentrations of effluents at the M.A. endpoints. Moreover, it claims that the cost-effective benchmark in which the environmental authority minimizes the aggregate abatement costs subject to environmental constraints is the same as the model in which the environmental authority minimizes aggregate abatement costs subject to the Intra-M.A. trading constraints.

What are the trading ratios for inter-M.A. trades?

Similarly, the trading ratios for inter-M.A. trades are designed to preserve the water quality at each zonal endpoint. And since only the buyer's endpoint is subject to the negative impact by the trades, ensuring the water quality at the buyer's M.A. endpoint is adequate. Formally, let *j* be the seller and *k* be the buyer from different management areas J and K respectively ($j \in J, k \in K$) and so [*k*] is buyer *k*'s M.A. end-point, Δe_j is the change of effluent from *j*, Δe_k is the change of effluent from *k*. Equation (2.4.3-1) guarantees that the trade has zero net effects at the buyer's end-point [*K*].

$$\Delta e_j \cdot d_{j[k]} + \Delta e_k \cdot d_{k[k]} = 0 \qquad \text{-------(2.4.3-1)}$$

Solving equation (2.4.3-1), the inter-M.A. trading ratio γ_{ik} is:

$$\gamma_{jk} = -\frac{\Delta e_k}{\Delta e_j} = \frac{d_{j[k]}}{d_{k[k]}} \qquad \text{-------(2.4.3-2)}$$

Comparing equation (2.4.3-2) with equation (2.4.2-2) shows that the trading ratio for both intra-M.A. trades and inter-M.A. trades are described by the same simple relation------the trading ratio is equal to the relative diffusion rates to the end-point of buyer's M.A. (see equation (2.4.3-3)), or formally,

$$\gamma_{jk} \equiv \frac{d_{j[k]}}{d_{k[k]}} \quad , \qquad \tau_{k_1 k_2} \equiv \frac{d_{k_1[k_2]}}{d_{k_2[k_2]}} \qquad \text{-------(2.4.3-3)}$$

For this reason, unless otherwise specified, I adopt the convention “t” to indicate the trading ratio in the remainder of this thesis for both inter- and intra-M.A. trading..

To gain an intuitive understanding of the inter-M.A. trading process, it may be helpful for the reader to imagine such trades to be comprised of two steps, differentiating between reallocation of allowances within an M.A. and trades that occur between M.A.s. That is, one can apply a multiplicative effect over diffusion from *j* to [*k*], using the upstream end-point [*j*] as intermediary:

$$d_{j[k]} = d_{j[j]} \cdot d_{[j][k]} \qquad \text{-------(2.4.3-4)}$$

Hence, Equation (2.4.3-5) can be derived by substituting Equation (2.4.3-4) into (2.4.3-1):

$$\Delta e_j \cdot d_{j[j]} \cdot d_{[j][k]} + \Delta e_k \cdot d_{k[k]} = 0 \qquad \text{-------(2.4.3-5)}$$

And since we have $\Delta e_K = \Delta e_k \cdot d_{k[k]}$, and $\Delta e_J = \Delta e_j \cdot d_{j[j]}$, equation (2.4.3-5) can be further reduced to equation (2.4.3-6):

$$\Delta e_J \cdot d_{[j][k]} + \Delta e_K = 0 \qquad \text{-------(2.4.3-6)}$$

Finally, the equivalent trading ratio $t_{[j][k]}$ between the two end-points [*j*], [*k*] can be solved from equation (2.4.3-6):

$$t_{[j][k]} = -\frac{\Delta e_K}{\Delta e_J} = d_{[j][k]} \qquad \text{-------(2.4.3-7)}$$

Equation (2.4.3-7) demonstrates that the inter-M.A. trading between two sources j and k is as if the two M.A. end-points [*j*] and [*k*] were trading the "effective allowances" under the Hung and Shaw's TRS-----the trading ratio is set equal to the natural diffusion rate between the two end-points. This result can be further interpreted as if there were an imaginary broker at each M.A. end-point who buys (sells) allowances from (to) another broker following the TRS and sells (buys) them to (from) the sources within its M.A. In other words, one can think of the inter-M.A. trading as being carried out into two steps: allowances are traded across M.A.s by "brokers" at each M.A. end-point under the TRS, and the allowances are distributed to local sources within their respective M.A.s based on Intra-M.A. trading constraints.

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

Proposition 2:

The inter-M.A. trading system supports the cost-effective allocation of allowances among the whole watershed subject to the water quality constraints at all M.A. endpoints.

The proof of this proposition is provided in the Appendix One.

To incorporate the Management Area Approach, Hung and Shaw's trading model (Problem B) shall be re-written into the following set up:

Problem (C)

$$\min_{e_i} \sum_{i=1}^{n} C_i(e_i) \qquad \text{-----(2.4.3-8)}$$

subject to:

$$e_i - \sum_{k=1}^{n} t_{ki} \mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} \leq \overline{\mathrm{T}}_i \ \ (\ i = 1, ..., \mathrm{n}) \qquad \text{-----(2.4.3-9)}$$

$$t_{ki} = \frac{d_{k[i]}}{d_{i[i]}} \ \ \forall i, k \qquad \text{----(2.4.3-10)}$$

$$e_i \in [0, e_i^0] \qquad \text{----(2.4.3-11)}$$

$$T_{ki}, T_{ik} \geq 0 \quad \forall i, k \qquad \text{----(2.4.3-12)}$$

As noted previously, for *k* and *i* both in the same M.A. the trading equation (2.4.3-9) now allows some trades to take place in both directions. The actual rule of trading is explicit given by the ratio of exogenously determined natural diffusion rates. (equation 2.4.3-10) Further, because the trading ratio between any two sources is always equal to the ratio of natural diffusion rates to the buyer's M.A. endpoint, each summation arguments is "1 to n", which contrast with the Hung and Shaw formulation in Problem B that uses a summation process that distinguishes between upstream and downstream trading opportunities. Note that the above model specification is designed to be concise, so it does not explicitly indicate which trades are precluded. Implicitly, trades are precluded where trading ratios are zero.

To sum up, in this section, the Hung and Shaw (2005) Trading Ratio System (TRS) is broadly interpreted to enable firms to trade allowances upstream and across tributaries within a specified multi-discharger Management Area. The chapter demonstrates that aggregating firms with non-unitary exchange rates into “Management Areas” focusing on meeting environmental objectives at specific endpoints and adopting a TRS system between management areas can achieve cost-effectiveness given predetermined environmental standards at those end-points. The biggest merit of this Management Area approach is that the environmental authority can have the flexibility to choose exactly which locations are to be protected while the cost-effectiveness always holds, subject to that selection. In comparison, in a typical zonal approach, with one-to-one trading within a zone, control authorities would have to increase the amount of required emissions reductions for the whole watershed to create a margin of safety for the critical locations, which defeats one of the central purposes of a zonal permit approach--the prevention of over-control (Tietenberg, 2006). Moreover, from a programming perspective, the M.A. approach is convenient for considering various hydrological configurations, because it only involves re-grouping the M.A.s based on different critical locations.

Incorporating Fixed Upgrade Costs

The primary benefit of water quality trading that attracts consideration by policy makers is the potential to control pollutants at an overall lower cost to society. The trading model discussed in previous sections rests on the rationale of marginal cost trading, by which one point source can over control for a pollutant at a relatively low marginal cost, selling the over control as "allowances" to another point source that is not able to reduce pollutants as cost effectively. Through the trade, the second point source can achieve its share of responsibility at a lower cost, while the first point source can be compensated for the additional costs incurred. The net cost savings from marginal cost trading are indicated by the shaded area in figure 2.2-1.

In reality, there exists a second, perhaps more significant, source of cost savings. Through allowance trading, dischargers are given greater flexibility to determine their effluent level which could enhance planning for capital upgrades. In practice, most treatment plants have to design their abatement technology and make capital investments targeting on one of a few final concentration ranges, rather than accommodating every specific concentration determined by the permits trading. Because of these discrete "jumps" in facility upgrades, it is reasonable to assume that the capital costs (CC) costs generally increase in step-wise pattern. A simple capital cost structure of this type is represented below.

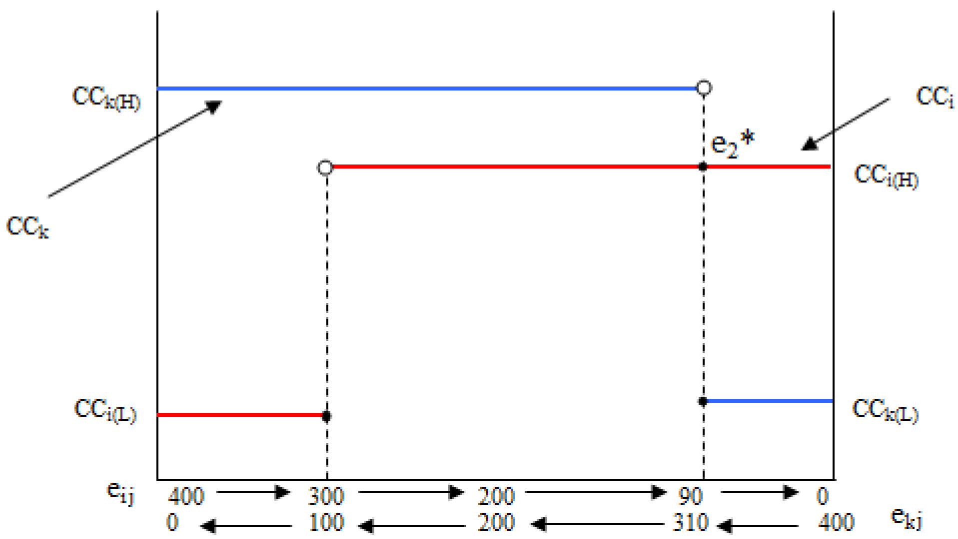


Figure 2.5-1 The capital upgrade costs

The optimal decisions of fixed capital investments can be described by considering the capital investment cost curves for the two firms *i* and *k* (Figure 2). Suppose that firms have a "low" (L) existing capacity to treat or reduce emissions, and each has the opportunity to invest in a “high” treatment capital investment: firm *i* can remain at a low level of capital spending ($CC_{i(L)}$) on its abatement facility, which will only enable *i* to reduce its emission to as low as 300 (spatially adjusted). If *i* wants to abate its emission even further, it would have to incur a higher level capital spending to upgrade its facility represented by $CC_{i(H)}$. Similarly, firm *k* can remain at its low level of capital spending ($CC_{k(L)}$) spending and high spatially adjusted emission level (more than 310 units), or undertake a higher level of capital spending ($CC_{k(H)}$) to be able to reduce its spatially adjusted emission below 310 units. As in the previous discussion related to Figure 2.2-1, assume that the initial allocation of pollution abatement strategies is that each source reduces it spatially-adjusted effluent by half (i.e. (200,200)) -- that is they are each allocated the right to pollute up to 200 units at receptor *j*. Given the capital cost configuration in Figure 2.5-1, there will be incentives for trade up to the point where firm *k* has a spatially adjusted emission level higher than 310 by buying permits from firm *i*, and discharger *k* has a spatially adjusted emission level less than 90 to supply permits for *i*. With such a reallocation, firm *k* would not have to incur high level capital spending. In other words, only one firm needs to upgrade to a high level of capital cost and the other can avoid upgrading through trade. If no trade had been possible, each discharger would have abated 200 units, and they both would have to incur high levels of capital costs to upgrade each of their abatement facilities.

As such, the optimal abatement allocation should be re-characterized as one that minimizes the sum of the firms’ total abatement cost, namely, the combination of both “continuous” variable cost (operation and maintenance cost) and the “discrete” capital investment cost. Once the variable cost and capital investment cost are considered at the same time, the spatially adjusted "equi-marginal" condition that derived from the marginal cost trading may no longer give the least-cost results.

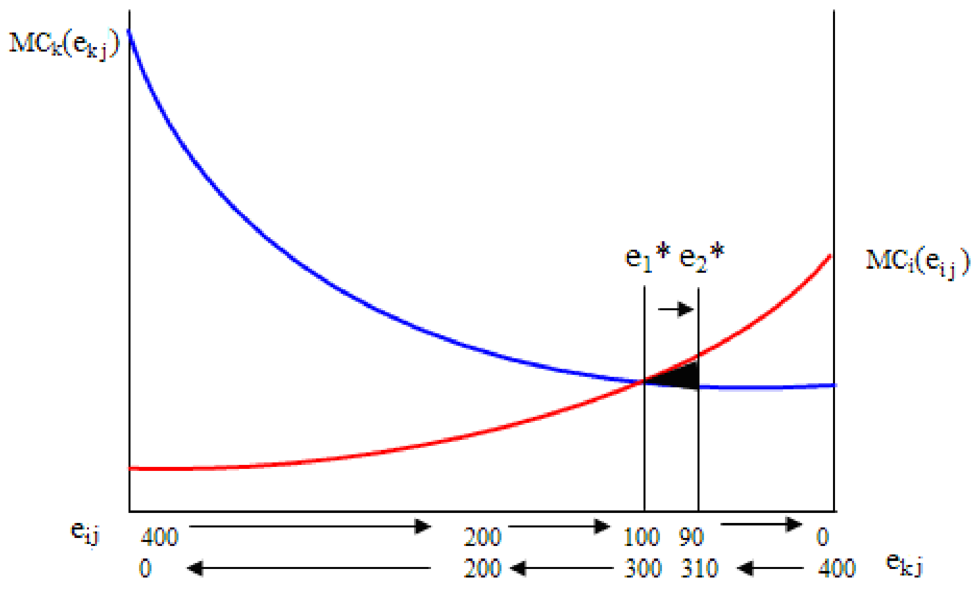


Figure 2.5-2 Deviation of the equi-marginal condition

The above graph demonstrates the optimal abatement allocation in which the total abatement cost is minimized. As in the previous discussion, the vector $(e_{ij}, e_{kj}) = (100, 300)$, corresponding to point e_1* the variable abatement costs are minimized (see Figure 2.2-1). However, when both variable costs and fixed capital costs are considered together, the vector $(e_{ij}, e_{kj}) = (100, 300)$ might not be the optimal allocation as it will induce high-level capital costs for both firms. Discharger *k* could avoid upgrading if trading arrived to abatement allocation e_2* or anywhere at its right; and discharger *i* could avoid upgrading if trading achieves $(e_{ij}, e_{kj}) = (300, 100)$ or anywhere at its left. Offsetting these potential capital costs savings is the fact that the further that the emission vector deviates from vector $(e_{ij}, e_{kj}) = (100, 300)$ the greater the variable abatement cost.

Accounting for both effects, the optimal abatement allocation must come from one of the three "candidates":

$(e_{ij}, e_{kj}) = (100, 300)$: *Firms' variable costs are minimized*

$(e_{ij}, e_{kj}) = (90, 310)$: *The "edge" where firm k just gets enough permits to avoid upgrade*

$(e_{ij}, e_{kj}) = (300, 100)$: *The "edge" where firm i just gets enough permits to avoid upgrade*

By comparing aggregate abatement costs at these three vectors, the least-cost allocation of pollution, or here pollution abatement responsibilities, can be identified. In this arbitrary example, suppose capital cost savings at $(e_{ij}, e_{kj}) =$ (90, 310) outweigh the efficiency lost in variable cost (represented by the shaded area), then $(e_{ij}, e_{kj}) =$ (90, 310) is the optimal allocation of abatements. If it does not, then the optimal allocation would be the interior solution $(e_{ij}, e_{kj}) =$ (100, 310).

In discussing the importance of considering fixed capital costs in trading, I recognize that capital cost considerations are not a novel issue in the pollution trading literature. Rose-Ackerman (1974), amongst other earlier studies, raised concerns about market incentives, specifically taxes, *vis-à-vis* substantial, discrete fixed costs likely to arise in water quality treatment. Later studies differ in the way to incorporate the lumpiness of abatement cost. Eheart designed an early computer iteration to optimize the abatement allocation accounting for the discrete costs (Eheart, 1980). He argued that, given the discrete nature of the possible treatment increments available, some dischargers were obliged to operate at a higher treatment level than the minimum requirement. Yet, Eheart did not make a clear distinction between variable abatement costs and lumpy capital upgrade costs. Instead, the marginal cost was approximated by the total cost divided by last technology step's corresponding incremental reduction achieved, the idea of which is echoed by Caplan (2008). In Caplan's investigation into what would be an appropriate approximation to firms' WTP for additional allowance, he similarly assumed that firms will only operate at the full capacity for each upgrade steps. Indeed, as I will discuss deeper in Chapter 5, Caplan's notion of "Average Cost" becomes less relevant once the variable component of abatement cost is introduced. In an empirical study, Rowles (2008) also seems to have imposed the similar type of "none-or-maximum capacity" type of assumption.

Hanley et al. (1998) accounted for the apparent 'lumpiness' of investment in abatement equipment by specifying the abatement cost to be "piece-wise linear stepped functions". In addition to the case of "none-or-maximum capacity", they also envisaged another scenario:

> ″…the reduction of each discharge could vary continuously between zero and the highest level of cut considered feasible, the associated cost being that of the 'next step'″. (Hanley, et al. 1998, pp 216)

Reflecting on these two scenarios, they note that the total abatement costs in the "none-or-maximum capacity" scenario are always higher since the constraints on abatement activity are more binding. They acknowledge that: "the actual situation depends on the method of reduction to be employed in each case, so that, *ceteris paribus*, real aggregate costs would probably lie in the region between those suggested in these scenarios" (Hanley, et al.,1998, pp. 216-217)

In comparison, Liao, Onal and Chen (2008) clearly distinguished between variable cost and capital cost. They decomposed total emission control cost into variable costs and fixed costs of installing equipment. Yet they imposed linearity of cost functions in order to derive the Average Shadow Prices which are based on average rather than marginal changes in pure integer linear programming problems. As an improvement, Sado et al. (2007) relaxed the linearity assumption of the variable abatement cost. However, this study did not explicitly incorporate the fixed capital upgrade cost into the optimization problem.

In addition to the several ways to deal with the lumpy capital costs, these studies also have different strategies to characterize the potential trading patterns. Eheart, et al. (1980) identified the potential market prices by finding a least-cost envelope in a study in Wisconsin. Bennett et al. (2000) adopted a similar approach to estimate the cost-savings for nitrogen trading on Long Island Sound. Specifically, "nitrogen control projects are selected in ascending order of cost until the required nitrogen reduction is achieved in a given area" (Bennett, et al., 2000, p. 3714). By focusing simply on deriving the least-cost envelope they could not specify who should be trading with whom, other than expressing that firms with costs above the uniform price would be seller while firms below this threshold would likely be buyer. Hanley, et al. (1998) as well as Liao, et al. (2008) applied a Mixed Integer Programming method to identify the minimum aggregate cost of cutting pollution to a given amount. The former focused on a one-point-ambient system, while the latter did not deal with the spatial effects of trading. Hence, neither of them addressed who should be trading with whom.

The contribution of this study is to bring these issues to the forefront in a formal empirical exploration of factors that could improve the cost-effectiveness of trading programs and enhance the viability of water quality trading. This study extends previous work on discrete abatement costs in three important ways: (1) It makes a clear distinction between variable abatement cost and fixed upgrade costs; (2) It relaxes the previous assumption that a firm's variable abatement cost needs be linear so that the marginal abatement cost can vary even if the upgrade level is fixed, allowing for an interior solution; (3) It directly incorporates the trading equation into the least cost model so that the pattern of trades can be identified explicitly.

To investigate these issues, a second modification to the standard model (problem B) is needed to account for discrete fixed costs associated with upgrading to enable treating effluent to a lower concentration level. In setting up the standard model, Hung and Shaw assume that the abatement cost function is “increasing and strictly convex”, consistent with the marginal cost approach utilized by Montgomery (“convex and twice differentiable"), Tietenberg (“continuous cost function”) and others. However, as suggested, the continuity of abatement cost is somewhat an unrealistic assumption and total abatement cost should be decomposed into variable costs and fixed capital investment costs. In other words, total abatement cost function should be seen as being controlled by two arguments, the continuous variable e_i and discrete variable x_i which denote final effluent level and capital investment level respectively. Specifically, equation (2.5-1) describes the decomposition of total annual abatement cost:

$$C_i(e_i, x_i) = OM_i^{x_i}(e_i) + CC_i(x_i) \qquad \text{-------(2.5-1)}$$

The total annual abatement cost, $C_i(e_i, x_i)$, is determined by continuous variable e_i and discrete integer variable x_i. The right hand side $OM_i^{x_i}(\cdot)$ denotes the Annual Operation and Maintenance cost (variable cost) of firm *i* with investment level x_i, at final effluent level e_i, and $CC_i(x_i)$ denotes the Annual Capital Cost of firm *i* when it upgrades the capacity to the level x_i. Note further that x_i is used as a superscript in the annual Operation and Maintenance (OM) cost function. This is because the facility upgrade of a firm may affect the variable cost function of that firm. Although, how exactly the OM cost functional form evolves with different upgrade levels remains an open empirical question.

Further assume that the maximal abatement capacity of each firm is determined by its own facility upgrade level x_i. Hence, each firm's maximal achievable level of abatement is bounded by a function of its upgrade level x_i :

$$e_i \geq \phi_i(x_i) \qquad \text{-------(2.5-2)}$$

Consequently, we have the following cost minimization problem, which considers explicitly the allocation of fixed capital investment, as well as the optimal abatement decisions among dischargers:

$$\text{Problem D}\quad \begin{cases} \min_{e_i, x_i, \mathrm{T}_{ki}} Z = \sum_{i=1}^{n} C_i(e_i, x_i) = \sum_{i=1}^{n} [OM_i^{xi}(e_i) + CC_i(x_i)] & \text{-----(2.5-3)} \\ \text{subject to:} & \\ e_i - \sum_{k=1}^{n} t_{ki}\mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} \le \overline{\mathrm{T}}_i \ \ (\, i = 1, ..., \mathrm{n}) & \text{----(2.5-4)} \\ t_{ki} = \dfrac{d_{k[i]}}{d_{i[i]}} \quad \forall i, k & \text{----(2.5-5)} \\ \phi_i(x_i) \le e_i \le e_i^0; \quad (\, i = 1, ..., \mathrm{n}\,) & \text{---(2.5-6)} \\ \mathrm{T}_{ki},\ \mathrm{T}_{ik} \ge 0 \qquad \forall i, k & \text{---(2.5-7)} \\ x_i \in Z_i \qquad (\, i = 1, ..., \mathrm{n}\,) & \text{---(2.5-8)} \end{cases}$$

The first inequality constraint (2.5-4) is equivalent to that presented in problem B (constraint 2.3-4). The second inequality (2.5-6) gives the constraint of maximal abatement capacity, equivalent to the lower bound of effluent level. In (2.5-8), each level of upgrade x_i belongs to a subset of integers Z_i . Note that each integer set Z_i may differ, meaning each firm faces a different spectrum of upgrade choices. In addition, since the capital investment is irreversible, each firm can only upgrade but never downgrade their facility level. Consequently, if firm *i* has a certain level of existing capacity to remove pollutant, than "0" must not be in its choice set Z_i

For the bench mark specification (Problem A), Montgomery (1972) has shown that the optimal vector of effluents exists. Hung and Shaw (2005) prove that trading constraints in problem B (equation 2.3-4) are exactly the same as the environmental constraints in problem A (equation 2.2-6). Therefore the optimal effluents allocation exists under the TRS and is exactly the same as the least cost effluents allocation under the cost-effective bench mark defined by problem (A). Moreover, Hung and Shaw also prove that the competitive equilibrium coincides with the optimal solution in problem B, concluding that the market equilibrium under TRS can always achieve cost-effectiveness both through simultaneous trading and sequential bilateral trading. It is important to note that most of these "nice" theoretical results demonstrated by Montgomery as well as Hung and Shaw rely heavily on the differentiability of the objective functions. Yet, as we relax the assumption of continuity in our analysis, we can no longer apply the similar kind of "derivative arguments".

Then, does an optimum always exist for problem D? The answer is yes. Since the objective function apparently has discontinuous arguments in problem D, it takes us a short detour to make the following arguments.

For any given vector of feasible upgrade allocation $\overline{X} = (\overline{x}_1, \overline{x}_2 ....\overline{x}_n)$, the upgrade level of each firm is fixed and so the capital investment cost of each firm is constant. Hence the objective function becomes $\sum_{i=1}^{n} C_i(e_i, \overline{x}_i)$ which would be continuous. And since the constraint set is compact $\Re^n$, the Weierstrass theorem guarantees the existence of minimum value for $\sum_{i=1}^{n} C_i(e_i, \overline{x}_i)$. In this manner one can also think of this minimization problem as a two-stage search process----search the minimum abatement costs for each chosen upgrade allocation, and then search the optimal upgrade allocation that gives the global minimum cost. This argument is valid as there are only a finite number of feasible upgrade vectors.

A more challenging question is: can one achieve the optimal solution in problem D through competitive equilibrium? Again, without differentiability of the cost functions, we cannot adopt the usual proof by applying the Kuhn-Tucker theorem to show the shadow price for each firm coincides with the market price of permits for that firm. Indeed, how to achieve this optimal under market conditions involves fairly complex issues, which I would like to defer to Chapter 5. For the moment however, I will discuss the range of prices that might be attained in the spot market, given one specific upgrade allocation $\overline{X} = (\bar{x}_1, \bar{x}_2 ....\bar{x}_n)$.

Relationship Between the Integer Model and the Basic Model

The standard model specified in section 2.2 rests on the ideal of open markets, in which firms buy and sell pollution allowances based on marginal abatement costs through a spot price mechanism. It is as if all firms have made their capacity choices, and so each firm minimizes only the annual variable costs of pollution abatement. In this sense, the standard model in section 2.2 captures only one specific branch of the integer model. i.e. once each firm's upgrade level is fixed by the specific investment vector[15] $\overline{X} = (\bar{x}_1, \bar{x}_2 ....\bar{x}_n)$, the integer model (problem D) is boiled down to the standard convex programming model (Problem $\overline{D}$).

[15] This specific investment vector is associated with the upgrade requirement of each firm such that each firm has existing capacity to abate to the designated concentration level by itself.

For the fixed $\overline{X}$

Problem $\overline{D}$

$$\begin{cases} \min\limits_{e_i, T_{ki}} \sum_{i=1}^{n} C_i(e_i, \overline{x}_i) = \sum_{i=1}^{n} [OM_i^{\overline{x}i}(e_i) + \overline{CC_i(x_i)}] & \text{---(2.6-1)} \\ \text{subject to:} & \\ e_i - \sum_{k=1}^{n} t_{ki} \mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} \le \overline{T}_i \quad (i = 1, ..., n) & \text{---(2.6-2)} \\ t_{ki} = \dfrac{d_{k[i]}}{d_{i[i]}} \quad \forall i, k & \text{---(2.6-3)} \\ \overline{\phi_i(x_i)} \le e_i \le e_i^0 \quad (i = 1, ..., n) & \text{---(2.6-5)} \\ T_{ki}, T_{ik} \in R_+ \quad \forall i, k & \text{---(2.6-6)} \end{cases}$$

Note that once vector X is fixed, the domain of the objective function above becomes a convex set, in addition, all the constraints are linear functions, hence the Arrow-Hurwicz-Uzawa constraint-qualification is trivially satisfied. Therefore, as long as the cost functions are convex on the domain, the Kuhn-Tucker conditions will give us the constrained global minimum.

The corresponding Kuhn-Tucker equation for this model is:

K(e_i, T_{ki}, λ_i, α_i, β_i)

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

---(2.6-7)

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

$\partial K / \partial e_i = Z_i' + \lambda_i + \alpha_i - \beta_i = 0$; (i = 1,…,n) ---(2.6-8)

$\partial K / \partial \mathrm{T}_{ki} = -t_{ki}\lambda_i + \lambda_k \le 0$ (k = 1,...,n; i = 1,…,n) ---(2.6-9)

$\mathrm{T}_{ki} \cdot (-t_{ki}\lambda_i + \lambda_k) = 0$ (k = 1,...n; i =1,…,n) ---(2.6-10)

$\partial K / \partial \lambda_i = e_i - \sum_{k=1}^{n} t_{ki} \mathrm{T}_{ki} + \sum_{k=i}^{n} \mathrm{T}_{ik} - \overline{T}_i \le 0$ (i = 1,…,n) ---(2.6-11)

$$\lambda_i \cdot (e_i - \sum_{k=1}^{n} t_{ki}\mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} - \overline{T}_i) = 0 \;\; (i = 1,\ldots,\mathrm{n}) \qquad \text{---(2.6-13)}$$

$$\partial K / \partial \alpha_i = e_i - e_0 \leq 0 \;\; (i = 1,\ldots,\mathrm{n}) \qquad \text{---(2.6-14)}$$

$$\alpha_i \cdot (e_i - e_0) = 0 \;\; (k = 1,\ldots\mathrm{n};\; i = 1,\ldots,\mathrm{n}) \qquad \text{---(2.6-15)}$$

$$\partial K / \partial \beta_i = \overline{\phi_i(x_i)} - e_i \leq 0 \;\; (i = 1,\ldots,\mathrm{n}) \qquad \text{---(2.6-16)}$$

$$\beta_i \cdot (\overline{\phi_i(x_i)} - e_i) = 0 \;\; (k = 1,\ldots\mathrm{n};\; i = 1,\ldots,\mathrm{n}) \qquad \text{---(2.6-17)}$$

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

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

In all, the results from Kuhn-Tucker condition can be summarized into six facts related to willingness to pay and willingness to sell an allowances in an *ex post* spot market. The term, "*ex post"*, refers here to the short-run or spot-market trading case in which the market trading takes place after firms make their capacity choices.

(1) For a discharger operating at an interior solution, its willingness to pay (WTP) and willingness to sell (WTS) are unique, being equal to its marginal cost of abatement.

(2) Trade between any pair of the "interior" dischargers has a unique price ratio which follows $t_{ki} == \frac{d_{k[i]}}{d_{i[i]}} = \frac{\lambda_k}{\lambda_i}$

(3) For a discharger constrained by the "primary" or uncontrolled emission rate e_i^0*, it is willing to sell the excess allowances at any positive price. In other words, WTS is NOT unique. On the other hand, WTP is trivial as the firm is not allowed to increase its effluent any further.*

(4) For a discharger who has reached its physical abatement capacity but has not yet met the required environmental standard, its willingness to pay for additional permits is higher than its marginal abatement cost. Indeed, if one assumes that the penalty of non-compliance is infinite, then the firm's WTP is not bounded from above. [16]

[16] This results from the assumption that the firm cannot upgrade its treatment capacity in the short term.

(5) Trade between an "interior" discharger and a discharger operating at the "edge" of its capital upgrade does not have a unique price ratio, while it is bounded from above (below) by the "interior" discharger's WTP (Or WTS).

(6) Trade between any pair of the "edge" dischargers does NOT have a unique price ratio, the actual trading price of permits depends on bargaining between the two dischargers. The possible price ranges from zero to positive infinity.

In closing this section, I would like to reiterate an important point: The above WTP and WTS relationships are derived under a spot market environment, where firms trade emission allowances marginally according to the market price. Since firms cannot expand their abatement capacity in the short run, they need to make their capacity choices before entering the spot market. From a programming perspective, the resulting *ex post* cost minimization problem only yields the local minimum on one specific branch of the integer capacity choices. To find the potential global least cost, one has to consider all feasible combinations of discrete investment choices. A mixed integer nonlinear programming model based on the setup in problem (D) can provide a solution. It is toward this objective that the next two chapters are directed.

CHAPTER THREE

THE EMPIRICAL SPECIFICATION OF THE COST FUNCTIONS AND THE DATA FOR THE UPPER PASSAIC RIVER BASIN CASE STUDY

Introduction

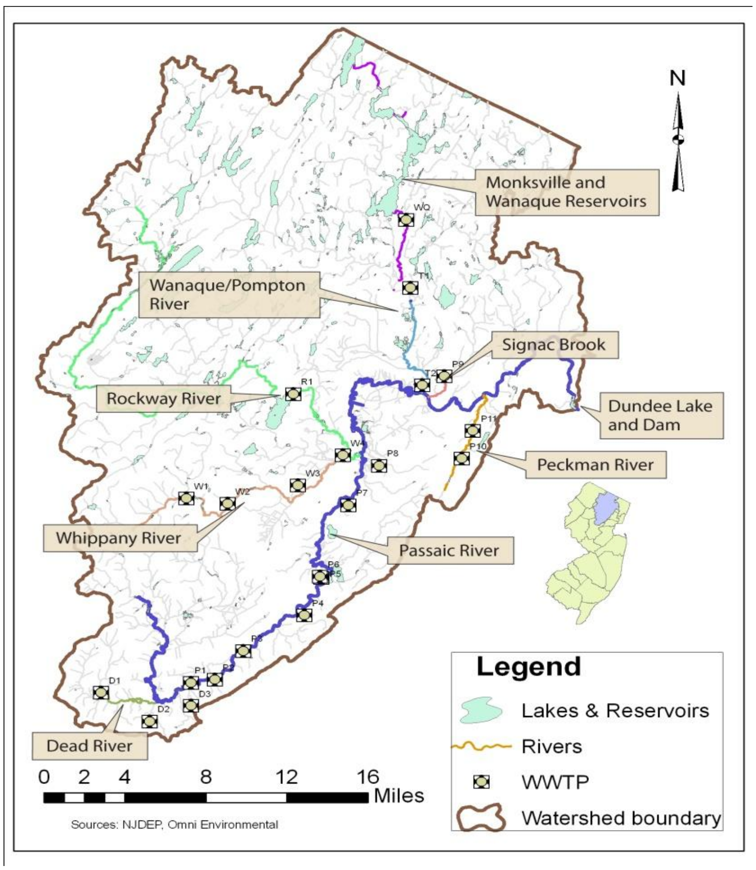
Several components are needed in order to assess the potential cost savings associated with implementing a phosphorous trading program in the Upper Passaic River Basin relative to a uniform standard for emissions. Data for the environmental standards and the allowable effluent for each source are required as parameters of the cost minimization problem. The transfer coefficients or trading ratios between each pair of sources must be obtained to identify trading opportunities throughout the watershed. Finally, in order to conduct the cost minimization "globally", it is necessary to have empirical specifications of both operating & management and capital cost functions over the entire feasible domains. The purpose of this chapter is to develop and describe the data and functional specifications needed to assess cost savings associated with a trading program that conforms to the management area approaches discussed in the preceding chapter and for which minimum cost solutions can be obtained using a Mixed-Integer Nonlinear Programming model.

A Geographical Overview of the Passaic Upper River Basin

The Upper Passaic River Basin encompasses 803 square miles, with 669 square miles of the watershed in northeastern New Jersey and the remainder extending northward in New York State. Approximately one-quarter of New Jersey's population lives within the boundaries of the basin.

As shown in Map 3.2.1, 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 Basin 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, and begins flowing in a northeasterly 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, providing the primary water supply for the Monksville and Wanaque Reservoirs. Some of this natural supply is retained in these reservoirs, which serve as a drinking water supply for Newark, a city located outside the watershed. The remainder, augmented by waters from a number of other minor tributaries, flows 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 dry periods with low water inflow, a water intake (Wanaque South Intake) at the south end of the Pompton river, near the confluence of the Pompton and the Passaic, diverts water through a pumping station to the Wanaque Reservoir, which is located upstream of the Pompton River. This is to maintain the water level in the reservoir. The reservoir is the primary source of water for consumers in Newark. This diversion fundamentally alters the hydrology of the watershed (Obrupta, et al, 2008): in an extremely dry season, the quantity of water diverted can be so great that the pumping station actually draws water from the Passaic, which is a few hundred feet downstream from the pumping station. Under these extreme diversion conditions, the Wanaque Reservoir actually receives water from the Upper Passaic. Thus, in certain drought years, this large reservoir essentially obtains water from nearly all areas of the watershed, most of which are naturally downstream. High quality water in the watershed's reservoirs is essential in maintaining people's health in the region, as well as for maintaining habitat for aquatic species and for providing recreational opportunities for residents. Because all streams and the reservoirs are connected by waterways, the water quality of reservoirs is inextricably tied to that of the streams and rivers. As is discussed below in this chapter, the trading ratios used in the water quality trading program are designed to account for the variation across several diversion scenarios, and, hence, to ensure that water quality standards are met at the Wanaque reservoir as well as at Dundee Lake and Dam.



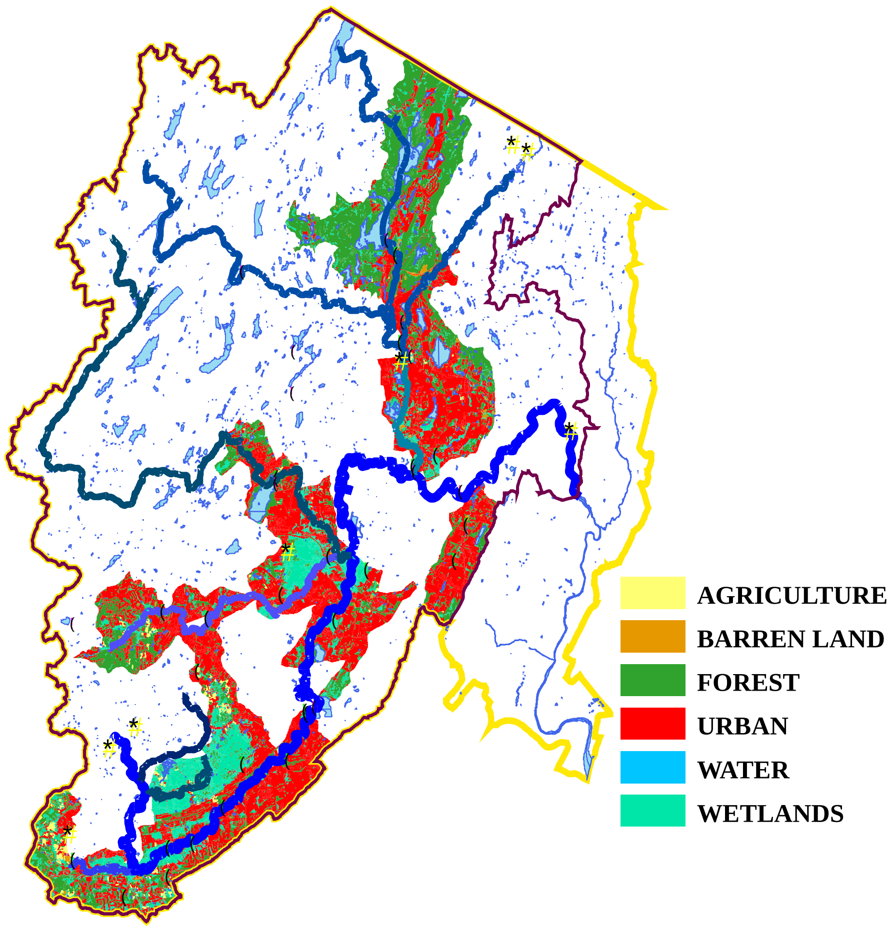
Map 3.2-1: The Upper Passaic River Basin. The square boxes indicate the 22 Wastewater Treatment Plants included in this study.
Source: NJDEP, Omni Environmental

A brief background of the case study

The rivers and streams in the watershed flow through some highly urbanized areas, although there are some areas (primarily in the North) of the watershed that remain forested (see Map 3.3-1). As the case of many watersheds in urban or urbanizing areas throughout the country, the quality of surface water within the Passaic River Watershed is threatened by population pressure. Several years ago, the New Jersey Department of Environmental Protection (NJDEP) funded watershed characterization and assessment studies of this watershed (North Jersey District Water Supply Commission, NJDWSC, 2002). These studies revealed that surface water quality standards for nutrients, dissolved oxygen, PH, temperature, pathogens, metals and pesticides are often exceeded. Consequently, most of the water resources within the watershed have been classified as being "impaired" under Clean Water Act, Section 305d, which states that "impaired water bodies are those that cannot meet numeric or narrative ambient based water quality standards established for the designated use or uses (e.g. recreational, water supply, aquatic species) for that water body." (EPA website, accessed in 2009) [17] For the Upper Passaic River Basin phosphorus is of particular concern at this time: a 2005 report by Najarian Associates documented that current discharges of phosphorus from Waste Water Treatment Plants (WWTPs) along the Passaic River pose one of the most serious threats to the quality of the Wanaque Reservoir. Although water from the Passaic River accounts for only 6% of the total inflow into the reservoir, Najarian Associates (2005) estimates that 35% of total phosphorus load in the reservoir comes from the Passaic River. Much of

[17] Depending on the degree to which designated uses are supported, States place assessed waters into the following categories (U.S. Environmental Protection Agency 2000b): (1) fully supporting overall use; (2) threatened overall use; (3) partially supporting overall use; (4) not supporting overall use; and. (5) not attainable.

this phosphorus loading comes from large WWTPs that release water into the Passaic River (NJDWSC, 2002). Thus, reducing phosphorus loads from these WWTPs has been identified as a critical element in improving the water quality of the reservoir.



Map 3.3-1: The land use of the Passaic Watershed
(Source: TRC Omni Environmental Corp)

To maintain water quality, the NJDEP has targeted 22 of the largest municipal WWTPs in the watershed for improvements in water quality by limiting their discharges of effluents into rivers in the watershed. As shown in Map 3.2-1, eight of those WWTPs are located on the Upper Passaic River, coded from P1 to P8, working from upstream to downstream, while other WWTPs are located on various tributaries: three of these WWTPs are on the Dead River (D1 to D3); five are on the Whippany River (W1 to W4) and Rockaway River (R1); one WWTP, (P9), is located on Signac Brook and two others are on the Peckman River (P10 and P11). Finally, the Pompton River has three WWTPs coded as WQ, T1 and T2.

The size of the plants varies significantly across WWTPs. The largest WWTP is W4, with an average flow around 12.58 Million Gallons per Day (MGD), whereas the smallest WWTP, P4, has an average flow around 0.12 MGD. The current phosphorous concentrations treated by WWTPs range from 0.16 mg/L (WQ) to 3.28 mg/L (P5). Only five out of 22 WWTPs, (P3, W1, W2, WQ, T1) currently treat phosphorous concentrations to below 1 mg/L. The details for each of the 22 WWTPs regarding the flow levels and phosphorous concentrations are reported in Table 3.3-1.

To establish the proper cap for the effluents, a Total Maximum Daily Load (TMDL) rule for phosphorus was adopted for the Non-Tidal Passaic River Basin in April 2008 (NJDEP, 2008). The TMDL specifies the maximum amount of a pollutant that a water-body can receive and still meet water quality standards, as well as an allocation of that load among the various sources of that pollutant[18] (U.S. EPA, Section 303d, TMDL program guidance). For the Upper Passaic River Basin, the final TMDL rule specifies that:

> "Except as necessary to satisfy the more stringent criteria…or where watershed or site-specific criteria are developed…phosphorus as total P shall not exceed 0.1 [mg/l] in any stream, unless it can be demonstrated that total P is not a

[18] "Water Quality Standards are the foundation of the water quality-based pollution control program mandated by the Clean Water Act. Water Quality Standards define the goals for a waterbody by designating its uses, setting criteria to protect those uses, and establishing provisions such as antidegradation policies to protect waterbodies from pollutants". (U.S EPA, Water Quality Standards for Surface Waters http://water.epa.gov/scitech/swguidance/waterquality/standards/)

limiting nutrient and will not otherwise render the waters unsuitable for the designated uses." (NJDEP, 2008, p. 15)

While this rule is intended to satisfy the water quality objectives of the Clean Water Act, concern was expressed by policy makers and WWTP operators in the Upper Passaic River Basin that meeting such a TMDL for total phosphorus may be extremely costly under a standard regulatory strategy, where water quality concentrations are uniformly capped throughout the watershed and every WWTP is required to treat to a unique concentration level for Phosphorus. Each of these concerns has been addressed through the Non-Tidal Passaic River Basin Water Quality Trading Project (PRB-WQTP), of which this thesis research is a part.

As part of the TMDL and the PRB-WQTD studies, a hydrodynamic model and a water quality model were developed for the Upper Passaic River Basin (Omni Environmental, 2007a). Using the terminology developed in Chapter 2, this study, coupled with the Najarian Associates' (2005) LA-WATERS model, identified the Wanaque Reservoir and Dundee Lake as potential hotspots. That is, this hydrodynamic study demonstrated that total phosphorous was not considered to be a limiting nutrient in other areas of the watershed due to specific hydrological characteristics such as the speed of water flow, depth of water, and streamside shading. Based on this hydrodynamic study and the flexibility allowed in the TMDL language quoted above, the NJDEP proposed watershed criteria be established in only those two locations as the best means to ensure protection of the designated uses in the watershed (N.J.A.C 7:9B-1.5(g)3). The watershed criteria were proposed in terms of a seasonal average concentration of the response indicator, chl-*a*, specifically, a seasonal average of 10 μg/L chl-*a* in the Wanaque

Reservoir and a seasonal average of 20 μg/L chl-*a* in Dundee Lake (NJDEP, 2008). Further reflecting concerns for political fairness, the effluent caps for wastewater treatment facilities were set on an equitable basis to be a long term average (LTA) effluent concentration of 0.4 mg/l of total phosphorus for all wastewater dischargers rather than specifying individual effluent standards for each WWTP.

With respect to phosphorus treatment, only six of the 22 major WWTPs in this watershed (those marked by an asterisk [*] in Table 3.2.1) presently treat for phosphorus before discharging effluent into streams, and most of these are relatively small in terms of daily flow. Moreover, four of the six WWTPs that currently remove phosphorus will also need some additional capital investment as the NDJEP requirements are beyond the current capacity for treatment. Consequently, if each WWTP is forced to meet the 0.4 mg/L total phosphorous concentration requirement, it is anticipated that there will be a heavy financial burden on many WWTPs, subsequently falling largely on water users and taxpayers throughout the watershed.

Thus, in an effort to achieve the intended environmental benefit at lower cost, both the government and the industry are interested in determining the extent to which a water quality trading program can reduce the costs of meeting the water quality standards. With this in mind, an active coalition of point sources, the NJDEP, a basin-wide public interest group, trade associations, and a team of experts from Rutgers and Cornell Universities were assembled to investigate the feasibility of an emissions trading program under the US EPA funded PRB-WQTP. Much of the data needed for empirical specification in this thesis has been developed by this study team.[19]

[19] In particular, the environmental standards and the trading ratios for the study are to be generated through the combined efforts of the EPA, the NJDEP, Rutgers University and Omni environmental L.L.C.

Table 3.3- 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 0.4mg/l (lbs/year)#
D1	Dead	1.76	16,780	3.13	2,144
D2	Dead	0.15	845	1.85	183
D3	Dead	0.31	1,804	1.91	378
P1	Passaic	1.00	8,011	2.63	1,218
P2	Passaic	0.36	1,831	1.67	439
P3*	Passaic	1.57	2,869	0.60	1,913
P4	Passaic	0.12	559	1.53	146
P5	Passaic	2.41	24,079	3.28	2,936
P6	Passaic	0.90	4,057	1.48	1,097
P7	Passaic	2.61	20,909	2.63	3,180
P8	Passaic	3.75	18,505	1.62	4,569
W1*	Whippany	1.90	4,862	0.84	2,315
W2*	Whippany	3.03	5,186	0.56	3,704
W3	Whippany	2.03	18,505	2.83	2,473
W4	Whippany	12.58	114,192	2.98	15,327
R1*	Rockaway	8.81	39,180	1.46	10,734
WQ*	Wanaque	1.00	487	0.16	1,218
T1*	Pompton	0.86	838	0.32	1,048
T2	Pompton	5.33	34,744	2.14	6,494
P9	Preakness Brook	7.47	51,652	2.27	9,602
P10	Passaic	2.46	23,004	3.07	2,997
P11	Passaic	1.26	8,636	2.25	1,535
Total			401,535	2.13**	75,650

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

Model Parameters

The management area model, based on meeting water quality objective at the Waunakee Intake and Dundee dam, provides a framework for the subsequent discussion. Recall that the final mathematical framework adopted in the case study is specified in Chapter 2 as Problem (D):

Problem D

$$\min_{e_i, x_i, \mathrm{T}_{ki}} Z = \sum_{i=1}^{n} C_i(e_i, x_i) = \sum_{i=1}^{n} [OM_i^{xi}(e_i) + CC_i(x_i)] \qquad \text{---(3.4-1)}$$

subject to:

$$e_i - \sum_{k=1}^{n} t_{ki} \mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} \le \overline{\mathrm{T}}_i \quad (\, i = 1, ..., \mathrm{n}) \qquad \text{---(3.4-2)}$$

$$t_{ki} = \frac{d_{k[i]}}{d_{i[i]}} \qquad \text{---(3.4-3)}$$

$$\phi_i(x_i) \le e_i \le e_i^0 \qquad \text{---(3.4-4)}$$

$$\mathrm{T}_{ki},\ \mathrm{T}_{ik} \ge 0 \qquad \text{---(3.4-5)}$$

$$x_i \in Z_i \quad (\, i = 1, ..., \mathrm{n}\,) \qquad \text{---(3.4-6)}$$

where T_{ki} is the number of permits sold by *k* to *i;* e_i is the final effluent at *i* measured in terms of load, (the effluent load after treatment at *i*); x_i is an integer indicating the level of fixed capital upgrade for discharger *i*; $OM_i^{xi}(e_i)$ is the annual OM cost function at upgrade level x_i for source *i;* $CC_i(x_i)$ is the annual capital cost associated with upgrade level x_i; e_i^0 is the initial unregulated effluent at *i;* t_{ki} is the trading ratio between seller *k* and buyer *i*, whose value depends on the demarcation of management areas; $\overline{\mathrm{T}}_i$ is the predetermined effluent cap for discharger *i* also measured in terms of load. The choice variables, e_i, x_i and T_{ki}, are endogenously determined in the model. Effluent caps $\overline{\mathrm{T}}_i$ and natural diffusion rates $d_{k[i]}$ are exogenous parameters to be specified in the following sections.

Effluent Caps (Initial Allocation of Discharge Allowances) -- $\bar{T}_i$

In the mathematical model developed in Hung and Shaw, the effluent load caps are derived by taking into account background and natural levels of pollutant and inflow from upstream sources adjusted for transfer coefficients. In this analysis, however, the effluent caps are derived based on the New Jersey Pollutant Discharge Elimination System (NJPDES) in which the background and natural levels of pollutant and the effluent from upstream sources are adjusted for natural diffusion rates, in a way that is consistent to Hung and Shaw's framework. In addition, the TMDL approach also includes a margin of safety to account for seasonal variation in water quality and the potential for un-modelled variation on water quality. Formally, The TMDL calculation is:

$$TMDL = WLA + LA + MOS$$

where *WLA* is the sum of waste load allocations (to point sources), *LA* is the sum of load allocations (nonpoint sources and background), and *MOS* is the margin of safety. (The U.S. EPA website, accessed in 2009). Referring to this framework, the TMDL study for the Passaic River basin concluded that the WLA for total phosphorus, expressed in terms of long term average effluent concentration, was 0.4 mg/l for each of the 22 WWTPs in order to achieve water quality goals in the Wanaque Reservoir and Dundee Lake.[20]

[20] A notable exception is dischargers downstream of the Pompton / Passaic River confluence (hereafter referred to as Confluence) whose LTA will be limited to 0.4 mg/l on a *seasonal* rather than *annual* basis (NJDEP, 2008). This additional complication is not addressed in this thesis.

Note that the discharge allowance $\overline{T}_i$ in problem (D) is measured in load as transactions must occur in units of mass, rather than in concentrations for trading to be viable. Therefore, the 0.4 mg/l concentration restriction established by the TMDL study needs to be translated to the effluents caps in units of mass. Here I use a recent history, three years (2005-2008), of actual discharger flow, rather than permitted flow, as the basis for conversion. For the Passaic Watershed, the actual discharger flows on average are about 63% of the permitted flows. Thus, if permitted flows were used instead to determine allocations, sellers would receive allowances for more pounds than they actually could emit, posing a risk to the water body and having a fundamental effect on the supply and demand for permits. Also the prior history of actual discharger flow, rather than actual discharger flow determined at the end of the trading period, provides a practical basis for allocations because potential buyers and sellers have clearly defined allocation before making any trades. It would increase uncertainty to design a credit trading such that allocations were not known until after trades had been agreed to (Shabman, Stephenson and Shobe 2002). Using a recent history of actual discharger flows, termed "Anticipated Actual Discharger Flow (AADF)",[21] as the basis for allocations helps to clearly define property rights, an essential precursor for a successful trading program. (See Boisvert, et al. (2010) for a discussion of the importance of clearly establishing property rights in a well-functioning trading program). In this case study, the AADF is equal to the average of the actual daily discharger's flow from 2005-2008. Finally, the effluent cap $\overline{T}_i$ is converted based on the following formula:

[21] Anticipated Actual Discharger Flow refers to the average flow from a discharger over the past three calendar years prior to the start of watershed trading.

$$\bar{T}_i(lbs/Y) = 3{,}046.063 \times 0.4(mg/L) \times AADF_i(MGD)$$

where effluent caps are in pounds (lbs). per year, which is the product of a conversion coefficient 3046.063143, 0.4 mg/l long term average concentration and Anticipated Actual Discharger Flow in million gallon per day. The conversion coefficient is calculated based on the formula below:

$$3{,}046.063 = 365(\text{day}) \times 3.7854 \times 10^6(\text{liters per million gallon}) \times 1/453{,}592.37(\text{pound per milligram})$$

Demarcation of the Management Areas

The structure and trading ratios in problem D are intimately related to the identification of critical locations in the watershed and the organization of management areas. In this section I explore three different management area configurations consistent with meeting the objectives of the Upper Passaic River TMDL, distinguishing between the Single Source Management Area Approach, in which each source is treated as a separate management area, and two alternative management area approaches that group sources based on a more limited set of critical areas in the Upper Passaic River Basin. These will be referred to as the Multiple Source Management Area - Alternative One and the Multiple Source Management Area - Alternative Two, both of which are specific to the hydrological structure of the Upper Passaic River Basin and the need to accommodate variations in hydrologic flows and associated “diversion scenarios” across seasons. This nomenclature will be used throughout the remainder of this thesis.

The presentation of alternative management area approaches is aided by the use of several simplified schematics of the Upper Passaic River Basin in Figures 3.6.1-1 to 3.6.2-1. The schematics are used to capture the basic spatial relationships between sources and critical locations in the watershed.

Single Source Management Area Approach

Using the Single Source Management Area Approach, all sites in the watershed are identified as critical locations. (See Figure 3.6.1-1, the WWTPs represented by black dots are overlapped by critical locations represented by red triangles). Therefore, each WWTP is treated as a separate management area. Downstream WWTPs are not permitted to sell to upstream WWTPs, as their direct physical effect on water quality upstream is zero. If WWTPs lie on different tributaries the trading ratio is again set to zero and trades of allowances thus do not occur. Thus, the Single Source Management Area Approach is an extreme version of the M.A. Approach that best comports with Hung and Shaw's presentation.

Analogous to Hung and Shaw's TRS, the Single Source M.A. is applicable to all watersheds, and it meets the water quality objectives at all sites in the watershed corresponding to the initial allocation of allowances under the TMDL and NPDES permitting program. On the other hand, the trading opportunities under the Single Source M.A. Approach may be limited. Since allowances can only be sold downstream in the Single Source M.A. Approach, the realization of such trades will occur only if upstream WWTPs have lower abatement costs than downstream WWTPs after appropriate adjustments for the transfer coefficient.

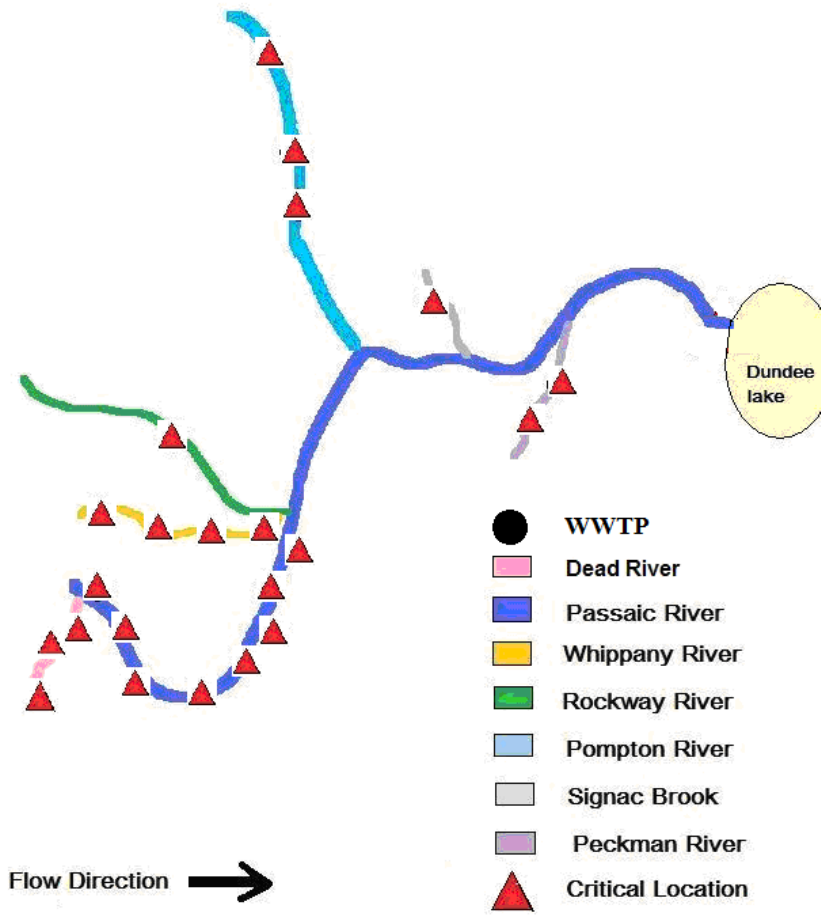


Figure 3.6.1-1 Simplified schematics of the Upper Passaic River Basin – All sites are identified as critical locations

Multiple Source Management Area Approach – Alternative One

As noted in the previous section, Dundee Lake and Wanaque Reservoir were identified as potential phosphorus-induced hot spots based on interpretation of the Omni Environmental (2007a) study, providing the critical locations for organizing the management areas. Dundee Lake is the natural watershed outlet while Wanaque Reservoir is the state's largest reservoir system.

An important hydrological feature of this watershed is that the surface water is pumped to the Wanaque Reservoir from intake points located near the confluence of Passaic River and Pompton River, with the rate of diversion varying with consumer demand, water availability and regulatory restrictions. This fundamentally alters the hydrology of the watershed, and diversions to the Wanaque Reservoir transform basic relationships of upstream and downstream between certain locations in the watershed. For example, during a “normal” rainfall season there is no diversion of water, and hence the Passaic River is not a source of water to the Wanaque reservoir. However, when the Wanaque Reservoir does require high volumes of diverted inflow, the Upper Passaic River waters can be diverted to the reservoir and the Upper Passaic becomes "upstream" of the reservoir (Najarian Associates 2005). Consequently the Wanaque Reservoir is vulnerable to phosphorus-induced hot spots from water quality trading only when surface water diversions occur; otherwise, none of the effluents from the 22 WWTPs enters the Wanaque Reservoir. In this way, the watershed hydrology fluctuates with the extent of surface water diversions, thus, the dynamic relationships of upstream and downstream must be accommodated in the trading models.

In contrast, the Dundee Lake receives upstream phosphorus loads under all flow conditions, regardless of the occurrence of surface water diversions. (Omni Environmental 2007a) Therefore, the lake is always vulnerable to phosphorus-induced hot spots from water quality trading and so it is a “must-protected” critical location under all hydrological conditions. The different demarcations of management areas associated with the three diversion scenarios are discussed in further details below. This discussion is aided by the use of several simplified schematics of the Upper Passaic River Basin in

Figures 3.6.2-1 to 3.6.3-1. The schematics are used to capture the basic spatial relationships in the watershed.

No diversion:

In the "no diversion" scenario, the Wanaque South intake is not activated. Thus, the Wanaque Reservoir does not receive any phosphorus loads from the 22 WWTPs in the trading project, as depicted in the schematic. The Wanaque South Intake is not a Critical Location in the No-Diversion hydrological setting. (See Figure 3.6.2-1.) This leaves Dundee Lake as the only Critical Location to be protected.

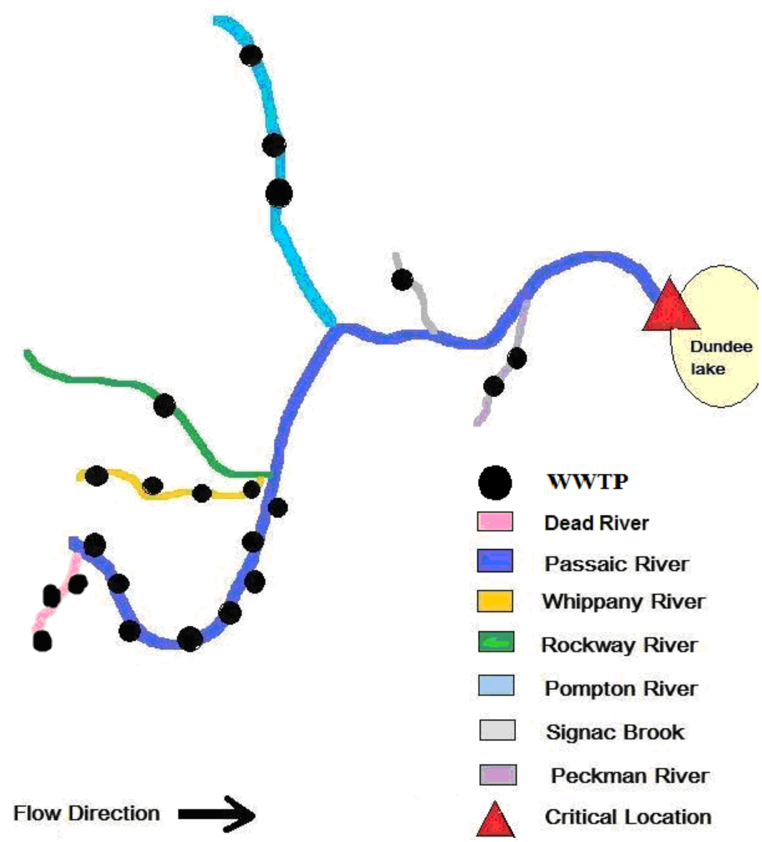


Figure 3.6.2-1 Simplified schematics of the Upper Passaic River Basin – one Critical Location for no diversion scenario

Diversion:

In the "diversion" scenario, the Wanaque South intake pumping demand is met fully by flow in the Pompton River and no water is drawn from the Passaic River. In this case, the Wanaque South intake located on the downstream portion of the Pompton river must be identified at as a second Critical Location in addition to Dundee Lake. (See Figure 3.6.2-2) This is because water, and hence some effluent, from WWTPs in the Pompton river is diverted upstream and flows into the Wanaque reservoir.

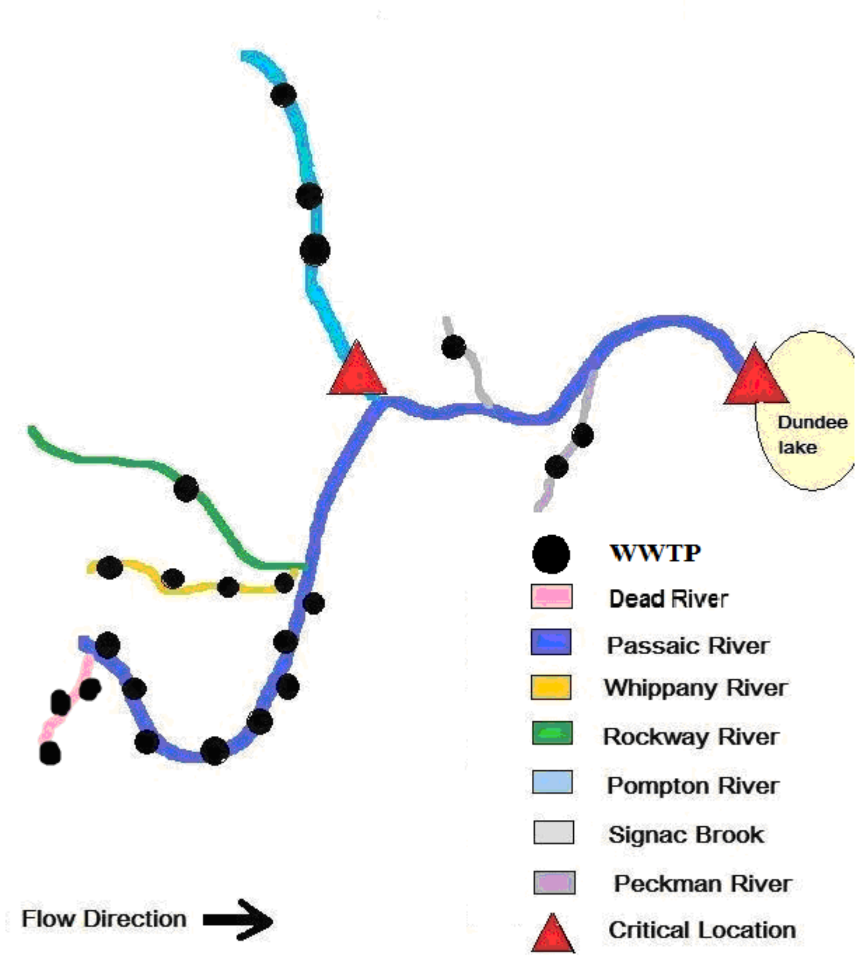


Figure 3.6.2-2 Simplified schematics of the Upper Passaic River Basin – two Critical Locations for diversion scenario

Extreme Diversion:

In the "extreme diversion" scenario, the Wanaque South intake pumping demand cannot be met by the Pompton River flow alone, and surface water is diverted to the Wanaque Reservoir from both the Pompton and Upper Passaic Rivers. Therefore, it is the mixed effluents from WWTPs in both the Pompton and Upper Passaic management areas that are diverted upstream to flow into the Wanaque Reservoir. In this case, the water quality at the confluence of Passaic and Pompton must be ensured, the resulting critical points are demonstrated in Figure 3.6.2-3.

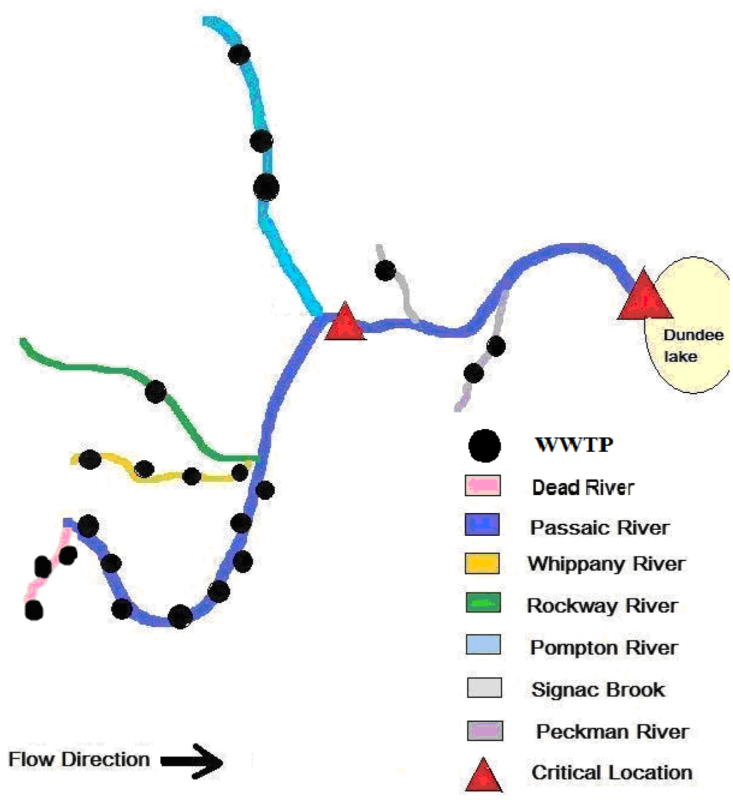


Figure 3.6.2-3 Simplified schematics of the Upper Passaic River Basin – two Critical Locations for extreme diversion scenario

Integrating the Diversion Scenarios:

Having illustrated the three diversion scenarios separately, it is important to note that the activation of the Wanaque South Intake is highly variable both within a year and between years. It would be ineffective to expect the WWTPs involved to constantly jump from one set of trading ratios to another associated with each diversion scenario: "That would likely increase transaction costs, as WWTPs would be forced to keep up to date with frequently changing trading restrictions." (Obrupta, et al., 2008, p. 954) One alternative approach that could protect water quality under all diversion conditions is to merge the three diversion scenarios in a way that protects all three critical locations regardless of diversion outcome realized. As discussed previously in this chapter, any possible range of water quality trading outcomes that meet the water quality objective at the identified critical locations will not lead to excessive loading in other areas of the watershed because of other factors that mitigate the impact of phosphorus, such as flow, shade cover and turbidity. Consequently, there would be three management areas (M.A.s) delineated, each having one of the three critical locations as its end-point. The grouping of M.A.s is shown in Figure 3.6.2-4, in which the following three M.A.s are delineated: 1) the Upper Passaic M.A., consisting of 16 Wastewater Treatment Plants[22] (WWTPs) on the Passaic River and its tributaries upriver of the point on the Passaic River immediately below the junction of the Passaic and the Pompton Rivers; 2) the Pompton River M.A., consisting of three WWTP's[23] above the Wanaque South Intake Point; and 3) the Lower Passaic M.A. consisting of three WWTPs[24] lying on tributaries that join the Passaic River

[22] Coded as D1, D2, D3, P1, P2, P3, P4, P5, P6, P7, P8, W1, W2, W3, W4, R1
[23] Coded as WQ, T1, T2
[24] Coded as P9, P10, P11

between the junction of the Passaic and the Pompton Rivers and the Dundee Lake endpoint. These are indicated in Figure 3.6.2-4 along with allowable patterns of trade between management areas indicated by dashed lines: under this management area approach WWTPs in the Upper Passaic M.A. and the Pompton M.A. can sell allowances to WWTPs in the Lower Passaic M.A. Moreover, WWTPs in the Pompton M.A. can sell allowances to those in the Upper Passaic M.A.

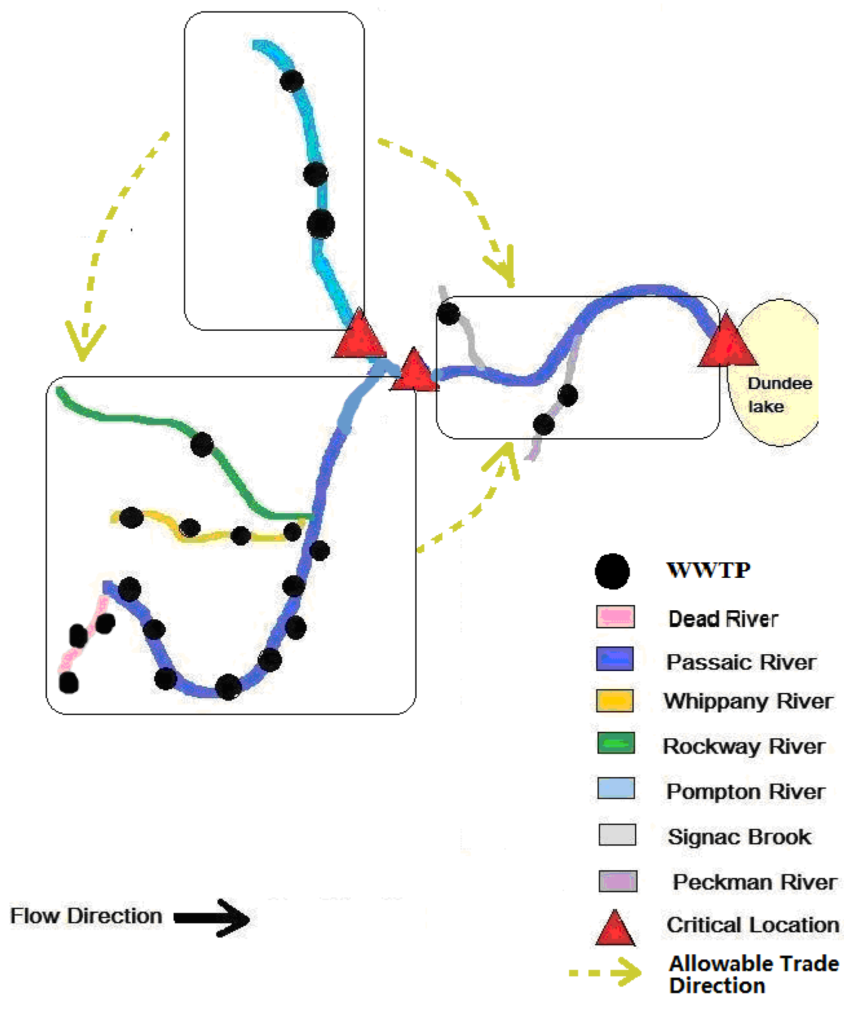


Figure 3.6.2-4 Simplified schematics of the Upper Passaic River Basin – demarcation of management areas – Multiple Source M.A. Approach Alternative One

Multiple Source Management Area Approach – Alternative Two

As discussed earlier, in the "extreme diversion" scenario, some of the effluents in the Pompton and Upper Passaic Rivers are diverted from their confluence to the Wanaque Reservoir, requiring that the management areas be designed to ensure the water quality at the confluence of Passaic and Pompton. This strategy is based on the assumption that the water is pumped up in the same proportion as how they are mixed at the confluence. For the purpose of testing the robustness of this modeling assumption, a more environmentally protective M.A. configuration is analyzed in this case study as well. In this alternative management area approach, water quality is protected at the end-point of Pompton and Upper Passaic separately. The way to do so is to identify the end-points of both Pompton and Upper Passaic as critical locations, rather than protect the water quality at the confluence alone. The resulting delineation is shown in Figure 3.6.3-1. One can see that the grouping of WWTPs remains unchanged in these two alternatives. The difference is that, in the previous approach, WWTPs in Pompton river can sell allowances to those in the Upper Passaic area as the Upper Passaic M.A. endpoint in Figure 3.4.1-4 is hydrologically below the Pompton M.A. However, those type of trades are not allowed in the modified M.A. approach. This is due to the fact that the discharge from Pompton river no longer affects the water quality at Upper Passaic M.A. end-point after the latter is moved above the confluence.

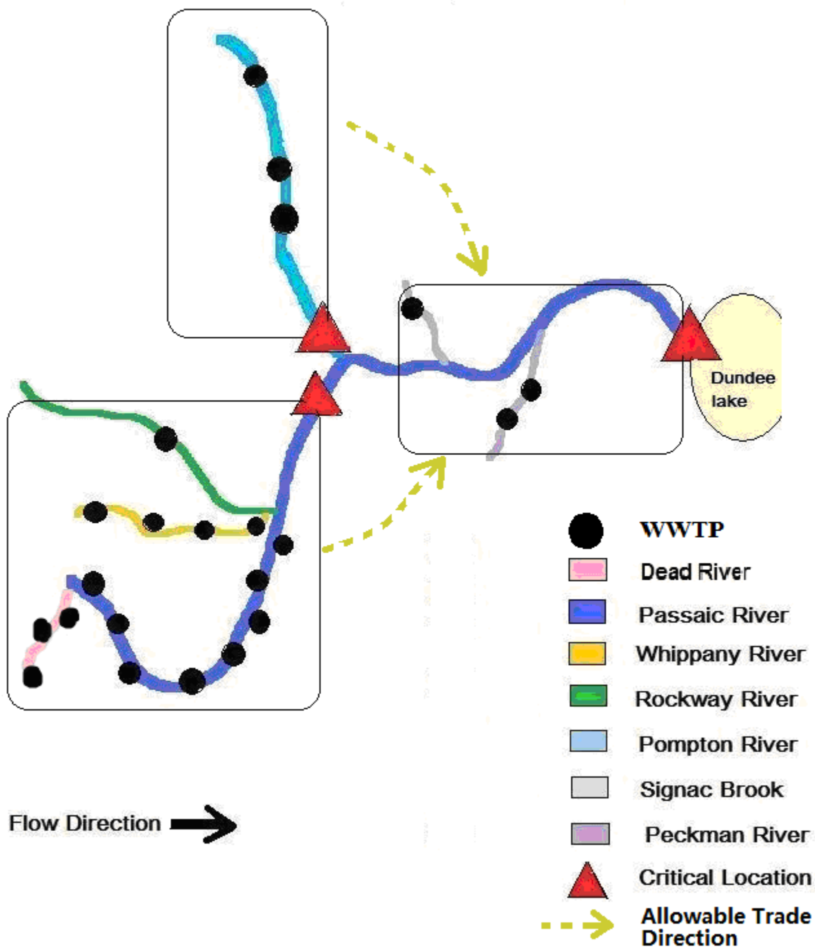


Figure 3.6.3-1 Simplified schematics of the Upper Passaic River Basin – demarcation of management areas – Multiple Source M.A. Approach Alternative Two

The Trading Ratios -- t_{ki}

The trading ratios t_{ki} are also important parameters for the empirical application of the effluent trading model. Because these ratios must reflect the attenuation of effluent between upstream WWTPs and those downstream, they will affect buyers' decisions to purchase allowances. Following the formula discussed in Chapter 2, trading ratios under each trading rule are equal to the relative natural diffusion rates to the end-point of buyer's M.A.[25] Note that for arbitrage not to occur, the ratios must be sub-multiplicative, i.e. the above setting of the trading ratios obtains a sub-multiplicative property, (i.e. $t_{ik} \cdot t_{kj} \leq t_{ij}$ for any WWTP *i*, *k* and *j*). Such a property eliminates arbitrage opportunities in which excessive circular trades can arise when the trading ratio from A-to-B multiplied by the trading ratio from B-to-C exceeds the trading ratio from A-to-C.

The natural diffusion rates are measured based on several scientific factors such as rate of inflow-outflow of pollutants, bio-physical conditions, and the geography of the designated areas. As discussed in Subsection 3.4.1, three potential surface water diversion scenarios can occur with respect to the Wanaque South intake due to the fluctuations in precipitation and demand for drinking water from the Wanaque Reservoir namely "no diversion", "diversion", and "extreme diversion". Each scenario alters the hydrological conditions of the watershed, and, as a result, the natural diffusion rates also differ with each diversion scenario. Those natural diffusion rates for the Passaic Watershed have been estimated by the TRC Omni Environmental Corporation, in consultation with the experts from the members of the Passaic Coalition. According to the report by TRC Omni, submitted in June 2006, the diffusion rates 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 from a given source to a target location, and the ratio of orthophosphate and organic phosphorus discharged from the point source.[26]

[25] The M.A end-points are determined according to the trading rule. In contrast, the natural diffusion rate itself does not depend on which trading rule is applied.

[26] TRC Omni divided the watershed into 10 zones, and WWTPs within each zone are clustered close enough to be assumed to have one-to-one diffusion rates. They calculated the attenuation rates at the end of each zone. For instance, if the reduction of 100 lbs. phosphorus at zone i is

Since the natural diffusion rates differ by diversion scenario, each trading rule specified in Section 3.4 generates three trading ratio matrices, each corresponding to one of the three diversion scenarios. For instance, Tables (3.7-1), (3.7-2) and (3.7-3) contain different trading ratios under the trading rule "*Multiple Source Management Area-Alternative One*", each associated with "no diversion" "diversion" "extreme diversion" respectively. [27] (The blank cells indicate trading ratios equal to zero or trades are not allowed.)

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equivalent to the reduction of 80 lbs. phosphorus at zone j, then the transfer coefficient between zone i and zone j is 0.8. These ratios are applied to each WWTP in zone i and zone j.

[27] Table (3.7-1), (3.7-2) and (3.7-3) were provided by Josef Kardos, Ph.D, at Rutgers University. Because of rounding errors associated with converting files across various electronic formats, each of the trading ratios was rounded down at the 9th decimal place. Such rounding preserves the sub-multiplicative properties and in turn precludes arbitrage opportunities.

Table 3.7-1 Trading Ratios Under Multiple Source M.A. Approach - Alternative One (No diversion)

Seller \ Buyer	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	1.079	1.079	1.079	1.206	1.079				0.833	0.851	0.851
D2	1.000	1.000	1.000	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	1.079	1.079	1.079	1.206	1.079				0.833	0.851	0.851
D3	1.000	1.000	1.000	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	1.079	1.079	1.079	1.206	1.079				0.833	0.851	0.851
P1	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.853	0.872	0.872
P2	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.853	0.872	0.872
P3	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.853	0.872	0.872
P4	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.853	0.872	0.872
P5	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.853	0.872	0.872
P6	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.853	0.872	0.872
P7	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.853	0.872	0.872
P8	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.853	0.872	0.872
W1	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.905	0.905	0.905	0.905	1.000	1.000	1.000	1.118	1.000				0.772	0.789	0.789
W2	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.905	0.905	0.905	0.905	1.000	1.000	1.000	1.118	1.000				0.772	0.789	0.789
W3	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.905	0.905	0.905	0.905	1.000	1.000	1.000	1.118	1.000				0.772	0.789	0.789
R1	0.829	0.829	0.829	0.810	0.810	0.810	0.810	0.810	0.810	0.810	0.810	0.895	0.895	0.895	1.000	0.895				0.691	0.706	0.706
W4	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.905	0.905	0.905	0.905	1.000	1.000	1.000	1.118	1.000				0.772	0.789	0.789
WQ	1.201	1.201	1.201	1.172	1.172	1.172	1.172	1.172	1.172	1.172	1.172	1.296	1.296	1.296	1.448	1.296	1.000	1.000	1.000	1.000	1.022	1.022
T1	1.201	1.201	1.201	1.172	1.172	1.172	1.172	1.172	1.172	1.172	1.172	1.296	1.296	1.296	1.448	1.296	1.000	1.000	1.000	1.000	1.022	1.022
T2	1.201	1.201	1.201	1.172	1.172	1.172	1.172	1.172	1.172	1.172	1.172	1.296	1.296	1.296	1.448	1.296	1.000	1.000	1.000	1.000	1.022	1.022
P9																				1.000	1.022	1.022
P10																				0.978	1.000	1.000
P11																				0.978	1.000	1.000

Table 3.7-2 Trading Ratios Under Multiple Source M.A. Approach - Alternative One (Diversion)

Seller \ Buyer	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.975	0.975	0.975	0.975	0.929	0.929	0.929	0.929	1.026	1.026	1.026	1.147	1.026				0.741	0.716	0.716
D2	1.000	1.000	1.000	0.975	0.975	0.975	0.975	0.929	0.929	0.929	0.929	1.026	1.026	1.026	1.147	1.026				0.741	0.716	0.716
D3	1.000	1.000	1.000	0.975	0.975	0.975	0.975	0.929	0.929	0.929	0.929	1.026	1.026	1.026	1.147	1.026				0.741	0.716	0.716
P1	1.026	1.026	1.026	1.000	1.000	1.000	1.000	0.952	0.952	0.952	0.952	1.053	1.053	1.053	1.176	1.053				0.760	0.734	0.734
P2	1.026	1.026	1.026	1.000	1.000	1.000	1.000	0.952	0.952	0.952	0.952	1.053	1.053	1.053	1.176	1.053				0.760	0.734	0.734
P3	1.026	1.026	1.026	1.000	1.000	1.000	1.000	0.952	0.952	0.952	0.952	1.053	1.053	1.053	1.176	1.053				0.760	0.734	0.734
P4	1.026	1.026	1.026	1.000	1.000	1.000	1.000	0.952	0.952	0.952	0.952	1.053	1.053	1.053	1.176	1.053				0.760	0.734	0.734
P5	1.077	1.077	1.077	1.050	1.050	1.050	1.050	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.798	0.771	0.771
P6	1.077	1.077	1.077	1.050	1.050	1.050	1.050	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.798	0.771	0.771
P7	1.077	1.077	1.077	1.050	1.050	1.050	1.050	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.798	0.771	0.771
P8	1.077	1.077	1.077	1.050	1.050	1.050	1.050	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.798	0.771	0.771
W1	0.974	0.974	0.974	0.950	0.950	0.950	0.950	0.905	0.905	0.905	0.905	1.000	1.000	1.000	1.118	1.000				0.722	0.698	0.698
W2	0.974	0.974	0.974	0.950	0.950	0.950	0.950	0.905	0.905	0.905	0.905	1.000	1.000	1.000	1.118	1.000				0.722	0.698	0.698
W3	0.974	0.974	0.974	0.950	0.950	0.950	0.950	0.905	0.905	0.905	0.905	1.000	1.000	1.000	1.118	1.000				0.722	0.698	0.698
R1	0.872	0.872	0.872	0.850	0.850	0.850	0.850	0.810	0.810	0.810	0.810	0.895	0.895	0.895	1.000	0.895				0.646	0.624	0.624
W4	0.974	0.974	0.974	0.950	0.950	0.950	0.950	0.905	0.905	0.905	0.905	1.000	1.000	1.000	1.118	1.000				0.722	0.698	0.698
WQ	0.746	0.746	0.746	0.727	0.727	0.727	0.727	0.693	0.693	0.693	0.693	0.766	0.766	0.766	0.856	0.766	1.000	1.000	1.000	0.553	0.534	0.534
T1	0.746	0.746	0.746	0.727	0.727	0.727	0.727	0.693	0.693	0.693	0.693	0.766	0.766	0.766	0.856	0.766	1.000	1.000	1.000	0.553	0.534	0.534
T2	0.746	0.746	0.746	0.727	0.727	0.727	0.727	0.693	0.693	0.693	0.693	0.766	0.766	0.766	0.856	0.766	1.000	1.000	1.000	0.553	0.534	0.534
P9																				1.000	0.966	0.966
P10																				1.035	1.000	1.000
P11																				1.035	1.000	1.000

Table 3.7-3 Trading Ratios Under Multiple Source M.A. Approach - Alternative One (Extreme diversion)

Seller \ Buyer	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	1.030	1.030	1.030	1.236	1.030				0.599	0.440	0.440
D2	1.000	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	1.030	1.030	1.030	1.236	1.030				0.599	0.440	0.440
D3	1.000	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	1.030	1.030	1.030	1.236	1.030				0.599	0.440	0.440
P1	1.059	1.059	1.059	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.091	1.091	1.091	1.309	1.091				0.634	0.466	0.466
P2	1.059	1.059	1.059	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.091	1.091	1.091	1.309	1.091				0.634	0.466	0.466
P3	1.059	1.059	1.059	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.091	1.091	1.091	1.309	1.091				0.634	0.466	0.466
P4	1.059	1.059	1.059	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.091	1.091	1.091	1.309	1.091				0.634	0.466	0.466
P5	1.132	1.132	1.132	1.069	1.069	1.069	1.069	1.000	1.000	1.000	1.000	1.167	1.167	1.167	1.400	1.167				0.678	0.499	0.499
P6	1.132	1.132	1.132	1.069	1.069	1.069	1.069	1.000	1.000	1.000	1.000	1.167	1.167	1.167	1.400	1.167				0.678	0.499	0.499
P7	1.132	1.132	1.132	1.069	1.069	1.069	1.069	1.000	1.000	1.000	1.000	1.167	1.167	1.167	1.400	1.167				0.678	0.499	0.499
P8	1.132	1.132	1.132	1.069	1.069	1.069	1.069	1.000	1.000	1.000	1.000	1.167	1.167	1.167	1.400	1.167				0.678	0.499	0.499
W1	0.971	0.971	0.971	0.917	0.917	0.917	0.917	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.200	1.000				0.582	0.427	0.427
W2	0.971	0.971	0.971	0.917	0.917	0.917	0.917	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.200	1.000				0.582	0.427	0.427
W3	0.971	0.971	0.971	0.917	0.917	0.917	0.917	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.200	1.000				0.582	0.427	0.427
R1	0.809	0.809	0.809	0.764	0.764	0.764	0.764	0.714	0.714	0.714	0.714	0.833	0.833	0.833	1.000	0.833				0.485	0.356	0.356
W4	0.971	0.971	0.971	0.917	0.917	0.917	0.917	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.200	1.000				0.582	0.427	0.427
WQ	0.637	0.637	0.637	0.602	0.602	0.602	0.602	0.563	0.563	0.563	0.563	0.656	0.656	0.656	0.788	0.656	1.000	1.000	0.970	0.382	0.280	0.280
T1	0.637	0.637	0.637	0.602	0.602	0.602	0.602	0.563	0.563	0.563	0.563	0.656	0.656	0.656	0.788	0.656	1.000	1.000	0.970	0.382	0.280	0.280
T2	0.657	0.657	0.657	0.620	0.620	0.620	0.620	0.580	0.580	0.580	0.580	0.677	0.677	0.677	0.812	0.677	1.031	1.031	1.000	0.393	0.289	0.289
P9																				1.000	0.735	0.735
P10																				1.361	1.000	1.000
P11																				1.361	1.000	1.000

As discussed in Section 3.6.2, under the "M.A. approach Alternative One", Management Areas are delineated in the way that the end-point of the Upper Passaic M.A. is located downstream to the confluence of Passaic and Pompton Rivers. Thus, allowances can be sold from the Pompton M.A. to the Upper Passaic M.A. In contrast, WWTPs in the Upper Passaic M.A. cannot sell their allowances to the Pompton M.A.. This explains the empty block in upper right of the matrices. Moreover, the empty block in the lower left of the matrices is attributed to the restriction that both the Upper Passaic M.A. and Pompton M.A. can sell allowances to the Lower Passaic M.A., but not vice versa. (see Figure 3.6.2-4)

Assuming that it is undesirable, practicably and politically, for WWTPs to constantly jump from one set of trading ratios to another in real trading, the three matrices need to be compiled into a single matrix for the actual trading program. For this purpose, a protective compiling strategy, "Selection of the Minimum Trading Ratios" is adopted. Under this protective compiling strategy, the minimum trading ratio from the corresponding cells in the three diversion scenarios was chosen to be the integrated ratio. Hence, the resulting trading ratio matrix represents the most conservative ratio configuration under all possible diversion scenarios. Note that because the most conservative ratios were selected, the sub-multiplicative property of trading ratios still holds, precluding the possibility of arbitrage.

Table 3.7-4 Compiled Trading Ratios Under Multiple Source M.A. Approach - Alternative One (Selection of Minimum Trading Ratios)

Seller \ Buyer	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	1.026	1.026	1.026	1.147	1.026				0.599	0.440	0.440
D2	1.000	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	1.026	1.026	1.026	1.147	1.026				0.599	0.440	0.440
D3	1.000	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	1.026	1.026	1.026	1.147	1.026				0.599	0.440	0.440
P1	1.024	1.024	1.024	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.053	1.053	1.053	1.176	1.053				0.634	0.466	0.466
P2	1.024	1.024	1.024	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.053	1.053	1.053	1.176	1.053				0.634	0.466	0.466
P3	1.024	1.024	1.024	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.053	1.053	1.053	1.176	1.053				0.634	0.466	0.466
P4	1.024	1.024	1.024	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.053	1.053	1.053	1.176	1.053				0.634	0.466	0.466
P5	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.678	0.499	0.499
P6	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.678	0.499	0.499
P7	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.678	0.499	0.499
P8	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.678	0.499	0.499
W1	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.118	1.000				0.582	0.427	0.427
W2	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.118	1.000				0.582	0.427	0.427
W3	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.118	1.000				0.582	0.427	0.427
R1	0.809	0.809	0.809	0.764	0.764	0.764	0.764	0.714	0.714	0.714	0.714	0.833	0.833	0.833	1.000	0.833				0.485	0.356	0.356
W4	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.118	1.000				0.582	0.427	0.427
WQ	0.637	0.637	0.637	0.602	0.602	0.602	0.602	0.563	0.563	0.563	0.563	0.656	0.656	0.656	0.788	0.656	1.000	1.000	0.970	0.382	0.280	0.280
T1	0.637	0.637	0.637	0.602	0.602	0.602	0.602	0.563	0.563	0.563	0.563	0.656	0.656	0.656	0.788	0.656	1.000	1.000	0.970	0.382	0.280	0.280
T2	0.657	0.657	0.657	0.620	0.620	0.620	0.620	0.580	0.580	0.580	0.580	0.677	0.677	0.677	0.812	0.677	1.000	1.000	1.000	0.393	0.289	0.289
P9																				1.000	0.735	0.735
P10																				0.978	1.000	1.000
P11																				0.978	1.000	1.000

Table 3.7-5 Compiled Trading Ratios Under Multiple Source M.A. Approach - Alternative Two (selection of Minimum Trading Ratios)

Seller \ Buyer	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	1.026	1.026	1.026	1.147	1.026				0.599	0.440	0.440
D2	1.000	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	1.026	1.026	1.026	1.147	1.026				0.599	0.440	0.440
D3	1.000	1.000	1.000	0.944	0.944	0.944	0.944	0.883	0.883	0.883	0.883	1.026	1.026	1.026	1.147	1.026				0.599	0.440	0.440
P1	1.024	1.024	1.024	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.053	1.053	1.053	1.176	1.053				0.634	0.466	0.466
P2	1.024	1.024	1.024	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.053	1.053	1.053	1.176	1.053				0.634	0.466	0.466
P3	1.024	1.024	1.024	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.053	1.053	1.053	1.176	1.053				0.634	0.466	0.466
P4	1.024	1.024	1.024	1.000	1.000	1.000	1.000	0.935	0.935	0.935	0.935	1.053	1.053	1.053	1.176	1.053				0.634	0.466	0.466
P5	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.678	0.499	0.499
P6	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.678	0.499	0.499
P7	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.678	0.499	0.499
P8	1.024	1.024	1.024	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.105	1.105	1.105	1.235	1.105				0.678	0.499	0.499
W1	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.118	1.000				0.582	0.427	0.427
W2	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.118	1.000				0.582	0.427	0.427
W3	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.118	1.000				0.582	0.427	0.427
R1	0.809	0.809	0.809	0.764	0.764	0.764	0.764	0.714	0.714	0.714	0.714	0.833	0.833	0.833	1.000	0.833				0.485	0.356	0.356
W4	0.927	0.927	0.927	0.905	0.905	0.905	0.905	0.857	0.857	0.857	0.857	1.000	1.000	1.000	1.118	1.000				0.582	0.427	0.427
WQ																	1.000	1.000	0.970	0.382	0.280	0.280
T1																	1.000	1.000	0.970	0.382	0.280	0.280
T2																	1.000	1.000	1.000	0.393	0.289	0.289
P9																				1.000	0.735	0.735
P10																				0.978	1.000	1.000
P11																				0.978	1.000	1.000

Table 3.7-6 Compiled Trading Ratios Under Single Source M.A. Approach (selection of Minimum Trading Ratios)

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

Further note that, the compiled ratios in Tables (3.7-4) are all associated with the trading rule "Multiple Source Management Area Approach – Alternative One)" described in section 3.6.2. Trading ratios under the other two trading rules are also compiled based on the same strategy. Tables (3.7-5) contains those under the "Management Area approach alternative 2", while ratios under the "Standard Trading Ratio systems" for the TRS are given in Tables (3.7-6).

The empty cells on the rows "WQ", "T1" and "T2" in Table (3.7-5) reflect the fact that WWTPs in Pompton M.A. can no longer sell allowances to those in Upper Passaic M.A. under "M.A. Approach Alternative 2". In addition, as discussed previously, one important feature of the Standard Trading Ratio System is that the pollution allowances can be sold only from upstream dischargers to downstream dischargers. This is reflected by the empty cells below the diagonal of the trading ratio matrices in Tables (3.7-6).

For comparison purposes, two other compiling strategies, "Geometric Average" and "90% of the Minimum Ratios" are also applied in this case study. The Geometric Average is mathematically desirable in the sense that it provides symmetry in in trading ratios between buyers and sellers. However, as an average of ratios it will theoretically lead to water quality violations under some of the diversion scenarios. The 90% of the Minimum Ratios incorporates an added margin of safety above and beyond the Minimum Ratios approach. The detailed results are reported and discussed in the Appendix Two.

Estimating the Abatement Cost Functions

As argued in Chapter 2, in order to attain the optimal trading pattern with explicit consideration of the capital investment decision, the total abatement costs need to be decomposed into the Operating and Maintenance cost (OM) and the Capital Investment cost (CC). To implement the mixed integer model empirically, both annual OM costs function as well as capital cost functions need to be estimated.

Estimating OM Cost and Capital Costs

Because most of the wastewater treatment plants in the watershed currently have little or no capacity to remove phosphorus, they are unable at the present time to provide data on phosphorus abatement costs, particularly those necessary to achieve the TMDL standard. As a proxy for direct cost estimates from each plant, the cost functions for both yearly OM costs and capital costs used in this analysis are estimated from data on 104 treatment plants located in the Chesapeake Bay watershed. The report from the Chesapeake Bay watershed provides complete OM and capital cost estimates for 104 municipal WWTPs located in Pennsylvania, Maryland, Virginia, Delaware, West Virginia New York, and District of Columbia. (Report for Chesapeake Bay Program 2002) The estimates are for two target levels of effluent concentration, 1mg/L and 0.1mg/L, sufficiently encompassing those implied by the TMDLs under study. These data are also appropriate as the basis for the cost estimation because of the geographic proximity and other similarities between the Chesapeake Bay and Passaic Watersheds. In addition, the cost of land, labor and materials are likely to be similar in northeastern watersheds that encompass or are near large population centers.

The Chesapeake Bay data are not completely ideal in the sense that, the Chesapeake study is only for WWTPs that rely on chemical technologies to remove the phosphorus. Although the inexpensive chemical technology can be assumed to be adopted by the plants that currently have no capacity to treat phosphorus, there are three plants in the Passaic Watershed (W1, W2, R1) that already operate biological phosphorus removal processes.[28] In order to accommodate the different technologies, this thesis draws also on the data from an extensive simulation analysis by the University of Georgia for eight designs of wastewater treatment facilities representing a wide range of phosphorus removal. The important characteristic of the Georgia study is that it estimates costs for differentiated phosphorus removal technologies, such as chemical precipitation, biological removal, ion exchange, and combinations of various technologies. Further, the Georgia study examined these technologies for five different effluent concentrations: 2mg/L, 1mg/L, 0.5mg/L, 0.13mg/L; and 0.05mg/L. (Jiang, et al. 2005). While it is necessary to use the results from the Georgia study to adjust the cost functions for different technologies, these data do not have the advantage of proximity to the Upper Passaic River Basin that was previously argued for the Chesapeake Bay data. The Georgia data are further limited because the Georgia study was conducted on only one plant, the Athens#2 WWTP.

Having considered the *pros* and *cons* of the two data sources, the abatement cost functions for this thesis are estimated by pooling the Chesapeake and Georgia data, while using a regional binary variable "R" to account for the differences between the two data sources and another binary variable "T" to account for different technologies.

For the model building, the "General-To-Simple" strategy (downward reduction of the model to the preferred specification) is adopted. The most general model is specified in equation (3.8.1-1).

[28] This assumption is consistent with the advice of other members of the study team.

$$\ln OM = \alpha_1 + \alpha_2 \ln C + \alpha_3 \ln F + \alpha_4 \ln C \ln F + \alpha_5 T + \alpha_6 T \ln C + \alpha_7 T \ln F$$
$$+ \alpha_8 T \ln C \ln F + \alpha_9 R + \alpha_{10} R \ln C + \alpha_{11} R \ln F + \alpha_{12} R \ln C \ln F + u_0 \qquad \text{-------(3.8.1-1)}$$

In the above equation, OM is annual operating cost, C is final phosphorus concentration, in mg/L, and F is daily flow in million gallons per day. To isolate the effect of technology on the annual OM costs, the technology of reference was assumed to be that associated with using chemical technology to remove phosphorus.[29] Thus a binary variable for technology, T, was created: if an observation corresponds to chemical technology, T=0; if phosphorus is removed by a biological process, then T=1. Similarly, R is created as the regional indicator: if an observation is from the Georgia study, R=1; if the observation is from Chesapeake study, R=0. The coefficients α_1 to α_{12} are parameters to be estimated.

Whether the OM cost function of a single WWTP differs at the alternative facility levels remains an open empirical question. In the contexts of the theoretical framework developed in Chapter 2, variables indicating the facility upgrade levels should also be included in this regression so that the statistical significance of the impact from facility upgrade could be tested and upgrade-specific "OM" cost functions could be estimated. Unfortunately, such upgrade specific cost functions are not estimable with the existing data. The data from the Chesapeake Bay study provide insufficient information on the level of facility upgrades for each plant and only provides information for two treatment levels. Therefore, I make an untestable, limiting assumption that a WWTP's facility upgrade does not affect its OM (variable) cost function.

[29] The chemical removal technology is commonly referred to as activated sludge.

Assuming the error term, u_0, is normally distributed, the general cost function in equation (3.8.1-1) is in the "translog flexible form" which can be seen as the second order Taylor approximation for the unknown general form $\ln OM = f(\ln C, \ln F, T, R)$.[30] This flexible form enables the testing of the second-order effects such as cost elasticities. Specifically, the elasticity of cost of phosphorus removal with respect to one characteristic depends on the level of the other.

Another concern with the data is the failure to account for multiple observations from each WWTP which will result inefficient standard errors. Specifically, the Chesapeake data are based on 208 observations from 104 WWTPs, with cost data for each plant to treat to 0.1 mg/L and 1 mg/L. Hence, each pair of data observed from the same plant may not be independent, which may affect the variance-covariance matrix, and enlarge standard errors. One way to address with this intra-plant dependency issue is to separate the plant-specific effect by applying a One Way Fixed-Effects Model. However, since the cost function contains a limited number of variables whose values do not vary within each group, applying a Fixed-Effect model would inevitably result in dropping these group-specific variables. Moreover, estimating multiple plant-specific cost functions using a Fixed-Effect Modesl also contradicts the original intention of finding an universal cost function for the 22 WWTPs in Passaic Watershed.

An alternative way to adjust the calculation of the variance-covariance matrix is to directly adjust the standard errors allowing for intra-group correlation. This method (Froot, 1989), can be seen as a straightforward generalization of the White correction,

[30] Boisvert (1982) and Vinod (1972) discuss the general properties of a translog functional form, and of special cases of the form similar to those used here. Boisvert and Schmit (1997) as well as Feigenbaum and Teeples (1983) apply the translog flexible form to estimate the abatement cost functions for drinking water treatment and delivery system.

and is accomplished by applying the "VCE-cluster" option in STATA for equation 3.8.1-1.[31] (See STATA reference Manual 2007, released 10, VCE Options.) The estimated result using the VCE cluster option is reported in column (1) of Table 3.8.1-1.

Overall, the general specification seems to fit the data from the Chesapeake study quite well. Based on the R square coefficient, the regression explains about 95% of the variation in the logarithm of the cost of removing phosphorus. At the same time, controlling the Type One Error at 5%, the t tests indicate that four terms "T*lnF", "T*lnC*lnF", "R*lnC" and "R*lnF" are statistically insignificant, suggesting these terms might be redundant. To test the relevance of these terms, a joint F test with these four targeted variables is conducted. The results from these tests confirm the joint insignificance of the four terms (F(4,108)=1.45, Prob>F=0.22).

To further check this result, two joint F tests are conducted sequentially. The first of which reconfirm the joint insignificance of the two terms ""R*lnC" and "R*lnF". (F(2,108)=0.43, Prob>F=0.65) After dropping the terms "R*lnC "and "R*lnF", the new estimation is reported in column (2) of Table 3.8.1-1.

Subsequently, a joint F test is used to estimate the relevance of the two term "T*lnF" and "T*lnC*lnF". The result of this test suggests that these two terms could also be reduced from the OM cost function (F(2,108)=0.45, Prob>F=0.64).

After dropping TlnF and TlnClnF, the OM cost function comes to its final specification (Equation 3.8.1-2).

---

[31] VCE-cluster relaxes the usual requirement that the observations be independent. That is, the observations are independent across groups (clusters) but not necessarily within groups.

$$\ln OM = 9.876 - 0.9899 \ln C + 0.7956 \ln F + 0.0464 \ln C \ln F + 0.6494T + 0.3138T \ln C$$
$$+ 1.18R - 0.0501R \ln C \ln F$$

---------(3.8.1-2)

Based on the test statistics reported in column (3) of Table 3.8.1-1, the standard errors suggest that the coefficients for all the remaining explanatory variables are independently statistically significant. Combined estimated model explains more than 95% of the total variation. To a great extent, this high explanatory power of the model is due to the fact that a large proportion of the Chesapeake data are created from engineering models.

Some possible concerns motivate the following post-regression investigation. To begin, the correlation between error term and independent variables is tested to check whether the estimation results in column (3) of Table 3.8.1-1 are unbiased. The correlation between the residual and the independent variable was found to be zero to the fourth decimal point in all cases, providing evidence that the estimation is unbiased. Moreover, the potential impact of multicollinearity is evaluated using the Variance Inflation Factor (VIF) test. The mean VIF is "3.77", far below the rule of thumb alert level (Mean VIF greater or equal to 10); thus, the result basically eliminates the worries of Multicollinearity. (see STATA reference manual, release 10, VIF test).

Table 3.8.1-1 Regression Result (OM Costs)			
	(1)	(2)	(3)
R-squre	0.953	0.952	0.952
LnC	-0.996**	-0.993**	-0.990**
	(.019)	(.019)	(.020)
LnF	0.785**	0.800**	0.796**
	(.060)	(.043)	(.030)
LnC*LnF	0.043*	0.049**	0.046**
	(.018)	(.015)	(.014)
T	0.707**	0.693**	0.650**
	(.140)	(.133)	(.083)
T*LnC	0.287**	0.358**	0.314**
	(.063)	(.040)	(.022)
T*LnF	-0.037	-0.022	-
	(.022)	(.042)	
T*LnC*LnF	-0.007	-0.022	-
	(.007)	(.023)	
R	1.177**	1.188**	1.180**
	(.253)	(.193)	(.179)
R*LnC	0.074	-	-
	(.106)		
R*LnF	0.0308	-	-
	(.068)		
R*LnC*LnF	-0.054*	-0.045	-0.050*
	(.021)	(.026)	(.020)
Constant	9.870**	9.872**	9.876**
	(.061)	(.060)	(.058)

(.) gives the robust standard error adjusted for intra-plant correlation
* denotes 5% confidence level.
** denotes 1% confidence level.

The same strategy used to specify the OM cost functions is also used to estimate the capital costs function. Following to the "translog flexible form", the natural logarithm of capital cost from the Chesapeake study was regressed on the logarithms of concentration, logarithms of flow levels, binary variables T and R and the interaction terms. The starting general form is specified in equation (3.8.1-3):

$$\ln CC = \ln\beta_1 + \beta_2 \ln C + \beta_3 \ln F + \beta_4 \ln C \ln F + \beta_5 T + \beta_6 T \ln C + \beta_7 \ln F \\ + \beta_8 T \ln C \ln F + \beta_9 R + \beta_{10} R \ln C + \beta_{11} R \ln F + \beta_{12} R \ln C \ln F + v_0 \qquad \text{------(3.8.1-3)}$$

where CC is capital investment cost; C is final phosphorus concentration, in mg/L; F is daily flow in million gallons per day; T is the technological dummy, R is the regional dummy, v_0 is error term assumed to be normally distributed, and β_1 to β_{12} are parameters to be estimated. Since the fixed cost estimation has the issue of intra-group correlation as well, the VCE-cluster is also applied to adjust the standard errors. The estimated parameters are shown in column (1) of Table 3.8.1-2.

Using the 5% Type-One Error as a criterion, the t tests show that four terms "RlnC", "R*lnF" and "R*lnC*lnF" are statistically insignificant, suggesting these terms might be redundant. To test the relevance of these terms, a joint F test was conducted, which confirms the joint insignificance of the three terms (F(3,108)=1.62; Prob>F=0.1885).

To double check this result, the terms are dropped in a subsequent fashion. Another F test is conducted with "RlnF" and "RlnClnF", which reconfirms the joint insignificance of the two terms ""RlnF" and "RlnCnF" (F(2,108)=0.24; Prob>F=0.7863).

After dropping the terms "RlnF" and "RlnClnF", the t statistics indicate that the term "RlnC" becomes insignificant, and so it is dropped in subsequent estimations.[32] (The new estimation is reported in column (2) of Table 3.8.1-2.)

After dropping "R*LnC", the capital cost function comes to its final specification (Equation 3.8.1-4).

$$\ln CC = 11.888 - 0.9851 lnC + 0.3473 lnF - 0.1276 lnClnF + 0.9963T + 0.4422T lnC + 0.2903T lnF + 0.1137T lnClnF + 0.6795R$$

---(3.8.1-4)

The test statistics are reported in column (3) of Table 3.8.1-2; the standard errors suggest that all remaining explanatory variables are statistically significant allowing for 10% Type One Error. Note that the regression fits the data extraordinarily well, with R-squared as high as 0.97. As with the OM cost this is largely because the capital cost data from both studies are engineering data, so the above regression essentially recovered the capital cost functions used for the engineering estimation.

Similar to the post-regression analysis done for the OM costs, the correlation between error term and independent variables are tested to verify the unbiasedness of the estimation. The correlation between the residual and the independent variable was found to be zero to the fourth decimal point in all cases. The results show that the explanatory variables are independent from the residuals, therefore the OLS estimation should be unbiased.

[32] The selection criteria are set to control the probability of Type One Error at 10%.

In addition the potential impact of multicollinearity is evaluated using VIF test. The mean VIF is "5.41", a fairly moderate level, (VIF=10 is the rule of thumb alert level) showing that the impact of multicollinearity, even if exists, is likely to be mild.

Table 3.8.1-2 Regression Result (Capital Costs)

	(1)	(2)	(3)
R-squre	0.970	0.970	0.969
LnC	-0.995**	-0.996**	-0.985**
	(.005)	(.005)	(.010)
LnF	0.302**	0.313**	0.347**
	(.005)	(.016)	(.041)
LnC*LnF	-0.164**	-0.158**	-0.128**
	(.005)	(.008)	(.031)
T	0.878**	0.788**	0.996**
	(.160)	(.286)	(.230)
T*LnC	0.281**	0.245*	0.442**
	(.052)	(.102)	(.044)
T*LnF	0.292**	0.324**	0.290**
	(.067)	(.019)	(.038)
T*LnC*LnF	0.131**	0.144**	0.114**
	(.033)	(.011)	(.031)
R	0.809*	0.900*	0.680
	(.317)	(.455)	(.368)
R*LnC	0.171	0.208	-
	(.094)	(.149)	
R*LnF	0.044	-	-
	(.069)		
R*LnC*LnF	0.019	-	-
	(.031)		
Constant	11.879**	11.879**	11.889**
	(.005)	(.006)	(.011)

(.) gives the robust standard errors adjusted for intra-plant correlation

* denotes 5% confidence level.

** denotes 1% confidence level.

Given geographic proximity and other similarities between the Chesapeake Bay and Passaic watersheds, the Chesapeake data are thought to provide the preferred baseline for cost estimates. To accomplish this, the regional dummy R is set equal to "0" for the 22 firms in the Passaic watershed. Accordingly, the abatement cost functions in this case study can be specified by the following four equations:

For firms (WWTPs) using Chemical Removal Technologies (T=0):

$$\ln OM = 9.876 - 0.990 \ln C + 0.796 \ln F + 0.046 \ln C \ln F \quad \text{-----------(3.8.1-5)}$$

$$\ln CC = 11.889 - 0.985 \ln C + 0.347 \ln F - 0.128 \ln C \ln F \quad \text{--------------(3.8.1-6)}$$

For firms (WWTPs) using Biological Removal Technologies (T=1):

$$\ln OM = 10.525 - 0.676 \ln C + 0.796 \ln F + 0.046 \ln C \ln F \quad \text{-----(3.8.1-7)}$$

$$\ln CC = 12.885 - 0.543 \ln C + 0.637 \ln F - 0.014 \ln C \ln F \quad \text{------- (3.8.1-8)}$$

Cost Elasticities

Due to the flexibility of the "translog" functional form, the cost elasticity with respect to one characteristic depends on the level of the others. The elasticities of both OM cost and Capital cost can be derived by taking the logarithmic partial derivatives of above equations.

The cost elasticity for chemical plants (with respect to the concentration level)

$$\partial \ln OM / \partial \ln C = -0.990 + 0.046 \ln F \quad \text{-----------------(3.8.2-1)}$$

$$\partial \ln CC / \partial \ln C = -0.985 - 0.128 \ln F \quad \text{-----------------(3.8.2-2)}$$

The cost elasticity for biological plants (with respect to the concentration level)

$$\partial \ln OM / \partial \ln C = -0.676 + 0.046 \ln F \quad \text{-----------------(3.8.2-3)}$$

$$\partial \ln CC / \partial \ln C = -0.543 - 0.014 \ln F \quad \text{-----------------(3.8.2-4)}$$

The general properties of the cost elasticities (both OM cost and capital cost) with respect to the concentration level follow directly from above derivatives: (1) The elasticities for both OM cost and Capital cost are negative over the range of flows in this study, indicating that as final concentration goes down, both costs would rise; (2) The OM cost is more elastic for smaller plants (with lower discharge flow) than for larger plants; and (3) The capital costs required to retrofit facilities are more elastic for larger plants. All these properties conform to the basic economic intuition as well as common sense. In addition, one can easily see that the coefficients for the biological plants shift the cost functions upward but at the same time, the cost elasticities with respect to concentration decline. This difference conforms with the results obtained from the Georgia study. Biological removal processes generally incur higher operating cost and more intensive investment, but they are more efficient in abating the phosphorus to low concentration levels than the chemical process.

To highlight these results, the plant specific cost elasticities are reported in table (3.8.2-1) and table (3.8.2-2). In the tables, the "average flows" are sorted in an ascending order.

Table 3.8.2-1 Cost Elasticity for Plants using Chemical Removal Technologies

Plant Code	Average Flow	OM Cost elasticity	Capital cost elasticity
P4	0.120	-1.088	-0.714
D2	0.150	-1.077	-0.742
D3	0.310	-1.044	-0.835
P2	0.360	-1.037	-0.854
T1	0.860	-0.997	-0.966
P6	0.900	-0.995	-0.972
P1	1.000	-0.990	-0.985
WQ	1.000	-0.990	-0.985
P11	1.260	-0.979	-1.015
P3	1.570	-0.969	-1.043
D1	1.760	-0.964	-1.057
W3	2.030	-0.957	-1.076
P5	2.410	-0.950	-1.098
P10	2.460	-0.949	-1.100
P7	2.610	-0.946	-1.108
P8	3.750	-0.929	-1.154
T2	5.330	-0.913	-1.199
P9	7.470	-0.897	-1.242
W4	12.580	-0.874	-1.309

Table 3.8.2-2 Cost Elasticity for Plants using Biological Removal Technologies

Plant Code	Average Flow	OM Cost elasticity	Capital cost elasticity
W1	1.900	-0.646	-0.552
W2	3.030	-0.625	-0.559
R1	8.810	-0.576	-0.573

The "translog flexible form" gives a convenient derivation of the cost elasticities with respect to the phosphorus concentration. However, in terms of solving the optimization model, it is also important to look at the marginal OM cost with respect to the final effluent in units of pounds, as trading is partially driven by the incentives for allocating abatement to firms with lower marginal OM costs.[33]

Marginal OM Cost---Transforming the Annual OM Cost Functions

Recall that OM costs are specified as the following form in the regression analysis:

$$\ln OM = 9.876 - 0.990 \ln C + 0.796 \ln F + 0.046 \ln C \ln F + 0.649T + 0.314T \cdot \ln C \quad \text{---(3.8.3-1)}$$

However, as listed in the beginning of this chapter, the argument of OM cost function $OM_i\,(e_i)$ is the final effluent measured in pounds per year. This type of specification is convenient for optimization purposes. Also, the specification of final effluent in pounds per year is consistent with the unit of discharge allowances and the environmental standards. To transform equation (3.8.3-1) to a function of the final effluent measured in pounds per year, the variable, "C", in equation (3.8.3-1) is replaced

[33] It is also partially driven by the incentive to avoid the capital upgrades.

by $C_i = \dfrac{e_i}{3046.063 \times F_i}$ (where 3046.063 is a coefficient to adjust the measurement unit).

The equation can be transformed into the following form (equation 3.8.3-2) by taking the exponential on both sides. (The detailed derivation is provided in Appendix Three)

$$OM_i\,(e_i) = \exp(m_i) \cdot e_i^{n_i} \qquad \text{-------------------------(3.8.3-2)}$$

where

$$m_i = 17.817 - 0.046(\ln F_i)^2 + (1.417 - 0.314T_i)LnF_i - 1.870T_i \quad \text{----------(3.8.3-3)}$$

$$n_i = -0.990 + 0.046\ln F_i + 0.314T_i \quad \text{-----------------------(3.8.3-4)}$$

In this way, the firm-specific parameters in the transformed functions embody the differences in daily flows across the WWTPs. The converted coefficients are shown in Table (3.8.3-1).

Table 3.8.3-1 Parameterization of the OM Cost Functions

Code	Average Flow	m	n
D1	1.760	18.603	-0.964
D2	0.150	14.963	-1.077
D3	0.310	16.094	-1.044
P1	1.000	17.817	-0.990
P2	0.360	16.321	-1.037
P3	1.570	18.447	-0.969
P4	0.120	14.606	-1.088
P5	2.410	19.028	-0.950
P6	0.900	17.667	-0.995
P7	2.610	19.134	-0.946
P8	3.750	19.610	-0.929
W1	1.900	16.636	-0.646
W2	3.030	17.113	-0.625
W3	2.030	18.797	-0.957
R1	8.810	18.129	-0.576
W4	12.580	21.110	-0.874
WQ	1.070	17.913	-0.987
T1	0.860	17.602	-0.997
T2	5.330	20.059	-0.913
P9	7.470	20.480	-0.897
P10	2.460	19.055	-0.949
P11	1.260	18.142	-0.979

From Table (3.8.3-1), one can easily see that the exponential parameters "n" are always negative. Therefore, the annual OM cost functions $OM_i\ (e_i)$ are strictly convex for all WWTPs in the Passaic Watershed, which is convenient in terms of the mathematical programming.[34] As mentioned in Chapter 2, the cost minimization problem D is formulated based on a Mixed-integer nonlinear programming model. In this case study, the optimal allocation of allowances is solved on the **General Algebraic Modeling System** (**GAMS**) which provides an algorithm "DICOPT" designed for solving mixed-integer nonlinear programming problems that involve linear binary and linear and nonlinear continuous variables. The OM cost function being convex satisfies one of the necessary conditions for this algorithm to work effectively[35].

The marginal OM cost with respect to the final effluent e_i follows directly from the new specification:

$$|\ \partial OM_i\ (e_i) \big/ \partial e_i\ | = |\ n_i \cdot \exp(m_i) \cdot e_i^{\,n_i - 1}\ | \quad \text{---------------------(3.8.3-5)}$$

Let final effluent equal to the permitted effluent $e_i = \overline{\mathrm{T}}_i$, the marginal OM cost of each plant at its TMDL is equal to:

$$MC(\overline{T}_i) = |\ n_i \cdot \exp(m_i) \cdot \overline{T}_i^{\,n_i - 1}\ | \quad \text{---------------------(3.8.3-6)}$$

The marginal cost of each firm at the corresponding 0.4mg/L is listed in tables (3.8.3-2) and (3.8.3-3). Sorting the "average flow" in an ascending order, one can easily see that, at the initial 0.4mg/L allocation for the discharge allowances, WWTPs with larger discharge

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[34] Strictly concave on the whole domain

[35] One of the necessary condition for DICOPT to work effectively is that the upper contour set of OM cost function must be pseudo-convex. The concavity of OM cost function guarantees the upper contour set is convex, which is a special case of pseudo-convex.

flows have smaller marginal OM cost. This conforms to the basic economic intuition that large firms are more effective in removing phosphorus. In this sense, one could expect that, holding other conditions equal, large firms are more likely to sell their allowances to small firms. Moreover, it can be shown that, by comparing the marginal OM costs between, say, "W3" and "W1", biological plants have higher marginal OM cost than chemical plants with similar flow levels. This also conforms to the findings from Georgia study that biological phosphorus removal is more costly than removal by the activated sludge (chemical) method.

Table 3.8.3-2 Marginal OM Cost for Chemical Plants at the TMDL

Code	Average Flow	Marginal OM cost wrt Effluents
P4	0.120	72.476
D2	0.150	67.955
D3	0.310	55.073
P2	0.360	52.733
T1	0.860	40.914
P6	0.900	40.374
P1	1.000	39.149
WQ	1.070	38.381
P11	1.260	36.587
P3	1.570	34.300
D1	1.760	33.168
W3	2.030	31.805
P5	2.410	30.239
P10	2.460	30.056
P7	2.610	29.536
P8	3.750	26.540
T2	5.330	23.916
P9	7.470	21.634
W4	12.580	18.521

Table 3.8.3-3 Marginal OM Cost for Biological Plants at the TMDL

Code	Average Flow	Marginal OM cost wrt Effluents
W1*	1.900	31.321
W2*	3.030	26.994
R1*	8.810	19.127

The discrete nature of capital upgrade---transforming the capital cost function

Before progressing to solve the optimal allocation of discharge allowances in the next chapter, it is important to make several comments with respect to capital upgrade costs.

Capital Level " x_i "

In the regression analysis above, capital cost functions were estimated to be continuous in both concentration and actual flow. While the continuity is convenient from an estimation point of view, the annual capital upgrade costs $CC_i(x_i)$ specified in the mixed integer model depend on one of small number of capital levels x_i. This comes with the fact that most capital upgrades in reality would be "lumpy" rather than changing continuously with every specific concentration. In this case study, the WWPTs are arbitrarily assumed to be able to target their capital upgrade at six discrete concentration levels; they are: 1.5 mg/L, 1mg/L, 0.5mg/L, 0.25mg/L, 0.1mg/L and 0.05 mg/L.[36] Each of these target concentrations is associated with a required capital level x_i, which takes the value from one of the six integers, 0, 1, 2, 3, 4 and 5.

[36] 0.05 mg/L is assumed to be the minimum concentration achievable by the current technologies.

In practice, a WWTP may abate to any concentration above the target level, but it cannot reduce its final concentration to levels below the range. In this sense, the target concentration level is associated with the maximum abatement capacity that the treatment facility is designed for. This constraint is imposed in the mixed-integer model by inequality (2.5-6) in Problem D, where $\phi_i(x_i)$ denotes the target concentration level which is the lowest concentration can be reached by discharger *i* with capital level x_i. It is assumed that a bigger x_i is associated with a smaller $\phi_i(x_i)$. Specifically, this relationship is described by a piecewise correspondence shown in table (3.8.4-1):

Table 3.8.4-1 Maximum Capacity for Each Capital Level

Capital Level X_i	**Feasible Concentration**
0	≥ 1.5 mg/L
1	≥ 1 mg/L
2	≥ 0.5 mg/L
3	≥ 0.25 mg/L
4	≥ 0.1 mg/L
5	≥ 0.05 mg/L

Implicit in this strategy is the assumption that even the firm with the minimum capital level can treat to a concentration of 1.5 mg/L. Moreover, note that this correspondence is not "one-to-one". For example, if a WWTP plans to treat phosphorus emission to 0.6 mg/L, the lowest capital level required is "2". However, the firm could upgrade to capital level 4 and still abate at 0.6 mg/L concentration, a case of "over-investment" which incurs unnecessary capital cost. It is also important to acknowledge that the minimum concentration associated with each capital level is chosen arbitrarily here, as no information is available regarding the capital investment schedule specific to each WWTP, and the specific value or range of values corresponding to each firm's capital investment edges. Nonetheless, the lumpy nature of the capital upgrade is evident in reality, and as will be argued in the next chapter, it plays an important role in explaining how the allowance trading is motivated.

Annualizing the Capital Cost

The capital cost functions were estimated as equation (3.8.1-6) for chemical plants and equation (3.8.1-8) for biological plants. For each WWTP, its target concentration level and actual flow are substituted into the function to determine the capital cost.[37] Note that $CC_i(x_i)$ is specified in the mixed integer model as the "annualized" capital upgrade cost, whereas the capital cost estimated in the regression analysis is the total capital cost. To annualize the capital cost of facilities upgrades, the amortized payment must be calculated, based on a prescribed interest rate and some assumed useful life or years to pay off. The annualized capital upgrade cost is calculated as:

$$ACC_i(x_i) = \frac{r \cdot CC_i(x_i)}{1-(1+r)^{-N}} \qquad \text{-------------------(3.8.5-1)}$$

where r is an interest rate, and N is the useful life of the investment. The duration of payments and annual interest rates would depend on the particular circumstances in every plant. For simplicity, I assume that plants uniformly pay back the capital investment over 15 years. In addition, the interest rates can be as low as for municipal bonds, as dischargers are municipal waste water treatment plants. Thus, the interest rate is assumed to be 5%. With r=0.05 and N=15, the Annualized Capital Cost of each WWTP, associated with six capital levels are listed in table (3.8.5-1).

[37] Note that the "C" in equation (3.8.4-2) and (3.8.4-4) is the target concentration instead of the final concentration.

Table 3.8.5-1: Annualized Capital Cost of each WWTP, associated with six capital levels

WWTP	Capital level	0	1	2	3	4	5	Annual capital cost per million gallon**
	Target concentration	1.5	1	0.5	0.25	0.1	0.05	
	Discharge flow	Annualized Capital Cost						
P4	0.12	5,034.54	6,723.88	11,026.48	18,082.30	34,771.72	57,022.09	289,764.36
D2	0.15	5,377.23	7,265.20	12,152.42	20,327.21	40,125.12	67,116.82	267,500.81
D3	0.31	6,661.85	9,346.45	16,673.75	29,745.41	63,934.48	114,056.97	206,240.26
P2	0.36	6,962.40	9,844.21	17,796.29	32,171.99	70,373.58	127,220.79	195,482.17
T1	0.86	n/a	n/a	n/a	50,795.02	123,057.95	240,332.63	143,090.64
P6	0.9	9,124.12	13,529.02	26,529.01	52,020.66	126,701.00	248,447.63	140,778.89
P1	1	9,412.27	14,032.79	27,775.29	54,976.00	135,563.90	268,323.43	135,563.90
WQ	1	n/a	n/a	n/a	n/a	135,563.90	268,323.43	135,563.90
P11	1.26	10,076.59	15,204.52	30,717.96	62,060.04	157,237.07	317,668.85	124,791.32
P3	1.57	n/a	n/a	33,807.77	69,648.52	181,075.17	373,038.99	115,334.50
D1	1.76	11,121.03	17,074.07	35,533.18	73,948.81	194,848.52	405,503.16	110,709.39
W1*	1.9	n/a	n/a	83,836.23	122,912.50	203,823.08	298,825.52	107,275.30
W3	2.03	11,599.42	17,940.94	37,813.04	79,696.29	213,537.30	450,059.80	105,190.79
P5	2.41	12,201.90	19,041.62	40,748.55	87,200.77	238,394.48	510,157.61	98,918.87
P10	2.46	12,276.07	19,177.79	41,114.78	88,144.94	241,556.75	517,867.44	98,193.80
P7	2.61	12,492.37	19,575.75	42,188.92	90,923.98	250,908.36	540,748.36	96,133.47
W2*	3.04	n/a	n/a	113,615.33	167,333.18	279,162.98	411,152.52	91,829.93
P8	3.75	13,902.44	22,198.97	49,405.71	109,956.61	316,604.91	704,631.21	84,427.98
T2	5.33	15,422.39	25,079.47	57,585.11	132,221.50	396,741.24	910,959.77	74,435.51
P9	7.47	17,037.72	28,195.92	66,708.98	157,827.38	492,698.07	1,165,678.77	65,956.90
R1*	8.81	n/a	151,932.61	226,089.50	336,441.68	569,001.53	846,725.86	64,585.87
W4	12.58	19,870.57	33,785.72	83,717.18	207,441.62	688,403.53	1,705,785.52	54,722.06

* WWTPs that are using biological treatment technologies

** The average annual capital cost is calculated as the annualized capital cost at capital level 4 divided by discharge flow

Sorting the "average flow" in an ascending order, one can easily see that the average capital cost per gallon, which is often referred to as levelized cost, falls with flow level. These economies of scale again conform to the basic economic intuition that large firms should be more effective in removing phosphorus, which is also consistent with the result for OM costs. Moreover, it concurs with the findings from Georgia study that the minimum investment for biological facilities is more costly than the chemical facilities, but biological facilities are much more effective in abating to low concentration levels.

Existing Capacities and Irreversibility

As introduced in the beginning of this chapter, Six WWTPs "T1, WQ, P3, W1, W2, R1" currently have existing capacity to remove phosphorus. Based on the additional assumption that the capital investment is NOT reversible, the capital levels of these six plants cannot be smaller than their existing level, which explains why some of the capital levels are shown "not applicable (N/A)" in table (3.8.5-1). Moreover, the cost of capital upgrades for those six WWTPs are calculated as the incremental capital cost, which is equal to the final capital cost minus the existing capital cost.[38]

Finally, to provide some perspective on this strategy for developing the annual capital upgrade costs, table (3.8.6-1) provides the elements needed to calculate the annual capital upgrade cost in the no trade scenario. Using WWTP "P3" which has current concentration at 0.60 mg/L as an example, the calculations are as follow: from table (3.6.4-2), P3's existing capital level is identified as level 2, associated with existing capital cost of 33,807.77 in U.S. dollars.[39] In the no trade scenario, P3 must upgrade its capital level to at least level 3 in order to independently meet the 0.4mg/L requirement. This means that P3 has to incur the capital upgrade cost of 35,840.75 USD (69,648.52 minus 33,807.77) to upgrade its capital from level 2 to 3.

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[38] To keep notation consistent, $CC_i(x_i)$ is the annualized incremental capital cost for these six plants, although it does not affect the final solution from the optimization point of view.

[39] Assume P3 did not over-invest.

Table 3.8.6-1: Costs on Capital Upgrade

WWTP	Current Concentration	Existing Capital Level	Existing Capital Value	Final Concentration	Required Capital Level	Final Capital Value	Capital Upgrade Cost
D1	3.13	0	0	0.4	3	73,948.81	73,948.81
D2	1.85	0	0	0.4	3	20,327.21	20,327.21
D3	1.91	0	0	0.4	3	29,745.41	29,745.41
P1	2.63	0	0	0.4	3	54,976.00	54,976.00
P2	1.67	0	0	0.4	3	32,171.99	32,171.99
P3	0.6	2	33,808	0.4	3	69,648.52	35,840.74
P4	1.53	0	0	0.4	3	18,082.30	18,082.30
P5	3.28	0	0	0.4	3	87,200.77	87,200.77
P6	1.48	0	0	0.4	3	52,020.66	52,020.66
P7	2.63	0	0	0.4	3	90,923.98	90,923.98
P8	1.62	0	0	0.4	3	109,956.61	109,956.61
W1*	0.84	2	83,836	0.4	3	122,912.50	39,076.27
W2*	0.56	2	113,615	0.4	3	167,333.18	53,717.85
W3	2.83	0	0	0.4	3	79,696.29	79,696.29
W4	1.46	0	0	0.4	3	207,441.62	207,441.62
R1*	2.98	1	151,933	0.4	3	336,441.68	184,509.06
WQ	0.16	4	135,564	0.16	4	135,563.90	0.00
T1	0.32	3	50,795	0.32	3	50,795.02	0.00
T2	2.14	0	0	0.4	3	132,221.50	132,221.50
P9	2.27	0	0	0.4	3	157,827.38	157,827.38
P10	3.07	0	0	0.4	3	88,144.94	88,144.94
P11	2.25	0	0	0.4	3	62,060.04	62,060.04

* WWTPs that using biological removal technology

There is one additional issue that should be addressed before moving on to the next chapter. Based on discussions with members of the study team and others involved in program design, it was reasonable to assume that all facilities upgrades would be in the form of chemical treatment, unless the plant already was using a biological process. There is no information that would suggest it reasonable to do otherwise, and many of the plants are likely to adopt chemical technologies in the near future, particularly if a 0.4mg/L standard is adopted initially. In turn, such a strategy would clearly limit their ability to switch to a biological technology, if a more stringent standard were adopted several years from now.

CHAPTER FOUR

THE MODEL RESULTS

Introduction

As discussed in previous chapters, this study endeavors to extend the way that water quality trading is typically portrayed in theoretical economic presentations by drawing attention to the lumpy nature of capital cost and the configuration of management areas. To highlight how the reallocation of pollution allowances might be affected by the incentives to avoid lumpy capital spending, two stylized trading scenarios are simulated and compared with a no-trade baseline in a case study using data from the Upper Passaic River Basin.

The first scenario resembles the "Marginal Cost Trading" envisioned in traditional emission trading theory. It assumes that each Waste Water Treatment Plant (WWTP) has to invest in treatment capacity upgrades so as to be able to independently meet its National Pollution Discharge Elimination System (NPDES) permit requirements (at 0.4mg/L), and then trade their allowances on a spot market. Hence, there are no opportunities for capital cost savings via trading. As such, any incentives for allowance trading are embodied only in the differential marginal Operating and Maintenance (OM) costs following the canonical presentation of pollution permit trading. In other words, only OM costs are accounted for in determining whether individual WWTPs buy, sell, or do not trade allowances. Assuming that the market is competitive, this “Marginal Cost” trading scenario can be viewed in terms of the social planner’s Problem D in Chapter Two with the implicit assumption of an immutable set of capital investments, or explicitly as the following (Problem $\overline{D}$):

$$\text{Problem } \overline{D} \quad \begin{cases} \min\limits_{e_i, \mathrm{T}_{ki}} \sum_{i=1}^{n} C_i(e_i, \bar{x}_i) = \sum_{i=1}^{n} [OM_i\ (e_i) + \overline{CC_i(x_i)}] & \text{-(4.1-1)} \\ \text{subject to:} & \\ e_i - \sum_{k=1}^{n} t_{ki} \mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} \le TMDL_i \ \ (\ i = 1, ..., \mathrm{n}) & \text{-(4.1-2)} \\ t_{ki} = \dfrac{d_{k[I]}}{d_{i[I]}} & \text{-(4.1-3)} \\ \overline{\phi_i(x_i)} \le e_i \le e_i^0; & \text{-(4.1-4)} \\ T_{ki}, T_{ik} \in R_+ & \text{-(4.1-5)} \end{cases}$$

where the fixed integer upgrade levels, $(\bar{x}_1, \bar{x}_2 ....\bar{x}_{22})$ are identified in the sixth column of Table (3.8.6-1) for each of the 22 WWTPs ($\overline{x_i}$ represents the fixed levels of capital, corresponding to the minimum capital level that allows plant *i* to treat to 0.4 mg/l. See Section 3.8.6 for detail.). Hence, the resulting fixed upgrade costs $\overline{CC_i(x_i)}$ equal those in the no-trade baseline, summarized in Table (3.8.6-1). The OM cost functions, expressed in equation 4.1-1, are obtained from the parameters in Table (3.8.3-1). TMDL loads for each WWTP are drawn from Table (3.3-1). The coefficient t_{ki} represents the trading ratio matrix, the specification of which will differ across various alternatives of the M.A. Approach considered, and thus will be presented in more detail below. At this juncture, it suffices to say that each *i*, *j* element of the matrix $\{t_{ij}\}$ represents the number of allowances sold from plant *i* to plant *j*.

The "Optimal Trading" scenarios assume that capital upgrade costs are explicitly considered in determining the trades. In other words, the watershed total abatement costs, consist of aggregate OM costs and aggregate Capital investment (CC) costs are jointly minimized. In this setting, re-allocation of pollution allowances is motivated not only by the difference in the marginal abatement costs of pollution abatement, but also by the desire to preempt unnecessary lumpy and costly upgrades of the treatment facility. Given this extra flexibility to determine the level of capital upgrades one can expect that the saving results from the second scenario is to be greater than those in the first scenario.

The "Optimal Trading" scenarios assume that WWTPs jointly minimize their aggregate abatement cost in an optimal way, accounting for the fixed upgrade costs. One way to think of "Optimal Trading" is that it is dictated by a benevolent social planner with perfect information whose goal is to minimize the watershed's total costs. In this sense, the "Optimal Trading" can be readily characterized by the integer model specified in equations (4.1-6) to (4.1-11). (It is the same as problem D in Chapter 2).

Problem D

$$\min_{e_i, x_i, \mathrm{T}_{ki}} \sum_{i=1}^{n} C_i(e_i, x_i) = \sum_{i=1}^{n} [OM_i^{xi}(e_i) + CC_i(x_i)] \qquad \text{---(4.1-6)}$$

subject to:

$$e_i - \sum_{k=1}^{n} t_{ki} \mathrm{T}_{ki} + \sum_{k=1}^{n} \mathrm{T}_{ik} \leq \overline{\mathrm{T}}_i \quad (i = 1, ..., \mathrm{n}) \qquad \text{---(4.1-7)}$$

$$t_{ki} = \frac{d_{k[i]}}{d_{i[i]}} \quad \forall i, k \qquad \text{---(4.1-8)}$$

$$\phi_i(x_i) \leq e_i \leq e_i^0; \quad (i = 1, ..., \mathrm{n}) \qquad \text{---(4.1-9)}$$

$$\mathrm{T}_{ki},\ \mathrm{T}_{ik} \geq 0 \quad \forall i, k \qquad \text{---(4.1-10)}$$

$$x_i \in Z_i \quad (i = 1, ..., \mathrm{n}) \qquad \text{---(4.1-11)}$$

Note that here the capital level x_i is no longer fixed, which is now an integer variable to be chosen from the corresponding integer set Z_i [40]. Therefore, the "Optimal Trading" will also result the optimal capital levels x_i for each WWTP.

Following the presentation in Chapter 3, three configurations of the Management Areas "Single Source M.A. Approach", "Multiple Source M.A. Approach – Alternative One" and "Multiple Source M.A. Approach – Alternative Two" are proposed to compare the cost-savings from pollution allowance trading under different trading rules. For each trading scenario (i.e. “Marginal Cost Trading” and “Optimal Trading”), three simulations are done based on these three distinct trading rules. For completeness, I also report and compare the simulation results using different compiling strategies (i.e. "geometric average" and "90% of the minimum ratios") in the Appendix Two.

Trading Details

Before identifying the trades that take place, it is worth noting that the “patterns of trades” may not be unique. In other words, there could be different patterns of trade which give the same optimal cost savings. Thus, the trading patterns described below aim to provide just one example of the set of possible transactions.

Trading Details for Marginal Cost Trading

This trading scenario assumes that each WWTP chooses to invest in the capacity upgrade to independently meet its NPDES requirement (at 0.4mg/L), and then buys and sells allowances based on its marginal abatement cost and the market price. In other words, only OM costs are accounted for in determining the trades.

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[40] As discussed in section 3.6.6, for most of the plants, the set Z_i contains six capital levels. Yet, this is not the case for plants which have existing abatement capacity. (see table 3.6.6-2 for detail)

Single Source Management Area Approach

The Single Source M.A. Approach treats each source as a separate management area. This extreme version of the M.A. approach best comports with the Hung and Shaw's Trading Ratio System in the sense that, only downstream trades in the same tributary are allowed as those with non-zero trading ratios *t*, corresponding to the matrices in Table 3.7-6. The patterns of trades are reported in Tables 4.2.1-1. There are eight WWTPs (D1, P1, P3, P5, W2, WQ, T1 and P10) that act as sellers, and eight WWTPs (D2, D3, P2, P4, P6, P11, W3 and T2) that buy permits. The rest of six WWTPs (P7, P8, P9, R1, W1 and W4) do not participate in trading. The volume of trades is very low due to the limited trading opportunities as a result of prohibiting upstream or cross-tributary trading and the reliance on marginal OM cost-based trading. In total, there are nearly 1,549 units traded, representing just over 2% of the total allowable emissions in the watershed. As would be expected with downstream trading， all trades between the eight buyers and eight sellers are above the main diagonal in the trading pattern matrices. Most of these trades are between immediately adjacent WWTPs.

Table 4.2.1-1 Marginal Cost Trading (Single Source M.A. Approach)

Seller \ Buyer	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1		57	71		33																	
D2																						
D3																						
P1					27																	
P2																						
P3							57															
P4																						
P5									120													
P6																						
P7																						
P8																						
W1																						
W2														139								
W3																						
R1																						
W4																						
WQ																			731			
T1																			210			
T2																						
P9																						
P10																						103
P11																						

Multiple Source Management Area Approach – Alternative One

Under the Multiple Source M.A. Approach – Alternative One, three critical locations, Dundee Lake, the endpoint of Pompton River, and the downstream of the confluence between Upper Passaic River and Lower Passaic River are identified. The trading ratios under this configuration (Table 3.7-4) are specified according to the relative effects of each transaction on the buyer's endpoints, in particular, inter M.A. trading is allowed from the Upper Passaic M.A. to the Lower Passaic M.A., and from the Pompton M.A. to the Lower Passaic M.A. Moreover, trades are also allowed from Pompton M.A. to the Upper Passaic M.A., but not the converse. As discussed in Chapter 3, these trading ratios no longer have the upper bound of one, indicating that sources can sell allowances to firms hydrologically more distant from the relevant critical location.

The trading pattern that results from this trading rule is depicted in Table 4.2.1-2. Seven WWTPs (P8, P9, P10, W4, WQ, T1 and R1) act as sellers, and 15 WWTPs (D1, D2, D3, P1, P2, P3, P4, P5, P6, P7, P11, W1, W2, W3 and T2) buy permits. In other words, all 22 firms participate in trading. Interestingly, most of these trades occur with sellers located hydrologically downstream from buyers as indicated by the predominance of trading entries below the main diagonal of the trading matrices. This is partially due to the marginal cost structure of firms, namely, large efficient firms happen to be located downstream. Besides, another factor is that most trading ratios for upstream trading are greater than or equal to one, as the discharges from upstream firms have less impact to the end-point. The volume of trade increases significantly compared with the Single Source M.A. Approach. There are 3,663 units of allowances traded, representing nearly 5% of the total allowable emissions in the watershed.

Table 4.2.1-2 Marginal Cost Trading (Multiple Source M.A Appoach - Alternative One)

Buy / Seller	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1																						
D2																						
D3																						
P1																						
P2																						
P3																						
P4																						
P5																						
P6																						
P7																						
P8								97		66												
W1																						
W2																						
W3																						
R1	339	132	205																			
W4				280	190	278	98		247			384	231	363								
WQ																			731			
T1																			210			
T2																						
P9																						170
P10																						23
P11																						

Management Area Approach - Alternative Two

The trading ratios Table 3.7-5 are similar to the other alternative of the Management Area Approach. The only difference is that, for this alternative, trades are no longer allowed from Pompton M.A. to the Upper Passaic M.A..

The trading patterns Table 4.2.1-3 of this trading rule are identical to the alternative Management Area Approach. This is because the additional restrictions on trades between Pompton and Upper Passaic M.A. are not binding at the equilibrium.

Table4.2.1-3 Marginal Cost Trading (Multiple Source M.A Appoach - Alternative Two)

Buy / Seller	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									91	66												
W1																						
W2																						
W3																						
R1	339	132	205																			
W4				280	190	278	98	113	141			384	231	363								
WQ																			731			
T1																			210			
T2																						
P9																						170
P10																						23
P11																						

Trading Details for Optimal Trading

In the Optimal Trading scenario, incentives for allowance trading are embodied not only in the differential marginal OM costs, but also in avoiding the costly capital upgrades. For example, in this setting, it is expected that some WWTPs would purchase enough allowances so that they are able to avoid facility upgrades and maintain a low level of capital cost.

Single Source Management Area Approach

The trading ratio depicted in Table 3.7-6 is analogous to the Hung and Shaw Trading Ratio System (TRS) which treats each WWTP as a separate management area. As a result, only downstream trades in the same tributary are allowed as those with non-zero trading ratios *t*.

The pattern of trades is reported in Tables 4.2.2-1. There are nine WWTPs (D1, P1, P5, P7, W1, W2, WQ, T1 and P10) act as sellers, and 10 WWTPs (D2, D3, P2, P3, P4, P6, P8, P11, W3 and T2) buy permits. The other three WWTP (R1, W4 and P9) do not participate in trading. Compared with the marginal cost trading, the optimal trading has much larger trading volumes as the incentive to avoid capital upgrade stimulates more trades. There are 4,150 units of allowances traded, about 2.6 times as many as in the marginal cost trading. This represents about 5% of the total allowable emissions in the watershed.

Table 4.2.2-1 Optimal Trading (Single Source M.A. Approach)

Buyer / Seller	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1		46	95		35	351	11															
D2																						
D3																						
P1					77	147	26															
P2																						
P3																						
P4																						
P5									274		392											
P6																						
P7											752											
P8																						
W1														115								
W2														504								
W3																						
R1																						
W4																						
WQ																			731			
T1																			210			
T2																						
P9																						
P10																						384
P11																						

<u>Multiple Source Management Area Approach – Alternative One</u>

As in Marginal Cost Trading, the trading ratios (Table 3.7-4) under this configuration of the management areas are specified according to the relative effects of each transaction on the buyer's endpoints. In particular, inter M.A. trading is allowed from Upper Passaic M.A. to Lower Passaic M.A., and from Pompton M.A. to Lower Passaic M.A. Moreover, trades are also allowed from Pompton M.A. to the Upper Passaic M.A. (but not the converse). The trading pattern is depicted in Table 4.2.2-2. Six WWTPs (R1, W4, WQ, T1, T2 and P9) act as sellers, and 16 WWTPs (D1, D2, D3, P1, P2, P3, P4, P5, P6, P7, P8, P10, P11, W1, W2 and W3) buy permits. As such, all 22 plants participate in trading. Compared with the marginal cost trading, the optimal trading has much larger trading volumes as the incentive to avoid capital upgrade stimulates more trades. There are 9633 units of allowances traded, nearly three times as many as in the marginal cost trading. The volume of trade represents nearly 13% of the total allowable emissions in the watershed.

Table 4.2.2-2 Optimal Trading (Multiple Source M.A. Approach - Alternative One)

Buye / Seller	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																						
W1																						
W2																						
W3																						
R1	301	41	56	178	75	627	68	111		335	822											
W4								764	320	649	649	579	927	619								
WQ	463		45	143	87																	
T1		58	37	114																		
T2				21																		
P9																					1021	523
P10																						
P11																						

Multiple Source Management Area Approach – Alternative Two

The trading ratios (Table 3.7-5) are similar to the Multiple Source Management Area Approach – Alternative One, except that, for this alternative, trades are no longer allowed from Pompton M.A. to the Upper Passaic M.A.

The trading patterns are depicted in Table 4.2.2-3. There are five WWTPs (R1, P9, W4, WQ and T1) act as sellers, and 17 WWTPs (D1, D2, D3, P1, P2, P3, P4, P5, P6, P7, P8, P10, P11, W1, W2, W3 and T2) buy permits. Again, all 22 WWTPs participate in the market. In contrast to the Multiple Source M.A. Approach – Alternative One, this time

T2 becomes a buyer. This is not unexpected as T2 is no longer allowed to sell its allowances to Pompton M.A.

Compared with the marginal cost trading, the optimal trading has much larger trading volumes. There are 10,269 units of allowances traded, about 2.5 times as many as in the marginal cost trading. This volume of trade represents nearly 14% of the total allowable emissions in the watershed.

Table 4.2.2-3 Optimal Trading (Multiple Source M.A. Appoach - Alternative Two)

Seller \ Buyer	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																						
W1																						
W2																						
W3																						
R1	663	69		400	143		59				1601											
W4			105			528		857	320	928		579	927	619								
WQ																			731			
T1																			210			
T2																						
P9																					1021	523
P10																						
P11																						

Cost Savings

The previous section demonstrates that the pattern of trade varies with the two trading scenarios (i.e. Marginal Cost Trading *v.s.* Optimal Trading) as well as different configuration of the Management Area Approach. This section explores the potential cost savings from allowances trading under each simulation.

The Baseline Case---No trade is allowed

To estimate the potential cost-savings from allowance trading under each simulation, the sum of the annual OM costs, as well as the sum of the annualized capital upgrade costs for all 22 WWTPs, need to be compared with a properly defined baseline. The appropriate baseline situation for evaluating potential 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. The estimated treatment costs for each plant and for the entire watershed are summarized in Table 4.3.1-1.

Table 4.3.1-1 Estimated Abatement Costs for each WWTP

WWTP	Annual OM Cost ($)	Annualized Capital Upgrade Cost ($)	Total Annual Abatement Cost ($)	Proportion of Annual Capital Expense in the Total Annual Abatement Cost (%)
D1	73,784.01	73,948.81	147,732.82	50.1%
D2	11,528.82	20,327.21	31,856.03	63.8%
D3	19,927.36	29,745.41	49,672.77	59.9%
P1	48,181.90	54,976.00	103,157.90	53.3%
P2	22,305.14	32,171.99	54,477.13	59.1%
P3*	67,695.80	35,840.74	103,536.55	34.6%
P4	9,743.83	18,082.30	27,826.13	65.0%
P5	93,511.56	87,200.77	180,712.33	48.3%
P6	44,503.06	52,020.66	96,523.71	53.9%
P7	99,303.84	90,923.98	190,227.82	47.8%
P8	130,501.10	109,956.61	240,457.72	45.7%
W1*	112,158.17	39,076.27	151,234.44	25.8%
W2*	159,122.85	53,717.85	212,840.70	25.2%
W3	82,165.23	79,696.29	161,861.52	49.2%
W4	324,991.54	207,441.62	532,433.16	39.0%
R1*	356,499.49	184,509.06	541,008.55	34.1%
WQ*	133,992.62	0.00	133,992.62	0.0%
T1*	53,735.59	0.00	53,735.59	0.0%
T2	170,107.38	132,221.50	302,328.89	43.7%
P9	219,397.56	157,827.38	377,224.94	41.8%
P10	94,970.37	88,144.94	183,115.31	48.1%
P11	57,351.88	62,060.04	119,411.92	52.0%
SUM	2,385,479.08	1,609,889.45	3,995,368.54	40.3%

* Plants that currently have some capacity to remove phosphorus, whose annual capital upgrade cost is computed as the incremental capital cost

In treating to a 0.4mg/L standard, it is estimated that total annual costs of phosphorus removal would be about 4 million dollars[41]. Of this total, 40.3% would be accounted for by the annualized cost of the capital upgrades needed. This percentage varies from 0 (for those plants that currently can treat to this level) and 65%. The capital costs are a particularly large fraction of total costs for small plants where, given the low flows, annual OM costs are relatively small.

To estimate the watershed cost saving from allowances trading under each case, the sum of the annual OM costs, as well as the sum of the annualized capital upgrade costs for all 22 WWTPs, are be reported for each case and compared to the costs of a baseline case defined above.

Cost-savings from Marginal Cost Trading

Under Marginal Cost Trading, no savings on Capital Costs are available. Only OM costs are accounted for in the cost minimization problem.

The cost-savings from Marginal Cost trading under the Single Source Management Area Approach is reported in the first column of Table 4.3.2-1. Total costs under this program fall a nominal $23,489, or 0.59% relative to the baseline case, with savings being attributed solely to reduced OM costs. Limited trading opportunities and the consequent 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.

The cost-savings from Marginal Cost trading under the Multiple Source M.A. Approach – Alternative One and Alternative Two are reported in the second and third column of Table 4.3.2-1. Despite the additional trading activity, the cost savings remain

[41] Thus, a 1% savings represents about $40,000 per year.

at a relatively meager level. Further, the cost savings under the two Multiple Source M.A. Approaches are identical, as the extra trading constraint in Alternative Two is not binding at the equilibrium. The total cost savings is $41,385 or 1.04% relative to the baseline. The low level of cost saving under both trading rules again can be attributed to the relative homogeneity of waste water treatment costs.

Table 4.3.2-1 Cost Savings under Marginal Cost Trading

	Single Source M.A. Approach	Multiple Source M.A. Approach - Alternative One	Multiple Source M.A. Approach - Alternative Two
Baseline OM Cost	$2,385,479.08	$2,385,479.08	$2,385,479.08
OM Cost after Trading	$2,361,990.48	$2,344,093.14	$2,344,093.14
Savings on OM Cost	$23,488.61	$41,385.94	$41,385.94
Percentage Savings on OM Cost	0.98%	1.73%	1.73%
Baseline CC Cost	$1,609,889.45	$1,609,889.45	$1,609,889.45
CC Cost after Trading	$1,609,889.45	$1,609,889.45	$1,609,889.45
Savings on CC Cost	$0	$0	$0
Percentage Savings on CC Cost	0%	0%	0%
Baseline Total Cost	$3,995,368.54	$3,995,368.54	$3,995,368.54
Total Cost after Trading	$3,971,879.93	$3,953,982.60	$3,953,982.60
Total Savings	$23,488.61	$41,385.94	$41,385.94
Percentage Savings on Total Cost	0.59%	1.04%	1.04%

Cost savings from Optimal Trading

The Optimal Trading scenario assumes optimal capital upgrades, that is, the aggregate watershed costs of abatements consisting of both aggregate OM costs and aggregate Capital upgrade costs are jointly minimized through allowances trading.

The cost-savings from Marginal Cost trading under the Single Source M.A. Approach is reported in the first column of Table 4.3.3-1. The watershed capital costs fall a considerable $237,787, amounting to a 15% reduction relative to the baseline capital costs. Interestingly, the watershed OM costs after the trades is even slightly higher than the no-trade baseline, as many allowances are sold from high marginal cost WWTPs to low marginal cost WWTPs driven by the incentive to avoid capital upgrade cost. The resulted total cost-savings is $221,927 (or 5.55% relative to the no trade baseline), with all savings being attributed to the reduced Capital Costs. This level of total savings is about 10 times of those attained under the Marginal Cost Trading.

The cost-savings from Optimal trading under the two alternative M.A. approaches are reported in the last two column of Table 4.3.3-1. Trades under these two M.A. approaches generate significant capital cost savings, to the order of $538,141.51 (or 33% relative to the baseline capital costs). Since the benefit of avoiding capital upgrade costs outweigh the rise in variable abatement costs, the watershed OM costs after the optimal trading are slightly higher than those in the no-trade baseline for both Multiple Source M.A. approaches. In total, the cost savings for Multiple Source M.A. Approach – Alternative One and Multiple Source M.A. Approach – Alternative Two are $523,417.16 (13.10% relative to the baseline total costs) and $519,982.72 (13.01% relative to the baseline total costs). The level of total savings is nearly eight times that of the Marginal Cost Trading.

Table 4.3.3-1 Cost Savings under Optimal Trading

	Single Source M.A. Approach	Multiple Source M.A. Approach - Alternative One	Multiple Source M.A. Approach - Alternative Two
Baseline OM Cost	$2,385,479.08	$2,385,479.08	$2,385,479.08
OM Cost after Trading	$2,401,338.95	$2,400,476.44	$2,403,910.88
Savings on OM Cost	-$15,859.86	-$14,997.35	-$18,431.80
Percentage Savings on OM Cost	-0.66%	-0.63%	-0.77%
Baseline CC Cost	$1,609,889.45	$1,609,889.45	$1,609,889.45
CC Cost after Trading	$1,372,102.85	$1,071,474.94	$1,071,474.94
Savings on CC Cost	$237,786.60	$538,141.51	$538,414.51
Percentage Savings on CC Cost	15%	33%	33%
Baseline Total Cost	$3,995,368.54	$3,995,368.54	$3,995,368.54
Total Cost after Trading	$3,773,441.80	$34,971,951.38	$3,475,385.82
Total Savings	$221,926.74	$523,417.16	$519,982.72
Percentage Savings on Total Cost	5.55%	13.10%	13.01%

Prices

Prices for Marginal Cost Trading

For any interior equilibrium of the Marginal Cost Trading, the competitive price of pollution allowances at each WWTP is equal its marginal abatement cost. As discussed in Chapter Two, the pollution allowances are traded to the point where the spatially adjusted equil-marginal condition holds. There is a unique price at each location: that is, the price of allowances at the seller's location must be equal to the price at the buyer's location adjusted by the transfer coefficient (i.e. trading ratios). These prices are reported in Table 4.4.1-1.

For example, under the Multiple Source M.A. Approach – Alternative One, the allowances price at R1 is equal to 21.2 $/lbs, and the price at D1 is 26.2 $/lbs (see the second column of Table 4.4.1-1. Also, from Table 4.4.1-1, we know the trading ratio between R1 and D1 is 0.809. These numbers verify the spatially adjusted equi-marginal condition at the equilibrium, as 26.2 multiplied by 0.809 is equal to 21.2.

Comparing the prices in the first column with the last two columns, one can see that the allowances prices are more equalized under the Multiple Source M.A. approaches. This is because the Multiple Source M.A. Approach provides more trading opportunities than the Single Source M.A. Approach. Moreover, note that the allowances prices at WQ and T1 cannot be determined because their non-degradation constraints are binding at the equilibrium.

Table 4.4.1-4 The Price of Allowances at Each WWTP

WWTP	Single Source M.A. Approach	Multiple Source M.A. Approach - Alternative One	Multiple Source M.A. Approach - Alternative Two
D1	38.7	26.2	26.2
D2	38.7	26.2	26.2
D3	38.7	26.2	26.2
P1	40.9	26.9	26.9
P2	40.9	26.9	26.9
P3	36.4	26.9	26.9
P4	36.4	26.9	26.9
P5	32.8	28.4	28.4
P6	32.8	28.4	28.4
P7	29.5	28.4	28.4
P8	26.5	28.4	28.4
W1	31.3	24.3	24.3
W2	28.6	24.3	24.3
W3	28.6	24.3	24.3
W4	18.5	24.3	24.3
R1	19.1	21.2	21.2
WQ	n/a	n/a	n/a
T1	n/a	n/a	n/a
T2	18.6	18.6	18.6
P9	21.6	22.4	22.4
P10	32.2	30.5	30.5
P11	32.2	30.5	30.5

Prices for Optimal Trading

In contrast with the Marginal Cost Trading, the prices for allowances may not be uniquely determined in each trade, because many WWTPs operate at their maximum abatement capacity in equilibrium avoiding upgrading to the higher level. So the allowances price could vary as the result from the bargaining and bilateral negotiations between seller and buyer.[42] (See the Kuhn Tucker conditions in Chapter 2 for a detailed discussion.) In this subsection, I shall briefly discuss the cost savings for individual WWTP which are then used to give a rough estimation of its Willingness-to-Pay (WTP) and Willingness-to-Sell (WTS) of allowances. These metrics on the individual level may provide a bit of taste on the potential outcomes of price negotiation.

Using Multiple Source M.A. Approach – Alternative Two as an example to illustrate the point, five multilateral contracts can be assigned in the following way to achieve the Optimal Trading outcome.

[42] Although the unique price is not available, the possible range of the price between the willingness to buy of the buyer and the willingness to sell of the seller can be identified.

Table 4.4.2-1 One Possible Price Negotiation under Optimal Trading

Seller	Units of allowances sold	WTS per unit of allowance	Buyer	Units of allowances bought	WTP per unit of allowance	Possible price range
R1	2935	$24.38	D1	663	$79.50	$24.38 to $53.13
			D2	69	$160.27	
			P1	400	$91.90	
			P2	144	$131.85	
			P4	59	$161.53	
			P8	1600	$53.13	
W4	4862	$26.45	D3	102	$90.35	$26.45 to $72.89
			P3	530	$92.49	
			P5	857	$75.05	
			P6	320	$107.37	
			P7	928	$72.89	
			W1	579	$93.53	
			W2	927	$80.31	
			W3	619	$154.30	
P9	1543	$25.80	P10	1021	$63.82	$25.80 to $63.82
			P11	523	$81.47	
WQ & T1	941	$0.00	T2	941	$20.46	$0.00 to $20.46

As shown in Table 4.4.2-1, the top three group contracts are established between one seller and multiple buyers. The bottom row shows that the fourth group contract is established between two joint sellers WQ, T1 and one buyer T2.

Further, in order to give a parsimonious estimation of possible price range, I make the following simplifying assumption: (1) a firm would be excluded from the market if it chooses not to trade based on this designed grouping; (2) the price negotiation is simultaneous in each group and the there will be one uniform price for each group contract; (3) everyone in the group must be happy with the contract without any further compensation. With these simplifying assumptions, one can have a parsimonious estimation of the WTP and WTS for each firm. Each buyer's WTP is defined as the highest price per allowance the buyer is willing to and able to afford in order to have this group contract. In other words, a buyer would be indifferent between having this contract and being excluded from the market, if the price for each allowance is at his WTP. Thus, the WTP is computed as the average cost saving per unit of abatement. For instance, the WTP of P5 is $75.05 per unit allowance which is equal to the total cost savings from the trade, $64,322, divided by the number of allowances bought, 857. Note that the total cost savings, $64,322, is the sum of both removal cost saving, $17,870, and capital cost saving, $46,452, relative to the baseline no trade scenario.

In a similar fashion, the seller's WTS is defined as the lowest price per allowance the seller is willing to sell its allowances based on the group contract. In other words, a seller would be indifferent between having this contract and being in the autarky, if the price for each allowance is at his WTS. Therefore, the WTP is computed as the additional abatement cost incurred divided by the units of allowances sold. For instance, the WTS of

R1 is \$24.38 which is equal to the additional abatement cost \$71,555 divided by the additional units of abatement 2935, relative to the no-trade baseline.

It is worth spending a few more words on the fourth contract, where the WTS is recorded at \$0.00, and the WTP is recorded at \$20.46. The WTS being zero is due to the fact that, the current unregulated abatements by WQ and T1 already over-comply with the required target. Thus, they can simply dump all their unused allowances without any additional cost. The buyer T2's WTP is \$20.46, the lowest among all contracts. It is partially due to the fact that, T2's cost savings are from variable removal cost alone (i.e. it still upgrades). Thus, its WTP is relatively low compared with other buyers.

The above parsimonious estimation of the possible price range is based on a set of simplifying assumptions, whereas the actual market mechanism may be more complex. For example, it is assumed that if a firm cannot reach the deal with its designated trading partners, it will be excluded from the market, and so it has to independently abate to the required environmental standard. Yet, in practice, the firm may be able to form an alternative coalition where it can generate a higher cost savings. In this sense, the above example provides a very rough estimate of the range of possible price to demonstrate the complications associated with capital cost edges in price negotiation. A refined price range can be derived using the concept of "Core" in the cooperative game theory. This refined price range should be contained in the price range provided above and is not explored further in this study.

Summary of the case study

In retrospect, two types of trading scenarios were simulated in the case study. In the scenario of Marginal Cost Trading, WWTPs are assumed to expand their abatement capacity to be able to independently meet the NDPES requirement before participating in trade. Therefore optimal capital planning is precluded, as the capital expansion is made by each WWTP before trading in the spot market. In other words, WWTPs minimize only the OM costs of abatement by trading at the equi-marginal point, given the capital capacity to meet the abatement standard independently. In contrast, the scenario of Optimal Trading stands on the assumption that each WWTP can minimize the total abatement cost by choosing the optimally capital upgrade plan.

The potential cost savings from effluent trading programs reflect differences in total abatement cost compared with the no trade baseline case. The estimated potential cost savings for both trading scenarios are summarized in Table 4.5-1.

Table 4.5-1 Saving Summary

Trading Scenario / M.A Approaches	Marginal Cost Trading	Optimal Trading
Single Source M.A. Approach	$23,489 (0.59%)	$221,927 (5.55%)
Multiple Source M.A. Approach - Alternative One	$41,386 (1.04%)	$523,417 (13.10%)
Multiple Source M.A. Approach - Alternative Two	$41,386 (1.04%)	$519,983 (13.01%)

The following results are reflected by the summary presented above:

Result 1: The maximum total costs savings from the various Management Area approaches are nominal under the Marginal Cost trading scenario, (See the first column of table 4.5-1) ranging from 0.59% to 1.04% relative to the no trade scenario. This low level of savings follows *a priori* expectations. Recall that there are only two alternative technologies currently existing in the Passaic Watershed, so the differences in marginal abatement costs arise primarily from differences in the economies of scale based on flow levels. It is not surprising that the volumes of trade account for only between 2 to 6 percent of the total allowable emissions in the watershed. These small trading volumes and disappointing saving results are consistent with the experience from other water quality trading programs where there are homogeneous technologies (U.S. EPA, 2006).

Result 2: In sharp contrast with the Marginal Cost trading, the Optimal Trading scenario yields a much more optimistic saving result. The trading program that supports optimal capital upgrade planning generates about 10 times of the savings as the marginal cost trading under the same Management Area approach. With optimal allocation of the capacity upgrade, the maximum percentage cost savings from the various trading regimes range from 5.6% to 13.1% relative to the no trade scenario. The trading volume rises considerably. Specifically, the volume of trade accounts for between 5 to 14 percent of the total allowable emissions in the watershed. As the result, almost all buyers end up being able to acquire enough allowances to stay within the maximum capacity of capital level 2 (i.e. emissions related to higher than

0.5mg/L concentration). They do not need to upgrade their abatement capital to the level 3 as in the no-trade baseline scenario. It is also important to note that, as the trading equilibrium deviates from the equi-marginal point, the variable OM costs are not necessarily minimized. However, the savings on the lumpy capital costs outweigh the loss of efficiencies on the OM costs and thus greater total savings are realized.

Result 3: The percentage savings increase as different alternatives of the M.A. Approach become less restrictive. The Single Source M.A. Approach does not allow increased phosphorous load at any point in the watershed relative to the original NDPES (See the top row of Table 4.5-1). Permitting upstream trade within management areas accomplishes twice as much savings as in the Single Source M.A. Approach (See the bottom row). These additional cost savings are due in large measure to an ability to trade in any direction within an M.A. As a result, some low-cost downstream plants can now sell permits to high abatement cost plants located upstream. When capital planning is feasible, these expanded trading opportunities also allow some high-cost upstream plants to avoid the capital costs of treatment upgrades. In addition, allowing trade from the Pompton M.A. to the Upper Passaic M.A. (i.e. the Multiple Source M.A. Approach – Alternative One) can further increase the savings slightly.

Another way to think about these trading rules is that the Single Source M.A. Approach treats all points in the watershed as critical locations, whereas the two alternative Multiple Source M.A. Approaches relax these constraints to accommodate the hydro-ecological reality and impose only three critical locations.

In fact, the key message to convey here is that the Single Source M.A. Approach, and hence the standard Trading Ratio System may be overly restrictive, if, under the physical reality of some watersheds (such as the case of Passaic Watershed), only a few but not all locations are of water quality concern. The Multiple Source Management Area Approach could potentially generate much higher cost savings without putting the water quality at the critical locations at risk. Again, these possibilities are due to the nature of the watershed, and they may not generalize.

The results above suggest that moderate cost savings from trading phosphorus allowances can be achieved through the Multiple Source Management Area approach (Results 3) and that substantial gains are possible if trades can facilitate the efficient allocation of fixed cost investments across WWTPs (Result 2). The former issue is primarily driven by the hydrology of a particular watershed and whether managing water quality in a flexible way to protect a selected number of locations is deemed appropriate. The later issue is more of a humble suggestion to environmental policy makers as it offers a new perspective on the market mechanisms of water quality trading (with particular emphasis on the fixed cost planning). In the concluding chapter, I will discuss further about why a more structured trading approach may be desirable to achieve the capital cost savings.

CHAPTER FIVE

CONCLUSION AND POLICY IMPLICATIONS

The case study suggests that substantial cost savings are possible for water quality trading if trades can facilitate the efficient allocation of fixed cost investments across WWTPs. In large, fluid pollution allowance 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 an individual discharger's decision to upgrade its facility is likely to have no noticeable effect on the market supply or demand for permits.

However, in watersheds like the Upper Passaic River Basin, there are a small number of potential traders, with discrete and homogeneous abatement technologies across firms. Most, if not all, firms do not have the present capacity to meet the specified standard. In such an environment, firms that do not upgrade are not guaranteed that a supply of permits will be available as a substitute at any price. Therefore, firms that would defer or do not want to upgrade their systems fully would have to make the premature investment nonetheless. As a result, the actual upgrade decision made by each firm may well deviate from the optimal portfolio of capital investments. If the firms' managers are highly risk averse or the penalty for not being able to meet the environmental standard is sufficiently large, a likely outcome is consistent with the scenario of Marginal Cost Trading – all WWTPs will have to upgrade fully so as to be able to independently meet their NPDES permit requirement.

Based on the simulations of Marginal Cost Trading, cost savings accomplished under an open market mechanism range from 0.59% to 1.04% of total costs relative to 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 with the disappointing level of water quality trading observed to date.

On the other hand, the simulation results of Optimal Trading results suggest that if WWTPs are able to jointly optimize their capital investment levels, the costs savings can increase dramatically (up to 13.10% of the baseline total cost). Thus, in practice, the achievement of such cost savings for the typical watershed might necessitate a movement away from the open market exchange approaches such as implemented by the U.S. acid rain program. The major remaining policy issue is: what type of market mechanism is best suited for typical water quality trading programs?

Appropriate Market Mechanisms and Policy Implications

To derive a suitable market mechanism for typical water quality trading programs, it is necessary to look at the features of the optimal abatement allocations reflected in the Optimal Trading Scenario. Using the Optimal Trading under Multiple Source M.A. Approach – Alternative Two as an example, one possible grouping of the trading partners is summarized in Table 5.1-1.[43]

Table 5.1-1 One Potential Grouping of Trading Partners

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

[43] The trading ratios under the Multiple Source M.A. Approach – Alternative Two is designed to protect the water quality at the endpoints of Upper Passaic River, Lower Passaic River and Pompton River at all possible hydrological conditions. It is likely that this will be the actual configuration of the watershed for trading purposes. Therefore, I am particularly interested in the cost savings from this scenario.

Among the five sellers, WQ and T1 are currently abating to less than 0.4mg/L, over-complying with the prospective NDPES requirements. Therefore, they can simply dump their excess allowances into the market.[44] The other three sellers, W4, R1, P9, do not have present capacity to meet the NDPES. It is expected that they will upgrade their abatement capacities fully and then sell the leftover allowances to the buyers. On the other hand, the sixteen buyers can avoid upgrading their facilities fully (e.g. to level 3) by acquiring allowances from the sellers. This pattern of trade, which conforms to *a priori* expectations, can be summarized as follows: Large firms (taking advantage of economies of scale in capital treatment costs), that are well positioned (in terms of trading ratios relative to ambient measurement points) become sellers, allowing the higher than average cost, capital intensive smaller WWTPs to avoid full upgrades. Specifically, among the three WWTPs who decide to upgrade fully and become sellers:

- W4 is the largest (and most efficient) WWTP in the watershed;
- R1 is the second largest WWTP in the watershed, and, due to external factors it has already adopted a biological treatment technology which has relatively lower cost elasticity of abatement than the chemical technology (i.e. more efficient when treating to a low concentration level) ;
- P9 has the highest flow in the Lower Passaic M.A.

Based on this optimal allocation of fixed-cost upgrades, the market can be cleared at the minimum overall abatement cost for the whole watershed. In practice, however, it is very difficult for firms to achieve the optimal fixed-cost upgrade under standard spot market conditions. Due to the lumpy nature of the capital upgrades, firms cannot

[44] Remember that WQ and T1 cannot abate less because they are bounded by the non-degradation principle (discussed in the chapter 2). However, they can sell their excess allowances through market trading.

instantaneously adjust their abatement capacities according to the actual trading outcomes in the market. Instead, firms need to make *ex ante* capacity choices before entering the spot market. In some cases where too few WWTPs choose to upgrade, the market cannot be cleared at any price. Moreover, since the capital investment is irreversible, even if the market is cleared at some price, it is unlikely to be optimal (For example, the scenario of Marginal Cost Trading gives the savings estimates in the case of a precautionary over-investment).

Therefore, the market mechanism must be modified such that all WWTPs can efficiently come to an agreement on which firms should to allow for excess allowances to be sold to firms that could as a result avoid what would now be unnecessary upgrade. In this sense, I believe a more structured market approach is necessary to replace the laissez faire market model based on the ideal of marginal cost trading. Specifically, two critical implications on the market structure are discussed below:

(1) For firms to be able to make the inter-temporal optimal investment decisions, the market must secure a long term stable demand of permits for those that would undertake upgrades as well as an ample supply for others that would not upgrades, because the market is so small, the spot trading is unlikely to ensure the stable demand and supply in the long term. Therefore, it is necessary to incorporate the **long-term multi-year contracts** in the trading mechanism.

(2) Another critical element of the fixed-cost trading is the **simultaneous multilateral contracting**. For instance, the optimal solution in planner’s problem suggests that W4 should upgrade fully and sell allowances to eight buyers, D3, P3, P5, P6, P7, W1, W2, and W3. However, from buyers' perspective, they would choose not to

upgrade fully only if W4 promises to upgrade and guarantee the supply of allowances to all of them. On the other hand, from the seller's perspective, W4 would be able to guarantee the supply of allowances to all sellers only if W4 has information on total demand. Therefore, to secure this arrangement, a multilateral contract must be signed between W4 and the five buyers simultaneously.

The gains from fixed-cost 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 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)

To sum up, my suggestion to the Passaic watershed would be to develop a "*structured fixed-cost trading program*".

The previous discussion on the features of fixed-cost trading suggest that achieving a cost-effective reallocation of abatement responsibilities may require a more structured approach than "blind" market house transactions. 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. The sellers, on the other hand, needs joint assurance of future demand from all those buyers. 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 WWTPs.

APPENDIX A

PROOF OF PROPOSITION 1

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

The cost-effective benchmark for Intra-M.A. trading is given by problem (B), which is a special case of the problem (A-2).

$$\min_{e_{k_i}} \sum_{i=1}^{n} C_{k_i}(e_{k_i})$$

subject to:

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

(B-2) $$e_{k_i} \in [0, e_{k_i}^0] \qquad \forall i \in \{1,2,.....n\}$$

On the other hand, the Intra-M.A. trading based on the trading ratio specified by (2.3.3-3) can be described by the following cost minimization problem (E).

$$\min_{e_{k_i}} \sum_{i=1}^{n} C_{k_i}(e_{k_i})$$

subject to:

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

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

(E-3) $\quad \mathrm{T}_{k_j k_i} \geq 0 \qquad \forall i, j \in \{1,2,\ldots..n\}$

To prove the cost-effectiveness of intra-M.A. trading, it is sufficient to show the equivalence of problem (B) and problem (E).

Let Ω_B denote the constrained choice set for problem (B), (i.e. the set of all possible vector ($e_{k_1} e_{k_2} \ldots.. e_{k_n}$) that satisfies the constraints (B-1) and (B-2). Similarly, let Ω_E denote the set of vector ($e_{k_1} e_{k_2} \ldots.. e_{k_n}$) that satisfies the constraints (E-1), (E-2) and (E-3).

For any element $(e_{k_1} e_{k_2} \ldots.. e_{k_n}) \in \Omega_E$, it must satisfy:

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

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

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

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

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

Summing the inequalities from 1 to n yields:

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

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

Also, since:

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

Therefore, the above weak inequality becomes:

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

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

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

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

and

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

Define:

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

We know:

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

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

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

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

(ii) $K^{-}\neq\phi$, that is, if not all firms have nonnegative ω , let S^{+} define the sum of all positive ω_{k_i} , that is: $S^{+}=\sum_{i=1}^{n}\max\{\omega_{k_i},0\}$. Then there exists a nonnegative matrix $\{\mathrm{T}_{k_j k_i}\}$ with $\mathrm{T}_{k_j^+ k_i^-}=\dfrac{\omega_{k_i^-}\cdot\omega_{k_j^+}/d_{k_j^+[K]}}{S^{+}}>0$ for all $k_i^{-}\in K^{-}$, $k_i^{+}\in K^{+}$; and all other elements are equal to zero. I claim that with $\{\mathrm{T}_{k_j k_i}=0\}$, and constraints (E-1), (E-2) and (E-3) are satisfied and so are $(e_{k_1} e_{k_2} .....e_{k_n}) \in \Omega_E$

Now verify the claim:

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

For $k_j^{+}\in K^{+}$

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

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

Therefore, constraints (E-1), (E-2) and (E-3) are satisfied.

For $k_i^{-}\in K^{-}$

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

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

Therefore, constraints (E-1), (E-2) and (E-3) are satisfied.

Combining (i) and (ii), we know

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

Since I have already shown

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

Therefore, I have shown that: $\Omega_B = \Omega_E$

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

PROOF OF PROPOSITION 2

Without loss of generality, suppose that there are *m* Management Areas $\{K_1, K_2, ...K_m\}$ ordered from upstream to downstream in the whole watershed, with n_i sources $\{k_1^i, k_2^i, ...k_{n_i}^i\}$ in the Management Area K_i. The total number of sources in the watershed is: $N = \sum_{i=1}^{m} n_i$. Further, let $\overline{\mathrm{T}}_{k_i^j}$ denote the initial allocation of allowances at the *i*th source in the *j*th M.A. Thus, the implied environmental target at the endpoint

$[K_h]$ is $E_{[K_h]} = \sum_{i=1}^{m} \sum_{j=1}^{n_i} d_{k_j^i [K_h]} \overline{T}_{k_j^i}$

The cost-effective benchmark for watershed trading subject to the water quality at all M.A. endpoints is given by problem (B*) , which is a special case of the problem (A-2).

$$\min_{e_{k_i}} \sum_{i=1}^{N} C_{k_i}(e_{k_i}) \qquad\qquad N = \sum_{i=1}^{m} n_i$$

subject to:

(B1*) $\sum_{i=1}^{m} \sum_{j=1}^{n_i} d_{k_j^i [K_h]} e_{k_j^i} \le E_{[K_h]} = \sum_{i=1}^{m} \sum_{j=1}^{n_i} d_{k_j^i [K_h]} \overline{T}_{k_j^i}$; $\forall h \in \{1,2,...m\}$

(B2*) $e_{k_j^i} \in [0, e^0_{k_j^i}]$ $\qquad \forall i \in \{1,2,...m\},\ j \in \{1,2,.....n_i\}$

On the other hand, the watershed trading based on the trading ratio specified by (2.3.3-3) can be described by the following cost minimization problem (E*).

$$\min_{e_{k_i}} \sum_{i=1}^{N} C_{k_i}(e_{k_i}) \qquad\qquad N = \sum_{i=1}^{m} n_i$$

subject to:

(E1*) $e_{k_l^h} - \sum_{i=1}^{m} \sum_{j=1}^{n_i} \frac{d_{k_j^i [K_h]}}{d_{k_l^h [K_h]}} \mathrm{T}_{k_j^i k_l^h} + \sum_{i=1}^{m} \sum_{j=1}^{n_i} \mathrm{T}_{k_l^h k_j^i} \le \overline{\mathrm{T}}_{k_l^h}$;

$\forall h \in \{1,2,.....m\},\ l \in \{1,2,.....n_h\}$

(E2*) $e_{k_j^i} \in [0, e^0_{k_j^i}]$ $\qquad \forall i \in \{1,2,...m\},\ j \in \{1,2,.....n_i\}$

(E3*) $\mathrm{T}_{k_l^h k_j^i} \ge 0$ $\qquad \forall i \in \{1,2,...m\},\ j \in \{1,2,.....n_i\}$

Since the two problem have the same objective function, it is sufficient to show that the choice set described by constraints (B1*) and (B2*) (denoted by Ω_B^*) are equivalent to the set described by constraints (E1*), (E2*) and (E3*) (denoted by Ω_B^*). In other words, I will show that for any emissions vector $(e_{k_j}^{k_i} : i \in (1,..m), j \in (1,..n_i))$ in Ω_B^*, must also be in Ω_E^* and vice versa.

Hung and Shaw has demonstrated the equivalence of the following two sets, namely:

Ω^{eff} ,the set of emission vector $(e_{[k_1]}, e_{[k_2]} \ldots . e_{[k_j]})$, constrained by (A1) and (A2)

(A1) $\sum_{i=1}^{m} d_{[K_i][K_j]} e_{[K_j]} \le E_{[K_j]} \quad \forall j \in \{1,2,3\ldots m\}$

(A2) $e_{[K_i]} \in [0, e_{[K_i]}^0]$; $\quad \forall i \in \{1,2,3\ldots m\}$

and Ω^{TRS}, the set of emission vector $(e_{[k_1]}, e_{[k_2]} \ldots . e_{[k_j]})$, constrained by (H1), (H2) and (H3)

(H1) $e_{[K_j]} - \sum_{i=1}^{j-1} d_{[K_i][K_j]} \mathrm{T}_{[K_i][K_j]} + \sum_{i>j}^{m} \mathrm{T}_{[K_j][K_i]} \le \bar{\mathrm{T}}_{[K_j]}$ (i = 1, ..m)

(H2) $e_{[K_j]} \in [0, e_{[K_j]}^0]$; $\quad \forall j \in \{1,2,3\ldots m\}$,

(H3) $\mathrm{T}_{[K_i][K_j]} \ge 0$; $\quad \forall i, k$

For any element $(e_{k_j}^{k_i} : i \in (1,..m), j \in (1,..n_i)) \in \Omega_B^*$, it must satisfy:

(B1*) $\sum_{i=1}^{m} \sum_{j=1}^{n_i} d_{k_j^i [K_h]} e_{k_j^i} \le E_{[K_h]} = \sum_{i=1}^{m} \sum_{j=1}^{n_i} d_{k_j^i [K_h]} \bar{T}_{k_j^i}$; $\quad \forall i \in \{1,2,\ldots m\}$

(B2*) $e_{k_j^i} \in [0, e_{k_j^i}^0]$ $\forall i \in \{1,2,...m\},\ j \in \{1,2,.....n_i\}$ since:

$$\sum_{i=1}^{m}\sum_{j=1}^{n_i} d_{k_j^i[K_h]} e_{k_j^i} = \sum_{i=1}^{m}\sum_{j=1}^{n_i} (d_{k_j^i[K_i]} d_{[K_i][K_h]}) e_{k_j^i} = \sum_{i=1}^{m}\sum_{j=1}^{n_i} (d_{k_j^i[K_i]} e_{k_j^i}) d_{[K_i][K_h]}$$

$$= \sum_{i=1}^{m}\sum_{j=1}^{n_i} e_{k_j^i}^{[K_i]} d_{[K_i][K_h]}$$

$$= \sum_{i=1}^{m} e_{[K_i]} d_{[K_i][K_h]} \le E_{[K_h]}$$

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

And set $e_{[K_i]}^0 \equiv +\infty$ so that (A2) and (H2) are always trivially satisfied.

Therefore, $(e_{k_j}^{k_i} : i \in (1,..m),\ j \in (1,..n_i)) \in \Omega^{(B1^*)} \Leftrightarrow (e_{[K_1]}, e_{[K_2]}....e_{[K_j]}) \in \Omega^{eff}$

By Hung and Shaw's result,

$$(e_{[K_1]}, e_{[K_2]}....e_{[K_j]}) \in \Omega^{eff} \Leftrightarrow (e_{[K_1]}, e_{[K_2]}....e_{[K_j]}) \in \Omega^{TRS}$$

Now, I will show that:

(i) $(e_{[K_1]}, e_{[K_2]}....e_{[K_j]}) \in \Omega^{eff} \Rightarrow (e_{k_j}^{k_i} : i \in (1,..m),\ j \in (1,..n_i)) \in \Omega^{(E1^*)}$

(ii) $(e_{k_j}^{k_i} : i \in (1,..m),\ j \in (1,..n_i)) \in \Omega^{(E1^*)} \Rightarrow (e_{[K_1]}, e_{[K_2]}....e_{[K_j]}) \in \Omega^{eff}$

For (i), we know that for any vector $(e_{[K_1]}, e_{[K_2]}....e_{[K_j]}) \in \Omega^{eff}$, it must have:

$$e_{[K_h]} - \sum_{i=1}^{m} d_{[K_i][K_h]} \mathrm{T}_{[K_i][K_h]} + \sum_{i=1}^{m} \mathrm{T}_{[K_h][K_i]} \le \bar{\mathrm{T}}_{[K_h]},$$

$\forall h \in \{1,2,.....m\}$.

$$e_{k_l^h} - \sum_{i=1}^{m}\sum_{j=1}^{n_i} \frac{d_{k_j^i[K_h]}}{d_{k_l^h[K_h]}} \mathrm{T}_{k_j^i k_l^h} + \sum_{i=1}^{m}\sum_{j=1}^{n_i} \mathrm{T}_{k_l^h k_j^i} \le \overline{\mathrm{T}}_{k_l^h}$$, by some non-negative volume

{ $\mathrm{T}_{[K_i][K_h]}$ }.

For (ii), we know that for any $(e_{k_j}^{k_i} : i \in (1,..m), j \in (1,..n_i)) \in \Omega^{(E1*)}$, it must have:

$$e_{k_l^h} - \sum_{i=1}^{m}\sum_{j=1}^{n_i} \frac{d_{k_j^i[K_h]}}{d_{k_l^h[K_h]}} \mathrm{T}_{k_j^i k_l^h} + \sum_{i=1}^{m}\sum_{j=1}^{n_i} \mathrm{T}_{k_l^h k_j^i} \le \overline{\mathrm{T}}_{k_l^h}$$

$$\forall h \in \{1,2,.....m\},\ l \in \{1,2,.....n_h\}$$

which can be re-written as:

$$d_{k_l^h[K_h]} e_{k_l^h} - \sum_{i=1}^{m}\sum_{j=1}^{n_i} d_{k_j^i[K_h]} \mathrm{T}_{k_j^i k_l^h} + d_{k_l^h[K_h]} \sum_{i=1}^{m}\sum_{j=1}^{n_i} \mathrm{T}_{k_l^h k_j^i} \le d_{k_l^h[K_h]} \overline{\mathrm{T}}_{k_l^h}$$

Summing the above inequalities over all sources in the *h*th M.A. we obtain:

$$\sum_{l=1}^{n_h} d_{k_l^h[K_h]} e_{k_l^h} - \sum_{l=1}^{n_h}\sum_{i=1}^{m}\sum_{j=1}^{n_i} d_{k_j^i[K_h]} \mathrm{T}_{k_j^i k_l^h} + d_{k_l^h[K_h]} \sum_{l=1}^{n_h}\sum_{i=1}^{m}\sum_{j=1}^{n_i} \mathrm{T}_{k_l^h k_j^i}$$
$$\le \sum_{l=1}^{n_h} d_{k_l^h[K_h]} \overline{\mathrm{T}}_{k_l^h}$$

which is equivalent to (by the associative rule of additions):

$$\sum_{l=1}^{n_h} d_{k_l^h[K_h]} e_{k_l^h} - \sum_{i=1}^{m} \left(\sum_{j=1}^{n_i}\sum_{l=1}^{n_h} d_{k_j^i[K_h]} \mathrm{T}_{k_j^i k_l^h}\right) + d_{k_l^h[K_h]} \sum_{i=1}^{m} \left(\sum_{j=1}^{n_i}\sum_{l=1}^{n_h} \mathrm{T}_{k_l^h k_j^i}\right)$$
$$\le \sum_{l=1}^{n_h} d_{k_l^h[K_h]} \overline{\mathrm{T}}_{k_l^h}$$

Now, we can find a set of { $\mathrm{T}_{[K_i][K_h]}$ }, where

$\mathrm{T}_{[K_i][K_h]} = \sum_{j=1}^{n_i}\sum_{l=1}^{n_h} d_{k_j^i[K_i]}\mathrm{T}_{k_j^i k_l^h} = \sum_{j=1}^{n_i}\sum_{l=1}^{n_h} \frac{d_{k_j^i[K_h]}}{d_{[K_i][K_h]}}\mathrm{T}_{k_j^i k_l^h}$, such that the above inequality can be transformed to:

$$\sum_{l=1}^{n_h} d_{k_l^h[K_h]} e_{k_l^h} - \sum\nolimits_{i=1}^{m} d_{[K_i][K_h]}\mathrm{T}_{[K_i][K_h]} + d_{k_l^h[K_h]}\sum_{i=1}^{m}\left(\sum_{j=1}^{n_i}\sum_{l=1}^{n_h}\mathrm{T}_{k_l^h k_j^i}\right)$$
$$\leq \sum_{l=1}^{n_h} d_{k_l^h[K_h]}\overline{\mathrm{T}}_{k_l^h}$$

The above inequality can be re-written as:

$$\sum_{l=1}^{n_h} e_{k_l^h} d_{k_l^h[K_h]} - \sum\nolimits_{i=1}^{m} d_{[K_i][K_h]}\mathrm{T}_{[K_i][K_h]} + \sum\nolimits_{i=1}^{m}\mathrm{T}_{[K_h][K_i]} \leq \sum_{l=1}^{n_h} d_{k_l^h[K_h]}\overline{\mathrm{T}}_{k_l^h}$$

By proposition one , we know there exists non-negative trades such that:

$$e_{k_l^h} - \sum_{i=1}^{m}\sum_{j=1}^{n_i}\frac{d_{k_j^i[K_h]}}{d_{k_l^h[K_h]}}\mathrm{T}_{k_j^i k_l^h} + \sum_{i=1}^{m}\sum_{j=1}^{n_i}\mathrm{T}_{k_l^h k_j^i} \leq \overline{\mathrm{T}}_{k_l^h}$$

$$d_{k_l^h[K_h]} e_{k_l^h} - \sum_{i=1}^{m}\sum_{j=1}^{n_i} d_{k_j^i[K_h]}\mathrm{T}_{k_j^i k_l^h}$$
$$+ \sum_{i=1}^{m}\sum_{j=1}^{n_i} d_{k_l^h[K_h]}\mathrm{T}_{k_l^h k_j^i} \leq d_{k_l^h[K_h]}\overline{\mathrm{T}}_{k_l^h}$$

$$\Leftrightarrow$$

$$e_{k_l^h} - \sum_{i=1}^{m}\sum_{j=1}^{n_i}\frac{d_{k_j^i[K_h]}}{d_{k_l^h[K_h]}}\mathrm{T}_{k_j^i k_l^h} + \sum_{i=1}^{m}\sum_{j=1}^{n_i}\mathrm{T}_{k_l^h k_j^i} \leq \overline{\mathrm{T}}_{k_l^h}$$

Therefore:

$$(e_{[k_1]}, e_{[k_2]}....e_{[k_j]}) \in \Omega^{eff} \Leftrightarrow (e_{k_j}^{k_i} : i \in (1,..m), j \in (1,..n_i)) \in \Omega^{(E^*-1)\&(E^*-3)}$$

Hence:

$$(e_{k_j}^{k_i} : i \in (1,..m), j \in (1,..n_i)) \in \Omega^{(B^*-1)} \Leftrightarrow (e_{k_j}^{k_i} : i \in (1,..m), j \in (1,..n_i)) \in \Omega^{(E^*-1)\&(E^*-3)}$$

$$\Omega^{(B^*-1)} = \Omega^{(E^*-1)\&(E^*-3)}$$

Moreover, since $\Omega^{(B^*-2)} = \Omega^{(E^*-2)}$

So, $\Omega^{B^*} = \Omega^{(B^*-1)} \cap \Omega^{(B^*-2)} = \Omega^{(E^*-2)} \cap \Omega^{(E^*-1)\&(E^*-3)} = \Omega^{E^*}$

QED

APPENDIX B

TRADING RATIOS USING TWO OTHER COMPILING STRATEGIES

For comparison purposes, two other compiling strategies, "Geometric Average" and "90% of the Minimum Ratios" are also applied in this case study. The Geometric Average is mathematically desirable in the sense that it provides symmetry in in trading ratios between buyers and sellers. However, as an average of ratios it will theoretically lead to water quality violations under some of the diversion scenarios. The 90% of the Minimum Ratios incorporates an added margin of safety above and beyond the Minimum Ratios approach. The corresponding trading ratios are presented in Table A2.1-1 to A2.1-6.

Table A2.1-1 Compiled Trading Ratios Under Single Source M.A. Approach (Geometric Average)

Buy / Seller	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.965	0.965	0.965	0.965	0.929	0.929	0.929	0.929											
D2		1.000	1.000	0.965	0.965	0.965	0.965	0.929	0.929	0.929	0.929											
D3			1.000	0.965	0.965	0.965	0.965	0.929	0.929	0.929	0.929											
P1				1.000	1.000	1.000	1.000	0.962	0.962	0.962	0.962											
P2					1.000	1.000	1.000	0.962	0.962	0.962	0.962											
P3						1.000	1.000	0.962	0.962	0.962	0.962											
P4							1.000	0.962	0.962	0.962	0.962											
P5								1.000	1.000	1.000	1.000											
P6									1.000	1.000	1.000											
P7										1.000	1.000											
P8											1.000											
W1												1.000	1.000	1.000		1.000						
W2													1.000	1.000		1.000						
W3														1.000		1.000						
R1															1.000							
W4																1.000						
WQ																	1.000	1.000	0.990			
T1																		1.000	0.990			
T2																			1.000			
P9																				1.000		
P10																					1.000	1.000
P11																						1.000

Table A2.1-2 Compiled Trading Ratios Under Multiple Source M.A. Approach - Alternative One (Geometric Average)

Buy Seller	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.965	0.965	0.965	0.965	0.929	0.929	0.929	0.929	1.045	1.045	1.045	1.196	1.045				0.718	0.645	0.645
D2	1.000	1.000	1.000	0.965	0.965	0.965	0.965	0.929	0.929	0.929	0.929	1.045	1.045	1.045	1.196	1.045				0.718	0.645	0.645
D3	1.000	1.000	1.000	0.965	0.965	0.965	0.965	0.929	0.929	0.929	0.929	1.045	1.045	1.045	1.196	1.045				0.718	0.645	0.645
P1	1.036	1.036	1.036	1.000	1.000	1.000	1.000	0.962	0.962	0.962	0.962	1.083	1.083	1.083	1.239	1.083				0.744	0.668	0.668
P2	1.036	1.036	1.036	1.000	1.000	1.000	1.000	0.962	0.962	0.962	0.962	1.083	1.083	1.083	1.239	1.083				0.744	0.668	0.668
P3	1.036	1.036	1.036	1.000	1.000	1.000	1.000	0.962	0.962	0.962	0.962	1.083	1.083	1.083	1.239	1.083				0.744	0.668	0.668
P4	1.036	1.036	1.036	1.000	1.000	1.000	1.000	0.962	0.962	0.962	0.962	1.083	1.083	1.083	1.239	1.083				0.744	0.668	0.668
P5	1.077	1.077	1.077	1.039	1.039	1.039	1.039	1.000	1.000	1.000	1.000	1.125	1.125	1.125	1.288	1.125				0.773	0.695	0.695
P6	1.077	1.077	1.077	1.039	1.039	1.039	1.039	1.000	1.000	1.000	1.000	1.125	1.125	1.125	1.288	1.125				0.773	0.695	0.695
P7	1.077	1.077	1.077	1.039	1.039	1.039	1.039	1.000	1.000	1.000	1.000	1.125	1.125	1.125	1.288	1.125				0.773	0.695	0.695
P8	1.077	1.077	1.077	1.039	1.039	1.039	1.039	1.000	1.000	1.000	1.000	1.125	1.125	1.125	1.288	1.125				0.773	0.695	0.695
W1	0.957	0.957	0.957	0.924	0.924	0.924	0.924	0.889	0.889	0.889	0.889	1.000	1.000	1.000	1.144	1.000				0.687	0.617	0.617
W2	0.957	0.957	0.957	0.924	0.924	0.924	0.924	0.889	0.889	0.889	0.889	1.000	1.000	1.000	1.144	1.000				0.687	0.617	0.617
W3	0.957	0.957	0.957	0.924	0.924	0.924	0.924	0.889	0.889	0.889	0.889	1.000	1.000	1.000	1.144	1.000				0.687	0.617	0.617
R1	0.836	0.836	0.836	0.807	0.807	0.807	0.807	0.776	0.776	0.776	0.776	0.874	0.874	0.874	1.000	0.874				0.600	0.539	0.539
W4	0.957	0.957	0.957	0.924	0.924	0.924	0.924	0.889	0.889	0.889	0.889	1.000	1.000	1.000	1.144	1.000				0.687	0.617	0.617
WQ	0.829	0.829	0.829	0.800	0.800	0.800	0.800	0.770	0.770	0.770	0.770	0.867	0.867	0.867	0.992	0.867	1.000	1.000	0.990	0.595	0.535	0.535
T1	0.829	0.829	0.829	0.800	0.800	0.800	0.800	0.770	0.770	0.770	0.770	0.867	0.867	0.867	0.992	0.867	1.000	1.000	0.990	0.595	0.535	0.535
T2	0.838	0.838	0.838	0.809	0.809	0.809	0.809	0.778	0.778	0.778	0.778	0.876	0.876	0.876	1.002	0.876	1.010	1.010	1.000	0.601	0.540	0.540
P9																				1.000	0.899	0.899
P10																				1.113	1.000	1.000
P11																				1.113	1.000	1.000

TableA2.1-3 Compiled Trading Ratios Under Multiple Source M.A. Approach - Alternative Two (Geometric Average)

Buyer Seller	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.965	0.965	0.965	0.965	0.929	0.929	0.929	0.929	1.045	1.045	1.045	1.196	1.045				0.718	0.645	0.645
D2	1.000	1.000	1.000	0.965	0.965	0.965	0.965	0.929	0.929	0.929	0.929	1.045	1.045	1.045	1.196	1.045				0.718	0.645	0.645
D3	1.000	1.000	1.000	0.965	0.965	0.965	0.965	0.929	0.929	0.929	0.929	1.045	1.045	1.045	1.196	1.045				0.718	0.645	0.645
P1	1.036	1.036	1.036	1.000	1.000	1.000	1.000	0.962	0.962	0.962	0.962	1.083	1.083	1.083	1.239	1.083				0.744	0.668	0.668
P2	1.036	1.036	1.036	1.000	1.000	1.000	1.000	0.962	0.962	0.962	0.962	1.083	1.083	1.083	1.239	1.083				0.744	0.668	0.668
P3	1.036	1.036	1.036	1.000	1.000	1.000	1.000	0.962	0.962	0.962	0.962	1.083	1.083	1.083	1.239	1.083				0.744	0.668	0.668
P4	1.036	1.036	1.036	1.000	1.000	1.000	1.000	0.962	0.962	0.962	0.962	1.083	1.083	1.083	1.239	1.083				0.744	0.668	0.668
P5	1.077	1.077	1.077	1.039	1.039	1.039	1.039	1.000	1.000	1.000	1.000	1.125	1.125	1.125	1.288	1.125				0.773	0.695	0.695
P6	1.077	1.077	1.077	1.039	1.039	1.039	1.039	1.000	1.000	1.000	1.000	1.125	1.125	1.125	1.288	1.125				0.773	0.695	0.695
P7	1.077	1.077	1.077	1.039	1.039	1.039	1.039	1.000	1.000	1.000	1.000	1.125	1.125	1.125	1.288	1.125				0.773	0.695	0.695
P8	1.077	1.077	1.077	1.039	1.039	1.039	1.039	1.000	1.000	1.000	1.000	1.125	1.125	1.125	1.288	1.125				0.773	0.695	0.695
W1	0.957	0.957	0.957	0.924	0.924	0.924	0.924	0.889	0.889	0.889	0.889	1.000	1.000	1.000	1.144	1.000				0.687	0.617	0.617
W2	0.957	0.957	0.957	0.924	0.924	0.924	0.924	0.889	0.889	0.889	0.889	1.000	1.000	1.000	1.144	1.000				0.687	0.617	0.617
W3	0.957	0.957	0.957	0.924	0.924	0.924	0.924	0.889	0.889	0.889	0.889	1.000	1.000	1.000	1.144	1.000				0.687	0.617	0.617
R1	0.836	0.836	0.836	0.807	0.807	0.807	0.807	0.776	0.776	0.776	0.776	0.874	0.874	0.874	1.000	0.874				0.600	0.539	0.539
W4	0.957	0.957	0.957	0.924	0.924	0.924	0.924	0.889	0.889	0.889	0.889	1.000	1.000	1.000	1.144	1.000				0.687	0.617	0.617
WQ																	1.000	1.000	0.990	0.595	0.535	0.535
T1																	1.000	1.000	0.990	0.595	0.535	0.535
T2																	1.010	1.010	1.000	0.601	0.540	0.540
P9																				1.000	0.899	0.899
P10																				1.113	1.000	1.000
P11																				1.113	1.000	1.000

Table A2.1-4 Compiled Trading Ratios Under Single Source M.A. Approach (90% of Minimum Ratios)

Seller \ Buy	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.850	0.850	0.850	0.850	0.795	0.795	0.795	0.795											
D2		1.000	1.000	0.850	0.850	0.850	0.850	0.795	0.795	0.795	0.795											
D3			1.000	0.850	0.850	0.850	0.850	0.795	0.795	0.795	0.795											
P1				1.000	1.000	1.000	1.000	0.842	0.842	0.842	0.842											
P2					1.000	1.000	1.000	0.842	0.842	0.842	0.842											
P3						1.000	1.000	0.842	0.842	0.842	0.842											
P4							1.000	0.842	0.842	0.842	0.842											
P5								1.000	1.000	1.000	1.000											
P6									1.000	1.000	1.000											
P7										1.000	1.000											
P8											1.000											
W1												1.000	1.000	1.000		1.000						
W2													1.000	1.000		1.000						
W3														1.000		1.000						
R1															1.000							
W4																1.000						
WQ																	1.000	1.000	0.873			
T1																		1.000	0.873			
T2																			1.000			
P9																				1.000		
P10																					1.000	1.000
P11																						1.000

Table A2.1-5 Compiled Trading Ratios Under Multiple Source M.A. Approach - Alternative One (90% of Minimum Ratios)

Seller \ Buy	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.850	0.850	0.850	0.850	0.795	0.795	0.795	0.795	0.924	0.924	0.924	1.032	0.924				0.539	0.396	0.396
D2	1.000	1.000	1.000	0.850	0.850	0.850	0.850	0.795	0.795	0.795	0.795	0.924	0.924	0.924	1.032	0.924				0.539	0.396	0.396
D3	1.000	1.000	1.000	0.850	0.850	0.850	0.850	0.795	0.795	0.795	0.795	0.924	0.924	0.924	1.032	0.924				0.539	0.396	0.396
P1	0.922	0.922	0.922	1.000	1.000	1.000	1.000	0.842	0.842	0.842	0.842	0.947	0.947	0.947	1.059	0.947				0.571	0.420	0.420
P2	0.922	0.922	0.922	1.000	1.000	1.000	1.000	0.842	0.842	0.842	0.842	0.947	0.947	0.947	1.059	0.947				0.571	0.420	0.420
P3	0.922	0.922	0.922	1.000	1.000	1.000	1.000	0.842	0.842	0.842	0.842	0.947	0.947	0.947	1.059	0.947				0.571	0.420	0.420
P4	0.922	0.922	0.922	1.000	1.000	1.000	1.000	0.842	0.842	0.842	0.842	0.947	0.947	0.947	1.059	0.947				0.571	0.420	0.420
P5	0.922	0.922	0.922	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	1.112	0.995				0.611	0.449	0.449
P6	0.922	0.922	0.922	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	1.112	0.995				0.611	0.449	0.449
P7	0.922	0.922	0.922	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	1.112	0.995				0.611	0.449	0.449
P8	0.922	0.922	0.922	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	1.112	0.995				0.611	0.449	0.449
W1	0.834	0.834	0.834	0.814	0.814	0.814	0.814	0.771	0.771	0.771	0.771	1.000	1.000	1.000	1.006	1.000				0.523	0.385	0.385
W2	0.834	0.834	0.834	0.814	0.814	0.814	0.814	0.771	0.771	0.771	0.771	1.000	1.000	1.000	1.006	1.000				0.523	0.385	0.385
W3	0.834	0.834	0.834	0.814	0.814	0.814	0.814	0.771	0.771	0.771	0.771	1.000	1.000	1.000	1.006	1.000				0.523	0.385	0.385
R1	0.728	0.728	0.728	0.688	0.688	0.688	0.688	0.643	0.643	0.643	0.643	0.750	0.750	0.750	1.000	0.750				0.436	0.321	0.321
W4	0.834	0.834	0.834	0.814	0.814	0.814	0.814	0.771	0.771	0.771	0.771	1.000	1.000	1.000	1.006	1.000				0.523	0.385	0.385
WQ	0.573	0.573	0.573	0.541	0.541	0.541	0.541	0.506	0.506	0.506	0.506	0.591	0.591	0.591	0.709	0.591	1.000	1.000	0.873	0.343	0.252	0.252
T1	0.573	0.573	0.573	0.541	0.541	0.541	0.541	0.506	0.506	0.506	0.506	0.591	0.591	0.591	0.709	0.591	1.000	1.000	0.873	0.343	0.252	0.252
T2	0.591	0.591	0.591	0.558	0.558	0.558	0.558	0.522	0.522	0.522	0.522	0.609	0.609	0.609	0.731	0.609	1.000	1.000	1.000	0.354	0.260	0.260
P9																				1.000	0.661	0.661
P10																				0.880	1.000	1.000
P11																				0.880	1.000	1.000

TableA2.1-6 Compiled Trading Ratios Under Multiple Source M.A. Approach - Alternative Two (90% of Minimum Ratios)

Seller \ Buyer	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1	1.000	1.000	1.000	0.850	0.850	0.850	0.850	0.795	0.795	0.795	0.795	0.924	0.924	0.924	1.032	0.924				0.539	0.396	0.396
D2	1.000	1.000	1.000	0.850	0.850	0.850	0.850	0.795	0.795	0.795	0.795	0.924	0.924	0.924	1.032	0.924				0.539	0.396	0.396
D3	1.000	1.000	1.000	0.850	0.850	0.850	0.850	0.795	0.795	0.795	0.795	0.924	0.924	0.924	1.032	0.924				0.539	0.396	0.396
P1	0.922	0.922	0.922	1.000	1.000	1.000	1.000	0.842	0.842	0.842	0.842	0.947	0.947	0.947	1.059	0.947				0.571	0.420	0.420
P2	0.922	0.922	0.922	1.000	1.000	1.000	1.000	0.842	0.842	0.842	0.842	0.947	0.947	0.947	1.059	0.947				0.571	0.420	0.420
P3	0.922	0.922	0.922	1.000	1.000	1.000	1.000	0.842	0.842	0.842	0.842	0.947	0.947	0.947	1.059	0.947				0.571	0.420	0.420
P4	0.922	0.922	0.922	1.000	1.000	1.000	1.000	0.842	0.842	0.842	0.842	0.947	0.947	0.947	1.059	0.947				0.571	0.420	0.420
P5	0.922	0.922	0.922	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	1.112	0.995				0.611	0.449	0.449
P6	0.922	0.922	0.922	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	1.112	0.995				0.611	0.449	0.449
P7	0.922	0.922	0.922	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	1.112	0.995				0.611	0.449	0.449
P8	0.922	0.922	0.922	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	1.112	0.995				0.611	0.449	0.449
W1	0.834	0.834	0.834	0.814	0.814	0.814	0.814	0.771	0.771	0.771	0.771	1.000	1.000	1.000	1.006	1.000				0.523	0.385	0.385
W2	0.834	0.834	0.834	0.814	0.814	0.814	0.814	0.771	0.771	0.771	0.771	1.000	1.000	1.000	1.006	1.000				0.523	0.385	0.385
W3	0.834	0.834	0.834	0.814	0.814	0.814	0.814	0.771	0.771	0.771	0.771	1.000	1.000	1.000	1.006	1.000				0.523	0.385	0.385
R1	0.728	0.728	0.728	0.688	0.688	0.688	0.688	0.643	0.643	0.643	0.643	0.750	0.750	0.750	1.000	0.750				0.436	0.321	0.321
W4	0.834	0.834	0.834	0.814	0.814	0.814	0.814	0.771	0.771	0.771	0.771	1.000	1.000	1.000	1.006	1.000				0.523	0.385	0.385
WQ																	1.000	1.000	0.873	0.343	0.252	0.252
T1																	1.000	1.000	0.873	0.343	0.252	0.252
T2																	1.000	1.000	1.000	0.354	0.260	0.260
P9																				1.000	0.661	0.661
P10																				0.880	1.000	1.000
P11																				0.880	1.000	1.000

TRADING DETAIL FOR MARGINAL COST TRADING

This trading scenario assumes that each WWTP chooses to invest in the capacity upgrade to independently meet its NPDES requirement (at 0.4mg/L), and then buys and sells allowances based on its marginal abatement cost and the market price. In other words, only OM costs are accounted for in determining the trades.

Single Source Management Area Approach

Table A2.2-1 Marginal Cost Trading: Single Source M.A. Approach (Geometric Average)

Seller \ Buyer	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1		56	70		44																	
D2																						
D3																						
P1					19																	
P2																						
P3							57															
P4																						
P5									120													
P6																						
P7																						
P8																						
W1																						
W2														139								
W3																						
R1																						
W4																						
WQ																			731			
T1																			210			
T2																						
P9																						
P10																						103
P11																						

Table A2.2-2 Marginal Cost Trading: Single Source M.A. Approach (90% of Minimum Ratios)

Buyer / Seller	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1		60	77																			
D2																						
D3																						
P1					49																	
P2																						
P3							57															
P4																						
P5									120													
P6																						
P7																						
P8																						
W1																						
W2														139								
W3																						
R1																						
W4																						
WQ																			731			
T1																			210			
T2																						
P9																						
P10																						103
P11																						

Multiple Source Management Area Approach – Alternative One

Table A2.2-3 Marginal Cost Trading: Multiple Source M.A Appoach - Alternative One (Geometric Average)

Buyer / Seller	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									61													
W1																						
W2																						
W3																						
R1				337	85	181	60															
W4	70	116			121	145	47	182	200	152		392	244	370								
WQ	92		211																428			
T1	210																					
T2																						
P9																					204	292
P10																						
P11																						

Table A2.2-4 Marginal Cost Trading: Multiple Source M.A Appoach - Alternative One (90% of Minimum Ratios)

Seller \ Buyer	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								42	189	7												
W1																						
W2																						
W3																						
R1	192	131	198																			
W4	43			240	182	204	98					427	295	401								
WQ																			731			
T1																			210			
T2																						
P9																						
P10																						103
P11																						

Management Area Approach - Alternative Two

Table A2.2-5 Marginal Cost Trading: Multiple Source M.A Appoach - Alternative Two (Geometric Average)

Seller \ Buyer	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										96												
W1																						
W2																						
W3																						
R1				105	217	326	112															
W4	312	114	179	191				155	258	15		368	208	348								
WQ																			731			
T1																			210			
T2																						
P9																					204	292
P10																						
P11																						

Table A2.2-6 Marginal Cost Trading: Multiple Source M.A Appoach - Alternative Two (90% of Minimum Ratios)

Seller \ Buyer	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								42	189	7												
W1																						
W2																						
W3																						
R1	192	131	198																			
W4	43			240	182	204	98					427	295	401								
WQ																			731			
T1																			210			
T2																						
P9																						
P10																						103
P11																						

TRADING DETAIL FOR OPTIMAL TRADING

In the Optimal Trading scenario, incentives for allowance trading are embodied not only in the differential marginal OM costs, but also in avoiding the costly capital upgrades. For example, in this setting, it is expected that some WWTPs would purchase enough allowances so that they are able to avoid facility upgrades and maintain a low level of capital cost.

Single Source Management Area Approach

Table A2.3-1 Optimal Trading: Single Source M.A. Approach (Geometric Average)

Buyer / Seller	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1		46	95		29	354	16															
D2																						
D3																						
P1					82	137	21															
P2																						
P3																						
P4																						
P5									274		392											
P6																						
P7											752											
P8																						
W1														115								
W2														504								
W3																						
R1																						
W4																						
WQ																			731			
T1																			210			
T2																						
P9																						
P10																						384
P11																						

Table A2.3-2 Optimal Trading: Single Source M.A. Approach (90% of Minimum Ratios)

Buye / Seller	D1	D2	D3	P1	P2	P3	P4	P5	P6	P7	P8	W1	W2	W3	R1	W4	WQ	T1	T2	P9	P10	P11
D1		46	95		31	348	10															
D2																						
D3																						
P1					84	183																
P2																						
P3																						
P4																						
P5									274		392											
P6																						
P7											752											
P8																						
W1														115								
W2														504								
W3																						
R1																						
W4																						
WQ																			731			
T1																			210			
T2																						
P9																						
P10																						384
P11																						

Multiple Source Management Area Approach – Alternative One

Table A2.3-3 Optimal Trading: Multiple Source M.A Appoach - Alternative One (Geometric Average)

Buyer / Seller	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									274	810												
W1																						
W2																						
W3																						
R1																						
W4								810				579	823	619	2347							
WQ	437	58	114										122									
T1	210																					
T2				377	136	592	51															
P9																					835	428
P10																						
P11																						

Table A2.3-4 Optimal Trading: Multiple Source M.A Appoach - Alternative One (90% of Minimum Ratios)

Buyer / Seller	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																						
W1																						
W2																						
W3																						
R1	691		67	165	41	406					1424											
W4								953	356	1032	295	579	927	619								
WQ				201	92	369	70															
T1				152	58																	
T2	56	73	60																			
P9																					1134	581
P10																						
P11																						

Multiple Source Management Area Approach – Alternative Two

Table A2.3-5 Optimal Trading: Multiple Source M.A Appoach - Alternative Two (Geometric Average)

Seller \ Buyer	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																						
W1																						
W2																						
W3																						
R1	642	71	113	378	136	593	62			946												
W4								827	309	69	1287	579	927	619								
WQ																			731			
T1																			210			
T2																						
P9																					835	428
P10																						
P11																						

Table A2.3-6 Optimal Trading: Multiple Source M.A Appoach - Alternative Two (90% of Minimum Ratios)

Seller \ Buyer	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																						
W1																						
W2																						
W3																						
R1	737	63	130	444	160	696		953														
W4							53		427	1032	1564	579	927	619								
WQ																			731			
T1																			210			
T2																						
P9																					1134	581
P10																						
P11																						

SAVING SUMMARY

The potential cost savings from effluent trading programs reflect differences in total abatement cost compared with the no trade baseline case. The estimated potential cost savings for marginal cost trading using various M.A. approaches are summarized in

Table A2.4-1 to A2.4-3. The estimated potential cost savings for optimal trading using various M.A. approaches are summarized in Table A2.4-4 to A2.4-6.

	Selection of Minimum Ratios	90% of Minimum Ratios	Geometric Average
Baseline OM cost	$2,385,479.08	$2,385,479.08	$2,385,479.08
OM cost after trading	$2,361,990.48	$2,363,747.40	$2,361,610.88
Savings on OM Cost	$23,488.61	$21,731.69	$23,868.21
Percentage Savings on OM Cost	0.98%	0.91%	1.00%
Baseline CC Cost	$1,609,889.45	$1,609,889.45	$1,609,889.45
CC Cost after Trading	$1,609,889.45	$1,609,889.45	$1,609,889.45
Savings on CC Cost	0	0	0
Percentage Savings on CC Cost	0%	0%	0%
Baseline Total Cost	$3,995,368.54	$3,995,368.54	$3,995,368.54
Total Cost after Trading	$3,971,879.93	$3,973,636.85	$3,971,500.33
Total Savings	$23,488.61	$21,731.69	$23,868.21
Percentage Savings on Total Cost	0.59%	0.54%	0.60%

Table A2.4-1: Cost Savings Under Marginal Cost Trading (Single Source M.A. Approach)

	Selection of Minimum Ratios	90% of Minimum Ratios	Geometric Average
Baseline OM cost	$2,385,479.08	$2,385,479.08	$2,385,479.08
OM cost after trading	$2,344,093.14	$2,349,542.98	$2,340,145.25
Savings on OM Cost	$41,385.94	$35,936.11	$45,333.84
Percentage Savings on OM Cost	1.73%	1.51%	1.90%
Baseline CC Cost	$1,609,889.45	$1,609,889.45	$1,609,889.45
CC Cost after Trading	$1,609,889.45	$1,609,889.45	$1,609,889.45
Savings on CC Cost	0	0	0
Percentage Savings on CC Cost	0.00%	0.00%	0.00%
Baseline Total Cost	$3,995,368.54	$3,995,368.54	$3,995,368.54
Total Cost after Trading	$3,953,982.60	$3,959,432.43	$3,950,034.70
Total Savings	$41,385.94	$35,936.11	$45,333.84
Percentage Savings on Total Cost	1.04%	0.90%	1.13%

Table A2.4-2: Cost Savings Under Marginal Cost Trading (Multiple Souce M.A. Approach - Alternative One)

	Selection of Minimum Ratios	90% of Minimum Ratios	Geometric Average
Baseline OM cost	$2,385,479.08	$2,385,479.08	$2,385,479.08
OM cost after trading	$2,344,093.14	$2,349,542.98	$2,340,932.84
Savings on OM Cost	$41,385.94	$35,936.11	$44,546.25
Percentage Savings on OM Cost	1.73%	1.51%	1.87%
Baseline CC Cost	$1,609,889.45	$1,609,889.45	$1,609,889.45
CC Cost after Trading	$1,609,889.45	$1,609,889.45	$1,609,889.45
Savings on CC Cost	0	0	0
Percentage Savings on CC Cost	0.00%	0.00%	0.00%
Baseline Total Cost	$3,995,368.54	$3,995,368.54	$3,995,368.54
Total Cost after Trading	$3,953,982.60	$3,959,432.43	$3,950,822.29
Total Savings	$41,385.94	$35,936.11	$44,546.25
Percentage Savings on Total Cost	1.04%	0.90%	1.11%

Table A2.4-3: Cost Savings Under Marginal Cost Trading (Multiple Souce M.A. Approach - Alternative Two)

	Selection of Minimum Ratios	90% of Minimum Ratios	Geometric Average
Baseline OM Cost	$2,385,479.08	$2,385,479.08	$2,385,479.08
OM Cost after Trading	$2,402,189.42	$2,406,312.09	$2,401,338.95
Savings on OM Cost	-$16,710.34	-$20,833.01	-$15,859.86
Percentage Savings on OM Cost	-0.70%	-0.87%	-0.66%
Baseline CC Cost	$1,609,889.45	$1,609,889.45	$1,609,889.45
CC Cost after Trading	$1,372,102.85	$1,372,102.85	$1,372,102.85
Savings on CC Cost	$237,786.60	$237,786.60	$237,786.60
Percentage Savings on CC Cost	14.77%	14.77%	14.77%
Baseline Total Cost	$3,995,368.54	$3,995,368.54	$3,995,368.54
Total Cost after Trading	$3,774,292.27	$3,778,414.94	$3,773,441.80
Total Savings	$221,076.27	$216,953.60	$221,926.74
Percentage Savings on Total Cost	5.53%	5.43%	5.55%

Table A2.4-4: Cost Savings Under Optimal Trading (Single Source M.A. Approach)

	Selection of Minimum Ratios	90% of Minimum Ratios	Geometric Average
Baseline OM Cost	$2,385,479.08	$2,385,479.08	$2,385,479.08
OM Cost after Trading	$2,400,476.44	$2,426,755.38	$2,408,106.87
Savings on OM Cost	-$14,997.35	-$41,276.30	-$22,627.79
Percentage Savings on OM Cost	-0.63%	-1.73%	-0.95%
Baseline CC Cost	$1,609,889.45	$1,609,889.45	$1,609,889.45
CC Cost after Trading	$1,071,474.94	$1,071,474.94	$1,021,673.67
Savings on CC Cost	$538,414.51	$538,414.51	$588,215.78
Percentage Savings on CC Cost	33.44%	33.44%	36.54%
Baseline Total Cost	$3,995,368.54	$3,995,368.54	$3,995,368.54
Total Cost after Trading	$3,471,951.38	$3,498,230.32	$3,429,780.55
Total Savings	$523,417.16	$497,138.22	$565,587.99
Percentage Savings on Total Cost	13.10%	12.44%	14.16%

Table A2.4-5: Cost Savings Under Optimal Trading (Multiple Souce M.A. Approach - Alternative One)

	Selection of Minimum Ratios	90% of Minimum Ratios	Geometric Average
Baseline OM Cost	$2,385,479.08	$2,385,479.08	$2,385,479.08
OM Cost after Trading	$2,403,910.88	$2,433,345.11	$2,386,389.10
Savings on OM Cost	-$18,431.80	-$47,866.03	-$910.01
Percentage Savings on OM Cost	-0.77%	-2.01%	-0.04%
Baseline CC Cost	$1,609,889.45	$1,609,889.45	$1,609,889.45
CC Cost after Trading	$1,071,474.94	$1,071,474.94	$1,071,474.94
Savings on CC Cost	$538,414.51	$538,414.51	$538,414.51
Percentage Savings on CC Cost	33.44%	33.44%	33.44%
Baseline Total Cost	$3,995,368.54	$3,995,368.54	$3,995,368.54
Total Cost after Trading	$3,475,385.82	$3,504,820.05	$3,457,864.03
Total Savings	$519,982.72	$490,548.49	$537,504.50
Percentage Savings on Total Cost	13.01%	12.28%	13.45%

Table A2.4-6: Cost Savings Under Optimal Trading (Multiple Souce M.A. Approach - Alternative Two)

APPENDIX C

THE DETAILED DERIVATION OF EQUATION (3.8.3-2), (3.8.3-3) AND (3.8.3-4)

Recall that OM costs are specified as the following form in the regression analysis:

$$\ln OM = 9.876 - 0.990\ln C + 0.796\ln F + 0.046\ln C\ln F + 0.649T + 0.314T\cdot\ln C \quad \text{---(3.8.3-1)}$$

However, as listed in the beginning of this chapter, the argument of OM cost function $OM_i\,(e_i)$ is the final effluent measured in pounds per year. This type of specification is convenient for optimization purposes. Also, the specification of final effluent in pounds per year is consistent with the unit of discharge allowances and the environmental standards. To transform equation (3.8.3-1) to a function of the final effluent measured in pounds per year, the variable, "C", in equation (3.8.3-1) is replaced by $C_i = \dfrac{e_i}{3046.063\times F_i}$ (where 3046.063 is a coefficient to adjust the measurement unit).

The equation can be transformed into the following form (equation 3.8.3-2) by the plugging in $C_i = \dfrac{e_i}{3046.063\times F_i}$:

$$\ln OM_i = 9.876 - 0.990\ln(\frac{e_i}{3046.063\times F_i}) + 0.796\ln F_i + 0.046\ln(\frac{e_i}{3046.063\times F_i})\ln F_i$$
$$+ 0.649T_i + 0.314T_i\cdot\ln(\frac{e_i}{3046.063\times F_i})$$

Then, take the exponential on both sides:

$$OM_i = \exp[9.876 - 0.990\ln(\frac{e_i}{3046.063\times F_i}) + 0.796\ln F_i + 0.046\ln(\frac{e_i}{3046.063\times F_i})\ln F_i$$
$$+ 0.649T_i + 0.314T_i\cdot\ln(\frac{e_i}{3046.063\times F_i})]$$

Re-arrange terms:

$$OM_i = \exp[9.876 - 0.990(\ln e_i - \ln 3046.063 - \ln F_i) + 0.796 \ln F_i$$
$$+ 0.046(\ln e_i - \ln 3046.063 - \ln F_i)\ln F_i + 0.649T_i + 0.314T_i \cdot (\ln e_i - \ln 3046.063 - \ln F_i)]$$

$$OM_i = \exp[(-0.990 + 0.046 \ln F_i + 0.314T_i)\ln e_i + 9.876 + 0.990(\ln 3046.063 + \ln F_i)$$
$$+ 0.796 \ln F_i - 0.046(\ln 3046.063 + \ln F_i)\ln F_i + 0.649T_i - 0.314T_i \cdot (\ln 3046.063 + \ln F_i)]$$

$$OM_i = \exp[(-0.990 + 0.046 \ln F_i + 0.314T_i)\ln e_i + 9.876 + 0.99 \ln(3046.063) + 0.99 \ln F_i + 0.796 \ln F_i$$
$$- 0.046 \ln(3046.063)\ln F_i - 0.046(\ln F_i)^2 + 0.649T_i - 0.314T_i \ln(3046.063) - 0.314T_i \ln F_i]$$

$$OM_i = \exp[(-0.990 + 0.046 \ln F_i + 0.314T_i)\ln e_i + (9.876 + 0.99 \ln(3046.063)) - 0.046(\ln F_i)^2 +$$
$$(0.99 + 0.796 - 0.046 \ln(3046.063) - 0.314T_i)\ln F_i + (0.649 - 0.314 \ln(3046.063))T_i]$$

$$OM_i = \exp[(-0.990 + 0.046 \ln F_i + 0.314T_i)\ln e_i + 17.817 - 0.046(\ln F_i)^2 +$$
$$(1.417 - 0.314T_i)\ln F_i - 1.870T_i]$$

So, if let

$$m_i = 17.817 - 0.046(\ln F_i)^2 + (1.417 - 0.314T_i)LnF_i - 1.870T_i \text{ ----------(3.8.3-3)}$$

$$n_i = -0.990 + 0.046 \ln F_i + 0.314T_i \text{ -----------------------(3.8.3-4)}$$

We have:

$$OM_i\,(e_i) = \exp[n_i \ln e_i + m_i] = \exp(m_i) \cdot e_i^{n_i} \qquad \text{---------------(3.8.3-2)}$$

In this way, the firm-specific parameters in the transformed functions embody the differences in daily flows across the WWTPs.

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