A THEORETICAL AND EMPIRICAL EXAMINATION OF DECENTRALIZED ENVIRONMENTAL REGULATION

by

Joseph J. Bial

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF ECONOMICS

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

1998

THE UNIVERSITY OF ARIZONA ®
GRADUATE COLLEGE

As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Joseph J. Bial

entitled A Theoretical and Empirical Examination of Decentralized Environmental Regulation

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy

Gary Libecap — Date 3/30/98

Bruce Billings — Date 3/30/98

Price Fishback — Date 3/30/98

Gordon Tullock — Date 3/31/98

Date

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director Gary Libecap — Date 3/30/98

STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgement of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the copyright holder.

SIGNED: Joseph J. Dial

ACKNOWLDEGEMENTS

I would like to thank Price Fishback, Robert Innes, Ronald Johnson, and Gary Libecap for comments and support.

To Leigh and Sarah

TABLE OF CONTENTS

TABLE OF CONTENTS - *Continued*

TABLE OF CONTENTS - *Continued*

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This dissertation closely examines the merits, weaknesses, and potential of decentralized environmental regulation. I examine three areas of particular concern in the structure of environmental regulation.

In the first chapter, I examine how information problems resulting from incorrectly specified atmospheric models are likely to affect economic efficiency in a permit market. While permit markets have been heralded as a promising solution for controlling environmentally damaging emissions, there is no formal research linking the atmospheric model, which directly affects permit prices, with economic outcomes. In the chapter, I develop a generalized theoretical model that demonstrates the problems that are likely to arise when there is uncertainty in the underlying atmospheric parameter estimates. As it turns out, permit markets operating with incorrectly specified atmospheric models may result in large losses in economic efficiency, even if the permit market is operating ideally in an economic sense.

The second chapter analyzes a much broader issue, that of state versus federal environmental regulation. The chapter focuses on the methods used by states attempting to control interstate water pollution in the Ohio Valley in the early 1900s. The time period was chosen to predate federal intervention into environmental regulation and, hence, allows for a clean test of how states might be expected to address difficult pollution problems under a system of state regulation. Using a simple game theoretic model, the paper explores interstate water pollution control compacts and their uses in

addressing interstate water pollution. I find that states were able to overcome significant bargaining difficulties in formulating the compacts, which ultimately led to effective control of interstate water pollution.

The final chapter focuses on voluntary overcompliance by firms facing environmental standards. The paper models environmental regulation according to the EPA's Best Available Control Technology (BACT). The model predicts voluntary overcompliance by firms as they attempt to raise the (endogenous) environmental standard and, in the process, raise their rivals' costs. The paper also demonstrates the merits of nonuniform environmental standards. In attempting to elicit efficient levels of R&D investment, the regulatory authority may discourage socially wasteful overinvestment in pollution technology through the use of nonuniform standards.

Chapter 1

Marketable Emission Permit Systems: Atmospheric Models and Economic Efficiency

1.1 Introduction

Marketable emission permit systems have emerged as a method for combating pollution in an age where a great deal of emphasis is placed on economic efficiency. The command and control approach associated with the majority of previous environmental regulations has been criticized by economists for its inability to achieve least cost solutions to many important environmental problems. This ineffectiveness has led to the development of a range of permit systems designed to minimize the costs of reaching a given environmental standard.[1] The existence of a permit system capable of obtaining the least cost outcome was proven formally by Montgomery (1972). The approach, now known as an ambient permit system (APS), takes advantage of the spatial characteristics specific to the area of implementation in its design.[2] Other approaches capable of reaching efficient outcomes include emission permit systems (EPS) and pollution offset systems (POS).[3]

While marketable permit systems have numerous desirable properties, they are not immune to many standard economic arguments. These include imperfect competition in both the permit market and the output market (Hahn, 1984; Malueg, 1990; Innes, Kling, and Rubin, 1991) and high transaction costs (Krupnick, Oates, and Van De Verg, 1983; Stavins, 1995). The APS, for example, requires that firms hold a portfolio of permits for each receptor where their pollution degenerates air quality levels. In a system with many receptors, this may lead to high transaction costs and subsequently few trades—a result that has been documented in the empirical literature (McGartland, 1988). Relaxing the spatial importance in the design of a permit system may lead to fewer transaction costs, but will likely lead to inefficiency. Under an EPS permits trade one-for-one in the region of operation. But while this may lead to cost minimization across the entire region, it also leads to undesirable "hot spots." "Hot spots" result from the application of permits purchased in cleaner areas to other areas plagued by high levels of pollution (Atkinson and Tietenberg, 1982; Baumol and Oates, 1988). The APS requires air quality standards to be met at each receptor, but "hot spots" may still develop as the effect of trades alter spatial parameters. The POS avoids this by limiting trades to only those that will not violate air quality standards at any location in the air shed.[4] In addition to the spatial problems, the EPS has been criticized for its high information demands on the regulator. To obtain an efficient outcome in a market with more than one receptor, the environmental authority requires cost information on each firm. This severely limits the usefulness of an EPS. For these reasons, the APS and POS are often cited as the most reasonable methods for obtaining efficiency in a permit system (McGartland, 1988)[5].

As noted by Montgomery (1972), the spatial characteristics of an air shed are crucial for cost efficiency in a permit system. This result has been demonstrated both empirically (Atkinson and Tietenberg, 1982; Hahn and Noll, 1982) and theoretically (Montgomery, 1972; Krupnick, Oates, and Van De Verg, 1983). Considering the atmospheric properties of an air shed in the design of a permit system urges polluters to consider the effect of their pollution on the surrounding environment in their pollution abatement decisions. In fact, it is precisely this property, along with competitive bidding, that determines the market price of a permit in an APS. As mentioned above, allowable trades in a POS are also determined by the spatial parameters. Given the reliance of these permit systems on the spatial characteristics of the air shed, it worth inquiring into the role that atmospheric models have in the design of a permit system and the resulting economic efficiency. Surprisingly, though, this latter point has been neglected in the literature on permit markets. Tietenberg (1980) has argued that average air flow patterns are the only requirement for the implementation of a permit system. This assumption, though, unlikely to hold in areas of complex terrain or where the estimation of atmospheric parameters is unreliable.[6]

The purpose of this chapter is to investigate the role of atmospheric models in the attainment of economic efficiency in a marketable permit system. In particular, the chapter examines the conditions under which the assumptions of the standard model fail.

This chapter also asks addresses the sensitivity of economic efficiency of permit systems to the underlying atmospheric model. As it turns out, misspecification of the atmospheric model will lead to improper pricing of permits and sizable inefficiencies. This will be demonstrated using a generalized model that allows for a wider range of atmospheric variation than the standard model. The generalized model will include the standard model as a special case. Given the results of the model, it is easy to show that the cost minimizing level of emission will differ from that of the standard model under a variety of conditions. Obviously this will lead to inefficiencies in a permit system, but the problem is compounded when the regulator and the polluting firms do not realize that they are operating at an inefficient level. In this case, firms "get stuck" at an outcome that is not cost minimizing. This interesting outcome is the result of informational problems as well as the institutional properties of the permit systems in question.

The outline of this chapter is as follows: Section 1.2 includes a brief discussion of the standard model. In particular, the APS and POS and their properties are established for use in later comparisons with the generalized model. Section 1.2 also discusses the desirability of a spatial approach in permit markets. Section 1.3 presents the generalized model along with a discussion of atmospheric models that are relevant to marketable permit systems. The existence of a competitive equilibrium that coincides with the least cost emission vector is proven. This will be useful when comparing the standard model to the generalized model. Section 1.3 also examines the outcome of the standard model when the basic assumptions are relaxed. The chapter concludes comments and directions for future research.

1.2 Marketable Emission Permit Systems

I have already mentioned the advantages of including the spatial characteristics of polluting firms in the design of a permit system. In the absence of these features, it is unlikely that a permit system will achieve the cost minimizing outcome. Tietenberg (1985) compiles a list of studies that report substantial cost savings when the use of spatial characteristics are used in the design of a permit system. The cost savings reported by different studies range from 1.07 to 22.0 times larger than a command and control approach. Most of the studies included in the compilation involve nonuniformly mixed assimilative pollutants. The effect of these pollutants will vary according to atmospheric parameters such as distance, wind speed, and weather conditions. While it is more difficult to design a permit system that can efficiently control these pollutants, they remain among the most important to address. This is due largely to the types of pollutants that are included as nonuniformly mixed pollutants such as sulfur dioxide, ozone, and total suspended particles. These pollutants have historically contributed significantly to undesirable air quality. The APS and the POS , which use knowledge of the atmospheric properties of an air shed in their designs, are applicable to these nonuniformly mixed pollutants. These baseline models are reviewed below.

1.2.1 The Ambient Permit System

The APS was used by Montgomery (1972) to prove the existence of a competitive equilibrium that coincided with the cost minimizing emission vector. This result is significant because the APS places minimal information demands on the regulator. In particular, the abatement costs of individual firms are not needed for obtaining cost efficiency. The APS does require that the firm operate in a multitude of permit markets that may potentially lead to high transaction costs. Under the APS, each receptor location has its own permit market. A firm operating under an APS is required to purchase permits in an amount equal to the total emission that reaches any given receptor. It follows that a firm whose pollution reaches numerous receptors will be obligated to purchase permits from each of these markets. This will necessitate a portfolio of permits that changes according to the pollution profile of the firm. For example, some firm i desiring to increase their total emission must find sellers in each receptor market j where their pollution level will increase. The total level of pollution for each firm at a receptor point is determined by the spatial parameters of the region. Specifically, each firm has a transfer coefficient, d_{ij}, which relates the amount of pollution emitted from firm i (emission is denoted e_i), to receptor j. These transfer coefficients include both atmospheric variables and firm specific attributes such as stack height, scrubbers, and other pollution control devices. The spatial characteristics will be examined in detail in

Section 1.3. For the remainder of Section 1.2, it is assumed that d_{ij}'s are constant and that total pollution levels are simply the summation of these transfer coefficients multiplied by the level of emission measured at the point source, $\Sigma_i d_{ij} e_i$. The joint cost minimization problem is presented below.

The social planner wishes to minimize the joint cost of pollution abatement for all firms subject to the environmental standard at *each* receptor, q_j. Each firm faces a control cost, $C_i(e_i)$ which may vary across firms. The cost function has the property that cost is decreasing in the level of emission but increasing in the level of abatement.[7] As emission levels increase, the firm moves toward the unconstrained level of pollution. Lower levels of emission are met with higher abatement costs. This may be seen in Figure 1.1 where there are two firms and one receptor. Point A is associated with higher costs than either the efficient outcome (point B) or point C, an unobtainable outcome given the constraint set. The efficient emission vector follows from the cost minimization problem.

$$(1.0) \quad \text{Min} \sum_{i=1}^{n} C_i(e_i) \quad \text{subject to} \quad \sum_{i=1}^{n} d_{ij} e_i \leq q_j \qquad j = 1, \ldots, k$$

To obtain the necessary conditions for a cost minimizing vector of emission, maximize the negative of (1.0) subject to the same constraint yielding the following Kuhn-Tucker conditions:

$$(1.1) \quad C_i'(e_i) + \sum_{j=1}^{k} \lambda_j d_{ij} \geq 0$$

(1.2) $\sum_{i=1}^{n} d_{ij}e_i \; - \; q_j \; \leq \; 0 \quad j = 1, \ldots, k$

(1.3) $e_i\left[C_i(e_i) \; + \; \sum_{j=1}^{k} \lambda_j d_{ij}\right] \; = \; 0$

(1.4) $\lambda_j\left[\sum_{i=1}^{n} d_{ij}e_i \; - \; q_j\right] \; = \; 0$

(1.5) $e_i \; \geq \; 0$

(1.6) $\lambda_j \; \geq \; 0 \quad j = 1, \ldots, k$

A receptor may not be binding, in which case λ_j equals zero. Montgomery (1972) establishes the conditions for the existence of a competitive equilibrium in the permit market, but for our purposes we may simply examine the choice problem facing firm i and its relation to the social planner's problem. The firm wishes to minimize abatement costs and the cost of additional emission permits. Each firm is endowed with an initial allocation of permits, $\ell^o ij$, which represents the maximum amount that they may pollute at any given receptor before having to purchase additional permits. A firm is a net seller if their endowment is greater than the number of licenses required to meet their level of emissions. The individual firm cost minimization problem is given below.

(2.0) $\text{Min } C_i(e_i) \; + \; \sum_{j=1}^{k} P_j(\ell_{ij} \; - \; \ell^o_{ij})$

I restrict the analysis to the case where $\ell_{ij} = d_{ij}e_{ij}$. Montgomery (1972) derives the more general case where $\ell_{ij} \geq d_{ij}e_{ij}$. The above problem yields the following conditions:

(2.1) $C_i'(e_i) + \sum_{j=1}^{k} P_j d_{ij} \geq 0 \quad j = 1, \ldots, k$

(2.2) $e_i \left[C_i'(e_i) + \sum_{j=1}^{k} P_j d_{ij} \right] = 0 \quad j = 1, \ldots, k$

(2.3) $e_i \geq 0$

Comparison of conditions (1.1) - (1.6) with (2.1) - (2.3) establishes the sufficient condition that the operation of a permit market with the above properties will lead to the efficient emission vector. This result is proven formally by Montgomery (1972), but the intuition is straightforward. Given the correct d_{ij}'s, and any initial allocation of permits, the APS will obtain the cost minimizing outcome.[8] In an interior equilibrium, each firm's marginal cost of abatement will be equal to the permit price at each receptor weighted by the transfer coefficients.

1.2.2 A System of Pollution Offsets

The limitations of an APS in its operation have been noted by (Krupnick, Oates, and Van De Verg, 1983; McGartland and Oates, 1985; Baumol and Oates, 1988; McGartland, 1988). Krupnick, et. al. (1983) offer their POS as a less restrictive alternative to an APS. Under this system a prospective trade is subject only to the condition that the resulting level of air quality does not violate any air quality standards.[9] This allows firms to trade without having to operate in a multitude of permit markets.

Only binding receptors matter in the trading of permits. Figure 1.2 depicts a situation with two firms and two receptors.[10] The constraints are represented by the line segments, ZY and UW. Given that pollution levels cannot exceed either constraint, the appropriate constraint set becomes RUVY, and the cost minimizing outcome is at point a along cost curve C_0. (Notice that the receptor associated with constraint UW is binding at the optimum, while the other receptor associated with the constraint ZY is not binding at the optimum.) Firms start with an initial allocation of permits, say at point c. The two firms will then trade at the rate d_1/d_2 until they reach point a. This ratio, d_1/d_2, allows firms to trade permits without violating air quality standards at the binding receptor. Notice that each trade along UV from point c to point a reduces joint costs. Once the firms reach point a there exist no further opportunities for cost reducing trades. Say instead that firms begin with an initial allocation of permits that puts them at point b; under the rules of a POS "firms can always obtain from the environmental authority additional permits so long as the air quality standard is not violated at any receptor point." (p. 241, Krupnick, Oates, and Van De Verg, 1983). The constraint set will increase accordingly from RTQY to RUVY with the addition of new permits. This will move firms toward some point on UV and trading will then take place as above. It follows that firms will achieve a cost minimizing outcome given any initial allocation of permits. Krupnick et. al. demonstrate the equivalence of their POS and an APS under perfect competition.[11]

1.2.3 Limitations of Permit Systems

I have shown with the above analysis that both the APS and the POS may, in theory, obtain the cost minimizing vector of emissions. This result has been useful in the EPA's design of a permit system for controlling sulfur dioxide emissions (Forster, 1993; Archer and Brooks, 1994). The two systems also require little in the way of cost information by the regulator. This may be the greatest advantage a permit system has over other forms of pollution control.[12] Given the promising qualities inherent in these permit systems, economists have still been able to demonstrate shortcomings of the models where certain economic conditions may exist that would hamper efficiency. Transaction costs are often cited as a likely limitation of permit systems (Stavins, 1995).[13] This is particularly true in an APS where permit markets exist for each receptor. The transaction costs of operating a permit system may be mitigated by the existence of brokers who have facilitated the trading of permits (McGartland, 1988). These brokers have also familiarized themselves with the atmospheric models used to forecast the effect trades will have on air quality, which is important in a system of pollution offsets when proposed trades take place at binding receptors.

In addition to transaction costs, imperfect competition in the permit market and the output market may create inefficiencies in permit markets. In fact, the presence of imperfect competition has been shown to create significant differences in the outcomes of an APS and a POS (McGartland, 1988). Given the above economic arguments, I find limitations in the application of permit systems. In the absence of these problems or where the resulting inefficiencies are small, permit systems may still be the most likely choice for controlling pollution in a cost efficient manner. Unfortunately, the standard economic arguments are not the only issues relevant to the attainment of economic efficiency in a permit system. As Section 1.3 demonstrates, the *atmospheric* model has implications for *economic* efficiency in both the APS and the POS due to its direct effect on the market price of permits.[14] This limitation in the economic efficiency of marketable permit systems has gone relatively unnoticed in the literature even though the importance of spatial characteristics has been well-documented (Montgomery, 1972; Atkinson and Tietenberg, 1982; Hahn and Noll, 1982; Krupnick, Oates, and Van De Verg, 1983; McGartland and Oates, 1985; Tietenberg, 1985; Tietenberg, 1980; McGartland, 1988. The relationship between the true spatial parameters and the permit system is formalized in Section 3.1.

1.3 General Model

This section formulates a general model for the attainment of a cost minimizing emission vector. The general model contains the standard model presented above as a special case. I have thus far established the well known result that an APS is capable of achieving the cost minimizing level of emissions. The POS may also obtain this outcome under certain conditions that were established in Section 1.2. Both systems rely on the accuracy of the atmospheric model for achieving economic efficiency and the assumption that pollution levels emitted from point sources are linearly related to the receptors where ambient air quality measurements are taken.[15] This linear relationship is often presumed to remain constant in the analysis of permit markets.[16] The accuracy of atmospheric models, though, is highly variable. A study conducted by the U.S. General Accounting Office (1988) examining the accuracy of thirty-four commonly used air quality dispersion models reported overestimation in many models by 200% to 590% and over 1700% in one model used for complex terrain parameter estimation. Of course, these figures do not accurately depict all models, but a majority of the models examined in the study reported highly variable results when evaluated at different sites[17]. I will demonstrate that inaccuracies in the measurement of atmospheric parameters may result in large inefficiencies in a marketable permit system. This is not to say that permit markets that take advantage of spatial characteristics should be ruled out. Just as economic arguments such as transaction costs and imperfect competition present challenges for the efficiency of a permit system, so do the problems demonstrated here.

1.3.1 Atmospheric Properties of Permit Systems

Before presenting the general model, it is important to understand how atmospheric models relate to each of the permit systems I examine in this chapter.[18] Although atmospheric models are often quite complex, the requirements of a permit system are relatively modest. An APS requires only the estimates of the transfer coefficients and the resulting matrix of transfer coefficients, D.[19] The transfer coefficients are assumed to reflect a linear relationship between a point source and a receptor.[20] They also determine the firm's marginal cost of concentration reduction (MCCR) , i.e. the cost of reducing a unit of emission measured at the receptor. Recalling (2.1), it is seen that the firm equates marginal cost to the price of a permit in each market weighted by the transfer coefficient. If there is a measured change in the transfer coefficient, MCCRs will be revised and a new market price will result.

The atmospheric parameters enter a POS in a slightly different manner. Recall that under a system of pollution offsets, the only restriction on trades is that no trade results in a violation of the air quality standard at *any* receptor. Non-binding receptors do not enter a firm's decision about a proposed trade unless they become binding as a result of the trade.[21] With a POS, trade continues until the efficient outcome is reached. Notice there is no explicit mention of atmospheric parameters under a POS, but before any trade is allowed it is simulated by an atmospheric model and trades that are predicted to increase pollution levels above the air quality standard at any receptor are not permitted.

This is not to say that trades will not take place at binding receptors. Firms may still trade at these receptors, but the resulting level of pollution must meet the environmental standard. Referring back to Figure 1.2, it is seen that trades at the binding receptor (along line segment UW) take place at the ratio of the transfer coefficients until the efficient outcome at point a is reached. With changing atmospheric parameters, air quality from trades may become difficult to determine. To simplify these transactions, the transfer coefficients are often replaced by a simpler measures such as distance from receptors (Krupnick, Oates, and Van De Verg, 1983). This allows for the operation of a system without constantly changing trading ratios.

It follows from the above description of the spatial requirements of the APS and POS that estimates of the transfer coefficients are all that are needed for the operation of these systems. These parameter estimates, however, are dependent upon the atmospheric model that is being used to analyze the air shed in the region of operation. The reliability of these estimates is often overlooked in the analysis of permit systems. This property must be taken into account when designing and implementing a permit system. For example, a permit system implemented in Baltimore using a Gaussian plume model (see REA, 1978 and Moroz, 1987) for a thorough discussion of Gaussian Dispersion modeling) will not be the correct model choice in areas of complex terrain. The atmospheric parameters (i.e. transfer coefficients) in an air shed are *not* immutable constants (Krupnick, Oates, and Van De Verg, 1983; McGartland, 1988). Different models are required for different regions of implementation. In Krupnick et. al.'s (1983) proposed system of pollution offsets they argue that changes in transfer coefficients are more readily accommodated by their POS than a similar situation in an APS. If transfer coefficients are correctly revised after each trade, the two systems remain efficient, but there is little evidence that this result holds in general.[22]

Atmospheric models are sophisticated enough to admit normal deviations into their analysis. As noted earlier, a "Gaussian plume" is simply the result of averaging well-behaved plumes over a fixed duration of time. Deviations such as seasonal changes are routinely incorporated in the atmospheric models used for permit systems (Tietenberg, 1985). The appropriate number of receptors as well as their proper location has been developed to avoid other atmospheric concerns such as "hot spots" (Ludwig, Javitz, and Valdes, 1983). Clearly, a host of concerns regarding the problems inherent in a permit system designed to take advantage of spatial characteristics have been addressed. And while this work certainly increases the feasibility of a spatially designed permit system, there remain problems that must be overcome in order to ensure that permit systems are capable of consistently minimizing costs.

Studies involving the use of permit systems have been conducted in a variety of areas.[23] Many of these areas include what atmospheric scientists would refer to as "complex terrain." Complex terrain includes, but is not limited to, areas where building profiles are highly irregular, coastal regions, and mountainous regions. The atmospheric models designed to address these problems are still highly contestable in the literature (Paumier, Perry, and Burns, 1992; Touma, Irwin, Tikvart, and Coulter, 1995), and complex terrain models have been targeted by the EPA as an area of concern (Paumier, Perry, and Burns, 1992). There have been advances in the modeling of air pollution dispersion in areas of complex terrain, but there is not yet a consensus about the correct way to model it. Unfortunately, many of the areas of highest concern in terms of air quality are located in these areas (e.g. Los Angeles and Mexico City). While the gains available from a permit system in these areas may be high, it is unlikely that the joint cost minimizing vector of emissions would be attained. But not all areas are characterized by large cost savings from a permit market (Tietenberg, 1985). In these areas, the measurement problems seriously limit the use of permit systems for achieving cost minimizing levels of emissions. In all areas, though, the measurement problems will lead to a distortion in the benefits available from a permit system. This is because the weighting of sources in a linear model is such that where one firm receives a favorable measure, another firm receives an unfavorable measure.[24] Under these conditions, a buyer of permits under the correct estimates could end up being a seller under incorrect measurements. This surprising outcome is developed later in this section.

The inaccuracies of atmospheric models are not limited to the above problem. Other atmospheric properties may contribute to highly variable and possibly inaccurate measurements.[25] In addition, problems may arise from using simple proxy variables as substitutes for transfer coefficients. While simple measurements are desirable for use in a permit system, they result in incorrect pricing of permits when they are inaccurate. Another concern relates to how emissions are measured. Often, pollutants are measured at potential emission rates rather than actual rates (APCA, 1981). The procedure used to measure emissions will have varying effects across firms depending upon how far they operate from their potential. An exhaustive list of concerns relating to the correct pricing of permits is not possible in a single paper, but the above concerns are particularly relevant and may be incorporated into a generalized model.

Montgomery (p. 397, 1972)] notes in his original work on permit markets "the assumption that concentrations are a linear function of emissions is the only part of this problem that does not generalize easily." He goes on to mention pollutants for which this relationship is at least approximately true.[26] The work following Montgomery retains his original assumptions (Krupnick, Oates, and Van De Verg, 1983; McGartland, 1988). Here, we are interested in a more general formulation of the problem that admits cases like those mentioned above (e.g. complex terrain). This will allow a comparison of the true cost minimizing outcome with that of the standard model where the simplifying assumptions are relaxed. As will be seen, these two emission vectors are different and the market price will, in general, differ in the two cases. The implications of this are important. In particular, it will be shown that operation of a permit system under certain conditions will not lead to the cost minimizing pollution vector.

1.3.2 The Model

The social planner would like to minimize total abatement costs subject to an environmental constraint, as before. Let each firm's cost again be represented by $C_i(e_i)$. It follows directly that the joint cost is the same as in Section 1.2. The environmental constraint differs in the general model. Recall that in the standard model, the constraint set facing the social planner is $D'\cdot e \leq Q$.[27] We would now like to allow for a more (less) general (explicit) form for the relationship between emissions and the atmospheric parameters. This will be represented by the following environmental constraint: $g_j(e) \leq q_j$ for each j.[28] Here, the function $g_j(e)$ needs some development. In the standard model, $g_j(e)$ is simply the summation of $d_{ij}e_i$ for all i at a particular receptor, j. It is easily seen that the standard model is a special case of the general model with $g_j(e) = \Sigma_i d_{ij} e_i$ and $g_j'(e_i) = d_{ij}$.[29] The function $g_j(e)$ is not limited to a linear form, though. For example, transfer coefficients may be affected by a strong influence from local sources in which case they are related to the level of emission (p. 73, Bartnikci, 1992). This is illustrated in Figure 1.3. As emissions increase from a point source, so does the sources effect on the receptor measurement.[30] Notice that the linear measurement will be equivalent to the true value at point A. It follows that there is some "chance" that the estimate will be equal to the true parameter value even if the model is misspecified as linear. Of course, this is not true in general and misspecification will usually result in an inefficiency. Finally, if the true atmospheric relationship is identified (i.e. the form of $g_j(e)$ is known), the operation of a permit market will still yield the cost minimizing outcome as will be seen below.

Other specifications of $g_j(e)$ are allowed, but certain restrictions must be placed on the function.[31] The g( ) function allows for changes in atmospheric parameters that result from measurement problems. For our purposes, the parameters of the g( ) function will be the true parameters while those in the standard model will be the estimated parameters. This will admit cases such as those where firm emission rates are measured at their potential level rather than actual levels.[32] I also assume that the function is continuously differentiable and increasing in e_i.[33] This assumption makes comparison with the standard model easier. I could have simply allowed $g_j(e)$ to be increasing without loss of generality in the qualitative results.

It is necessary to establish the existence of a cost minimizing vector in the general model in order to compare the results with the standard model. The cost minimizing vector does, in fact, exist. The proof is identical to Montgomery's Theorem 2.1 (p. 401, 1972) where $EH \leq Q$ is replaced by $g_j(e) \leq q_j$ for each j. The proof extends to this case because the constraint set, $g_j(e) \leq q_j$, remains nonempty with the new constraint—it contains zero—and bounded. The remainder of the proof is identical to Montgomery's. We are interested in formulating the cost minimization problem of the social planner. Given that the planner has identified the true environmental constraint, the minimization problem is as follows:

(3.0) $\text{Min} \sum_{i=1}^{n} C_i(e_i)$ subject to $g_j(e) \leq q_j \quad j = 1, \ldots, k$

Maximizing the negative of (3.0) subject to the same constraint yields the following necessary conditions for a cost minimizing vector of emissions:

(3.1) $C_i'(e_i) + \sum_{j=1}^{k} \mu_j \frac{\partial g_j}{\partial e_i} \geq 0$

(3.2) $g_j(e) - q_j \leq 0 \quad j = 1, \ldots, k$

(3.3) $e_i \left[C_i'(e_i) + \sum_{j=1}^{k} \mu_j \frac{\partial g_j}{\partial e_i} \right] = 0$

(3.4) $\mu_j \left[g_j(e) - q_j \right] = 0 \quad j = 1, \ldots, k$

(3.5) $e_i \geq 0$

(3.6) $\mu_j \geq 0 \quad j = 1, \ldots, k$

When $\mu_j = 0$, the receptor is not binding.

The first difference between the standard model and the general model is the necessary conditions for an interior, cost minimizing vector. In the standard model, all that is required is the condition that $C_i''(e_i) > 0$.[34] This still holds in the general model along with the requirement that $g_j''(e_i) \geq 0$. This is true as long as a firm's share of total pollution increases with their emissions (which is expected under the assumptions of the function, $g_j(e)$). Given conditions (3.1) - (3.6), we want to establish conditions for the existence of a competitive equilibrium in the general model. Again, I set up a licensed permit market so that the firm faces the following cost minimization problem:

$$(4.0) \quad \text{Min } C_i(e_i) + \sum_{j=1}^{k} P_j(\ell_{ij} - \ell^o_{ij})$$

Here, ℓ_{ij} represents the true share firm i has on receptor j. It is assumed that the firm purchases only as many permits as are needed to satisfy their individual effect on emission levels at the receptor, $g_{ij}(e_i) = \ell_{ij}$.[35] The following necessary conditions result from the above minimization:

$$(4.1) \quad C_i'(e_i) + \sum_{j=1}^{k} P_j \frac{\partial g_j}{\partial e_i} \geq 0$$

$$(4.2) \quad e_i\left[C_i'(e_i) + \sum_{j=1}^{k} P_j \frac{\partial g_j}{\partial e_i}\right] = 0$$

$$(4.3) \quad e_i \geq 0$$

A comparison of (3.1) - (3.6) with (4.1) - (4.3) establishes the conditions for the operation of a permit system that yields the cost minimizing outcome. The permit system in this case, howver, operates differently from the standard APS. Recall that in an APS, a firm must purchase a license to pollute a specified amount at a given receptor. This remains true in the generalized version of the permit system, but the firm's share of total pollution changes with the changing parameters of the spatial model. This leads to higher transaction costs than those associated with the standard model. It has already been noted that the APS is characterized by high transaction costs, therefore the generalized version of an APS is likely to be difficult to operate.[36] Given this limitation, other permit systems must be considered, including the POS. This will be taken up in Section 1.4. It may be the case that cost savings are unlikely to overcome the efficiency loss from inaccurate spatial parameters. This depends upon how far the vector of emissions resulting from the standard approach lies from the true least cost solution.

Given the derivation of the cost minimizing vector above, we may now proceed to a comparison of the emission levels from the two formulations. Let e^* be the cost minimizing solution to the social planner's problem in the standard formulation. Similarly, let e^{**} be the solution to the true, generalized formulation.

Result 1: In general, $e^* \neq e^{**}$.

The result follows from a comparison of conditions (1.1) - (1.6) and (3.1) - (3.6). There are two exceptions to Result 1. The first is when the standard model is the correct formulation, i.e. $g_j'(e_i) = d_{ij}$. In this case, the two models are identical. This is true if the assumptions of linearity (and hence the assumptions of the Gaussian dispersion model) hold. But as I have demonstrated, this result is not true in general. Indeed, the interesting cases are those where the standard assumptions are violated.

There is one other exception to Result 1 where $g_j'(e_i) = d_{ij}$ does not hold for all e_i's, but where the true cost minimizing outcome is reached. This is when $g_j'(e_i)\backslash[e^{**}] = d_{ij}$ and $\lambda_j = \mu_j$.[37] In this case, $e^* = e^{**}$ because the derivative of $g_j(e_i)$ is equivalent to d_{ij} when evaluated at the true cost minimizing vector e^{**}. This may be interpreted as "luck." Because there is only one point where this is true, and it is sensitive to the environmental constraint. Therefore, a small change in q_j will result in a new vector of emissions that is not cost minimizing if the standard model is used. This may be seen in Figure 1.5 at point d.[38] If the slope of the curve UV evaluated at point d is equal to the ratio of the transfer coefficients *and* $\lambda_j = \mu_j$, than $e^* = e^{**}$ even though $g_j'(e_i)$ does not equal d_{ij} everywhere. Notice that if the environmental standard, q_j, is perturbed, e^* will no longer equal e^{**} because the Lagrange multipliers are of different forms in the two models and the perturbation will result in $\lambda_j \neq \mu_j$. Even if the least cost outcome results by chance from using the standard model, this efficiency will last only as long as the environmental standard is left unchanged.[39]

The two exceptions given above should not obscure the importance of Result 1. In general, the two vectors will differ and there will be resulting inefficiencies in the permit system. The size of the inefficiencies will depend upon the level of inaccuracy in the estimation as well as the convexity of the joint cost functions. This is discussed later in sub-section *1.3.3*.

The second result involves the pricing of permits in the two models. Let P^* be the resulting permit price under the standard formulation. Let P^{**} be the resulting permit price under the general formulation.

Result 2: In general, $P^* \neq P^{**}$.

This result follows from conditions (2.1) - (2.3) and (4.1) - (4.3). As with Result 1, there are also exceptions to Result 2. When the standard model is the true model, the resulting Lagrange multipliers will be equivalent, and the prices will be the same in the two models.[40] The permit prices may also be the same under a variety of other conditions, although these are outweighed by outcomes where they are different. This is most easily seen by examination of Figure 1.4 (adapted from Tietenberg (1985)). Firm reduction refers to the amount of abatement that must be achieved to obtain the environmental standard. For example, if the firms are emitting 30 units of pollution per time period and the environmental constraint calls for 20 units per time period, then 10 units must be controlled. Therefore, at each point along the horizontal axis, Firm 1 reduction plus Firm 2 reduction must equal 10 units.

Consider the one receptor case where $MCCR_1$ and $MCCR_2$ are the marginal costs of concentration reduction ($MCCR_i = MC_i / g_j'(e_i)$ where MC_i is the marginal cost of pollution abatement, $C_i'(e_i)$). The intersection of the two curves gives the resulting permit price. This price is P^o in Figure 1.4. $MCCR_1'$ and $MCCR_2'$ are the marginal costs of concentration reduction using the estimated parameters of the standard model ($MCCR_i' = MC_i/d_{ij}$). When the estimated d_{ij}'s differ from $g_j'(e_i)\backslash[e^{**}]$ the two MCCRs will differ. This is the case in Figure 1.4 where the intersection of $MCCR_1'$ and $MCCR_2'$ give the price of the permit that would be observed in the market, P^1. In the example, $P^1 < P^o$, but this is not generally true. In fact, the price of the permit observed in the market may lie anywhere in region A or B.[41] Given this result, it is seen that the intersection of $MCCR_1'$ and $MCCR_2'$ anywhere along a line extending horizontally from P^o will yield a permit price equivalent to the true market price. As seen by the size of regions A and B, however, these outcomes are unlikely. Even if the observed market price coincides with the true market price, there is still only one point where the amount of reduction is correctly distributed between the two firms (i.e. the distribution of reduction measured along the horizontal axis). This is the intersection of the true MCCRs. Hence, efficiency may only result in this one case where the estimated standard model happens to coincide with the true, generalized model.

From the two results above, it is apparent that the standard permit system model may not lead to a cost minimizing outcome. This outcome is not surprising given the reliance of permit systems on atmospheric model estimation. When the estimates of the atmospheric models are highly variable, it is difficult to establish an accurate model of the required spatial characteristics necessary for the operation of an efficient permit system. If a permit system is to be used as a method for achieving cost efficiency, these concerns must be addressed. Results 1 and 2 lead to perhaps the most interesting and important results of the chapter. This is the possibility that firms may "get stuck" operating at an inefficient outcome where neither the firms nor the regulating authority realize that the outcome is not cost minimizing.

1.3.3 Information Problems in Permit Systems ("Getting Stuck")

An interesting feature of the two permit systems studied in this chapter is that when the underlying atmospheric model is misspecified, firms in the APS and POS continue to operate as if they are at the cost minimizing outcome. That is, there is no tendency for them to move from the inefficient outcome given the institutional characteristics of the permit systems. In addition, the environmental authority is unaware of the resulting inefficiency. Simply put, the firms "get stuck" at an outcome that is not cost minimizing. This is a problem for both systems because the advantage that they maintain over other permit systems is their supposed ability to reach the cost minimizing outcome.

The existence of this problem follows from Results 1 and 2, but it is most easily illustrated using Figure 1.5.[42] Figure 1.5 depicts the two firm example with one receptor. The true constraint set is RUV. Suppose that the original estimation of the parameters of the standard model yield d_{ij}'s such that the constraint set is RQV.[43] The cost minimizing point given these estimates is at point a, but the receptor will not be binding here. Both the firms and the environmental authority will realize that the receptor is not binding when pollution levels are observed to be "too low." Each system handles this situation differently. The estimates may be reestimated under an APS as the environmental authority believes the estimates are incorrect.[44] Say that the new estimates result in the constraint set RDW. Firms will minimize costs subject to this constraint which will put them at b. But given the true constraint set, RUV, operation at b results in a binding receptor. The new estimates lead firms to *believe* that they have reached a cost minimizing outcome because their abatement costs have been minimized given the new, incorrect estimates. The environmental authority also believes that they have estimated the correct spatial parameters because the receptor is now binding, and there are no new trades taking place. In addition, the ambient air quality is met at the receptor. The permit system is seemingly in equilibrium at the cost minimizing outcome, but the true cost minimizing outcome is really at point d.

This situation may also arise under a POS but in a different manner. Under a system of pollution offsets, firms may freely obtain permits from the environmental authority at nonbinding receptors. Assume that the firms again begin with the same original estimates and constraint set RQV. The cost minimizing outcome given this constraint set is on C_3 at point a. Again, the firms and the environmental authority realize that the receptor is not binding, under a POS firms retain the same transfer coefficients and simply obtain more permits from the environmental authority. Therefore, the trading ratio does not change, and the constraint set becomes RTW. Given this constraint set, firms minimize costs on C_1 at point c. Once more, the outcome is acceptable by both the firms and the environmental authority because the receptor is binding, and the firms have minimized costs given the incorrect, estimated parameters. Firms have once again gotten "stuck".

Given the above results, should we rule out the use of these permit systems? The answer is no for the following reasons. First, the cost of the resulting inefficiency may be small. This depends upon the distance between point b, point c and point d and the convexity of the joint cost function. Also, the gains from any cost saving trades may be large enough to outweigh the inefficiencies. The above outcome should not be overlooked, though. There is not only an inefficiency in the operation of the permit system, there is also a distributional problem because the costs facing polluters are incorrect. In particular, some firms are selling permits when they should be buying and others are buying permits when they should be selling. Furthermore, the institutional features of the two permit systems do not allow movement away from these inefficient outcomes.

1.4 An Extension to a System of Pollution Offsets

I demonstrated in Section 1.3 that the cost minimizing vector resulting from the use of an APS or POS will not, in general, be the true cost minimizing vector. The inefficiencies attributable to inaccurate atmospheric models may vary widely, but it remains that the solution is unlikely to be cost minimizing. This result is especially true in areas where atmospheric properties have not been accurately modeled. To complicate the situation, I also demonstrated how firms may "get stuck" at inefficient outcomes. This result follows from the regulator's use of an inaccurate model. Both the APS and the POS rely on the estimates of the regulator's model so that there is little flexibility in parameter estimates. This inflexibility may result in the inefficient outcome described above. The final section of the paper proposes a simple extension to the POS which allows the cost minimizing outcome to be reached. The extension relies on the use of a wider array of atmospheric models for establishing the spatial parameters. It will be shown that the extension may result in the efficient outcome, but when it does not, it only allows movement toward the efficient outcome. That is, the outcome under the extension will never be less efficient than the outcome of the standard POS.[45]

Why would an environmental authority consider a polluting firm's costs in their social objective function? After all, even when firms are stuck at an inefficient outcome, there are no violations of the ambient air quality standard. The answer is that the firm's costs are a significant part of the social costs. A neutral environmental authority who considers all of the costs of environmental regulation is socially desirable.[46] The institutional structure of the APS and POS, however, may not allow for the attainment of the cost minimizing outcome regardless of the preferences of either the firms or the environmental authority. Because the atmospheric model used by the regulator has a direct effect on the price of permits in both systems, the cost minimizing outcome may only arise when the model specified by the regulator is the correct one.[47] We seek a mechanism which allows the cost minimizing outcome to be achieved even when the regulator has incorrectly specified the relevant spatial parameters.

1.4.1 Firm Bargaining, Atmospheric Models, and Efficiency

The EPA has stringent standards for any atmospheric model before it may be used as a "preferred model". Preferred models "are designated by EPA as usable in regulatory decisions without prior special justification." (p. 3, U.S. GAO, 1988) The EPA allows the use of "alternate models" but only in certain situations (p. 3, U.S. GAO, 1988). Models must be tested thoroughly before they may be used in regulatory decisions and even then they may not be admitted for use. While this screening process provides a lengthy opportunity to study the proposed atmospheric models, not all participants in the regulatory process are in agreement. The industry concern on this matter may be summed up in an address made to the Air Pollution Control Association by John Wooten, a coal industry representative (p.5, APCA, 1981):

> "...when an air quality analyses is required, the procedures specified in the guideline on air models must be followed. The guideline specifies approved models to be used for various pollutants and in various situations. A non-guideline model can only be used if it can be show, according to EPA procedures that predictions agree within 2% of the predictions from an approved model. This provides very little latitude for using site or source specific models even though the non-guideline model may represent a more valid approach. This requirement more than any other discourages development of more accurate models."

We will see that this concern may be addressed in some settings by a natural extension of the POS to allow the use of non-guideline models with certain restrictions.

Recall that the only trade restriction in a POS is that the proposed trade does not result in a violation of the air quality standard at any receptor point. That is, any trade which takes place within the environmental constraint set ($D' \cdot e < Q$ in the standard model, $g_j(e) < q_j$ in the general model) is permitted. Those trades taking place on the frontier of the constraint set (equality in the two previous constraints) cannot exceed the standard. But under a POS, these trades take place at the ratio of the estimated transfer coefficients allowing firms to "get stuck" at inefficient outcomes. This is seen in Figure

1.6 as point c. Given the estimated parameters of the environmental authority's model, there will be no movement to point d. We now ask whether all parties would like to move to point d if the true parameters were known. Surprisingly, the answer is no. The environmental authority would like to move to point d as would firm 2 whose costs decrease by $C_2(e_2') - C_2(e_2'')$, but firm 1 would oppose this move because their costs increase by $C_1(e_1') - C_1(e_1'')$. Firm 2 may, however, pay firm 1 an amount greater than $C_1(e_1') - C_1(e_1'')$ to move to point d. This payment must be less than $C_2(e_2') - C_2(e_2'')$, otherwise firm 2 is better off staying at point c. As long as the transfer satisfies these conditions, the cost minimizing outcome will be reached. This argument relies on the trade being profitable to both firms and also the environmental authority knowing that point d is the efficient outcome.[48] But if this is information is known, the environmental authority could simply use a command and control approach and force firms to operate at this point. Say instead that the trade was thought to be profitable by both firms and the environmental authority only required that the air quality standard be met, the resulting outcome would still be at point d.[49] Firm 2 would pay firm 1 to move directly to point d as above, and the resulting air quality would be acceptable to the regulator.

1.4.2 Extending the POS

The proposed extension of the POS is essentially the situation described above. The only requirement of the extended POS is that *trades do not violate air quality* *standards at any receptor*. This differs from the standard POS in a very small, but significant manner. A proposed trade under the standard POS must be simulated using the environmental authority's atmospheric model. Therefore, the proposed trade described above could not be carried out under the standard POS. The trade could be transacted under the extended POS, though. It follows that the extended POS has the ability to reach the cost minimizing outcome where the standard POS fails. There are obvious concerns with a permit system that allows firms to carry out trades which seemingly violate an atmospheric model which has been held to stringent EPA testing. There is also no obvious reason to think that firms can predict atmospheric parameters any better than the environmental authority. In fact, it would seem that the environmental authority is best equipped for estimating atmospheric parameters. These and other concerns are addressed below.

The proposed permit system seems to obviate the need for the environmental authority's model. Given that proposed trades may always be carried out under the extended POS, the environmental authority's model is seemingly unused—but this is not true for two reasons. First, the environmental authority's estimates are still used as the initial parameters, and they are also used as "default" values. Under the extended POS, firms begin by operating according to the trading rules of the standard POS. Hence, the environmental authority's model is not used until a proposed trade results in a receptor becoming binding. Under the extended system, firms would trade at the ratio of the estimated transfer coefficients at binding receptors unless one of the firms proposed a different trading ratio. If this proposed trading ratio is acceptable to both firms, the trade will take place and it will stand as long as the air quality standard is met. The extended POS, however, allows both firms the opportunity to reject the trade and default to the environmental authority's estimated parameters. This default option is required so that the outcome of the trade is, in fact, an improvement for both firms.[50] In addition to its use as a default model, the environmental authority may use their atmospheric model to decide whether a proposed trade is likely to result in a significant violation. For example, a trade may be predicted to result in highly damaging levels of pollution. The environmental authority may want to take these trades into consideration before allowing them.[51]

Even if a trade is deemed acceptable by both firms and is approved by the environmental authority, it may still lead to a violation of the air quality standard. Under the proposed system, firms would be held to a "full damage" tax.[52] Neither firm would willingly engage in a trade which they expect to result in a violation because they will *each* be required to pay the *full* amount of the damage which results from the exceedence.[53] One concern with a tax of this type is that firms do not know with certainty how the resulting emissions will affect the air quality standard. Thus the cost savings must be weighed against the possibility of facing the damage tax. But the tax does have the desirable property that firms will not engage in behavior which they think will result in the tax being levied. Unfortunately, the severity of the tax may limit some cost reducing trades.[54]

An example may best illustrate the proposed mechanism. Consider the simple case with two polluters and one receptor shown in Figure 1.7. The operation of a standard POS will result in the constraint set RTW.[55] Once firms reach point c, there are no remaining cost reducing trades under the standard POS. Under the extended POS, firm 2 may have access to an atmospheric model whose estimated parameters result in constraint set RTY.[56] Firm 2 may now offer firm 1 an amount greater than $C_1(e_1') - C_1(e_1''')$ to trade to point f but less than $C_2(e_2') - C_2(e_2''')$ to allow the use of this model for forecasting trades at the binding receptor. If firm 1 believes that the proposed model is accurate, they will agree to the trade because they benefit more from the transfer than the increase in abatement costs. Given the atmospheric model used in the trade, the true cost minimizing outcome is not obtainable but the firms have moved toward it. Also, the extended POS still allows firms to reach point d, but a different atmospheric model would have to be used.

A second example is illustrated in Figure 1.8. In this example, both firms agree to an atmospheric model which estimates the constraint set as RKL. This constraint is larger than the true constraint set RUV. As firms minimize costs subject to RKL will arrive at point e, which is a violation of the standard. The resulting damage tax must be larger than either $C_1(e_1'') - C_1(e_1''')$ or $C_2(e_2'') - C_2(e_2''')$.[57] Firms will then choose to default back to the environmental authority's model because the tax they face from violating the standard is larger than the cost savings from operating at point e.

1.4.3 The Role of Permit Brokers

The standard POS may involve significant transaction costs (McGartland, 1988). For this reason, permit systems have witnessed a rise in permit brokers who have facilitated the trading of permits (p. 36, McGartland, 1988). Essentially, the brokers have decreased the transaction costs to firms from searching for trading partners. These brokers are also adept at using the atmospheric models to forecast the resulting atmospheric conditions from proposed trades (Krupnick, Oates, Van De Verg, 1983). Under an extended POS, the brokers would play an integral part in the attainment of the cost minimizing outcome. Given the likely arrival of many atmospheric models to forecast atmospheric parameters under the extended POS, brokers could serve a useful role in deciding which models are accurate and which are not. It follows that a broker's success depends on their ability to use the available models to discover cost reducing trades. With an economic incentive for finding these trades, the accuracy of an atmospheric model becomes paramount. Brokers with a reputation for discovering cost reducing trades will be a valuable commodity to firms who face significant pollution abatement costs. Brokers who use inaccurate models to forecast trades may have their proposed trades refused by the environmental authority, but more likely, they will not be hired by firms seeking cost reducing trades.

The extended POS is intended to allow a degree of flexibility in the rigid parameters of the standard POS. This is especially important in areas where forecasting using standard models is difficult. The extended POS also allows site specific characteristics to be more easily incorporated in the estimation of atmospheric parameters—something that is lacking in the current EPA guidelines for dispersion modeling (U.S. EPA, 1978; APCA, 1981). It may be that the operation of the extended POS is permitted only when the standard is binding at a particular receptor and other conditions specified by the environmental authority are met.[58]

Extension of the POS as presented above addresses the industry concern that atmospheric modeling requirements are too stringent and at the same time holds firms responsible for the models (and subsequent trades) they choose. The system also allows the environmental authority the final say as to whether a trade will or will not be permitted. Brokers, who currently play an integral role in permit markets, become even more important in the extended POS. The broker's purpose in a standard POS is to discover cost reducing trades between firms. This role is expanded in the extended POS as brokers are able to use an array of different atmospheric models in their search for cost reducing trades. The economic incentive involved with discovering these trades places a premium on accurate atmospheric models. This is a large step toward obtaining the cost minimizing outcome in permit systems which incorporate spatial characteristics.

1.5 Concluding Remarks

Permit systems have been identified in the literature as a promising method for achieving cost minimizing outcomes for certain environmental regulations and standards. The systems are more flexible than the historically inefficient (from an economist's perspective) command and control approaches. I have shown that a permit system's efficiency is directly related to the accuracy of the underlying atmospheric model. The standard permit systems that incorporate important spatial characteristics in their design (e.g. APSs and POSs) use rigid estimates of spatial parameters that directly influence the price of permits. If these estimates are inaccurate, the resulting emission vector will not, in general, be cost minimizing. In addition to this problem, I have demonstrated that firms may "get stuck" at inefficient outcomes where neither they nor the environmental authority realize that they are operating at an outcome that is not cost minimizing.

This chapter lays out a general framework to investigate the economic consequences of the underlying atmospheric model in a marketable permit system. There are many atmospheric models available for forecasting these important spatial parameters. Further research would include simulations using actual dispersion models to identify particular areas of concern.[59] Finally, the general model introduced in this chapter addresses the concerns that are inherent in any discussion about extending permit systems beyond local areas. Regional permit systems have not received a great deal of attention in the literature, but their use in dealing with regional problems has been mentioned as a possible solution (Tietenberg, 1985). A permit system of this type would certainly face the problems mentioned in the chapter, as long range dispersion modeling is highly nonlinear (Johnson, 1983).

1.6 Endnotes

[1] The focus of this chapter is air pollution although it should be noted that the analysis is not specific to this type of pollutant. The control of water pollution is often cited as another application for permit systems.

[2] Spatial characteristics include various atmospheric variables such as wind patterns and seasonal effects as well as firm specific features like stack height, emission rates and pollution control technology (e.g. stack scrubbers).

[3] The EPA currently uses various features of these systems in its SO_2 Emission Permit Trading System.

[4] The effect of each trade on air quality is first simulated by an atmospheric model and those trades that are predicted to violate standards are not allowed.

[5] Limiting attention to the APS and POS does not limit the appropriateness of the results. The two permit systems considered in this chapter are the leading candidates for permit systems that are capable of achieving the cost minimizing outcome. I therefore restrict attention to these permit systems for the remainder of the chapter.

[6] Complex terrain refers to any region not characterized by "homogeneous" features (Moroz, 1987). This may include mountainous regions, coastal regions, and valleys. Often estimation of atmospheric parameters under these conditions is difficult (Paumier, Perry, and Burns, 1992). Section 1.3 discusses these problems in greater detail.

[7] Specifically, $C_i'(e_i) \leq 0$ and $C_i''(e_i) \geq 0$. Abating pollution requires decreasing e_i which increases cost. Therefore, the opposite holds as e_i increases, hence the sign of the inequality. The constraint is linear, and the constraint set is non-empty because it includes zero. Given continuously differentiable smooth cost functions, both inequalities above will be strict, and the cost minimizing vector will be unique. I assume that costs are strictly convex for the remainder of the chapter.

[8] The result follows from the fact that ℓ^o_{ij} does not enter the first order conditions in the firm's cost minimization problem. As firms become either net sellers or net buyers, they enter the market with excess permits or seeking permits. At binding receptors, the market price of a permit is positive and the market will clear under competitive conditions. This will lead to efficiency as permits are reallocated when firms compare the market price to their cost of abating pollution. In markets with non-binding receptors, the allocation of permits does not matter because the price of a permit is effectively zero.

[9] The POS implicitly includes another rule—each trade must be simulated by the environmental authority's atmospheric model before it is permitted. This requirement will be addressed in Section 1.4 where I extend the POS.

[10] The analysis here closely follows Krupnick, et. al. (1983).

[11] McGartland and Oates (1985) prove formally the equivalence of the APS and POS under perfect competition. The result does not hold under imperfect competition as any firm has an incentive to "free ride" off of the trades of others (McGartland, 1988). For example, firm 1 may sell permits at receptor A which also decreases their pollution level at receptor B. Because firms are free to pollute until a receptor is binding, firm 2 may "free ride" on the improved air quality at receptor B. This is not efficient because firm 2's cost of abatement is not calculated in the price of the permits at receptor B—i.e., they "free ride." This externality does not exist under an APS because firm 1 would retain their rights to permits at receptor B which they could sell.

[12] While Pigouvian taxes are also capable of achieving a cost minimizing outcome, they suffer problems that make them difficult to implement. The efficient tax would be equivalent to the weighted prices found in (2.1), but to set these taxes, the environmental authority would require information on cost. This is not required under the standard APS or POS. Also, the cost to the firm under a system of taxes is likely to be much higher. Baumol and Oates (1988) report two studies where the cost increase to the firm under a tax regime is substantially larger than that of a permit system or a command and control approach. One study estimates that a system of fees could be six times that of a command and control approach.

[13] It is worth mentioning that transaction costs vary not only across permit systems but also according to what pricing institution is being used. This has been pointed out in the experimental literature studying these institutions (Cason and Plott, 1996).

[14] Under an EPS, the spatial characteristics are not relevant in the actual trading of permits. This is because permits trade one-for-one in an EPS. An EPS, however, cannot generally achieve the least cost outcome (Baumol and Oates, 1988). This is particularly true where spatial characteristics are sufficiently different.

[15] This is also true for some water pollutants, most notably bacteriological oxygen demand (BOD).

[16] Here I am referring to the d_{ij}'s in the summation, $\Sigma_i d_{ij} e_i$. Reestimation of these parameters may be costly to implement so they are often substituted by distance measures

(Krupnick, Oates, and Van De Verg, 1983). Montgomery (1972) points out that the assumption of linearity does not easily generalize.

[17] The study also reported that at least one model *underestimated* parameters at one site by 70%, but *overestimated* parameters at another site by 270% (p. 3, U.S. Congress, 1990) using the same model. The models were particularly inaccurate at sites characterized by complex terrain. These problems are taken up in greater detail in sub-section *1.3.1*.

[18] It is worth reemphasizing that limiting our analysis to the APS and POS does not limit the importance of the results. Both systems have shown that under certain conditions they are capable of achieving cost minimizing outcomes. This is not the case with an EPS for the reasons mentioned in Section 1.2.

[19] $D = \begin{bmatrix} & \cdot & \\ \cdot & d_{ij} & \cdot \\ & \cdot & \end{bmatrix}$, where "i" denotes the firm and "j", the receptor.

[20] This assumption holds when the standard assumptions of a "Gaussian Dispersion Model" are satisfied. The Gaussian dispersion model results from averaging actual plumes emitted from point sources over a certain length of time. Essentially, the average of the actual plumes gives a Gaussian plume. The model relies on a host of underlying assumptions; the more critical assumptions for our purposes include: 1. Pollutants are emitted at a constant rate (normally assumed to be of infinite strength), 2. The solution is valid over "relatively flat, homogeneous terrain. It should not be used routinely in coastal or mountainous areas, an area where building profiles are highly irregular." (pg. 130, Moroz, 1987). When the assumptions of the Gaussian Dispersion model do not hold, atmospheric scientists have formulated a host of different models that may apply. Unfortunately, the accuracy and behavior of these models is highly variable (Paumier, Perry, and Burns, 1992; Touma, Irwin, Tikvart, and Coulter, 1995).

[21] Whether a receptor becomes binding as the result of a trade is dependent upon the sensitivity of the parameters in an atmospheric model. The measurement of these parameters may be highly variable. McGartland (1972) finds that binding receptors are relatively insensitive to trades using a Gaussian plume-model in Baltimore. The study examines the use of a POS for controlling total particulate emissions. Atkinson and Tietenberg (1982) report that different receptors became binding as a result of the Clean Air Act in a study conducted in St. Louis. In a POS, decisions of firms are closely related to whether or not a receptor is binding. In this setting, higher variability in the atmospheric model could limit trades.

[22] Normal trading under the two systems are likely to lead to changes in relevant spatial parameters, but a more serious problem arises when ambient air quality standards are significantly altered. Phase I and Phase II of the 1990 CAA Amendments involve substantial changes in the air quality standards (U.S. Congress, 1990). Essentially, these "phases" call for increases in the air quality standards for many pollutants. These types of changes may have a significant effect on spatial parameters as well as the locations of binding receptors (Atkinson and Tietenberg, 1982). A more recent development involves the proposed changes in the current air quality standards. This comes at a time when permit markets are receiving a great deal of attention. The concerns of this chapter are particularly relevant for these types of changes in air quality standards because the uncertainties involved with parameter estimation are exaggerated.

[23] A short list includes: St. Louis (Atkinson and Tietenberg, 1982), Los Angeles (Hahn and Noll, 1982), Mexico City (Goddard, forthcoming), and Baltimore (McGartland, 1988).

[24] In a linear model concentration levels emitted from polluters are assumed to be additive. Often, the estimates of the concentrations are conducted using a least squares model APCA, 1982). Consider a simple example with two polluters (point sources) and one receptor. If a least squares model is being used, an underestimate of the share of pollution at one point source must be compensated by an overestimate at another point source. This is due to the fact that the total of the two sources must add up to the receptor measure.

[25] For a more complete list of these conditions, see (APCA, 1981, 1982; Cox and Tikvart, 1990; Paumier, Perry, and Burns, 1992).

[26] The pollutants Montgomery refers to are bacteriological oxygen demand (BOD) and nonreactive atmospheric pollutants. It is often overlooked that the linear relationship referred to in his original work is still subject to the assumptions of the underlying atmospheric model (for air pollutants).

[27] D is the $(n \times k)$ matrix of transfer coefficients, e is a $(n \times 1)$ vector of emissions and Q is a $(k \times 1)$ vector of air quality standards (note: the ambient air quality standard at each receptor may or may not be the same).

[28] The environmental constraint may no longer be written in matrix notation because it need not be a linear system. I use the notation $g_j(e)$ to represent some combination of atmospheric parameters and firm emission levels.

[29] The derivative, $g_j'(e_i)$, represents the marginal effect firm "i" has at receptor "j" by polluting an additional unit of pollution (where a unit is appropriately small). In the standard model, this is simply the constant transfer coefficient, d_{ij}.

[30] The actual relationship may be more complex, but a simple example is best for our purposes. Consider a function $g_i(e) = \Sigma_i d_{ij}(e_i)e_i$ where $d_{ij}(e_i) = \kappa e_i$ with κ (<1) simply a constant. In this example, the transfer coefficient is an increasing function of the level of emission. That is, as total emission increases at firm "i", so does the share of their pollution measured at receptor "j".

[31] For simplicity, I will assume that pollutants are nonreactive. This would be the case with nonuniformly mixed assimilative pollutants. As it turns out, this restriction is not too limiting. If pollutants are reactive, the operation of an efficient permit model would still be possible if the marginal effects of each firm on total pollution are known by the environmental authority. Note that the nonreactivity assumption implies that $g'_j(e_i)$ does not depend upon e_j. .

[32] When emission rates are measured at potential rather than actual rates, the resulting estimated transfer coefficients will deviate from the true transfer coefficients. In this case, I treat the standard model as the estimated model and the general model as the true model. This allows us to use the same analysis to treat this "non-atmospheric" case.

[33] This is true for the standard model as well. The $g_j(e)$ function is assumed to be quasiconvex. $[(g'_j(e_j) \geq 0), (g'_j(e_j) \leq 0]$. The inequality for the second derivative reflects the fact that the share of a firm's pollution that reaches the receptor increases as emissions increase. It is related to how much of the emission is concentrated into a volume of air (Tietenberg, 1985). Simply put, the transfer coefficients are increasing in the level of emissions.

[34] Remember that costs are decreasing in e_i. This condition simply requires that the firm face increasing costs of abatement.

[35] The operation of an APS for the generalized model relies on the ability of the environmental authority to specify each firm's effect on the receptor. As will be seen, it is unlikely that the environmental authority is capable of achieving this in general. If they could, though, they would require the firm to purchase at least as many permits as are needed to cover their individual effect on receptor measurements given the spatial characteristics of the system. In Section 1.4, I present an extension to the POS that is capable of reaching a cost minimizing outcome and which puts fewer demands on the environmental authority for identifying $g_j(e)$.

[36] The APS cannot easily incorporate changes in diffusion coefficients in a *linear* model (Krupnick, Oates, and Van De Verg, 1983). In the general model, firms would have constantly changing atmospheric parameters that would result in changing MCCRs. Even with brokers, the transaction costs are likely to be substantially higher in the generalized APS than those of the standard APS.

[37] The notation, $g_j'(e_i)\backslash[e^{**}]$, is intended to mean that the function $g_j'(e_i)$ is being evaluated at the true cost minimizing vector, e^{**}.

[38] Figures 1.5, 1.6, 1.7 and 1.8 use a simple example consisting of two firms and one receptor. The results of the analysis, though, are applicable to multiple firms and numerous receptors.

[39] Environmental standards are rarely left unchanged. As mentioned earlier, the Clean Air Act Amendments of 1990 call for increased standards in 2000 under Phase II. There has also been a recent proposal by the EPA to raise standards significantly in the next two years.

[40] The permit prices are the shadow prices of the social planner's problem.

[41] These two regions are the result of the least squares estimation procedure used to estimate the d_{ij}'s. If one estimate is biased upward, the other must be biased downward to compensate. Therefore, the regions to the north and south of the intersection of $MCCR_1$ and $MCCR_2$ are not feasible.

[42] Figure 1.5 uses the simple example from earlier where $d_i(e_i) = \kappa e_i$.

[43] Notice that the constraint set using the estimated parameters lies within the true constraint set. This may be the result of an increase in the standard at the receptor. With $g_j'(e_i) \geq 0$, a decrease in e_i resulting from a higher standard will decrease the share of an individual firm. If the d_{ij}'s are not changed to reflect this nonlinear relationship, the estimated d_{ij}'s will overestimate the shares of the two firms. If both d_{ij}'s are biased upwards, then it follows that the receptor cannot be binding, and the constraint set from the estimated parameters will lie inside the true constraint set.

[44] The estimates are incorrect, but it is the result of using the wrong atmospheric model. Reestimating parameters using the wrong model will lead to new estimates, but they too will be incorrect. This is a problem with atmospheric modeling—different models will yield different results depending upon the site specific attributes where the system is implemented (U.S. GAO, 1988).

[45] A similar extension could be implemented in an APS. We focus on a POS because it is resembles the current SO_2 Permit Trading system of the EPA.

[46] This need not be the case when firms and regulators bargain over the proposed environmental standard. Amacher and Malik (1996) argue that a biased regulator may be desirable when there is bargaining involved between the firm and regulator. We do not address this point in the paper. We will assume that the standard is imposed exogenously by the regulator and firms then minimize costs to achieve any level of the standard.

[47] This is not strictly true. There is the one case described in Result 1 where the cost minimizing outcome is obtained even though the true model is not used. Even if this "chance" event occurs, it cannot be sustained unless the air quality standard is forever unchanged. Observable evidence tells us that the standard does change (e.g. Phase I and Phase II of the CAA (U.S. Congress, 1990), and therefore an incorrect model will always lead to inefficiency.

[48] The environmental authority would need to know that point d is efficient because the trade would not be allowed under a POS given the estimated constraint set RTW. Only if the environmental authority knew that the true constraint set was RUV would the trade be allowed under the standard POS.

[49] It should be pointed out that this is not the standard POS. For this trade to be allowed, the environmental authority would have to overlook the estimated parameters of their atmospheric model. This is due to the fact that authority's estimated constraint set lies with in the relevant (cost minimizing) portion of the true constraint.

[50] Because the outcome is still contingent on the atmospheric model which is used, the result may not be what one/both firm(s) expect. If either is worse off as a result of the trade, they have an option to return to the standard POS.

[51] This option allows the environmental authority a reasonable degree of control over trading. As will be seen, exceedences will result in the use of a taxing scheme. Although the taxing scheme is set up so that firms would naturally avoid a "risky" trade, it is unlikely that the proposed permit system would be acceptable to an environmental authority without allowing them some degree of control over trading.

[52] This tax was proposed as a method for eliciting an efficient outcome with nonpoint pollution sources (Segerson, 1988). The tax calls for *each* firm to pay the full amount of the damage.

[53] There may be a case where the resulting full damage is smaller than the cost savings to each firm from violating the standard. If this is the case, the environmental authority could increase the tax until the firms decide to "default" to the environmental authority's model. I assume that damages are sufficiently large so that the damage tax is always larger than the cost savings.

[54] This is not necessarily true, though. Firms may move iteratively toward the cost minimizing outcome. In Figure 1.6, for example, firms may not move directly from point c to point d, but rather in smaller intervals. In this manner, an exceedence does not result in a large tax being levied. This iterative approach may involve higher transaction costs, but as we will see, permit brokers may mitigate the costs involved.

[55] This follows from Figure 1.5 where the original estimates resulted in constraint set RQV. Given the true constraint set RUV, the receptor is not binding for constraint set RQV because firms minimize costs at point a when facing this constraint. The standard POS allows firms the opportunity to obtain permits freely from the environmental authority when the receptor is non-binding. This leads to constraint set RTW and point c. This is the resulting constraint set for both Figures 1.7 and 1.8 using the estimated parameters of the standard model.

[56] We will see that brokers may be an integral part in the actual operation of the extended POS. Because some of these brokers are capable of using atmospheric models, they can reduce the costs to firms of finding efficient trades. This will be addressed in sub-section *4.3*.

[57] This must hold because the damage tax to each firm is equal to the amount of the full damage. Therefore, it is larger than the damage inflicted by either individual firm. It holds under our previous assumption that damage is sufficiently large and that the damage tax is greater than the cost savings to either firm. Of course, the environmental authority may tax the firms the full damage and then simply require them to abide by the original estimates. This will guarantee that the air quality standard is met because the environmental authority already knows where firms will operate under their original estimates (point c in Figure 1.6).

[58] For example, the environmental authority may have a great deal of historical information on pollution levels in certain areas. In this situation, the environmental authority may only allow trades which do not result in emissions which have historically resulted in the violation of standards. These extra conditions also allow the environmental authority the flexibility to incorporate local conditions into the operation of the permit system.

[59] The use of simulations of this type are common in the economics literature on permit systems (McGartland and Oates, 1985; McGartland, 1988). The author has conducted simulations using a simple atmospheric model that indeed identify inefficiencies of the type discussed in this chaper. The nonlinearities that may result in regions of complex terrain, however, are difficult to simulate with a simple model.

Figure 1.1

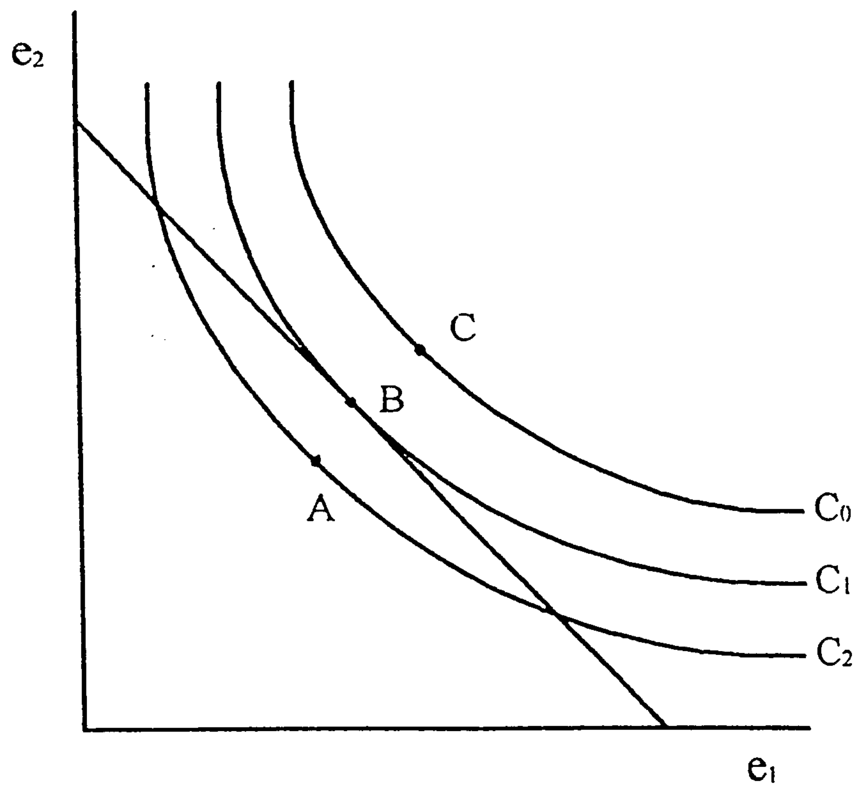


Figure 1.2

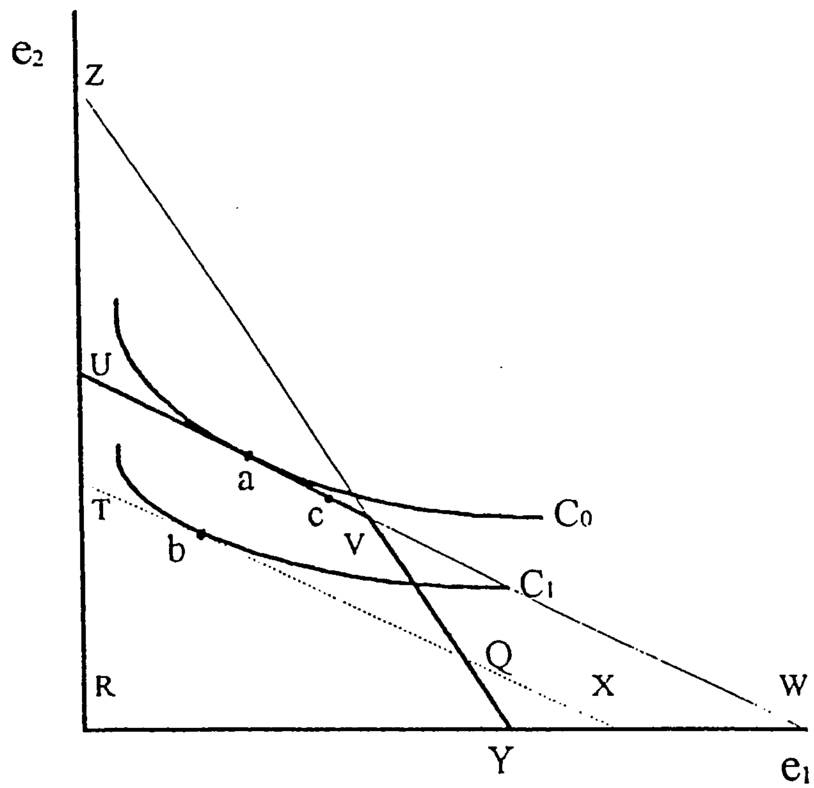


Figure 1.3

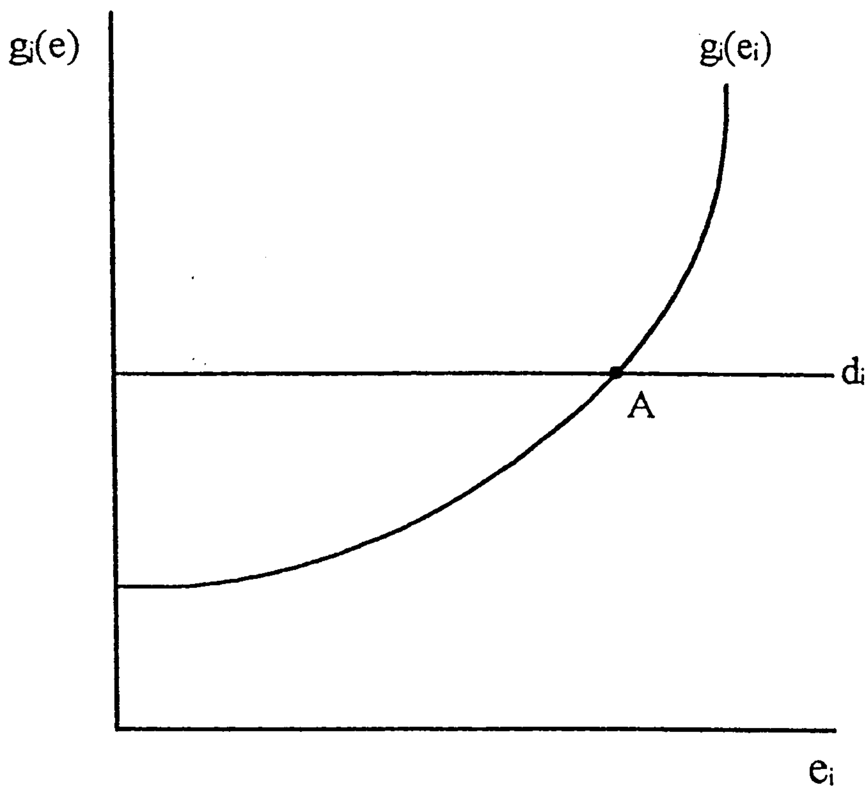


Figure 1.4

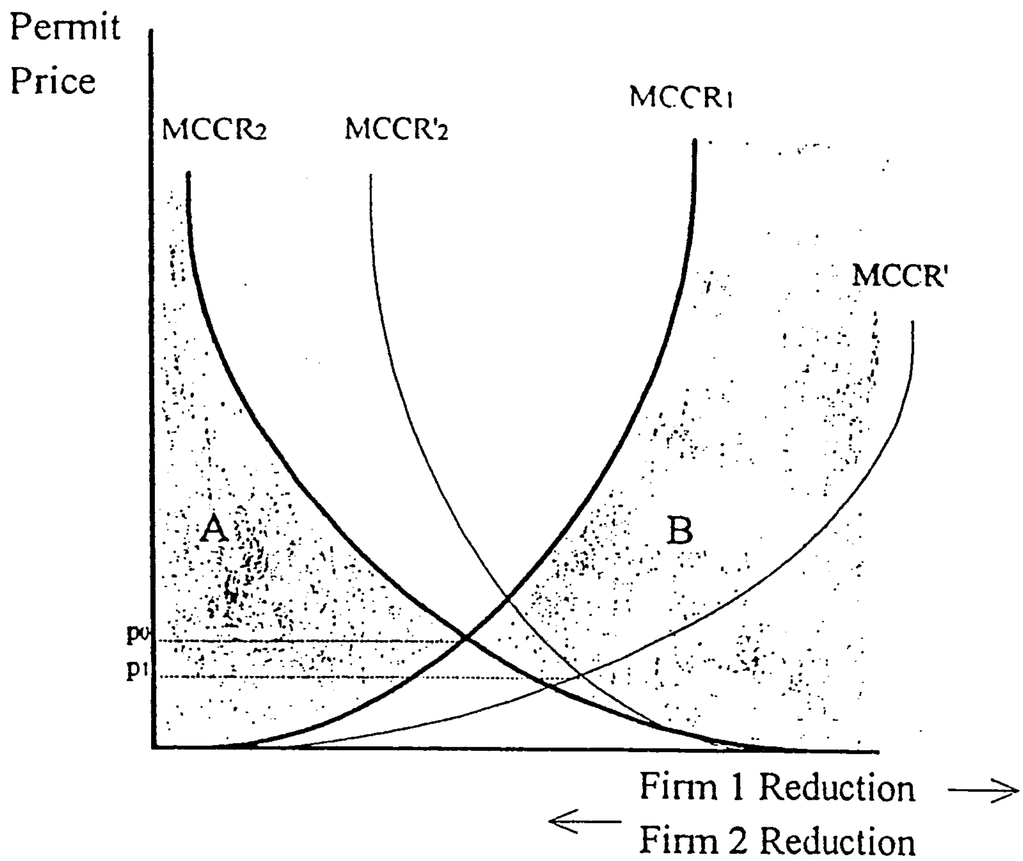

Permit
Price
MCCR2
MCCR'2
MCCR1
MCCR'
A
B
p0
p1
Firm 1 Reduction
Firm 2 Reduction

Figure 1.5

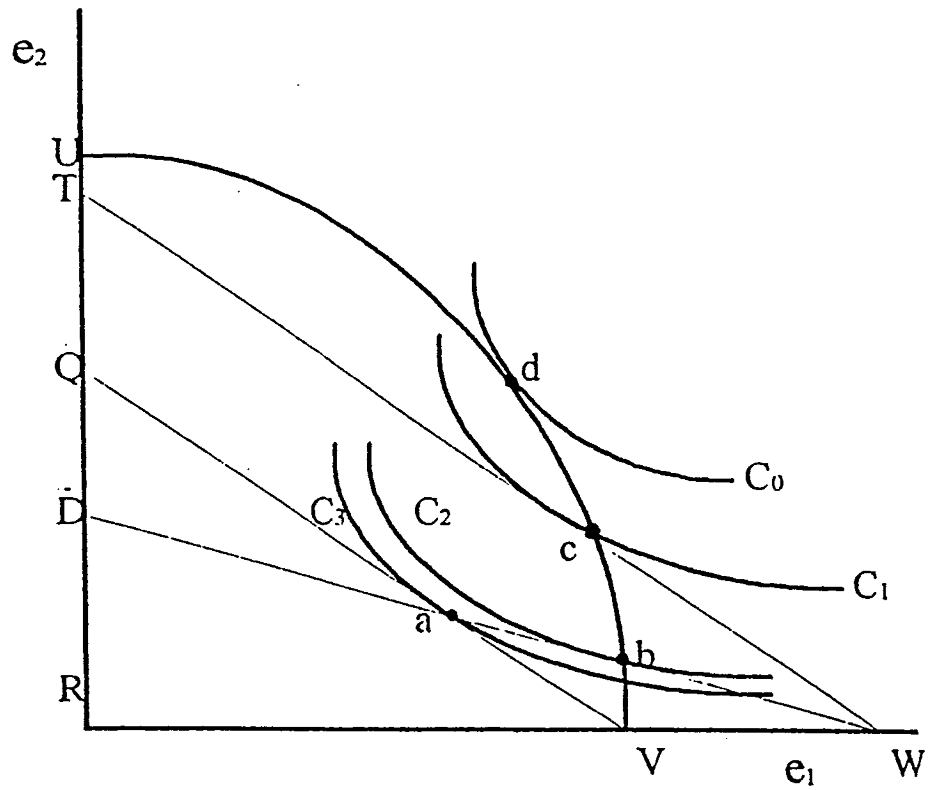


Figure 1.6

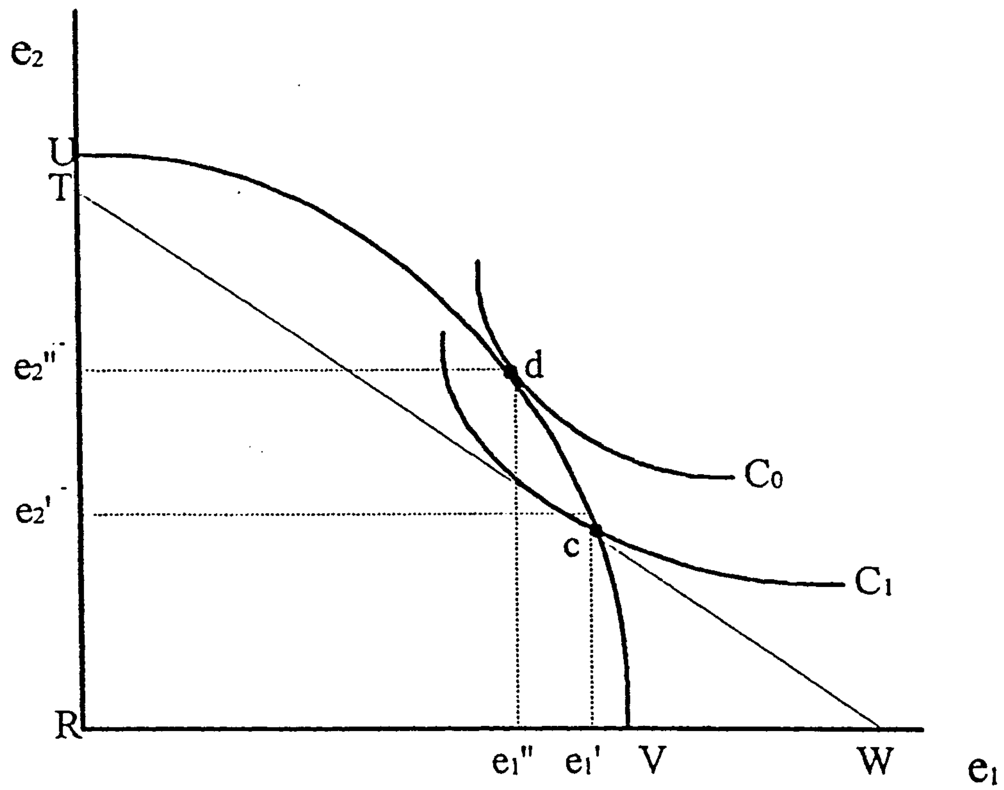


Figure 1.7

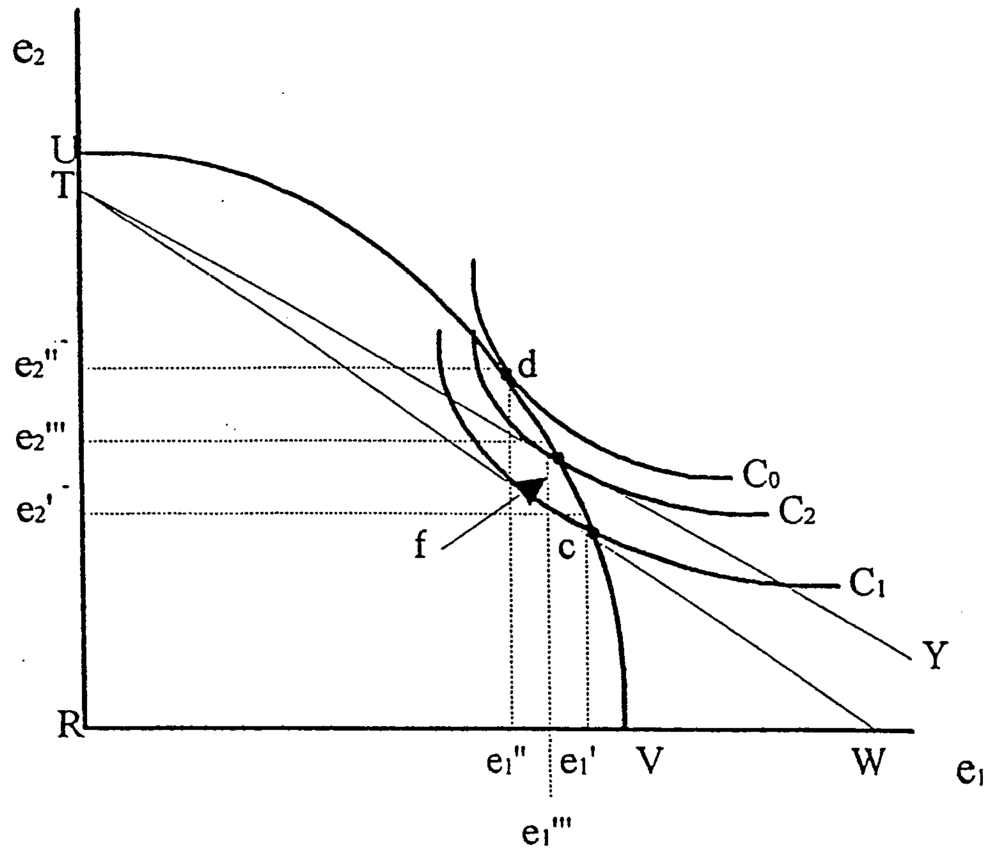
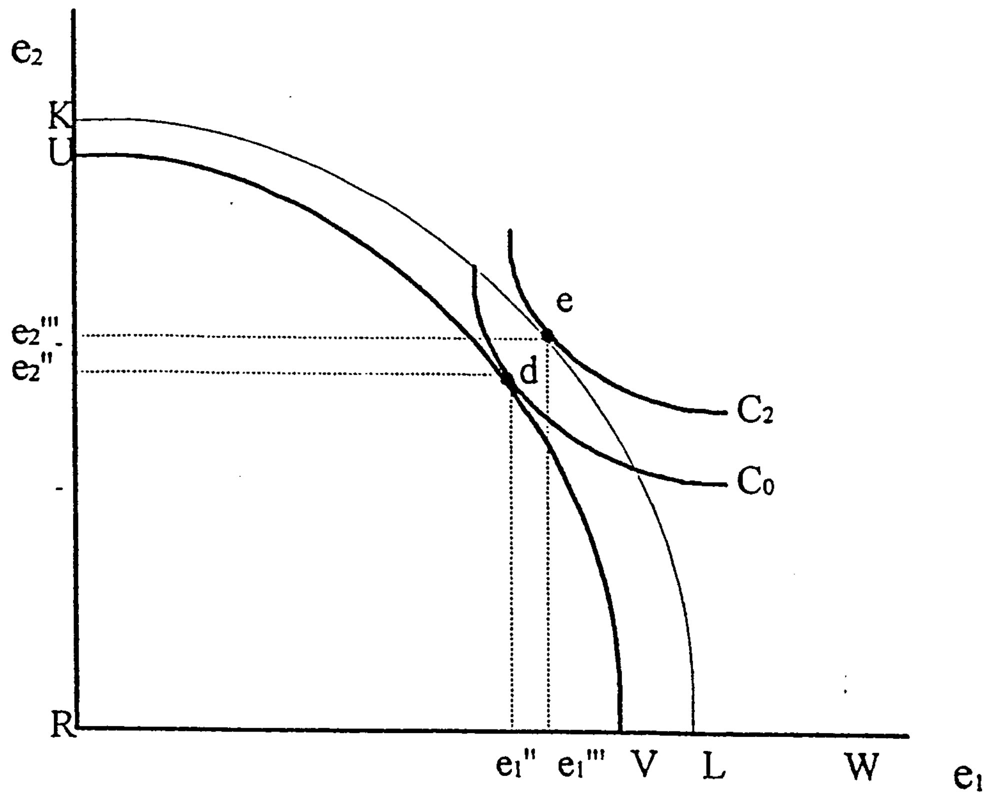


Figure 1.8



Chapter 2

The Origins of Interstate Compacts: Bargaining in the Presence of Interstate Externalities

2.1. Introduction[1]

Environmental regulation in the U.S. has undergone numerous changes in the twentieth century. The current regime, consisting of a centralized federal authority and numerous nationwide regulations, began in the late sixties and early seventies. But environmental regulation by the states dates back at least to the turn of the century, and court decisions involving pollution may be found well before 1850. These earlier forms of regulation were handled mainly through the states, with federal intervention coming much later. Although state environmental regulation has been dismissed for its ineffectiveness at cleaning up pollution (Stewart, 1977; Cumberland, 1979, 1981), recent work by economic and legal scholars has suggested that the state approach has numerable merits and is worthy of reconsideration (Oates and Schwab, 1988; Butler and Macey, 1996; Libecap, 1996; Haddock, 1997). This chapter focuses on a particular pollution problem, interstate water pollution, and how states dealt with the problem in the absence of the federal government. I find that states were responsive to concerns about interstate water pollution, adapting and changing their institutions in order to provide water quality more effectively and less costly.

Very little is understood about how and why early forms of environmental regulation changed. For example, use of the common law in water pollution cases in the late 1800s and early 1900s eventually gave way to state statutes. Interstate water pollution that was originally addressed in the courts, was later addressed through interstate water pollution control agreements and compacts. The hypothesis of the chapter is that the observed institutional change was a response to the high cost of alternative regulatory responses. In this regard, the chapter views institutional change in pollution regulation as an adaptive process to changing costs. This approach is similar to that found in Demsetz (1967), Davis and North (1971), Libecap (1989), Ostrom (1990), Williamson (1996), and Barzel (1997). The courts were effective at addressing pollution problems where liability was clear and causality was proved. In single polluter cases, there was little doubt where the damaging pollution originated, and cases were normally decided in favor of the downstream water user. As industrial and population growth continued pollution problems became more complex. Single polluters became the exception, replaced by numerous upstream polluters, with both industry and municipalities discharging wastes into rivers and streams. Under these conditions, it was difficult for downstream water users to identify individual polluters. This condition made use of the courts more expensive—prohibitively so in many cases. In dealing with water pollution within a state (intrastate pollution) state statutes and public health boards gave downstream water users an alternative to the courts. But these same regulations and agencies had little power when pollution crossed state boundaries. In these cases, the federal courts were the only available option until the emergence of interstate compacts.

This chapter examines the development of an interstate compact to control water pollution in the Ohio Valley, ORSANCO. The analysis shows that the Ohio Valley compact protected water quality rights through a system of water quality standards and pollution abatement orders. This lowered the cost of enforcing legal rights to water quality by lowering proof burdens relative to those required by federal courts.

In the Ohio Valley in the early 1900s interstate water pollution was becoming an increasing problem. Municipalities complained about water quality, but little action was taken by the states (Waring, 1928). Figure 2.1 illustrates the Ohio Valley, and it shows the intricate nature of interstate pollution. Numerous tributaries crossed state lines, making it nearly impossible to conclude where any particular discharge originated. Where pollution was from a single source, the courts were effective in reaffirming the property rights of downstream water users impacted by the pollution. Compensating side payments to downstream water users were common.[2] In these cases, reliance on private solutions to externalities as argued by Buchanan (1972) makes sense. But where there were multiple sources of pollution, private bargaining and use of the courts were less successful in reaffirming property rights to clean water. In these circumstances a regulatory solution was adopted. In the case of interstate pollution, interstate water quality compacts were formed. By examining stream pollution cases, I find a systematic difference in the courts' treatment of single and multiple polluter cases. Extending this analysis to the Ohio Valley further supports the hypothesis that courts were a relatively ineffective (and expensive) option for defining water quality rights in the presence of multiple polluters.

Interestingly, there was nothing to prevent downstream water users from acknowledging the advantageous position of their upstream neighbors and bargaining *as if* the upstream state had the right to pollute. Indeed, it appears that this is eventually what happened in the Ohio Valley. In interstate bargaining to control pollution, downstream states agreed to various terms that mainly benefited upstream states in order to reach agreements on interstate pollution limits. In this regard, the analysis departs from the oft held belief that the threat of federal intervention was the key to successful compact negotiations (see, for example, Cleary, 1967 and Hines, 1967). That bargaining was between states and not individuals was due to the larger numbers of parties involved and the associated free riding problem (Olson, 1971; Baumol and Oates, 1988; Sandler, 1992). The chapter argues that interstate compacts evolved in the presence of these bargaining difficulties to address difficult pollution problems. The observed institutional changes in state environmental regulation is consistent with predictions that efforts to define property rights will increase as the value of the asset rises.

2.2. Institutional Remedies to Water Pollution

The complexity of water pollution problems increased throughout the 1800s and early 1900s. Along with this complexity came an increased reliance on the courts to protect water quality rights. This is reflected in Table 2.1, illustrating stream pollution decisions in the U.S. and the Ohio Valley in the late nineteenth and early twentieth centuries.

Table 2.1: Stream Pollution Cases

Period	Ohio Valley States	United States
Before 1855	2	14
1855-1869	5	29
1870-1884	6	62
1885-1899	12	78
1900-1915	19	88
Total	44	271

Source: Compiled by the author from Montgomery and Phelps (1917). See text for details.

The cases were compiled from a comprehensive study on stream pollution by the U.S. Public Health Service conducted throughout the early 1900s (Montgomery and Phelps, 1917). The study identified judicial decisions in state and federal court cases relating to stream pollution. Over sixty percent of the water pollution cases cited in the study were decided in the last thirty years, 1885-1915. The increase in the Ohio Valley was even greater, with over seventy percent of cases in those states decided between 1885 and 1915. But the courts were not the only outlet for downstream water users attempting to protect their rights to clean water. In many areas, states forced polluters to control wastes through public health orders and local ordinances. Indeed, every state in the Ohio Valley had statutes allowing boards of health to issue orders and make regulations to control sewage wastes.[3] Regional agreements were a third method available to water users trying to protect water quality. And while these agreements were most often used when multiple states were involved, they were not limited to the interstate problem.

Courts, statutes, and pollution agreements each had associated costs depending upon the complexity of the pollution problem. Identification issues, free rider problems, and bargaining problems dictated the response of each institution to a particular pollution problem. The following section describes the hypothesized relationship between each institution and a given type of pollution problem.

2.2.1 Theoretical Framework: Costs of Alternative Institutions

In all stream pollution cases, the legal rights of the downstream parties were specified by the courts under the rule of reasonable use.[4] Reasonable use states, "A riparian owner may make reasonable use of his water for either natural or artificial wants. However, he may not so use his rights so as to affect the quantity or quality of water available to a lower riparian owner" (Black, 1991). But even with a well specified legal right, the actual quality of the water may be difficult to protect if the legal right is not enforced. This chapter views property rights to water quality as the right to actually consume a given quality of water.[5]

2.2.1.1 Single Polluter Cases

The likelihood of observing any of the three water pollution remedies described above depends upon the relative costs for a given pollution problem. Single polluter problems were easily handled in court. Here, the downstream water user only needed to demonstrate that damages were the result of "unreasonable use" of stream water by an upstream water user. State laws were available to the downstream water user but at a higher cost. Statutes and ordinances required passage by state legislatures, and it was not in the interest of any single downstream water user to gather support for the passage of a state law—especially when the courts were a viable option. Bargaining solutions, the third option, could also be expected in single polluter cases. Property rights to water quality were well defined by the courts, and bargaining costs were low due to the small number of bargaining parties. These conditions are suitable for successful private bargaining (Coase, 1960; Buchanan, 1972).

2.2.1.2 Multiple Polluter Cases: Intrastate

One of the hypotheses of this chapter is that court decisions in single polluter cases were significantly different from decisions in multiple polluter cases. In particular, downstream water users often had to prove damages incurred by individual upstream polluters when several were present. Not surprisingly, the costs associated with this burden of proof could be substantial. The hypothesis is examined in detail later in the chapter, but one implication is that downstream water users would seek other, less expensive methods to protect water quality. State legislatures were one alternative. For example, Ohio gave its state board of health the authority to issue orders for improvements of waterworks (Section 1255, Ohio General Code, 1912):

> When the State board of health finds, upon investigation, that any water or sewage purification works, … is not producing an effluent as pure as might reasonably be obtained from such plant, … , the board shall issue an order to the officer, board, or department of a city or village, or the corporation or person … , to secure an effluent as might be reasonably expected.

State laws reduced the evidentiary requirement needed to force pollution abatement. In the Ohio statute, there was no need to identify individual polluters; instead, the board of health only needed to show that the polluter was "not producing an effluent as pure as might reasonably be obtained." Hence, the cost of supporting property rights to clean water was lowered in relation to the courts. This is not to say that the cost of statutes and public health ordinances was inexpensive. The cost of passing these laws could still be substantial because it protected the rights of one constituency at the expense of another.[6] Subsequently, the battle for water quality wound up in state legislatures rather than the courtroom.

Pollution agreements were far less common than statutes and ordinances where intrastate pollution was involved. Property rights to water quality were not well defined due to the unreliability of the courts in multiple polluter cases. In addition, individual downstream water users had little incentive to pursue agreements for the collective good of all downstream water users. These incentives belonged to politicians in downstream regions, and they were more accustomed to pursuing their constituency's demands as lawmakers rather than mediators.[7]

2.2.1.3 Multiple Polluter Cases: Interstate

Interstate pollution is the focus of this chapter. It was the most difficult water pollution problem because it contained all the complexities of intrastate pollution, and it introduced multiple jurisdictions. The following letter, written by an Ohio county health officer, gives an accurate depiction of interstate pollution in the early 1900s (cited in Cleary, 1967, p. 20):

> Who should take what action against a hog farmer in my county who finds it most convenient to disposed of his diseased, dead animals by throwing them into the Ohio River? Although the farmer lives in the State of Ohio he is outside my jurisdiction when he dumps things into the river because the river belongs to the Commonwealth of Kentucky. While nobody in Kentucky has as yet complained about the hogs floating around, a lot of squawks could come from a municipality downstream in Indiana if these dead animals ever get into a waterworks intake.

Interstate pollution was dealt with much later than other types of pollution such as intrastate pollution. The first interstate agreements in the Ohio Valley were in the 1920s, decades after the first state water pollution ordinances. One reason for this was the cost of attempting to establish water quality rights. All three remedies were more costly in dealing with interstate pollution. Interstate pollution encompassed larger regions as well as numerous jurisdiction leading to more complex pollution problems. Hence, downstream users did not attempt to protect their rights until the value to doing so increased accordingly. This often led to significant deterioration of water quality. For example, by 1913 the Ohio River was referred to by some as an "open sewer" (p. 21, Cleary, 1967). But industrial growth was accompanied by higher incomes and larger populations, which led to higher valued uses of streams. As a result, water users sought more complete delineation of their property rights.

State laws did not apply to interstate regions, leaving public health boards helpless against interstate pollution. Ohio attempted to influence other states in 1908 with its "Bense Act."[8] This law stated that no municipality on the Ohio River would be required to install sewage treatment facilities until all upstream municipalities had done the same. The threat had no credibility and was ignored by all other states upstream and adjacent to Ohio. The courts were a second option, but downstream water users found themselves facing the same problems that plagued them in intrastate pollution cases.

In response to the high costs and ineffectiveness of the available institutions, the first interstate agreements and compacts arose. The compact lowered the burden of proof necessary to force pollution abatement. It gave compact commissions powers similar to those bestowed upon public health boards by state legislatures. In so doing, the water quality rights of downstream water users were secured. Like other institutions, the compacts were not without costs. Bargaining costs were high due to large numbers of individuals and associated free rider problems. No individual municipality had an incentive to address the problem of interstate pollution. Take for example a statement by Dr. A.T. McCormack, the state health commissioner of Kentucky in 1913 (p. 21, Cleary 1967):

> The purification of (the Ohio River) has been kept safe for cities like Cincinnati and Louisville only at an enormously increasing expenditure … Now, this problem (interstate water pollution) cannot be solved by Cincinnati or Louisville. *It would not make any difference what was done by one community.* [italics are mine]

To address free rider problems and bargaining costs, bargaining was conducted by state representatives. In addition, the compacts had to overcome reluctance by upstream states to join. Despite these problems, however, the compact emerged as the primary method for dealing with interstate pollution early in the 1900s.

Table 2.2: Costs of Using Alternative Institutions to address Water Pollution

Institution	Single Polluter	Multiple Polluter (Intrastate)	Multiple Polluter (Interstate)
Courts	Low	High	High
State Statutes/Boards of Health/Ordinances	High	Low	High
Agreements (Interstate Compacts or otherwise)	Low	High	Low

Table 2.2 summarizes the predictions relating institution costs to the pollution problems discussed in this section. The observed institution is predicted to be the one with the lowest associated costs. In providing evidence to support these hypothetical relationships, I examined numerous stream pollution cases as well as interstate pollution in the Ohio Valley. The cost of using the courts to address pollution problems is discussed next.

2.2.2 The Cost of the Courts: Single and Multiple Polluter Decisions

The cost of using the courts to enforce legal rights to clean water came mainly from the cost of supplying enough evidence to meet burdens of proof. The requirement in pollution cases was established by single polluter cases where downstream water users had to prove unreasonable use of stream water by upstream water users. This requirement was carried over to multiple polluter cases where courts were unwilling to treat evidentiary standards any differently than they did in single polluter cases. This led to varying outcomes when comparing single polluter and multiple polluter cases. To illustrate the difference, I examined over thirty stream pollution cases. Cases were classified as to whether there was a single polluter or multiple polluters involved. An exception to this rule was where more than one polluter was present, but it was easy to separate damages from their pollution (see *Georgia* v. *Tennessee Copper Co.*, 206 U.S. 230 (1907), below).[9] Below I report a subset of these cases that typify the courts' decisions.[10] I find that downstream water users normally had difficulties identifying upstream polluters where many were present. This resulted in costly litigation and poor specificity of property rights.

2.2.2.1 Single Polluter Cases

Most single polluter cases consisted of nuisance and trespass claims to which judges applied principles and precedents drawn from cases often unrelated to pollution (Meiners and Yandle, 1993 and Yandle, 1997). *George Morgan* v. *City of Danbury* 67, Conn. 484 (1896), is representative of many single polluter cases.[11] The plaintiff owned a cider mill downstream from the defendant city on the Still River. The City of Danbury, with a population of approximately 20,000, discharged raw sewage into the river. The city attempted to abate this waste after complaints by the plaintiff, by installing a sewage system costing $139,000.[12] The system was unsuccessful at adequately reducing the sewage waste, however, and the plaintiff was forced to cease cider mill operations. An injunction sought by the plaintiff was granted by the court. The estimated cost of a sewage system capable of properly abating the raw sewage was estimated to cost between

$1.85 million and $2.3 million. For the purposes of this chapter, it is important to note that Danbury was the only upstream polluter discharging sewage wastes in large quantities. Therefore, it was easy for the plaintiff to prove causality. Danbury denied the charges but the evidence was convincing to the court:

> The nuisance thus complained of consisted, then, of discharging into a river, above the plaintiff's premises, certain substances of such a kind and in such a manner that the water came to him polluted ... the result of which would be to fill up his mill-pond with filth and sewage, and make his property valueless. These allegations were denied, but have been found true; and there is nothing inconsistent with their truth in the special finding of fact. [p. 493]

Interstate cases involving easily identifiable polluters were decided in a fashion similar to that of other single polluter cases. In *Georgia* v. *Tennessee Copper Co.*, 206 U.S. 230 (1907), two copper smelters in Tennessee were accused of damaging forests, orchards, and crops in Georgia as well as harm to its citizens. And while the case involved air pollution, the same principles were likely to apply to water pollution.[13] The case was tried in the U.S. Supreme Court after unsuccessful attempts to have it heard in Tennessee. Although two polluters were involved, neither denied that its pollution damaged the plaintiff. In addition, the evidence presented to the court left little uncertainty regarding damages:

> The proof requires but a few words. It is not denied that the defendants generate in their works near the Georgia line large quantities of sulfur dioxide which becomes sulfurous acid by its mixture with the air. ... On the evidence the pollution of the air and the magnitude of that pollution are

> not open to dispute. ... it is proper to add that we are satisfied, by a preponderance of evidence, that the sulfurous fumes cause and threaten damage ...

The court decided in favor of the plaintiff in the case, and it required that each company install pollution control devices. The case also illustrates the feasibility of private contracting when legal rights are enforced.[14] To avoid future legal action, the Tennessee Copper Company entered into an agreement with the state of Georgia "to supply a fund to compensate those injured by fumes from its works." These types of agreements were common in single polluter cases where property rights were clearly defined.[15]

2.2.2.2 Multiple Polluter Cases

The courts viewed multiple polluter cases much the same way that they did single polluter cases. Downstream water users seeking relief from damaging discharges had to prove that damages resulted from an upstream user's unreasonable use of the water. If the acts of the upstream polluters were independent, they could not normally be held jointly liable. *Witland* v. *Redbank*, 151 Ill. App. 433 (1909) is representative of many multiple polluter cases during the late 1800s and early 1900s.[16] The defendants, several oil producers on lands upstream from the plaintiff, discharged effluent into the valley of Big Creek, which flowed to the plaintiff's land. The acts of the defendants were clearly independent of each other, although their wastes were indistinguishable by the time they accumulated and subsequently harmed the plaintiff's property. The court held that, "while it is true it is difficult or impracticable to separate the injury, that is no reason why one of the defendants should be liable as a joint tort-feasor…[p. 439]." It is easy to conceive of the high costs associated with attempting to separate the damages resulting from numerous upstream polluters. To make matters worse, courts did not normally allow plaintiffs to join together in suits for damages, although plaintiff's could join together in an action for an injunction (Montgomery and Phelps, 1917). They still faced free rider incentives under these conditions, though, making joint lawsuits less likely. Indeed, these are precisely the problems that state laws sought to overcome when dealing with intrastate pollution problems.

In some instances, polluters were permitted to be joined by the courts. This was meant to provide some form of relief to downstream water users suffering damages by numerous upstream polluters. But rather than strengthening the property rights of downstream water users, these decisions often resulted in greater uncertainty. A series of cases decided in California in the late 1800s illustrates the inconsistency of court decisions in multiple polluter cases. The two cases, both involving numerous polluters, were decided in the same court with completely opposite results. In *Keyes* v. *Little York Gold Washing and Water Company*, 53 Cal. 724 (1879), the court decided that a polluter could not be held liable for the actions of others and could not, therefore, be joined with other polluters in a suit. A year later the same court held that polluters could, in fact, be held jointly liable for damages in *Hillman* v. *Newington*, 57 Cal. 56 (1880).

Court decisions in interstate cases reflected the decisions of the lower courts. Proving causality in interstate cases, however, was even more difficult. Greater numbers of polluters were involved, and the pollution usually traveled longer distances. It appears that states recognized these difficulties because only two major interstate water pollution cases existed prior to the emergence of interstate compacts. In both of these cases, scientific evidence was the focus of the courts.

The first interstate court case involving interstate water pollution was *Missouri* v. *Illinois*, 200 U.S. 96 (1906). This landmark decision established the standard for scientific evidence in multiple polluter cases. Chicago, located upstream from the complainant city, St. Louis, discharged raw sewage into a stream that eventually drained into the Mississippi River. Missouri asserted that this sewage caused numerous cases of typhoid in St. Louis. It presented expert testimony relying on scientific evidence showing that bacteria could survive a trip down the Mississippi to St. Louis. Illinois argued that the bacteria causing typhoid outbreaks in St. Louis could not travel from Chicago, and it was the cities along the Mississippi, particularly those in Missouri, that were responsible for the damages. The court sided with Illinois, stating that the decision was based on the available scientific evidence, which it concluded indicated that Chicago could not be singled out as the culprit.

Another interstate case, *New York* v. *New Jersey*, 256 U.S. 296 (1921), resulted in similar results. In this case, New York sought an injunction against the state of New Jersey to enjoin discharge of sewage into Upper New York bay. New Jersey had built a sewage system that was to collect waste from the Passaic Valley and dispose it in the

New York bay. Like the *Missouri* case, this case relied on scientific evidence. The court interpreted the evidence as follows:

> The evidence introduced (by New York), … , is much too meager and indefinite to be seriously considered as ground for an injunction, … Considering all of this evidence, and much more which we cannot detail, we must conclude that the complainants have failed to show by the convincing evidence which the law requires that the sewage which the defendants intend to discharge into Upper New York bay, … , would so corrupt the water … as to create a public nuisance.

Given the decisions in the two interstate water pollution cases that made it to the Supreme Court, it is not surprising that other states, like those in the Ohio Valley, chose not to settle disputes in court. Litigation in these cases was costly due to the evidentiary requirements. Downstream states had legal rights to clean water, but those rights were not enforced in the courts. As a result, upstream states were able to capture a large share of the resource's value. This does not mean, however, that the total value of the asset was being maximized. With poorly specified property rights to water quality, private bargaining was unlikely even where gains could be significant. Indeed, it was not until downstream states recognized the informal rights of upstream polluters that interstate compacts finally emerged. But compacts had to deal with the same issues that confronted the courts such as multiple pollution sources. In addition, interstate compacts had to overcome free rider problems and bargaining difficulties between upstream and downstream states.

2.3. Interstate Water Pollution Control Agreements and Compacts

When enforcing legal rights is costly and incomplete, individuals are likely to undertake property rights delineation themselves (Barzel, 1997). In the case of interstate water pollution in the early 1900s, downstream water users became increasingly dismayed with the prevailing institution used to protect water quality rights—the courts. Resort to the federal government was not a realistic option at the time because federal involvement in pollution matters was very minor. In response, downstream states engaged neighboring states into various agreements and compacts designed to provide higher quality water. Some of these agreements were very informal. For instance, the Ohio River Interstate Stream Conservation Agreement was an unofficial agreement between the state health departments of Ohio, Pennsylvania, and West Virginia. Other agreements were legitimized by reciprocal legislation between the states involved.[17] The most popular form of agreement, however, was the interstate compact.[18]

Interstate compacts are legally binding agreements between states that allow the states involved to act in concert. Before a compact becomes binding, it must be approved by each state involved; it also requires Congressional Consent.[19] The interstate compact was historically used to settle interstate boundary disputes, but in the early 1900s its use was extended to various other problems between two or more states. In 1921, for example, the Port Authority of New York was used to address a dispute between New York and New Jersey over the development of the Port of New York. Another compact, the Colorado River Compact, was used to settle water quantity disputes in numerous western states in 1927. Between 1927 and 1947, there were no fewer than thirty-seven interstate compacts proposed or operating in the United States.[20]

The Tri-State Pollution Compact was the first compact to address interstate water pollution. The compact was ratified by New York and New Jersey in 1935, and it received Congressional approval the same year. The compact addressed the same issues that the courts failed to resolve in *New York* v. *New Jersey*, 256 U.S. 296 (1921). At the same time, pollution problems were worsening in many eastern river basins, and by 1940, four interstate water pollution control compacts involving fifteen different states had received Congressional approval.[21] How these compacts and other forms of agreement worked to lower the cost of reaffirming property rights is the subject of the next section.

2.3.1 Establishing Water Quality Rights: Interstate Agreements and Compacts as an Alternative Remedy

2.3.1.1. Phenol and the Ohio Valley

The first interstate water pollution control agreement in the Ohio Valley addressed phenol pollution. Phenol is a byproduct from the production of coke, a raw material used to make steel. Coke producing facilities require coal, which was abundant throughout the Ohio Valley in the early 1900s. Numerous coke plants were located in Pennsylvania, Ohio, and West Virginia with many of these plants located near state boundaries. For example, several producers were located in Youngstown, Ohio, which is less than twenty miles from Pennsylvania's border. Other producers were located in Monongalia County, West Virginia, near the Pennsylvania-West Virginia border; one producer was located in Beaver County, near the Pennsylvania-Ohio border; and many other producers were located along the Ohio River on the Ohio-West Virginia border (see Figure 2.2). Phenol pollution was a particularly complex interstate pollution problem because it was capable of traveling large distances, making it difficult to identify the polluter discharging the waste (see Appendix C for details on phenol in the Ohio Valley).[22] In addition, water treatment made matters worse by imparting a medicinal taste to the treated water.

From 1912 to 1925, several complaints related to phenol pollution were registered throughout the upper Ohio Valley.[23] Indeed, phenol pollution originating in other states affected the water quality of several municipalities in Pennsylvania, Ohio, West Virginia, and Kentucky making unilateral action to correct the problem impossible. Some of the complaints were addressed in court, but many others were neglected. State boards of health could issue abatement orders to facilities located within state boundaries, but they were helpless against pollution originating in upstream states. And judging by the decisions in *Missouri* v. *Illinois*, 200 U.S. 96 (1906) and *New York* v. *New Jersey*, 256 U.S. 296 (1921), the courts were likely to be an expensive and ineffective remedy. The complaints and the subsequent actions taken are listed in Table 2.3 along with other relevant characteristics.

Table 2.3: Actions Taken on Phenol Complaints in the Ohio Valley, 1912-1925

Date of Complaint	Origin of Complaint	Action Taken	Number of Upstream Polluters	Median Distance between Complainant and Polluter(s)	Number of States Involved
1912	New Castle, Pa.	Settlement and Abatement Order	1	15 miles	1
1916	Johnstown, Pa.	Abatement Order	1	Under 10 miles	1
1917	Cincinnati, Oh.	None	3	367 miles	3
1918	McKeesport, Pa	Abatement Order	1	Under 10 miles	1
1918, 1919[a]	Louisville, Ky.	None	5[b]	292 miles	3[c]
1919	Youngstown, Oh.	None	4	10 miles	1
1920	Morgantown, W. Va.	None[d]	1	20 miles	1
1925	Cincinnati, Oh./ Covington, Ky.	None	7	367 miles	4

Source: Compiled by the author from Waring (1928), ORSANCO Historical Archives (Vol. I), and the American Auto Association Road Map (1995).
[a] Cincinnati also registered numerous complaints during this time period.
[b] Two additional plants were located in Pennsylvania, but they had coke-quenching systems installed.
[c] This number does not include Pennsylvania.
[d] There was an attempt to abate the pollution, but it was unsuccessful. See text for more detail.

From Table 2.3, the single versus multiple polluter problem appears to have been a significant barrier in resolving phenol pollution complaints. This is not surprising given the complex nature of the pollutant. In each of the complaints where multiple polluters were present, no action was taken in court or elsewhere. But where only a single upstream polluter was involved, action was taken in each case, with three of these actions resulting in successful abatement. The only exception was in Morgantown, West Virginia where an order was issued, but the abatement techniques used were unsuccessful. The Domestic Coke Co., the accused polluter, attempted to control its phenol discharges by "lagooning," a cheap process for removing phenol, but the attempts were unsuccessful, and the project was discontinued. That West Virginia did not take further measures to force abatement may be a reflection of its relatively weaker stance on pollution than other states in the region.

By the early 1920s, health representatives in Cincinnati decided that the problem had worsened to the point where it proposed federal legislation. This action was a reflection of public discontent with the available remedies for addressing the interstate problem. Waring (1928) describes the attitude of the public to interstate pollution as follows [p. 12]:

> If legal powers are not deemed sufficient, make them so; or obtain injunctions to restrain the industrial operations causing the objectionable contamination of the water supplies. Failure to act thus and immediately seems to inspire in the average mind a contempt for the local or state official. Too often the public cannot understand why the problem cannot easily be solved and solved permanently by such simple expedients as passing new laws or local ordinances or asking the Federal Government to enact and enforce prohibitory legislation.

The approach recommended by Cincinnati was [p. 12, Waring, 1928] "openly contested by the health authorities (of Ohio and Kentucky) as not being the adequate or sensible way of eliminating phenol pollution or any other problem." Finally, in 1924, the health officers of Ohio, Pennsylvania, and West Virginia met and agreed upon a solution. Each state would issue abatement orders to polluting facilities within its boundaries. This would obviate the need to settle disputes in court, and it could be done entirely with powers already available to each state. In addition, cheating on the agreement was easily recognized in the quality of incoming water supplies.

The cost of using the courts to resolve interstate water pollution disputes is indicated by the use of alternative pollution control strategies. In Ohio, for example, the cost of controlling phenol pollution at its largest coke facility was over $2 million (Waring, 1928). The benefits resulting from emission controls on Ohio's industries were directly captured by downstream municipalities located in Pennsylvania.[24] Ohio benefited, though, by reciprocal action in West Virginia and Pennsylvania. That the courts were avoided in dealing with interstate phenol pollution suggests that they were a more costly and less effective solution.[25]

2.3.1.2 Sewage and the Ohio Valley

Interstate sewage pollution was the focus of most state regulatory efforts in the 1900s. Industrial pollutants, like phenol, were a problem, but they were secondary to sewage discharges. Sewage was normally discharged directly into rivers and streams without any treatment. In the Ohio Valley, only two municipalities had installed sewage treatment plants by the mid 1930s. But like other interstate water pollution problems, downstream states had few available options to protect their rights to water quality. As a result, the first interstate water pollution control compact in the Ohio Valley, the Ohio River Valley Sanitation Compact (ORSANCO), was given Congressional approval in 1936 (the two previous Ohio Valley agreements were informal and had no legal status).

Having to overcome numerous bargaining difficulties (the subject of *Section 3.2*), ORSANCO was not ratified until 1948.

ORSANCO was designed to force upstream municipalities to install treatment facilities without having to identify individual upstream polluters as the Supreme Court required in *Missouri* v. *Illinois*, 200 U.S. 96 (1906). To lower evidentiary requirements, and the cost of identifying individual polluters, ORSANCO established (nonuniform) water quality standards for the Ohio River and its interstate tributaries.[26] The agency was also given the power to enforce these standards with abatement orders (pgs.293-294, Cleary, 1967):

> Article VI (water quality standards): All sewage from municipalities or other political subdivisions, … , permitted to flow into these portions of the Ohio River and its tributary waters which form boundaries between, or are contiguous to, two or more signatory States, or which flow from one signatory State into another signatory State, shall be so treated, within a time reasonable for the construction of the necessary works, as to provide for substantially complete removal of settleable solids, …
>
> Article IX (enforcement powers): The Commission may from time to time, after investigation and after a hearing, issue an order or orders upon any municipality, corporation, person, or other entity discharging sewage or industrial waste into the Ohio River …

ORSANCO was given powers very similar to those given to state boards of health by their state legislatures. Cheating on the agreement was nearly impossible because noncompliance was observable—either a municipality installed treatment facilities as ordered, or it did not. The first time a municipality challenged an ORSANCO order was in 1957. Gallipolis, a city located on the Upper Ohio River, ignored a sewage abatement order issued by ORSANCO. The city soon changed its position when [p. 118, Cleary, 1967] "Gallipolis was formally notified of the intention of the eight states to bring suit for compliance." There was no need to demonstrate how much damage was caused by Gallipolis' sewage discharges as the courts required. And unlike the interstate cases tried in federal courts, ORSANCO was very effective at controlling interstate water pollution. In 1948, when ORSANCO began operations, less than one percent of the sewage in the Ohio Valley received treatment. By 1955, over forty-five percent of the Ohio Valley's population received adequate treatment and an additional thirty-six percent had plants under construction (Seventh Annual Report, 1955).

2.3.2 Bargaining in the Presence of Interstate Externalities

An interesting feature of interstate compacts is the wide ranging outcomes of compact negotiations. For instance, in the Ohio Valley there were three agreements addressing interstate water pollution: the phenol agreement and two sewage agreements. Of these, two were considered successful (the Ohio River Stream Conservation Agreement on *phenol* pollution and ORSANCO) and one was not (the Ohio River Stream Conservation Agreement on *sewage* pollution). Of the successful agreements in the Ohio Valley, one was negotiated quickly while the other took nearly twelve years to negotiate.

In explaining these differing outcomes, I examine how property rights structures changed under the interstate agreements.

Libecap (1989) stresses that as new property rights regimes are proposed or as they evolve, the affected parties attempt to alter these new arrangements to maximize their share of the aggregate returns. This includes prolonging shifts in property rights that would reduce a party's share of returns. Under these circumstances, these parties will attempt to cling to the status quo. In the case of water pollution in the Ohio Valley, some of these features are curiously missing. ORSANCO drastically altered existing property rights arrangements by enhancing the rights of downstream states. Yet the primary upstream state, Pennsylvania, eventually joined the compact even though it imposed large costs on them. The new property rights structure that emerged under the interstate compact forced Pennsylvania to clean up sewage discharges that mainly benefited the downstream states. Pennsylvania's action may have been a rational response to threats by the downstream states to engage the federal government in clean-up activities. An alternative explanation is that the downstream states compensated Pennsylvania through side payments and other concessions.

2.3.2.1 A Model of Interstate Water Pollution

The conflicts over interstate water pollution in the Ohio Valley involved many different dimensions, but much of the observed behavior may be explained with a simple model that considers geographical differences and differences in abatement technologies.

Property rights and political bargaining considerations are important in that they shape the resulting agreements, but the main purpose of the agreements was to provide water quality to highly polluted areas. Therefore, compacts are modeled to reflect their impact on water quality. Ströbele (1991) models international pollution treaties in a similar fashion, but emphasizes the effect of monitoring costs on outcomes. Cheating on sewage agreements in the Ohio Valley was nearly impossible because noncompliance was observable. Indeed, the first noncompliance case under ORSANCO did not occur until the compact had been operating for nine years.

The main feature of the interstate pollution model involves the cost of providing water quality. It was prohibitively costly for downstream municipalities to treat the high levels of discharges experienced in the Ohio Valley early in the century (Waring, 1928). To take account of this difference in costs, the cost functions differed according to where the discharge originated. Treatment at the source (upstream) included municipal waste treatment facilities and chemical treatment of outgoing water. Hence, much of the solid waste could be removed from the waste water before it was discharged, obviating the need for expensive treatment facilities. Downstream treatment was more costly because chemical treatment was the only available method to improve water quality. Therefore, chemical treatment was limited by the available technology. The cost of treating water upstream is $c(y,z)$ where y is the quality of water prior to treatment and z is the water quality after treatment. A higher y signifies the presence of more pollutants and, therefore, represents lower water quality. The same is true for z. Treatment downstream is more expensive for any y and z. The downstream cost is denoted by $k(y,z)$. The restrictions on the cost functions are noted below.

(1.0) $c(y,z),\ c_y > 0,\ c_z < 0,\ c(y,y) = 0$

(1.1) $k(y,z),\ k_y > 0,\ k_z < 0,\ k(y,y) = 0$

(1.2) $c(y,z) < k(y,z)$ for any (y,z)

The final conditions of (1.0) and (1.1) are assumptions that returning water of its incoming quality is costless (i.e., there is no treatment involved). Notice that the higher the level of incoming y, the higher the cost of returning water quality z.

The benefits of consuming water quality q is $b(q)$. Water quality is measured by units of pollutants present. For example, q could represent coliform organisms, a bacteria present in solid wastes. Here, river water would be acceptable to swim in if there were less than 1000 coliform organisms per 100 milliliters during a month. Therefore, q is a water quality measurement much like those used to monitor water quality early in the twentieth century. As defined, a higher q is less desirable than a lower q. It follows that benefits are decreasing with higher levels of q (i.e., $b(q_1) < b(q_2)$ for $q_1 > q_2$). Because incoming water quality is dependent upon polluting activities upstream, the model must account for the intensity of upstream water pollution. Interstate compacts primarily addressed municipal sewage. To proxy the intensity of upstream municipal sewage discharges, I use a simple population measure n. In the model, $p(n)$ denotes the amount of water pollution resulting from discharges by municipalities with population n (with

$p(n_1) > p(n_2)$ for $n_1 > n_2$). Higher levels of $p(n)$ represent the presence of more units of a given pollutant. Summing up, $c(p(n),q)$ measures the costs of treating incoming water quality $p(n)$ to outgoing quality q.

Case 1: Homogeneous States

With the above model basics, behavior in interstate compacts may be characterized fairly easily. Consider first a completely symmetric case where two adjacent states have two interstate rivers flowing through them. The first river runs from east to west and the second river runs west to east. Given this unique geography, interstate water pollution flows in both directions, and neither state is truly upstream. Indeed, both states suffer equally from interstate pollution assuming complete symmetry (i.e., identical populations, industry, etc.). Without a compact, the benefits to state A are as follows:

(1.3) $b(q_A) - k(p(n_B), q_A)$

Replacing the As with Bs gives the benefits for state B. State A receives benefits, $b(q_A)$ where q_A is the water quality that yields the largest value for (1.3). Without a compact, A must clean B's pollution, $p(n_B)$, but forgoes cleaning its own pollution, $p(n_A)$. This necessitates the use of more costly water treatment methods, $k(y,z)$.

In the model, states are assumed to maximize the total net benefits. Correspondingly, standards are set to satisfy:

(1.4) $\text{argmax}_{q_A, q_B} \; b(q_A) + b(q_B) - c(p(n_A), q_B) - c(p(n_B), q_A)$

Let the resulting water quality levels from (1.4) be denoted q_A^* and q_B^*. Then state A's benefits from joining the compact are:

(1.5) $b(q_A^*) - c(p(n_A), q_B^*)$

Again, replacing As with Bs yields net benefits to state B. Given the symmetry of the two states (i.e., perfect homogeneity in terms of geography), it is easy to show that the compact always yields higher payoffs. This is demonstrated below for state A, but the derivation is identical for B.

(1.6) $b(q_A^*) - c(p(n_A), q_B^*) \;=\; b(q_A^*) - c(p(n_A), q_A^*)$

(1.7) $b(q_A^*) - c(p(n_A), q_A^*) \; \geq b(q_A) - c(p(n_A), q_A)$ for all q_A

(1.6) follows from the symmetry of the water quality standards, $q_A^* = q_B^*$ and (1.7) follows from the optimality of q_A^*. Let $\hat{q}_A$ be the water quality level that maximizes (1.3) above. Then,

(1.8) $b(q_A) - k(p(n_B), q_A) \;=\; b(q_A) - k(p(n_A), q_A)$ for all q_A

(1.9) $b(\hat{q}_A) - k(p(n_B), \hat{q}_A) \;\geq\; b(q_A) - k(p(n_B), q_A)$ for all q_A

(1.8) follows from the symmetry of the states. With identical discharges emitted from each state, $p(n_A) = p(n_B)$. (1.9) follows from the optimality of $\hat{q}_A$. Given the relationship between the cost functions $c(y,z)$ and $k(y,z)$, we may write:

(2.0) $b(\hat{q}_A) - c(p(n_A), \hat{q}_A) > b(\hat{q}_A) - k(p(n_A), \hat{q}_A)$

(1.7) and (2.0) yield:

(2.1) $b(q_A{}^*) - c(p(n_A), q_A{}^*) > b(\hat{q}_A) - k(p(n_A), \hat{q}_A)$

Finally, (1.6), (1.7), and (2.1) give:

(2.2) $b(q_A{}^*) - c(p(n_B), q_A{}^*) > b(\hat{q}_A) - k(p(n_B), \hat{q}_A)$

From (2.2), we conclude that the net benefits to each state from the interstate compact are greater than the net benefits from no compact. Of course, this outcome relies on the assumption of symmetry (homogeneity). As the two populations change, however, the benefits from the compact change with them. To see this, let ${}^cU^A$ be A's benefits from the compact, and let ${}^{nc}U^A$ be A's benefits from no compact. Then,

(2.3) $$\frac{d({}^cU^A - {}^{nc}U^A)}{dn_A} = -c_p p'(n_A) < 0$$

(2.4) $$\frac{d({}^{c}U^{A} - {}^{nc}U^{A})}{dn_{B}} = k_{p}p'(n_{B}) > 0$$

From (2.3), it is seen that as population in one's own state increases, holding constant the other state's population, the benefits from being in a compact decrease. Alternatively, this may be thought of as state A assuming a greater upstream presence. If B's population decreases, then by (2.4) state A's benefits from joining the compact decrease as well. (2.3) and (2.4) illustrate the importance of the interstate relationship; as states become less homogeneous, or as the upstream/downstream distinction widens, benefits from joining a compact begin to differ across states.

Case 2: Heterogeneous States

Most of the interstate agreements that took place in the early 1900s involved significant heterogeneity between states. The upstream/downstream distinction often took center stage in compact negotiations. Heterogeneity is easily incorporated into the above model by altering the *n* parameters. Complete heterogeneity, for example, might have $n_A = 0$ and $n_B > 0$. In this case, only state A suffers from B's pollution; there is a single river flowing from B into A. In many instances tributaries run through numerous states so that one purely upstream state is unlikely. This is easily built into the model by varying the population parameters. Below, I consider the case where $n_B > n_A$, but where both are positive.

Consider an interstate setting where there is one large river flowing from B into A, and one smaller tributary flowing from A into B. Assume that n_B is much larger than n_A. In this case, the water quality flowing into A, $p(n_B)$, is more polluted than the water flowing from A into B, $p(n_A)$. Consequently, it is more expensive for A to treat incoming water to a certain level of quality than it is for B:

(2.5) $k(p(n_B),q) > k(p(n_A),q)$

Also, it is more costly for B to treat its own pollution to a certain quality level than it is for A:

(2.6) $c(p(n_B),q) > c(p(n_A),q)$

Given a large enough n_B, state B will find it cheaper to treat state A's polluted water than it is for B to treat its own water quality to A's standard.

(2.7) $c(p(n_B),q_A) > k(n_A),q_B)$

When this is the case, the benefits from B's membership in the compact are less than its benefits from not joining. In other words, there is so much heterogeneity between the two states that the compact is not individually rational for at least one of the parties. Unlike the homogeneous case, A's incentives are opposite B's:

(2.8) $[{}^{c}U^{A} + {}^{c}U^{B}] > [{}^{nc}U^{A} + {}^{nc}U^{B}]$

(2.9) ${}^{c}U^{A} - {}^{nc}U^{A} > 0$

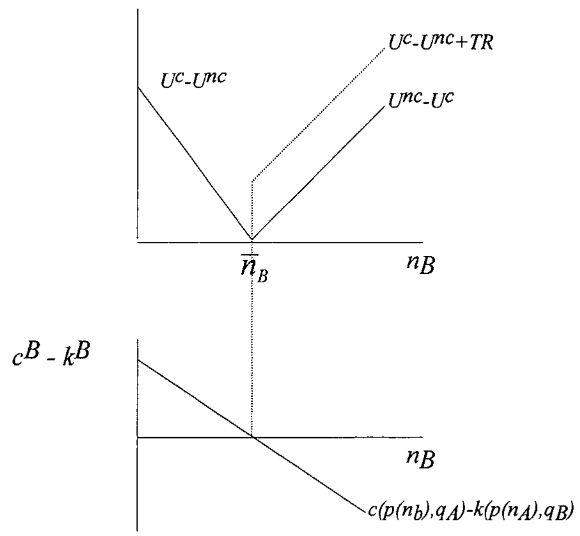
(3.0) ${}^{c}U^{B} - {}^{nc}U^{B} < 0$

The total benefits to a compact are greater than the total benefits from no compact, (3.0), because it is always cheaper to clean water upstream than downstream. By (3.0), though, it is not individually rational for B to join the compact. One way to make membership more enticing is a side payment to the upstream polluter. This side payment could be designed so that membership in the compact is beneficial for both states and total net benefits would be maximized. The condition on the transfer, *TR*, is:

(3.1) ${}^{nc}U^{B} - {}^{c}U^{B} < TR < {}^{c}U^{A} - {}^{nc}U^{A}$

Figure 2.3 illustrates B's incentives as its population parameter n_B changes. Up to $\overline{n}_B$, membership in the compact is beneficial to B because the cost of cleaning its own pollution is less than the cost of cleaning A's pollution. As n_B grows, however, the cost difference decreases, and at $\overline{n}_B$ the cost of B treating its own pollution is equal to its cost of treating A's incoming pollution. At population levels above $\overline{n}_B$, the benefits from not joining the compact are larger than those from joining the compact.

Figure 2.3



Without the transfer, the interstate compact fails because it is not in B's interest to join, but a transfer from A to B that meets condition (3.1) will result in the compact being individually rational for both states. This is illustrated in Figure 2.3 by the upward-sloped, dashed line beginning at $\bar{n}_B$. Hence, a compact can still be viable if a transfer is made to the upstream polluter.[27]

The distinction between homogeneous and heterogeneous states in the model is important because this characteristic is present to varying degrees in each of the agreements discussed below for the Ohio Valley. Among the predictions of the model are that bargaining is likely to become more difficult as heterogeneity (in terms of upstream/downstream geography) between states increases. This prediction is consistent with the predictions of several empirical studies on collective bargaining (Libecap, 1989, 1994; Ostrom, Walker, and Gardner, 1992). Furthermore, for a compact to succeed under conditions of heterogeneity, side payments or credible threats are necessary. On the other hand, when states are homogeneous in terms of geography, interstate agreements are likely to require much less bargaining for success. These predictions are tested below for the Ohio Valley.

2.3.3 Bargaining in the Ohio Valley

2.3.3.1 The Ohio River Interstate Stream Conservation Agreement and Phenol

The Ohio River Interstate Stream Conservation Agreement was the first cooperative interstate agreement in the Ohio Valley. The original agreement was negotiated in 1924 between the state health departments of Ohio, Pennsylvania, and West Virginia.[28] There were twenty-one coke plants producing phenol as a byproduct in the three states. Downstream water treatment was ineffective because it only worsened the taste of the water. Therefore, abating the pollution upstream was the only available method for removing the bad taste from the water. In terms of the interstate model, the cost of treating one's own pollution was much less than the cost of attempting to treat incoming water from the other states.

$c(p(n_i), q_{-i}) < k(p(n_{-i}), q_i)$ i = own state, $-i$ = other states

The total benefits to Ohio and West Virginia were higher under the agreement than those to Pennsylvania due to their downstream populations. After adjusting for cost, however, the net benefits to each state were similar.

Table 2.4: Ohio Valley Phenol Agreement: Benefits and Costs

State	Downstream Population receiving Benefits	Number of Plants Requiring Treatment	Total Coking Capacity[a] (*tons/24 hours*)
Ohio	624,267	7	16,090
West Virginia	233,290	4	6700
Pennsylvania	17,147[b]	1	1800

Source: Compiled from Tables I - IV (Waring, 1928) and *Census of Population* (1930).
[a] Summation of capacities from all plants operating in the state.
[b] Does not include cities on Monongahela. The population of these cities was not reported in the *Census of Population* due to their small size.

The benefits are reflected in Table 2.4 by the downstream population, which were cities in the Ohio Valley large enough to be reported in the 1930 census.[29]

"Total coking capacity" is reported as an approximate measure of cost to the industries in each state. Waring (1928) reports some abatement costs for phenol plants in the Ohio Valley, but there are too few reported to derive an accurate measure of average cost. The costs that were reported, however, are highly correlated with the size of the operation. Therefore, total coking capacity gives a reasonable approximation of the total control costs in each state for all of the coke plants requiring abatement. It is clear from Table 2.4 that the states with larger benefits had larger costs as well. Ohio, for example, had the largest population benefiting from the agreement; it also had the largest costs of abatement. Pennsylvania, which had already forced many producers to install pollution control facilities, had only one plant requiring abatement under the agreement. Although the costs from the agreement were small, Pennsylvania had a much lower population benefiting from the agreement than either of the other two states. The reciprocal nature of the phenol problem in the Ohio Valley is described in the following news release dated April 29, 1927 (ORSANCO Historical Archives, Vol. 1):

> An outstanding accomplishment in regard to elimination of phenol wastes is the result achieved by cooperation of three states as follows: The Beaver River system in Pennsylvania has been rid of the phenol so that the Pennsylvania cities taking water supplies from this stream are no longer embarrassed by the phenol originating in the Mahoning Valley District in Ohio. The Monongahela River in Pennsylvania has been rid of the phenol which originated in West Virginia through a tributary of this stream, and water supplies in Pennsylvania thus have been relieved of this nuisance. ... The effort of all three states has achieved a very marked success in removing the cause of complaint from the cities downstream along the Ohio River in Ohio, West Virginia, and Kentucky.

Given the peculiar nature of phenol pollution in the Ohio Valley, membership in the agreement was individually rational for each state. The agreement provided increased water quality in line with costs. In this regard, there was a high degree of homogeneity across states. In addition, cheating on the agreement was difficult because compliance was observable.[30] As a result, the agreement was successful even though it lacked any legal powers.

2.3.3.2 The Ohio River Interstate Stream Conservation Agreement and Sewage

Agreement between the health directors of the state in the Ohio Valley was sought again in the early thirties in an attempt to control sewage (ORSANCO Historical Archives, Vol. 1). But unlike the net benefits to each state under the phenol agreement, the sewage agreement was characterized by large asymmetries in net benefits across the states (see Table 2.5).

Table 2.5: First Agreement to Control Sewage in the Ohio Valley: Benefits and Costs

State	Downstream Population receiving Benefits	Total Population under Agreement	Ratio: Total to Downstream
Kentucky	487,032	487,032	1.00
Ohio	624,267	794,269	1.27
Pennsylvania	82,606	752,423	9.11
West Virginia	217,104	233,290	1.07

Source: *Census of the Population* (1930).

Again, benefits are represented by downstream population. This is, of course, an oversimplification since marginal benefits were not likely to be equal across states, but it allows for a simple comparison across states.[31] The downstream population receiving benefits in West Virginia was slightly lower under the sewage agreement because Morgantown, being completely upstream of all sewage, no longer received benefits. Costs were measured using total population under the agreement. If an agreement was reached, all municipalities would have been required to install treatment facilities, even those on the headwaters that received little or no benefits (such as Pittsburgh). There are problems with this simple measure due to economies of scale in the construction of sewage treatment facilities (Cleary, 1967). Even with these problems, Table 2.5 illustrates a clear difference between the net benefits of the states involved. It was cheaper for downstream states (Kentucky, West Virginia, and Ohio) to control their own discharges than it was for them to treat upstream discharges coming from other states:

$c(p(n_i), q_{-i}) < k(p(n_{-i}), q_i)$, $n_{-i} > n_i$, i = own state, $-i$ = other states

Here, n_{-i} denotes the total population of all upstream states.[32] Conversely, Pennsylvania's cost of treating its own sewage was much larger than the cost of treating incoming sewage from Ohio and West Virginia.

$k(p(n_{-p}), q_p) < c(p(n_p), q_{-p})$, $n_{-p} > n_p$, p = Pennsylvania, $-p$ = states other than Pennsylvania

Under these circumstances, the costs of an interstate sewage agreement would largely be born by Pennsylvania due to the large population in Pittsburgh, whereas the benefits accrued largely to downstream water users below Pennsylvania. Population figures confirm the disparity in costs and benefits. Under the terms of the agreement, Pittsburgh alone would have to install treatment facilities for over 650,000 residents (1930 *U.S. Census of the Population*). Referring to Figure 2.3, Pennsylvania's population put them to the right of $\bar{n}_B$. In this area, Pennsylvania's net benefits, *without any transfer* *payments*, were larger with no compact. The heterogeneity between the states resulted in an ineffective interstate agreement for sewage control. Compensation payments to Pennsylvania were unlikely because health authorities had little ability to offer these types of transfers. But these types of transfers could be accomplished by politicians, a group well versed in bargaining.

2.3.3.3 ORSANCO and Sewage

The impetus to draft ORSANCO, the second Ohio Valley sewage control agreement, began in Cincinnati. A group of industrial water users, health, officials, and residents formed the Cincinnati Stream Pollution Committee in the summer of 1935. The members of the committee included many influential industry leaders and politicians, including Ohio Senator Robert A. Taft. The Cincinnati group convinced the Governors of a majority of the states in the basin to send representatives to the *First Conference of Delegates Appointed to Draft and Ohio Valley Water Sanitation Compact* in 1936.[33]

In negotiating ORSANCO, the downstream states acknowledged that Pennsylvania had an enviable position in terms of geography. These states also realized that their legal rights were unenforceable, and as a result, Pennsylvania was able to use the Ohio River for sewage disposal with very few restrictions. To entice Pennsylvania into the agreement, the downstream states would either have to coerce the upstream state into joining or compensate it. Compensating Pennsylvania would put them at a point on the upward sloped, dashed line in Figure 2.3 to the right of $\bar{n}_B$. This transfer (*TR*) would have to make compact membership more beneficial to Pennsylvania than no compact.

$$TR > ncU^P - cU^P, \quad P = \text{Pennsylvania}$$

Threatening Pennsylvania, on the other hand, would have to decrease the benefits of not joining the compact below the benefits of joining. Therefore, the penalty would have to be larger than difference between not joining and joining.

$$\textit{Expected Penalty} > ncU^P - cU^P, \quad P = \text{Pennsylvania}$$

Either a transfer or a penalty by downstream states could induce Pennsylvania to join the compact. The evidence for the Ohio Valley suggests that the downstream states did not have a credible threat (penalty) to force Pennsylvania's membership, leaving side payments and other forms of compensation as the only option.

One of the first actions of downstream state politicians was to initiate federal legislation addressing interstate water pollution. Federal legislation could serve as a penalty or threat to upstream states because it threatened their sovereignty (Cleary, 1967 and Hines, 1967). The first bill seriously considered in Congress was legislation introduced by Congressional representatives from the downstream states in the Ohio Valley. This legislation, the Barkley-Hollister Bill, was introduced in 1936 by Alben

Barkley, a Senator from Kentucky, and John Hollister, a U.S. Representative from Cincinnati, Ohio.[34] The bill called for *state* environmental regulation with assistance from federal agencies in planning and coordinating activities.

In 1937, additional legislation was being considered with another sponsor, U.S. Representative Fred Vinson from Ashland, Kentucky.[35] Vinson represented the interests of an Ohio River city, and his proposal called for federal loans and grants-in aid to help construct water treatment facilities. This proposal became a common feature in future pollution control bills introduced by the Ohio Valley interests, and it was eventually incorporated into the Federal Water Pollution Control Act of 1948. Support for Vinson's legislation led to the passage of the Barkley-Vinson Bill in Congress, but it was later vetoed by the President.[36]

The Ohio Valley group did not give up, though. Another measure, the Barkley-Spence Bill, contained much of the earlier legislation and was gaining support in Congress (*Hearings*, 1945).[37] The bill's new sponsor, Brent Spence, was a U.S. Representative from an Ohio River district in Kentucky. The Barkley-Spence Bill, like its predecessors, called for a very limited federal role. The bill left water quality determinations to the states, but provided funding for interstate agencies, and allowed for federal loans and grants. At last, the Ohio Valley states had crafted a bill that supported their interests, and could be enacted into law in 1948. But the type of legislation pushed by the Ohio Valley states posed no threat to Pennsylvania for not joining ORSANCO. It did not include federal standards, and there were no regulations that would impose large costs on Pennsylvania. Indeed, Pennsylvania would have been the recipient of federal aid for any treatment plants they chose to build.

An alternative sort of legislation that called for a very significant federal role was the Mundt Bill.[38] Mundt's legislation called for limits on discharges into rivers and streams with a federal agency to administer and enforce these limits. The more strict proposals under Mundt's legislation outlawed pollution altogether, giving industries a two-year grace period to adjust. But this type of "prohibition" legislation was unpopular with all of the representatives at water pollution control Hearings (including the Ohio Valley representatives) except for the Izaac Walton League (*Hearings*, 1936, 1945). The Izaac Walton League was a lobby group for fishermen, and it fully supported bills that prohibited all discharges of pollution into the streams of the United States. While the Mundt Bill could, if taken seriously, be considered a threat to state sovereignty, its passage was never given serious consideration. In fact, it was never reported out of the Committee on Rivers and Harbors and subsequently failed to advance to Congress for a vote.

Without the (credible) threat of federal intervention, it was difficult for the downstream states to hold Pennsylvania's interest in the compact. While all the downstream states had agreed to join the compact by 1940, Pennsylvania demonstrated no indication that it would join (see Table 2.6).

Table 2.6: Status of Ohio Valley States in Compact

State[b]	Proximity	Signature Date
Virginia	Upstream	1948
Pennsylvania	Upstream[a]	1945
New York	Upstream	1940
Ohio	Downstream	1940
West Virginia	Downstream	1940
Kentucky	Downstream	1940
Indiana	Downstream	1940
Illinois	Downstream	1940

[a] Pennsylvania was entirely upstream on the Ohio River. They were not entirely upstream in the basin, though, due to the Mahoning-Beaver system (Ohio), Allegheny (New York), and Monongahela rivers (West Virginia).
[b] Some states qualified their membership by requiring that other states also become members before the agreement took effect.

To bring Pennsylvania into an interstate agreement for water pollution control, the downstream states tried a number of options. First, they drafted a pollution abatement voting rule in ORSANCO that was favorable to Pennsylvania. It was originally proposed that enforcement actions would be decided upon by majority rule of the members in ORSANCO, which was comprised of eight states with three members from each state. Thirteen votes in favor of a proposed action would be necessary for enforcement. The representatives from Pennsylvania strongly opposed this method of enforcement (*Second Meeting*, 1938). Instead, they suggested that an action could only be enforced if at least two of the three representatives from the state where the proposed action was to take place voted in favor of the enforcement. Ultimately, Pennsylvania's proposed voting rule was adopted.

Second, Ohio, in 1939, agreed to reciprocal state legislation that addressed acid mine wastes flowing into interstate rivers and streams. Pennsylvania already had laws covering acid mine waste, but Ohio did not. Pennsylvania argued that controlling the wastes put them at a disadvantage in the industry, and the legislation would [ORSANCO Communication No. 42, 1939] "place both states on a parity." Third, in 1941, the compact commission stated that one of the first actions of ORSANCO would be to improve the sanitation of the Mahohing-Beaver system, which flowed from Ohio into Pennsylvania (*Memorandum*, ORSANCO Historical Archives, Vol. 6, 1941). This area was increasingly becoming a problem because Ohio took little actions to correct pollution in the area.

> The State of Pennsylvania is quite anxious to abate pollution of the Mahoning River but the State of Ohio is moving slowly in this matter because Pennsylvania has not moved very fast in abating pollution of the streams that form the Ohio River. [ORSANCO Communication No. 42, Historical Archives, Vol. 6, 1939]

The benefits of the proposed action accrued mainly to Pennsylvanian municipalities along the Ohio-Pennsylvania border (see Figure 2.2). Even so, while the action kept Pennsylvania's interest in an interstate agreement, it was still reluctant to commit to a legally-binding interstate compact.

Finally, in the mid 1940s, the compact was helped along by an outside event—World War II. Pennsylvania, and Pittsburgh in particular, was the location of some of the nation's heaviest industry. As a result, Pittsburgh and other areas in the Ohio Valley experienced significant population growth.

Table 2.7: Population Growth in the Ohio Valley: 1940-1950

Location	Population Growth (%)
United States Average	*2.4*
Pennsylvania	6.0
Allegheny County, Pa.	7.3
Beaver County, Pa.	11.8
Ohio	15.0
Mahoning County, Oh.	7.2
Trumbull County, Oh.	20.1
West Virginia	5.4
Marion County, W. Va.	4.8
Monongalia County, W. Va.	18.6

Source: Compiled from Table 5, Parts 35, 38, and 48, Volume II, *Census of the Population*, 1950.

With the increase in industry and population in the region, the costs of inducing Pennsylvania to join the compact decreased significantly. Areas below Pittsburgh but still in Pennsylvania (in Beaver County) that were once sparsely populated experienced tremendous population growth during World War II. The sewage discharge from Pittsburgh that used to be the problem of municipalities in states below Pennsylvania was now becoming a problem to residents living in the Keystone State. In addition to this disturbing problem, population and industrial growth in the Youngstown, Ohio area was leading to heavy pollution in the Beaver-Mahoning system (see Figure 2.2). This is confirmed in a report by the U.S. Public Health Service and the Army Corps of Engineers released in 1943 (House Document, No. 266, 1943).

In addition to raising the net benefits of Pennsylvania joining the compact, World War II also provided the opportunity for the downstream states to compensate Pennsylvania by supporting postwar projects there. These projects were the most important side payments offered by the downstream states to Pennsylvania. Numerous flood control projects were authorized under various flood control acts in the Ohio Valley, but many had not yet been constructed.[39] This was mainly due to the number of projects spread throughout the Ohio Valley. Before a project in any state could be constructed, it had to be brought to the attention of Congressional representatives in the Ohio Valley. The project was then considered by the House Public Works Committee, and finally the Army Corp of Engineers' Chief of Engineers made an examination and held public hearings.[40] The negotiators of the ORSANCO compact fully understood the significance of these projects for reaching some kind of an agreement. In particular, construction of post war projects could be coordinated with compact operations to entice Pennsylvania into joining. Fred Waring, secretary of the negotiation committee, noted (ORSANCO Historical Archives, Vol. 8, 1948):

> Efforts to get Pennsylvania and Virginia to adopt the compact were interrupted by the war effort. However, anticipating postwar public works construction programs, an early renewal of such efforts was undertaken by the delegates appointed to negotiate the compact in a conference held at Pittsburgh, Pennsylvania, on December 7, 1944.

A particularly useful feature of flood control reservoirs at the time was low flow regulation. Low flow regulation entailed building larger reservoirs so that water levels could be increased during periods of particularly intense pollution, such as in summer months. These features would be very helpful in reservoirs near Pittsburgh as pollution problems in Pittsburgh and in downstream municipalities in Beaver County, Pennsylvania were worsening. It appears that the negotiators of ORSANCO realized that their support in Congress for the construction of flood control reservoirs near Pittsburgh was important for getting Pennsylvania to join the interstate compact. In January, 1945, shortly after the December, 1944 meeting of the ORSANCO negotiation committee, Cincinnati, the downstream city leading the compact negotiations, issued the following plea to Pittsburgh and Pennsylvania's General Assembly (ORSANCO Historical Archives, Vol. 6):

> The multiple-purpose use of flood control reservoirs in increasing low stream flows (in Pennsylvania) is valuable as a supplement to treatment and other pollution abatement practices, and the Ohio River Valley States can assist in supporting the construction of such reservoirs by the Federal Government.

At the next meeting of Pennsylvania's General Assembly in April, 1945, Pennsylvania finally agreed to the terms of ORSANCO.

Following Pennsylvania's membership in the compact, the downstream states followed through with support of flood control projects near Pittsburgh. Many of these projects included no benefits to the downstream regions that supported them. This is witnessed by the Congressional testimony of Congressman Jenkins, a U.S. Representative from a downstream Ohio district, in November, 1945, shortly after Pennsylvania joined the compact:

> I rise in support of the amendment (on postwar flood control projects by Congressman Eberharter, U.S. Rep., Pennsylvania). I cannot be accused of having any personal interest in the passage of this amendment because

> it will not provide for any improvements in my district or at any place within close proximity of my district. [Congressional Record, November 29, 1945]

The downstream states in the Ohio Valley could not use federal intervention as a credible threat to force Pennsylvania to join the interstate compact. The costs that "prohibition" legislation would impose on Pennsylvania would also impose large costs on downstream regions. As a result, the downstream states could not coerce Pennsylvania into joining by threatening them with federal intervention. The evidence suggests that the downstream states used a different option, compensation, to obtain Pennsylvania's membership (see Appendix D for details on flood control in the Ohio Valley during this period). Direct payments were not feasible because citizens downstream would likely be outraged by payments to Pennsylvania so that it would not pollute as much. Compensation at the federal level, however, through federally funded post war projects facilitated side payments. Flood control projects were easily marketable in downstream regions because there was always the possibility that they could provide some benefits, no matter how small. This gave the downstream states the opportunity to compensate Pennsylvania without suffering criticism for paying their upstream neighbor not to pollute.

2.4. Concluding Remarks

Pollution problems at the turn of the century were changing quickly due to changing economic conditions. At the same time, higher valued uses for many environmental assets arose. I focus on interstate pollution in the Ohio Valley and examine the responses of the states to this problem. Pollution that normally interfered with only a few water users became less common as more polluting sources located along rivers and streams. To make matters worse, water pollution crossing state boundaries became a concern to the downstream states. I find that these changes in the nature of water pollution led to changes in the institutions used to protect water quality. The courts were the primary method used to protect water quality rights in the late 1800s and early 1900s. But with multiple pollution sources proving causality was difficult, rendering the courts costly and ineffective. This problem was magnified in major river basins that included numerous polluters and multiple states. In addition, states could not appeal to the federal government for help because its role in environmental matters was very limited at the time. As a result, I find that the states in the Ohio Valley used the interstate compact as a remedy to control interstate pollution. This alternative method of addressing interstate pollution lowered the costs of establishing rights to water quality in downstream regions, rights that courts were unable to enforce. The observed institutional change in the Ohio Valley is consistent with predictions that new institutions and different property rights arrangements arise to address the changing costs associated with existing institutions (Demsetz, 1967; Davis and North, 1971; Libecap, 1989; Ostrom, 1990; Williamson, 1996; Barzel, 1997).

Not all of the states in the Ohio Valley were satisfied with the rearrangement of rights that coincided with interstate compacts. In particular, the upstream states were reluctant to join an interstate compact that would force additional costs on them with the benefits flowing mainly to the downstream states. To deal with this problem, downstream states had to devise compensating side payments to their upstream neighbors for their expected losses resulting from the new property rights arrangement under the compact. Evidence from the Ohio Valley suggests that the federal government was used as a medium for conducting side payments because direct payments to the upstream state, Pennsylvania, were infeasible; the costs to politicians suggesting payments to polluters were too high. This cases study provides empirical evidence of the use of side payments as a means of completing agreements in the manner argued by Buchanan and Tullock (1962), Olson (1965), and Tullock (1998).

State environmental regulation has been criticized for its inability to deal with a variety of pollution problems. Interstate pollution was one of the leading concerns of scholars and analysts suggesting a centralized approach to environmental regulation in the late sixties and seventies (Stewart, 1977; Cumberland, 1979, 1981). These individuals argued that the competing interests of the states would preclude effective environmental regulation at the state level. By examining the Ohio Valley, I find that states there successfully addressed one of the most difficult pollution problems—

interstate water pollution. The situation in the Ohio Valley is not, of course, representative of all pollution problems, but it is characteristic of many of the problems that states faced in designing environmental regulation: free rider problems, heterogeneity across states and bargaining problems, and technological limitations. That the states were successful in their efforts to control interstate water pollution in the Ohio Valley is at least an indication that states were not helpless against difficult pollution problems.

2.5 Endnotes

[1] Much of this chapter was completed while the author was a graduate fellow at the Political Economy Research Center (PERC). Financial support was provided by a University of Arizona Graduate College grant.

[2] See, for example, the 1912 case in New Castle, Pa. cited in Cleary (1967) and also found in Table 2.2 of this section.

[3] Illinois: Revised Statutes, 1915-1916, Chapter 42, sec. 263; Indiana: Annotated Statutes, 1914, sec. 7599; Kentucky: Carroll's Kentucky Statutes, 1915, sec. 2049; New York: Public Health Law, amended 1915, Chapter 665, sec. 73; Ohio: General Code, 1912, sec. 1255; Pennsylvania: Supplement of 1915, sec. 22 (also Act of April 22, 1905, Public Laws, Section 8); West Virginia: Code 1916, Chapter 150, Public Health, Section 2 (also Acts, 1915, Chapter 11).

[4] Interstate water pollution was primarily a problem in the eastern U.S., and this chapter focuses on riparian water doctrine. Appropriation doctrine governed water use in western regions of the U.S. See Rose (1990) for a thorough discussion on the differences between the two types of water law.

[5] Water users often had legal rights that were not enforced, which left them with low quality water. Under these circumstances, their property rights to water quality were poorly specified and not enforceable. In this regard, the distinction between legal rights and property rights to water quality is similar to that put forth by Barzel (1997).

[6] Yandle (1989) discusses numerous cases involving air pollution ordinances in the United States in the early 1900s (Chapter 3). For example, a 1917 ordinance by Pittsburgh officials was met with heavy opposition by industrial leaders (pgs. 50-51).

[7] There were instances of intrastate agreements. The Allegheny County Sanitary Authority was created in 1935. It provided water treatment for Pittsburgh and sixty-eight communities (p. 110, Clearly, 1967). The authority for the agreement, though, had to be approved first by the Pennsylvania legislature.

[8] Section 6111.11, Revised Code of Ohio.

[9] Perhaps a more accurate distinction would be "easy to identify" polluter cases and "difficult to identify" polluter cases.

[10] Full descriptions of many of the other cases may be found in Appendix A.

[11] Similar cases include: *Red River Roller Mills* v. *Wright*, 30 Minn. 249 (1883), *Indianapolis Water Co.* v. *American Strawboard Co.*, 57 Fed. Rep. 1000 (1893), *Patrick Nolan* v. *The City of New Britain*, 69 Conn. 668 (1897), *Parker* v. *American Woolen Co.*, 191 Mass. 591 (1907), *MacNamara* v. *Taft*, 196 Mass. 597 (1908), *Worthen & Aldrich* v. *White Spring Paper Co.*, 74 N.J. Eq. 647 (1908), *Packwood et ux.* v. *Mendota Coal and Coke Co. et al.*, 84 Wash. 47 (1915).

[12] Figures quoted in constant 1996 dollars. See Appendix B for a description of the price index.

[13] Air pollution cases were often cited in water pollution cases and vice versa. See, for example, *New York* v. *New Jersey*, 256 U.S. 296 (1921).

[14] One case where the courts were not willing to leave the outcome to private bargaining was the famous case *Pennsylvania Coal Co.* v. *Sanderson*, 113 Pa. 126 (1886). In the case, the plaintiff accused a single upstream polluter, Pennsylvania Coal Co., of harmful pollution. The trial court stated that the mining industry was of "vast importance to the community and the State of the coal mining industry required the plaintiff to give up her less important use of the stream for domestic purposes without compensation." The decision was very unpopular with other courts and was highly criticized. Montgomery and Phelps (1917) point out that the decision was only applied to mining cases in Pennsylvania. Further, they state that "the doctrine (was) followed only in Pennsylvania and Indiana, and expressly repudiated elsewhere" [p. 31].

[15] The case also illustrates the use of the court as a credible threat in single polluter cases. The other defendant, the Ducktown Co., refused a similar agreement. The result was a second court case with Georgia winning again, *Georgia* v. *Tennessee Copper Co.*, 237 U.S. 474 (1915).

[16] *Lull* v. *Improvement Co.*, 19 Wis. 101 (1865), *Little Shuylkill Navigation, Railroad and Coal Co.* v. *Richard's Administrator*, 57 Pa. 142 (1868); *Serley* v. *Alden*, 61 Pa. 302 (1869); *Bonte* v. *Postel*, 109 Ky. 64 (1900); *Bowman* v. *Humphrey*, 132 Iowa 234 (1906).

[17] The Interstate Commission on the Delaware River Basin (INCODEL) was made effective in 1936 through identical legislation in the states of New York, Pennsylvania, and New Jersey (Delaware joined in 1938).

[18] There are numerous scholarly works on interstate compacts. For comprehensive surveys and analysis, see: Zimmerman and Wendell (1951), Thursby (1953), and Leach and Sugg (1959).

[19] Article I, Section 10, U.S. Constitution.

[20] *The Book of States* (1958).

[21] (Compact, Member States, Year of Congressional Approval): (Tri-State Pollution Compact, New Jersey, New York, Connecticut, 1935), (Ohio River Valley Sanitation Compact, Ohio, West Virginia, Pennsylvania, Kentucky, Illinois, Indiana, New York, Virginia, 1936), (New England Pollution Compact, Connecticut, Massachusetts, Rhode Island, 1936), (Potomac Valley Pollution and Conservation Compact, Washington, D.C., Maryland, Virginia, West Virginia, 1937).

[22] Tastes and odors from phenolic waste have been detected in amounts of only one part of phenol to fifty million parts of water (Waring, 1928). As a comparison, bacteria is a problem only at much higher levels, approximately 2500 parts bacilli coli to 50 million parts water (Cleary, 1967). Phenolic waste was more of a nuisance than a health concern.

[23] Waring (1928) gives an in-depth description of the phenol pollution problem as it pertained to the Ohio Valley.

[24] Some tributaries of the Ohio River ran from Ohio into Pennsylvania. The Mahoning River ran from Youngstown, Ohio into the Beaver River, which supplied water to numerous small municipalities in Pennsylvania.

[25] The courts proved to be extremely expensive in other interstate cases. In a 1931 water *quantity* case between New Jersey, Pennsylvania, and New York (*New Jersey et al.* v. *New York*, 283 U.S. 336), the total cost of the case to the states involved was over $10 million. And water quantity cases did not involve the uncertainty present in water quality cases.

[26] This discussion draws heavily from Cleary (1967) and ORSANCO's annual reports.

[27] A credible threat from the downstream state, such as federal intervention, could result in the same outcome. This is discussed in detail for the Ohio Valley.

[28] Kentucky joined the agreement early in 1926 followed by Maryland, New York, Indiana, Illinois, and Tennessee later that year.

[29] Ohio: East Liverpool, Steubenville, Marietta, Ironton, Portsmouth, Cincinnati, Bellaire, Niles; Pennsylvania: Beaver Falls; West Virginia: Huntington, Parkersburg, Moundsville, Wheeling, Clarksberg, Fiarmont, Morgantown. Youngstown, with a population of

approximately 170,000, was not included in the Ohio estimate because it is not clear how much this city benefited from the agreement. There were phenol plants in Youngstown, but not all of them affected Youngstown's water supply. Likewise, the cities on the Monongahela River that certainly benefited from the agreement were not included because their population was not reported in the census due to their small size. Nevertheless, downstream population is a reasonable proxy for the amount of benefits accruing to each state.

[30] A polluting coke plant either installed abatement facilities or it did not. The agreement also allowed for [p. 16, Waring, 1928] "joint inspections of water works ... whenever deemed necessary."

[31] For example, a downstream municipality ten miles from an upstream polluter would have higher benefits than a downstream municipality fifty miles from the same upstream polluter. Both municipalities benefit, but the amount of benefits are likely to differ.

[32] Pennsylvania was the main upstream polluting state. But each state experienced pollution from other adjacent states. For example, downstream municipalities were affected by pollution from Pennsylvania, but also from upstream municipalities on the Ohio River in West Virginia and Kentucky. The same was true for West Virginia and Kentucky.

[33] Minutes of this and other proceedings were found in ORSANCO's historical archives (see references for complete citations).

[34] House bills: 12101, 12102, and 12103; these same bills were introduced in the Senate by Barkley.

[35] Ashland was one of only two Ohio River cities to have already installed sewage treatment facilities (Waring, 1941).

[36] Barkley-Vinson Bill: S-702, HR-2711. The bill was vetoed due to budgetary considerations by the President (*Hearings before the Committee on Rivers and Harbors*, 1936,).

[37] HR-4070, 67th Congress.

[38] HR-6723, 67th Congress.

[39] The Flood Control Act of 1936 was approved June 22, 1936, and it authorized numerous projects for flood control throughout the country. The Flood Control Acts of

1937 (50 Stat. 876), 1938 (52 Stat. 1215), 1941 (55 Stat. 638), and 1944 (58 Stat. 887) continued to authorize new projects.

[40] Leopold and Maddock (1954) give a complete description of the process (see especially Chapter 7).

Table of Cases

Blaisdell v. *Stephens* (1879), 14 Nev. 17
Bonte v. *Postel* (1900), 109 Ky. 64
Bowman v. *Humphrey* (1906), 132 Iowa 234
City of Cleveland v. *Standard Bag Company* (1905), 72 Oh. 324
Chipman v. *Palmer* (1879), 77 N.Y. 51
Columbus & H. Coal & Iron Co. v. *Tucker* (1891), 48 O. St. 41
Day v. *Louisville Coal & Coke Co.* (1906), 60 W. Va. 27
George Morgan v. *City of Danbury* (1896), 67 Conn. 484
Georgia v. *Tennessee Copper Co.* (1907), 206 U.S. 230
Georgia v. *Tennessee Copper Co.* (1915), 237 U.S. 474
Hillman v. *Newington*, 57 Cal. 56
Honsee v. *Hammond*, 39 Barb. (N.Y.) 89
Indianapolis Water Co. v. *American Strawboard Co.* (1893), 57 Fed. Rep. 1000
Keyes v. *Little York Gold Washing and Water Company* (1879), 53 Cal. 724
Little Shuylkill Navigation, R.R. & Coal Co. v. *Richard's Admin.* (1868), 57 Pa. 142
Lockwood Co. v. *Lawrence* (1885), 77 Me. 297
Lull v. *Improvement Co.*, 19 Wis. 101
MacNamara v. *Taft* (1908), 196 Mass. 597
Mayor of Baltimore v. *Warren Manufacturing Co.* (1882), 59 Md. 96
Missouri v. *Illinois* (1906), 200 U.S. 96
New Jersey et al. v. *New York* (1931), 283 U.S. 336
New York v. *New Jersey* (1921), 256 U.S. 296
Packwood et ux. v. *Mendota Coal and Coke Co. et al.* (1915), 84 Wash. 47
Parker v. *American Woolen Co.* (1907), 191 Mass. 591
Patrick Nolan v. *The City of New Britain* (1897), 69 Conn. 668
Pennsylvania v. *Sanderson*, 113 Pa. 126
Red River Roller Mills v. *Wright* (1883), 30 Minn. 249
Serley v. *Alden* (1869), 61 Pa. 302
State of West Virginia ex rel. *Dyer* v. *Sims* (1950), 341 U.S. 22
Strobel v. *Kerr Salt Co.* (1900), 164 N.Y. 303
West Muncie Strawboard Co. v. *Slack* (1904), 164 Ind. 21
Witland v. *Redbank* (1909), 151 Ill. App. 433
Wood v. *Sutcliffe*, 2 Sim (N.S.) 163
Worthen & Aldrich v. *White Spring Paper Co.* (1908), 74 N.J. Eq. 647

Figure 2.1

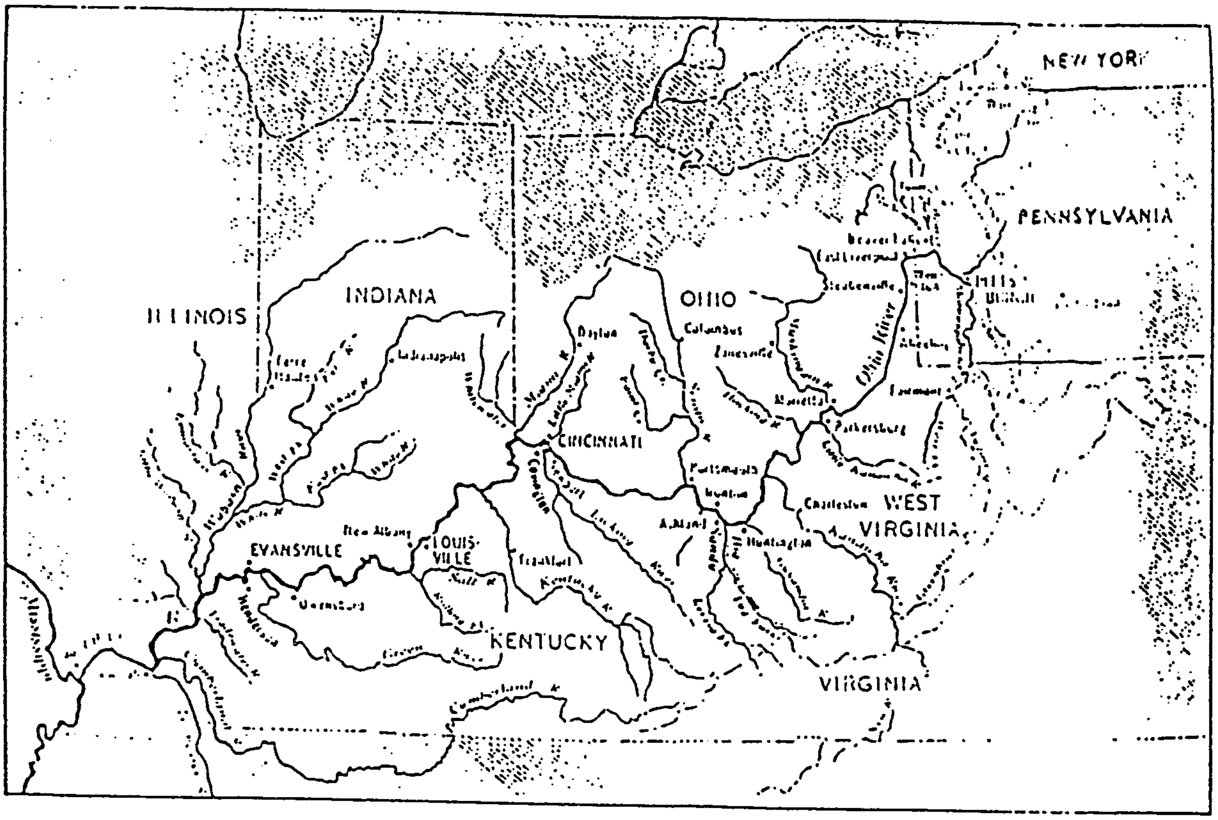
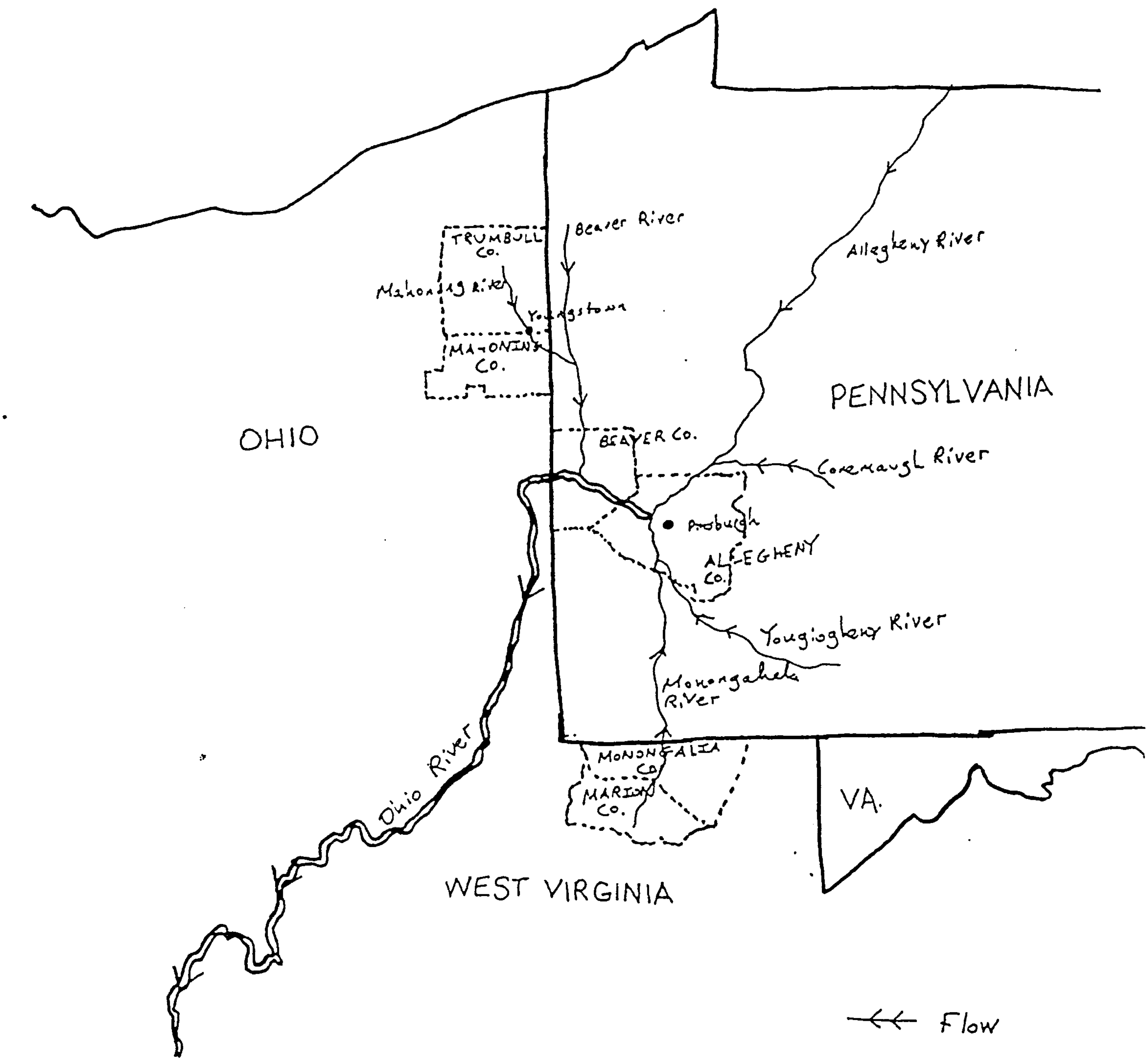


Figure 1. The Ohio River Valley Water Sanitation Compact district embraces portions of eight states and covers an area of 155,000 square miles.

Source: *The ORSANCO Story*, Cleary (1967), p. 5.

Figure 2.2



Source: *Census of the Population* (1930)

Chapter 3

Inducing Innovation in Environmental Technologies

3.1. Introduction[1]

The economic factors affecting R&D spending and incentives to innovate have long been a central focus of the Industrial Organization literature.[2] This research effort has demonstrated that underinvestment in R&D is most likely to occur when "spillovers" exist or where technology is easily imitated. As a result, patents or other inducements (such as awards and prizes) are necessary to correct underinvestment where it occurs. These same problems have recently been examined with regard to environmental technologies (Parry, 1995, 1996; Biglaiser and Horowitz, 1995). Using similar arguments, these authors claim that underinvestment in R&D is likely to exist in environmental technologies as well. The proposed remedies in the environmental setting are also like those found in the IO literature: prizes and research subsidies (Parry, 1995, 1996). Unfortunately, prizes and research subsidies are relatively unfamiliar methods of inducement and may suffer from additional criticisms (Scherer, 1980).

This chapter proposes the use of more familiar methods to induce innovation in environmental technologies. By using environmental standards, the environmental authority can control the level of investment in our model. We also show that overinvestment, rather than underinvestment, is the likely outcome under a system of Pigouvian taxes. In addition, overinvestment may occur under a system making use of best available control technologies (BACT), like the one currently employed by the EPA. BACT requires that firms adopt the technology that has been accepted as the best available by the EPA. Under BACT, our results suggest that the recently observed overcompliance with environmental standards may be reinterpreted as profit maximizing behavior designed to increase rivals' costs. This explanation is consistent with other producer driven explanations (Maloney and McCormick, 1982; Salop and Scheffman, 1983), and it offers an alternative to more recent explanations linking overcompliance to consumer demand for environmental quality (Arora and Cason, 1994, 1995, 1996; Arora and Gangopadhyay, 1995)

Environmental standards, when they are binding, impose costs on polluting firms. Given cost-minimization, there is no reason that a polluting firm would seek to increase the environmental standard if it would impose the same costs on itself that the new standard would impose on other firms. If, however, the cost of meeting the standard is higher for other firms than it is for the firm proposing the new standard, the firm may attempt to increase the environmental standard to raise its rivals' costs and thereby receive a larger market share (Salop and Scheffman, 1983). By similar reasoning, a group of incumbent firms might attempt to raise environmental standards to discourage entry into a particular polluting industry (Buchanan and Tullock, 1975; Maloney and McCormick, 1982). Indeed, with a BACT rule, firms may overinvest in R&D while attempting to raise rivals' costs if the proposed technologies or procedures are more costly to other firms than they are to the firm making the proposed changes. This is similar to the costs firms attempt to impose on each other by raising the environmental standard. Finally, note that the BACT rule does not only allow technology spillovers, it requires them; a technology that is proposed by a firm is forced upon other firms if it is accepted as the BACT.

Underinvestment in R&D is still possible under a rule of BACT. If the gains from increased market share (i.e. increased producer surplus) are smaller than the corresponding consumer gains from higher environmental quality, the socially optimal level of R&D will not be reached. Here, it will be seen that using environmental standards to induce innovation may yield socially optimal levels of R&D just as in the case of overinvestment.[3]

In addition to their affect on R&D, environmental standards decide, in part, the price of the goods produced by polluting industries. They also affect the level of environmental quality that may be reached in a particular area. Given that environmental standards have differing effects on prices, R&D spending, and environmental quality, the level of the standard becomes central to questions relating to efficiency. For example, given a fixed environmental standard, can efficient pricing coincide with efficient R&D spending? And if so, is the standard used to induce prices and R&D spending efficient as well (in terms of desired environmental quality)? As it turns out, the environmental standard is central to each of these questions and the use of a uniform standard is unlikely to yield efficiency in terms of pricing, R&D and standards. We show that, by using nonuniform standards, first best efficiency can be obtained in pricing, R&D, and environmental quality (i.e., efficient standards). And because environmental standards have long been a part of most regulatory systems, they may be adapted to induce efficiency in these crucial areas more easily than using unfamiliar remedies such as prizes and research subsidies.

3.2. The Model

Our model of innovation is similar to that found in Sah and Stiglitz (1987). Research projects are either successful or unsuccessful and innovating firms can only affect the probabilities of success. By investing in R&D, denoted I in the model, firms may increase the probability of success, $q(I)$ where $q'(I) > 0$ and $0 < q(I) < 1$. Successful innovation results in a lower cost of meeting any environmental standard. The environmental standard is denoted by s and success or failure is denoted by δ where $\delta = 0$ if unsuccessful and $\delta = 1$ if successful. The model is simplified with only two competitors who compete on price in a Bertrand setting. There are two time periods in the model. In the first period, firms choose their respective levels of I. Then, in the second period, success or failure of the innovations is realized and price competition takes place.

The per unit cost facing each firm and its properties are as follows:

(1.0) $c(s,\delta)$, $c_s > 0, c_{s\delta} < 0, c(s,0) > c(s,1)$ for any s

Per unit costs of production are assumed to be linear in the model. Higher levels of s imply greater environmental protection. By (1.0) it is seen that per unit costs increase with a higher standard, and per unit costs decrease with successful innovation. In addition to the costs associated with any standard s, there is also a corresponding per unit level of environmental damage $D(s)$ with $D'(s) < 0$. As the environmental standard increases, an additional unit of production causes less damage. Damage is assumed to be linear with respect to output in this model.

3.2.1 Social Optimum: First Best Outcome

Notice that there are three "states of the world" in time period two. First, both firms could be successful in their innovations. We assume that when both firms are successful, the resulting innovations are equally cost reducing.[4] Another outcome is that one firm could be successful, and the other firm unsuccessful. The third outcome is where both firms are unsuccessful. These three states are central to the analysis of this chapter because proper policy will be dependent upon a given state. For example, a social planner attempting to maximize the wealth in this economy would want to incorporate beneficial innovations into the output price any time at least one firm successfully innovates. We will see later that this is at odds with what is privately beneficial to the firms.

The social planner chooses standards and quantities to maximize ex post welfare for each given state as follows:

State A ($\delta =$ 1 for both firms): $\max_{s,Q} \int_0^Q P(z)dz - [D(s) + c(s,1)]Q$

$P(z)$ is inverse demand and $D(s) + c(s,1)$ is the full social cost of a unit of production. This yields the following first order conditions (assuming an interior solution) for quantity and standards, respectively.

(1A) $P(Q) - [D(s) + c(s,1)] = 0$

(2A) $-D'(s) - c_s(s,1) = 0$

(1A) and (2A) yield the optimal values for Q and s. Similarly for case C:

State C ($\delta =$ 0 for both firms): $\max_{s,Q} \int_0^Q P(z)dz - [D(s) + c(s,0)]Q$

The first order conditions for ex post efficient quantity and environmental standards are:

(1C) $P(Q) - [D(s) + c(s,0)] = 0$

(2C) $-D'(s) - c_s(s,0) = 0$

(1C) and (2C) yield the optimal values for quantity and the standard for state C. The interesting case here is state B. From the social planner's perspective, state B is treated identically to state A. Even though only a single firm successfully innovates in state B, the social planner chooses the same quantity and standard as state A because the technology innovation improves social welfare. This is seen by totally differentiating the first order conditions:

(2.0) $$\begin{bmatrix} P'(Q) & 0 \\ 0 & -(D'' + c_{ss}) \end{bmatrix} \begin{bmatrix} dQ \\ ds \end{bmatrix} = \begin{bmatrix} c_\delta \\ c_{s\delta} \end{bmatrix} d\delta$$

This leads to the following comparative statics:

(2.1) $\dfrac{dQ}{d\delta} = \dfrac{-c_\delta (D'' + c_{ss})}{|A|} > 0$ where A is the first matrix in (2.0).

(2.2) $\dfrac{ds}{d\delta} = \dfrac{c_{s\delta} P'(Q)}{|A|} > 0$

From (2.1), we may conclude that $Q_A^* > Q_C^*$. And from (2.2) we have that $s_A^* > s_C^*$. Innovation yields both a higher standard and more output, both of which improve consumer welfare. The "loser" in state B, i.e. the firm that does not successfully innovate, produces zero units because it is cheaper for the winning firm to produce every unit. Hence, the social planner chooses the same standard and output in state B as in state A, but only the successfully innovative producer operates in state B.

Choosing the efficient level of R&D depends upon the probability of ending up in any given state for a given level of *I*. The probability of state A is $[q(I)]^2$; the probability of state B is $q(I)(1-(q(I))$; and the probability of state C is $[1-q(I)]^2$. States A and B are desirable, but there is a cost associated with increasing the probability of ending up in these states, namely higher levels of *I*. Letting *W*(1) equal the welfare in states A and B (which are identical in the social planner's problem) and *W*(0) equal welfare in state C, the social planner chooses *I* to maximize the following expression:

$$(2.3) \quad \max_I \quad [q(I)^2 + 2\,q(I)\,(1-q(I))]\,W(1) + [1-q(I)]^2\,W(0) - 2I$$

The first order conditions resulting from (2.3) are:

$$(2.4) \quad [1-q(I)]\,q'(I)[W(1)-W(0)] - 1 = 0$$

The socially optimal level of investment I^* satisfies (2.4). Note also that, with diminishing returns to R&D spending, it is more efficient for both firms to invest the same amount.

3.2.2 Private Outcome

With the socially optimal values of price (quantity), standards, and R&D, we may now analyze the private outcome to determine its relationship to the optimal values of these variables. Given these values, we can make recommendations about the proper policies to bring about efficiency. In states A and C, the social planner only needs to assign a Pigouvian tax equivalent to the per unit damage *D*(*s*). For example, in state A the Pigouvian tax would be $t_A = D(s_A)$ where s_A is the standard in state A chosen by each firm. Firms would then choose the standard that minimizes costs:

(2.5) $s_A^* = \arg\min_{s_A} \quad c(s_A, 1) + D(s_A)$

Replacing the As with Cs in (2.5) gives the firm's choice problem for state C. The optimal value for the standard in (2.5) is identical to the standard that the social planner would choose in (2A). Also, because the two firms are identical (with respect to cost) in states A and C, Bertrand price competition ensures that the price will be equivalent to the socially maximizing price from (1A). As a result, the social planner only needs to assign a per unit damage tax and firms will choose the first best standard and price in states A and C.

As is the case throughout this chapter, state B is the interesting case. With only the Pigouvian damage tax the two firms will choose different standards, and hence their costs will differ. The losing firm (δ = 0) will choose standard s_C^* while the winning firm (δ = 1) will choose standard s_A^*. By (2.2), $s_A^* > s_C^*$. The winning firm faces cost $c(s_A^*,1) + D(s_A^*)$, and the losing firm faces cost $c(s_C^*,0) + D(s_C^*)$. With $D(s_C^*) > D(s_A^*)$ (because $D'(s) < 0$) and $c(s_C^*,0) > c(s_A^*,1)$ (because $c_{s\delta} < 0$—see 1.0), the total per unit cost facing the winning firm is less than that of the losing firm. With Bertrand price competition, the winning firm gains the entire market, and it will set its price equal to $c(s_C^*,0) + D(s_C^*)$ and sell quantity $Q_C^* < Q_A^*$.[5] We see that in state B the winning firm chooses the efficient standard (s_A^*) but does not price efficiently.

Because the two firms in the model receive positive rents only in state B, their investment in R&D is based upon reaching state B. Specifically, the firm chooses I to satisfy the following equation:

$$(2.6)\quad I_i^* = \arg\max_{I_i} \quad q(I_i)(1 - q(I_j))[c(s_C^*,0) + D(s_C^*) - (c(s_A^*,1) + D(s_A^*))]Q_C^* - I_i$$

Given a symmetric, interior equilibrium we have that $I_i^* = I_j^*$, and this I^{**} solves the following:[6]

$$(2.7)\quad [1-q(I^{**})]q'(I^{**})[c(s_C^*,0)+D(s_C^*)-(c(s_A^*,1)+D(s_A^*))]Q_C^*-1=0$$

By comparing (2.4), which gives the socially optimal level of R&D investment, with (2.7) we see that private decision-making by the two firms results in underinvestment (see Appendix 1 for proof). Although the correct standard arises under private decision-making, there are inefficiencies in both pricing and investment.

The pricing problem could be corrected with a per unit subsidy that induces the winning firm to price at its marginal cost, which is the price that the social planner chooses in state B to maximize total expected welfare. Here, the subsidy would be:

$$(2.8)\quad b=[(c(s_C^*,0)+D(s_C^*)]-[c(s_A^*,1)+D(s_A^*)]$$

With subsidy b, the winning firm in state B prices at the losers cost which is:

$$(2.9)\quad c(s_C^*,0)+D(s_C^*)-b=c(s_A^*,1)+D(s_A^*)$$

The sign of the net per unit tax/subsidy depends upon the size of b in relation to the per unit damage tax, but notice that this simple scheme results in efficient standards and efficient pricing.

We must still check the effects of the per unit subsidy on R&D investment. Here, the rents to the winning firm in the presence of the subsidy are:

$$(2.10)\quad \{[c(s_C^*,0)+D(s_C^*)]-[c(s_A^*,1)+D(s_A^*)]\}Q_A^*$$

The rents in (2.10) differ from the rents in the case without a subsidy because the output in (2.10) is greater. This is due to the correction of the pricing problem. Unfortunately, correcting the pricing problem leads to *overinvestment* (see Appendix 2).

From the analysis of this section, it becomes clear that achieving efficiency in environmental standards, pricing, and R&D investment is difficult under a system of uniform environmental standards. Attempting to correct the pricing problem leads to overinvestment by firms in our model. If there is no attempt to correct pricing, firms will underinvest in R&D, and there will also be inefficiencies associated with firms pricing above the socially efficient level. At this point, it is important to stress this relationship between pricing, standards, and investment decisions because, as we will see later, this relationship has implications for the current BACT rule. With nonuniform standards, it is possible to achieve first best efficiency in pricing, standards, and investment. Essentially, nonuniform standards can be used to induce the socially efficient level of investment. This is the subject of the following section.

3.3. Nonuniform Standards and Inducing Innovation

Inducing technological change has been addressed under a variety of conditions in the Industrial Organization literature. In the problem set forth in Section 3.2.2, we found that using Pigouvian taxes and uniform standards was unlikely to yield efficiency in standards, pricing, and R&D spending. Indeed, we found that underinvestment and inefficient pricing were the likely outcomes under a system of uniform standards while overinvestment is likely to arise with the addition of a Pigouvian tax. In this section, we consider the effect that nonuniform standards have on efficiency considerations. Nonuniform in this setting means that different firms are held to different environmental standards *within the same state.*[7] For example, in state B the losing firm in the technology race could be given a lower standard than the winning firm. We find that using standards in this manner can induce technological innovation. At the same time, we find that a Pigouvian damage tax is too large, but a lower output tax can yield efficiency in pricing. Given this system of nonuniform standards and taxes, firms reach the first best outcome through private decision-making.

3.3.1 Choosing the correct standards and tax

For states A and C, the tax only needs to be set up so that it equals the damage resulting from a given standard. Therefore, if the standard is set at the socially optimal level in these states, firms will bid the price level down to the welfare maximizing level. There is no need for a nonuniform standard in these states because choosing the correct uniform standard yields efficiency. Also, the optimal tax in states A and C is the Pigouvian tax.

Choosing the standard in state B is the interesting case. Given the Bertrand pricing scheme of the model, the winning firm in the technology race will set a price equal to the loser's cost. Let s_L denote the loser's standard and s_W the winner's. Because the winning firm's standard leads to the observed level of environmental quality (the winner is the only firm producing), its standard is chosen to be the optimal standard: $s_W = s_A^*$. In choosing the optimal tax in state B, the social planner chooses a tax, t_B, that will yield efficiency in pricing. To do this, the tax is chosen so that the loser's cost is equal to the optimal price:

$$(3.0) \quad c(s_L,0) + t_B = c(s_A^*,1) + D(s_A^*)$$

This ensures that competitive bidding will result in the efficient output Q_A^*. The rents to the winning firm are then:

$$(3.1) \quad \{c(s_L,0) + t_B - [c(s_A^*,1) + t_B]\}Q_A^* = [c(s_L,0) - c(s_A^*,1)]Q_A^*$$

Under this system of nonuniform standards, the choice of the loser's standard becomes paramount. If the loser's standard is set equal to the winner's standard s_A^* (as it would be under a BACT rule), the result is overinvestment. Let $s_L = s_A^*$. Then, by adding and subtracting $D(s_A^*)$ to the costs in (3.1) yields:

$$(3.2)\quad \{[c(s_A^*,0)+D(s_A^*)]-[c(s_A^*,1)+D(s_A^*)]\}\,Q_A^*$$

Note that (3.2) is larger than the rents from the subsidy case in (2.10) because $c(s_A^*,0)+D(s_A^*) > c(s_C^*,0)+D(s_C^*)$ due to the optimality of s_C^*. This leads to even greater overinvestment. As a result, the social planner must set a nonuniform standard where $s_L < s_W = s_A^*$. The optimal environmental standard setting scheme, then, includes nonuniform standards where the loser in the technology race receives a "break" on the environmental standard.[8]

In setting the loser's standard, the environmental authority wants to induce technology investment, but not too much. The standard will be set so that the following relationship holds:

$$(3.3)\quad [c(s_L,0)-c(s_A^*,1)]Q_A^* = W(1)-W(0)$$

Here, the social planner chooses a standard for the loser that will induce the optimal level of investment by the winning firm. This use of nonuniform standards gives the social planner the ability to control the rents available to the winning firm. Now, recall from (3.0) that the per unit tax t_B is set so that the efficient price results from competitive bidding. Rearranging (3.0) yields:

$$(3.4)\quad D(s_A^*)-t_B = [c(s_L\,0)-c(s_A^*,1)]$$

With $W(1) > W(0)$, (3.3) and (3.4) give us the following:

$$(3.5) \quad D(s_A^*) - t_B = \frac{W(1) - W(0)}{Q_A^*} > 0$$

Therefore, the optimal tax in state B is *less* than the Pigouvian damage tax.[9] This result derives from the fact that the cost to the losing firm from the lower standard is still greater than the cost facing the winning firm and its corresponding higher standard.

3.3.2 Technology Revelation and Compliance

The winning firm in the technology race will only reveal a successful innovation if the rents from doing so outweigh the rents from not revealing success. It may be reasonable to assume that under certain circumstances the environmental authority may detect a technological innovation. But as the following analysis demonstrates, the assumption of detection by the environmental authority is not necessary because a successfully innovative firm will find it in its own private interest to reveal success.

(3.3) gives the rents to the winning firm in the technology race. This may be seen as the areas E,F, and G in Figure 3.1.[10] This level of rents, arising from the choice of s_L, yields the socially optimal level of investment. By not revealing its innovation the winning firm receives the following rents:

(3.6) $[c(s_C^*,0) - c(s_c^*,1)]Q_C^*$

Adding and subtracting $D(s_C^*)$ inside the bracketed term in (3.6) allows for a simple comparison of rents to the winning firm in Figure 3.1. By withholding the innovation, the rents to the winning firm are depicted by the area E. Clearly, the winning firm's rents are larger by truthfully revealing the successful innovation. It follows that the winning firm will always reveal a successful innovation.

Under a BACT rule, firms have an incentive to invest in environmental technologies as they attempt to capture rents by being the single, successful innovator. That these firms will truthfully reveal an innovation suggests that overcompliance under a BACT rule may be associated with profit maximizing behavior. Of course, this result holds given the assumptions of our model, but it may be part of a rational scheme for firms under alternative assumptions. At the very least, the possibility that overcompliance is part of a profit maximizing strategy provides the basis for further investigation of the incentives under the current BACT rule.

3.4. Second Best Alternatives

The assumptions used to derive the results in Section 3.3 suffer the same criticisms normally associated with the Pigouvian approach. Particularly, taxing different firms at different rates has been attacked from a legal standpoint (Teitenberg, 1985). In this section, we examine the problem given a *fixed* per unit damage tax that is identical across firms. This approach leads to efficiency losses as the environmental authority loses a degree of freedom in its regulatory approach. By using a nonuniform standard, however, some of this efficiency loss may be avoided. This second approach is still second best, as it does not yield first best efficiency, but it is an improvement over the fixed tax and uniform standard approach, which most closely approximates the EPA's current regulatory approach. In addition, a standards scheme that treats firms differently is likely to encounter less problems in implementation than the Pigouvian tax scheme because firms *are* easily differentiated by their environmental technologies.

3.4.1 Fixed Tax, Uniform Standard

While the use of per unit damage taxes and nonuniform standards are capable of obtaining first best efficiency, as was shown earlier, it is more likely that a tax would be assessed independently of the different states (i.e., both firms innovate, both firms do not innovate, one innovates and the other is unsuccessful). Indeed, this tax may be zero. Given this limitation, it is worth examining how to optimally set standards in the presence of a fixed tax (perhaps zero). In this section, we examine how optimal standards may be selected given: (1) a fixed tax and, (2) a standard that varies from state to state, but not within a particular state. The output price within a given state is as follows:

(4.0) Price in state A (both firms successful): $c(s_A, 1) + t$

Price in state B (one successful, one unsuccessful): $c(s_B, 0) + t$

Price in state C (both firms unsuccessful): $c(s_C, 0) + t$

3.4.1.1 Standard-setting in state A and state C

For states A and C, the choice of the ex post efficient standard is straightforward. In state A, for example, if $t < D(s_A^*)$, then s_A is chosen to correct some of the overproduction resulting from the firm not facing the full social cost of production. Notice, however, that s_A will not be chosen to fully correct the underpricing:

(4.1) $c(s_A^{**}, 1) + t \neq c(s_A^*, 1) + D(s_A^*)$

Here, s_A^{**} represents the expost efficient standard in state A for the fixed tax case. Because there is efficiency loss associated with a standard that is not first best, the ex post efficient standard will not be so high that it corrects the entire pricing problem. Instead, the standard will correct pricing only up to the point where further increases in the standard would decrease social welfare as s_A^{**} moves further from the first best standard s_A^*. Hence, choosing the ex post efficient standard in the fixed tax case is seen as a trade off between efficient pricing and efficient standards.

Like state A, the ex post efficient standard in state C is greater than the first best standard for state C, assuming $t < D(s_C^*)$. We focus attention on the case where *t* is small because this is most likely to be the case (and *t* may very likely be zero). As a result of the small tax, $s_C^{**} > s_C^*$. Because firm investment is not a function of any variables of either state A or C (see, for example, (2.6)), the optimal standards in these two cases are the ex post efficient standards. Therefore, the standards are chosen to maximize the following expression:

$$(4.2) \quad W^{**}(\delta,t) = \max_s \int_0^{Q(c(s,\delta)+t)} P(z)dz - [c(s,\delta) + D(s)]\, Q(c(s,\delta)+t)$$

(4.2) gives rise to the following first order condition:

$$(4.3) \quad \frac{d\,c(s,\delta)}{d\,s}\left\{Q'(c(s,\delta)+t)\left[t - D(s)\right] - Q(c(s,\delta)+t)\right\} - D'(s)\,Q(c(s,\delta)+t) = 0$$

(4.2) and (4.3) may be used to establish the following results (see Appendix 3 for proofs):

$$(4.2.1) \quad \frac{dW^{**}(\delta,t)}{d\delta} > 0 \text{ if } t \geq D(s)$$

$$(4.2.2) \quad \frac{dW^{**}(\delta,t)}{dt} >=< 0 \text{ as } D(s) >=< t$$

$$(4.3.1)\quad \frac{ds^{**}(\delta,t)}{dt} < 0 \text{ as } t \leq D(s)$$

The first corollary, (4.2.1), is a sufficient condition for an innovation to be welfare enhancing. If the per unit tax is larger than corresponding damages, then the costs facing the firm are larger than the true social costs of production. This leads to too little production and welfare losses. Under these circumstances, an innovation mitigates a portion of the welfare losses arising from the tax by lowering the costs facing the firm and increasing production (recall that the standard is being held constant here). The corollary also produces a less intuitive result—that successful innovations may not always be welfare enhancing. Consider the case where the per unit tax is very small, perhaps zero. Under these circumstances, there is clearly too much production by firms due to the absence of the full damage tax. A successful innovation, *while holding the standard constant*, leads to further production and a corresponding welfare loss.

(4.2.2) is a straightforward result arising directly from the welfare losses associated with a tax that is either too high or too low. For example, if the per unit tax is below the per unit damage associated with a given standard, an increase in the tax towards the Pigouvian tax is welfare enhancing. The opposite is true for a tax that is too large.

Corollary (4.3.1) demonstrates the effect a change in the tax has on the optimal standard for states A and C. Consider a situation where again the tax is below the corresponding damages for a certain standard. In this case the standard is raised somewhat above the first best standard to correct some of the overproduction resulting from firms not facing the full social cost of production. An increase in the per unit tax in this case is a movement toward the Pigouvian tax and, thus, the standard may be adjusted toward the first best standard. The lowering of the standard in this case is the result of the increased tax alleviating some of the inefficiency arising from overproduction.

When the damage tax is fixed across states there will clearly be inefficiencies resulting from suboptimal levels of production. As a result, it is a straightforward exercise to adjust the standard appropriately in states A and C. When the tax is too low (i.e., below the Pigouvian tax), the standard is adjusted upward, away from the first best standard. The standard is not adjusted to fully correct for pricing inefficiencies because there are also welfare losses arising from a standard that is not first best. As a result, there is a trade off between efficient pricing and an efficient standard. A similar situation arises when the tax is initially set too high. In states A and C, however, there is no need to incorporate the effects that pricing and standard adjustments would have on firms' investment decisions because they only consider state B in their profit calculations. This introduces a complication into the setting of the environmental standard in state B. We turn now to that case.

3.4.1.2 Standard-setting in state B

Setting the environmental standard in state B involves choosing a standard that accounts for the investment incentives of firms. Because state B is the only state where firms earn rents, the probability of reaching any of the states will be dependent upon the standard chosen in state B. Consider the rents to the winning firm in state B:

(4.4) $[c(s_B,0)-c(s_B,1)]Q(c(s_B,0)+t)$

Given that the winning firm obtains (4.4), it is straightforward to calculate the firms optimal level of investment in environmental technologies:

(4.5) $\max_{I_i} \quad q(I_i)(1-q(I_i))\{[c(s_B,0)-c(s_B,1)]Q(c(s_B,0)+t)\}-I_i$

(4.5) gives rise to the following first order condition:

(4.6) $q'(I_i)(1-q(I_j))\{[c(s_B,0)-c(s_B,1)]Q(c(s_B,0)+t)\}-1=0$

Solving for I_i in (4.6) yields a level of investment that is a function of both the standard s_B and the fixed tax *t*. Hence, in choosing the optimal standard in state B, the social planner must consider the effect that the standard will have on resulting firm investment. We may examine the relationship between firm investment and the standard s_B by further inspection of (4.6). In particular:

(4.7) $\frac{\partial I_i}{\partial s_B}$ = (in sign)

$$\left[\frac{\partial c(s_B,0)}{\partial s_B} - \frac{\partial c(s_B,1)}{\partial s_B}\right] Q(c(s_B,0)+t) + [c(s_B,0) - c(s_B,1)]Q'(c(s_B,0)+t)\frac{\partial c(s_B,0)}{\partial s_B}$$

The first term in the summation on the RHS of (4.7) is positive but the second summation term is negative. The sign of (4.7), then, depends upon the magnitude of these terms. Because the sign is ambiguous, we must look more closely at how investment is determined. Figure 3.2 depicts a situation where the standard is increased from s'_B to s''_B. This increase widens the gap between the winner's cost and the loser's cost by assumptions on the cost of meeting a particular standard for different technologies (i.e., $c_s(s_B,0) > c_s(s_B,1)$). For the increase in standard to increase investment, the demand curve must also be sufficiently inelastic. This is seen in Figure 3.2 when A > C. If this is not the case then firm investment could decrease with an increase in s_B. The effect that changes in the standard have on investment cannot be understated in this model as they, along with the fixed tax, have the potential to significantly alter investment. According to (4.6), changes in the fixed tax will result in changes in firm investment. The fixed tax will alter the level of production by changing the costs facing the firm.

(4.8) $\frac{dI_i}{dt}$ = (in sign) $[c(s_B,0) - c(s_B,1)]Q'(c(s_B,0)+t) < 0$

(4.8) is unambiguously negative. An increase in the fixed tax decreases quantity, which always decreases the rents to the winning firm. This is seen in Figure 3.3 by the decrease in rents from A+B to A for an increase in the fixed tax from t_1 to t_2.

We now return to the planner's choice of s_B for state B. First, let $W^{**}(A)$ represent social welfare in state A for the optimal standard s_A^{**}. Likewise, let $W^{**}(C)$ be social welfare in state C with the optimal standard s_C^{**}. In choosing s_B, the social planner must take into account the effect that s_B has on investment. Therefore, the maximization problem facing the planner is:

$$(4.9)\quad \max_{s_B} \quad q(I)^2 W^{**}(A) + [1-q(I)]^2 W^{**}(C) + q(I)[1-q(I)]W_B(s_B,t) - 2I$$

with: (4.9.1) $I = I(s_B,t)$ (functional form derived from (4.6))

$$(4.9.2)\quad W_B(s_B,t) = \int_0^{Q(c(s_B,0)+t)} P(z)dz - [c(s_B,1) + D(s_B)]Q(c(s_B,0)+t)$$

(4.9) yields the following first order condition:[11]

$$(4.10)\quad \begin{aligned} &\frac{\partial I(s_B,t)}{\partial s_B}\{q'(I)[q(I)(W^{**}(A) - W_B(s_B,t)) + (1-q(I)(W_B(s_B,t) - W^{**}(C) - F_B)\} \\ &+ q(I)(1-q(I))\frac{\partial W_B(s_B,t)}{\partial s_B} = 0 \end{aligned}$$

By examining (4.10) we would like to see how the efficient standard $\hat{s}_B$ relates to the ex post efficient standard s_B^{**}. Because $dW_B / ds_B = 0$ at s_B^{**} (this is simply the first order condition for the ex post standard in state B), we need only sign ($W^{**}(A)$ - $W_B(s_B,t)$) and ($W_B(s_B,t)$ - $W^{**}(C)$ - F_B) to establish the relationship between $\hat{s}_B$ and s_B^{**} (where $F_B = [\, c(s_B,0) - c(s_B,1)\,]\, Q(c(s_B,0)+t)$).

(4.11) $(W_B(s_B,t) - W^{**}(C) - F_B) < 0$ for $s_B \neq s_C^{**}$ (see Appendix 4 for proof)

(4.11) relies on the fact that subtracting the rents from innovation, F_B, from $W_B(s_B,t)$ leaves social welfare equivalent to *W(C)* (welfare function in state C before maximization).

While (4.11) holds for any s_B not equal to s_C^{**}, establishing the sign of ($W^{**}(A)$ - $W_B(s_B,t)$) relies on some assumptions about the fixed tax. Because it is most likely that the fixed tax would be set too low (perhaps zero), it is this case that is most interesting. When the fixed tax is set below the per unit damage, social welfare may actually be higher in state B than state A because of the overproduction arising in state A from this low tax. Because firms have an incentive to raise price above marginal costs in state B, this naturally mitigates the affect of a tax that has been set below the marginal damage. The relationship between standard setting and the fixed tax is an important one so we fully develop the difference between $W^{**}(A)$ and $W_B(s_B,t)$ here.

Proposition: $W^{**}(A)$ - $W_B(s_B,t) < 0$ at s_B^{**}, the ex post optimal standard in state B

Proof:

First recall that $W^{**}(A) = \int_0^{Q(c(s_A^{**},1)+t)} P(z)dz - [c(s_A^{**},1) + D(s_A^{**})]Q(c(s_A^{**},1)+t)$

Evaluating $W_B(s_B,t)$ at s_A^{**} yields the following:

(4.12) $$W_B(s_B,t)\big|_{s_B=s_A^{**}} = \int_0^{Q(c(s_A^{**},0)+t)} P(z)dz - [c(s_A^{**},1) + D(s_A^{**})]Q(c(s_A^{**},0)+t)$$

Subtracting (4.12) from $W^{**}(A)$ gives:

(4.13) $$\int_{Q(c(s_A^{**},0)+t)}^{Q(c(s_A^{**},1)+t)} P(z) - [c(s_A^{**},1) + D(s_A^{**})]dz$$

And (4.13) is negative for $c(s_A^{**},0) + t < c(s_A^{**},1) + D(s_A^{**})$ (this is a sufficient, but not necessary condition—see Figure 3.4). We may rewrite this condition as follows:

(4.14) $$t \le D(s_A^{**}) - [c(s_A^{**},0) - c(s_A^{**},1)] < D(s_A^{**})$$

We have not yet proven that $W^{**}(A)$ - $W_B(s_B,t) < 0$ at s_B^{**}, but this follows immediately from the fact that evaluating (4.12) at s_B^{**} increases the difference between $W^{**}(A)$ and $W_B(s_B,t)$ due to the optimality of s_B^{**}. That is,

$$(4.15)\quad W^{**}(A) - W_B(s_B, t)\Big|_{s_B = s_B^{**}} \;<\; W^{**}(A) - W_B(s_B, t)\Big|_{s_B = s_A^{**}} \;<\; 0$$

Recall that in the first part of Section 3.4 we established that given a fixed tax below the per unit damage in states A and C, s_A^{**} would be above s_A^* and s_C^{**} would be above s_C^*. This was due to the inefficiencies in pricing due to a tax that was set too low. If the same situation arises in state B, though, we cannot make the same assertions due to the effect s_B has on investment. Indeed, we would like to know if the optimal standard in state B, $\hat{s}_B$, is greater than, less than, or equal to the ex post efficient standard in state B, s_B^{**}. By examining (4.10), it turns out that $\hat{s}_B < s_B^{**}$ if condition (4.14) holds *and* $dI/ds_B > 0$; we established the conditions for this to be true in (4.7).

Much of Section 3.4 has been spent examining the social planner's choice of standard in state B, but what does all of this tell us? The main result is that the planner should choose a standard that takes into account pricing, efficiency in the environmental standard, and investment in environmental technologies. Ignoring any one of these is likely to lead to inefficiency. We examined the (most likely) case where the fixed tax was set below marginal damages for a given standard. Under these conditions, the planner would like to raise the standard to the ex post efficient level, s_B^{**}, to control for inefficiencies in pricing, but this would lead to overinvestment incentives. We derive this result directly and find that the social planner's optimal choice of the standard, $\hat{s}_B$, is below s_B^{**} because of the effects of overinvestment (assuming that $dI/ds_B > 0$).[12] Hence, the optimal standard for state B considers the effect that the standard has on investment as well as pricing and efficiency in environmental standards.

While our analysis above details the relationship between the optimal standard and the ex post optimal standard in state B, we do not establish the relationship between $\hat{s}_B$ and s_A^{**} (ex post optimal standard in state A) or $\hat{s}_B$ and s_A^{*} (first best standard in state A). These relationships are interesting because in the first best case, state A and state B are identical in both total welfare and environmental standards. We examine the above relationships in detail in Appendices 5 and 6, respectively.

3.4.2 Fixed Tax, Nonuniform Standard

As was demonstrated in Section 3.3, nonuniform environmental standards may be used with a variable taxing scheme in our model to obtain first best efficiency. Essentially, the variable tax is used to correct pricing while the loser's standard is used to correct investment problems. The winner's standard is set equal to the welfare maximizing standard in this set-up. In this section, we consider the same nonuniform standard scheme but fix the per unit damage tax exogenously (perhaps at zero). The analysis becomes more complicated than the fixed tax/uniform standard that was considered earlier in the section, so we restrict our attention to a per unit tax that is initially set too low (i.e., below the marginal damage). The presence of the nonuniform standard gives the planner more flexibility and allows the environmental standard to be set closer to the first best standard. Not surprisingly, the extra degree of freedom allowed to the planner (from the nonuniform standard) results in higher social welfare.

3.4.2.1 Standard-setting in state A and state C

Because the standard remains uniform in states A and C the nonuniform standard/fixed tax case and the uniform standard/fixed tax case are identical (see Section 3.4.1.1 for details of states A and C). Hence, a tax that is set below the marginal damage in these states is countered by a higher environmental standard. In addition, corollaries (4.2.1), (4.2.2), and (4.3.1) remain valid here.

3.4.2.2 Standard-setting in state B

In state B, the social planner chooses a "loser's standard" and a "winner's standard." Because the winner obtains the entire market in our model, its standard is the observed standard. The loser's standard is very important, however, because it determines the output price in nonuniform standard/fixed tax case:

(4.15) Price in state B: $c(s_L, 0) + t$

The price in (4.15) leads to the following rents for the winning firm:

(4.16) $[c(s_L,0)-c(s_W,1)]Q(c(s_L,0)+t)$

In the uniform standard case, of course, $s_L = s_W$. This will not be true in the nonuniform standard case where the social planner chooses s_L and s_W separately. Given that the winning firm obtains (4.16), it is straightforward to determine its optimal level of investment in environmental technologies:

(4.17) $\max_{I_i} \quad q(I_i)(1-q(I_j))\{[c(s_L,0)-c(s_W,1)\,Q(c(s_L,0)+t)\}-I_i$

(4.17) gives rise to the following first order condition for firm investment:

(4.18) $q'(I_i)(1-q(I_j))[c(s_L,0)-c(s_W,1)]Q(c(s_L,0)+t)-1=0$

Solving for I_i in (4.18) yields firm investment as a function of s_W, s_L, and t—i.e., I_i = $I_i(s_W, s_L, t)$. The planner's flexibility in standard-setting in the nonuniform standard case is apparent; the planner chooses two standards, both of which determine a portion of firm investment. We may examine the relationship between firm investment, standards, and taxes by further investigation of (4.18). Note that:

(4.19) $\frac{\partial I_i}{\partial s_L}$ = (in sign)

$$q'(I_i)(1-q(I_i))\,c_s(s_L,0)\{Q(c(s_L,0)+t)+[c(s_L,0)-c(s_W,1)]Q'(c(s_L,0)+t)\}$$

The first product of the first three terms in (4.19) is positive, which implies that the sign of (4.19) depends on the bracketed term. Assuming overinvestment exists (the case of interest in this section), the bracketed term is comprised of a positive term and a negative term. As a result, the sign of (4.19) is ambiguous. Figure 3.6 gives some insight into the problem. The rents from standard s_L' are represented by A + B whereas the rents from an increase in the standard to s_L'' are represented by B + C. The increase in the loser's standard from s_L' to s_L'' results in a larger difference between the loser's costs and the winner's costs (implying higher rents *ceteris paribus*), but the increase in the loser's costs is also accompanied by a decrease in the quantity sold (implying lower rents *ceteris paribus*). Due to these conflicting effects, investment will increase with an increase in the loser's standard if C > A and will decrease if A > C.[13]

Increases in the winner's standard have no effect on output, which is determined entirely by the loser's costs (and hence, the loser's standard) and the fixed tax. An increase in the winner's standard does, however, lower the rents available to the winning firm in the technology race. The result is a decrease in investment when the winner's standard is increased. By (4.18) we get,

$$(4.20)\quad \frac{\partial I_i}{\partial s_W} = \text{(in sign)}\ \ q'(I_i)(1-q(I_j))(-c_s(s_W,1))\,Q(c(s_L,0)+t)\ <\ 0$$

We may also examine the effect that a change in the fixed tax has on investment. An increase in the tax lowers the quantity sold but does not affect the difference between the winner's and loser's costs (both face the same fixed tax). The result is a decrease in rents to the winning firm. Again by (4.18), this decrease in rents lowers investment:

$$(4.21)\quad \frac{\partial I_i}{\partial t} = \text{(in sign)}\ \ q'(I_i)(1-q(I_j))[c(s_L,0)-c(s_W,1)]Q'(c(s_L,0)+t)\ < 0$$

We now turn our attention to the social planner's choice of s_L and s_W. The ex post efficient winner's and loser's standards in state B are easy to determine, somewhat unlike the choice of s_B in the uniform standard/fixed tax case. Because the winner will set price slightly below the loser's costs, a pricing inefficiency results in state B—one of the central results of our model. In choosing s_W, however, the social planner does not need to consider the pricing problem that arises in state B because it may be corrected with the loser's standard. (4.22) gives the maximization problem facing the planner for the *ex post* case:

$$(4.22)\quad \max_{s_L,s_W} \int_0^{Q(c(s_L,0)+t)} P(z)dz - [c(s_W,1)+D(s_W)]Q(c(s_L,0)+t)$$

(4.22) gives rise to the following first order conditions:

$$(4.23)\quad s_L:\quad Q'(c(s_L,0)+t)\frac{\partial c(s_L,0)}{\partial s_L}\left\{[c(s_L\, 0)+t]-[c(s_W,1)+D(s_W)]\right\}=0$$

$$s_W:\quad -c_s(s_W,1)-D'(s_W)=0$$

The loser's standard that satisfies (4.23) will equate the loser's cost to the true social cost with the winner's standard. That is, the bracketed term will equal zero at the optimal choice of s_L. The winner's standard is seen to be the first best standard from (2A) in Section 3.2, $s_W^{**}=s_A^*$. Hence, (4.23) implies that the choice of standards *ex post* for state B will result in first best efficiency in environmental standards and pricing—even with a fixed, exogenous tax.

The optimal choice of s_L and s_W in the nonuniform standard/fixed tax case must account for investment inefficiencies. We examine the case of overinvestment in this section, and we restrict attention to the case where the fixed tax is set below environmental damage (the tax may be zero due to political considerations). The social planner's maximization problem in the nonuniform standard case may be stated as follows:

$$(4.24)\quad \max_{s_L,s_W}\quad q(I)^2W^{**}(A)+(1-q(I))^2W^{**}(C)+q(I)(1-q(I))W_B(s_L,s_W,t)-2I$$

$$(4.24.1)\quad I=I(s_L,s_W,t)$$

$W_B(s_L,s_W,t)$ is as it was in (4.22). (4.24) yields the following first order conditions:[14]

(4.25)

$$s_L: \ \frac{\partial I}{\partial s_L} q'(I)\left[q(I)(W^{**}(A) - W_B) + (1 - q(I)(W_B - W^{**}(C) - F_{BB})\right] + q(I)(1 - q(I))\frac{\partial W_B}{\partial s_L} = 0$$

$$s_W: \ \frac{\partial I}{\partial s_W} q'(I)\left[q(I)(W^{**}(A) - W_B) + (1 - q(I)(W_B - W^{**}(C) - F_{BB})\right] + q(I)(1 - q(I))\frac{\partial W_B}{\partial s_W} = 0$$

(4.25) gives the conditions necessary for the optimal values of s_L and s_W; we denote these values $\hat{s}_L$ and $\hat{s}_W$, respectively. F_{BB} = $[c(s_L,0)$ - $c(s_W,1)]$ $Q(c(s_L,0)+t)$ in (4.25). Note that $\hat{s}_W$ is the observed standard—$\hat{s}_L$ does not affect environmental quality. For this reason, we focus on the planner's choice of $\hat{s}_W$ for different values of s_L. I.e., we will focus our attention in this section to the first order condition for s_W.

In determining the relationship between the optimal winner's standard in state B and the ex post standard, we need only sign $(W^{**}(A) - W_B)$ and $(W_B - W^{**}(C) - F_{BB})$. We have, from (4.20), that $\partial I / \partial s_W < 0$. We evaluate (4.25) at the ex post optimal standard s_W^{**} (which is equivalent to the first best standard s_A^*). Hence, the last term in (4.25) is zero because $\partial W_B / \partial s_W = 0$ at the ex post optimal standard. Starting with the term $(W_B - W^{**}(C) - F_{BB})$, we examine the sign for different values of the loser's standard. There are three basic cases considered: 1. $s_L = s_C^{**}$, 2. $s_L < s_C^{**}$, and 3. $s_L > s_C^{**}$. The winner's standard is evaluated at the ex post optimal s_A^*. The relationship between s_A^* and s_C^{**} depends upon many factors including the properties of the cost curves and the demand curve. As a result, we look closely at the different possible relationships between these two standards. First consider the case where $s_L = s_C^{**}$.

$$(4.26)\quad (W_B(s_B,t)-F_{BB})\big|_{s_L=s_C^{**}} - W^{**}(C) = -[D(s_A^*)-D(s_C^{**})]Q(c(s_C^{**},0)+t)$$

(4.26) clearly depends upon the relationship between s_A^* and s_C^{**}. Particularly, $(W_B - W^{**}(C) - F_{BB})$ >=< 0 as s_A^* >=< s_C^{**}.

In the second case $s_L < s_C^{**}$. Under this condition, $c(s_L,0) < c(s_C^{**},1)$. A sufficient condition for $(W_B - W^{**}(C) - F_{BB})$ to be negative is:

$$(4.27)\quad c(s_L,0)+D(s_A^*) \geq c(s_C^{**},0)+D(s_C^{**})$$

Notice that because $s_L < s_C^{**}$, for (4.27) to hold it must be the case that $s_A^* < s_C^{**}$. Indeed, this difference must be large enough so that the resulting damages offset the cost differences in (4.27) (see Figure 3.7). Under certain conditions, $(W_B - W^{**}(C) - F_{BB})$ will be positive; these are detailed in Appendix 7.

The third case involves $s_L > s_C^{**}$. The following condition is sufficient for $(W_B - W^{**}(C) - F_{BB})$ to be positive (see Figure 3.8):

$$(4.28)\quad c(s_L,0)+D(s_A^*) < c(s_C^{**},0)+D(s_C^{**})$$

Condition (4.28) requires that $s_A^* > s_C^{**}$. Appendix 8 details the conditions for $(W_B - W^{**}(C) - F_{BB})$ to be negative in the third case.

We now turn our attention to the sign of $(W^{**}(A) - W_B)$. First, recall that for the case of overinvestment that we are considering, $s_A^{**} > s_A^{*}$. (4.29) expands $(W^{**}(A) - W_B)$ (with s_W evaluated at s_A^{*}):

(4.29)

$$W^{**}(A) - W_B = \int_{Q(c(s_L,0)+t)}^{Q(c(s_A^{**},1)+t)} P(z)dz - \{[c(s_A^{**},1) + D(s_A^{**})]\,Q(c(s_A^{**},1) + t) - [c(s_A^{*},1) + D(s_A^{*})]\,Q(c(s_L,0) + t)\}$$

In determining the sign of (4.29), we consider three cases: 1. $c(s_L,0) = c(s_A^{**},1)$, 2. $c(s_L,0) > c(s_A^{**},1)$, and 3. $c(s_L,0) < c(s_A^{**},1)$.

In the first case, where $c(s_L,0) = c(s_A^{**},1)$, the first term in (4.29) is zero while the second term reduces to the following:

$$(4.30)\quad -\{[c(s_A^{**},1) + D(s_A^{**})] - [c(s_A^{*},1) + D(s_A^{*})]\}\,Q(c(s_A^{**},1) + t)$$

(4.30) is negative because $c(s,1) + D(s)$ is minimized at the first best standard s_A^{*} and, hence, is smaller at s_A^{*} than it is at s_A^{**}. (4.29) is also negative in the second case where $c(s_L,0) > c(s_A^{**},1)$, as the bracketed term in (4.29) clearly outweighs the first term (see Figure 3.9).

In the third and final case considered $c(s_L,0) < c(s_A^{**},1)$. Given this condition, the first term in (4.29) is negative. To determine whether $(W^{**}(A) - W_B)$ is positive or negative in this third case, we must examine the bracketed term carefully. A sufficient condition for (4.29) to be negative is:

$$(4.31)\ [c(s_A^{**},1) + D(s_A^{**})]Q(c(s_A^{**},1) + t) > [c(s_A^{*},1) + D(s_A^{*})]Q(c(s_L,0) + t)$$

This is seen more clearly in Figure 3.10 when A + B < C. For $(W^{**}(A) - W_B)$ to be positive in the third case, B must be greater than C (necessary condition) in Figure 3.10.

We may now examine the relationship between the optimal standard for the winning firm and its relationship to the ex post standard for state B (which coincides with the first best standard s_A^*). We know first of all that $\partial I / \partial s_W$ in (4.25) is negative. Therefore, $\hat{s}_W >=< s_A^*$ as the bracketed term in (4.25) is < = > 0. By examining the different circumstances above, it appears that the bracketed term is more likely to be negative when $s_A^* < s_C^{**}$, and it is more likely to be positive when $s_A^* > s_C^{**}$. But unlike the uniform standard/fixed tax case, the conditions in the nonuniform standard/fixed tax case are more sensitive to the sensitivity of changing costs in response to innovations.

What emerges from careful examination of the nonuniform standard/fixed tax case is that the impact an innovation has on costs is central to setting standards and attempting to achieve efficiency. This is not surprising, but the implications are important. A nonuniform standard allows the planner a great deal of flexibility in achieving certain levels of efficiency. Indeed, when overinvestment is not a problem, the planner may proceed to set standards to obtain first best efficiency in pricing and environmental standards—even in the presence of a fixed, exogenous standard. When investment problems are present, like in the overinvestment case considered above, the planner may adjust standards in an attempt to correct for part of the overinvestment. It is this type of use of environmental standards that is stressed in this chapter and has not been considered elsewhere.

3.5. Concluding Remarks

As demand for environmental quality increases, so does the accompanying technology required to meet ever increasing levels of demand for cleaner environmental resources. The pace of development of this technology, as this chapter demonstrates, may rely significantly on market structure and the incentives to innovating firms. In addition, as we have suggested, voluntary overcompliance with standards may be a rational response to the EPA's current BACT rule for setting environmental standards. Indeed, firms have an incentive to increase the environmental standard in order to gain market share in our model. This strategic incentive may lead to overinvestment in environmental technologies, but the use of a nonuniform standard can mitigate some of this overinvestment. Indeed, we show that a first best outcome in pricing, standards, and investment is obtainable in a regulatory scheme making use of nonuniform standards. Of course, this approach requires further exploration. For example, it is likely that different market structures may lead to different outcomes than those derived in this chapter.[15] Even so, the analysis presented in this chapter offers an alternative way of looking at technological innovations in environmental standards.

3.6 Endnotes

[1] This chapter includes work completed jointly with Robert Innes.

[2] See Tirole (1988), Chapter 10 for a thorough development of R&D and technological innovation.

[3] Other researchers have examined the effects that different institutions have on environmental technology innovation (see, for example, McHugh (1985), Downing and White (1986), and Milliman and Prince (1989). While these issues are also relevant in our work, we do not directly address them in this chapter.

[4] We return briefly to the case where the innovations are not equally cost reducing later in the chapter.

[5] The winning firm would actually price slightly less than the losing firm's cost. Also, we assume that the losing firm's cost is less than the monopoly price. If this were not true, the winning firm would price at the monopoly price rather than the loser's cost.

[6] Given the shape of the relevant curves there is only one interior equilibrium, and it is unique.

[7] We do not consider different standards across different states to be nonuniform in this setting.

[8] Note that this is different from the BACT rule. This point is taken up in Section 3.4. It is also worth pointing out that it is indeterminate whether or not s_L is greater than, equal to or less than s_C^*. This depends upon the difference between $c(s_C^*,0)$ and $c(s_A^*,1)$.

[9] The optimal tax is: $t_B^* = D(s_A^*) - \dfrac{\int_{c(s_A^*,1)+D(s_A^*)}^{c(s_C^*,0)+D(s_C^*)} Q(P)dP}{Q_A^*}$.

[10] Recall that $W(1)\text{-}W(0) = \int_{c(s_A^*,1)+D(s_A^*)}^{c(s_C^*,0)+D(s_C^*)} Q(P)dP$.

[11] We also make use of the fact that $q'(I_i)(1-q(I_j))\left\{[c(s_B,0)-c(s_B,1)]Q(c(s_B,0)+t)\right\}=1$ in deriving (4.10).

[12] If dI/d s_B <0 so that an increase in the standard lowers investment, then the planner would choose a higher level of s_B because it would alleviate the pricing problem without encouraging further investment.

[13] Investment increases (decreases) with increases (decreases) in total rents. Let R =

$$[c(s_L,0) - c(s_W,1)]\, Q(c(s_L,0)+t).$$

Then, from (4.18),

$$\frac{dI_i}{dR} = \text{(in sign) } q'(I_i)(1-q(I_j)) > 0$$

[14] Making use of the fact that:

$$q'(I_i)(1-q(I_j))\left\{[c(s_L,0)-c(s_W,1)]\,Q(c(s_L,0)+t)\right\} = 1$$

[15] Isaac and Reynolds (1992) find that the conditions derived by Sah and Stiglitz (1987) do not hold under the assumption of Cournot competition in the product market. We are extending our model to address this case.

Figure 3.1

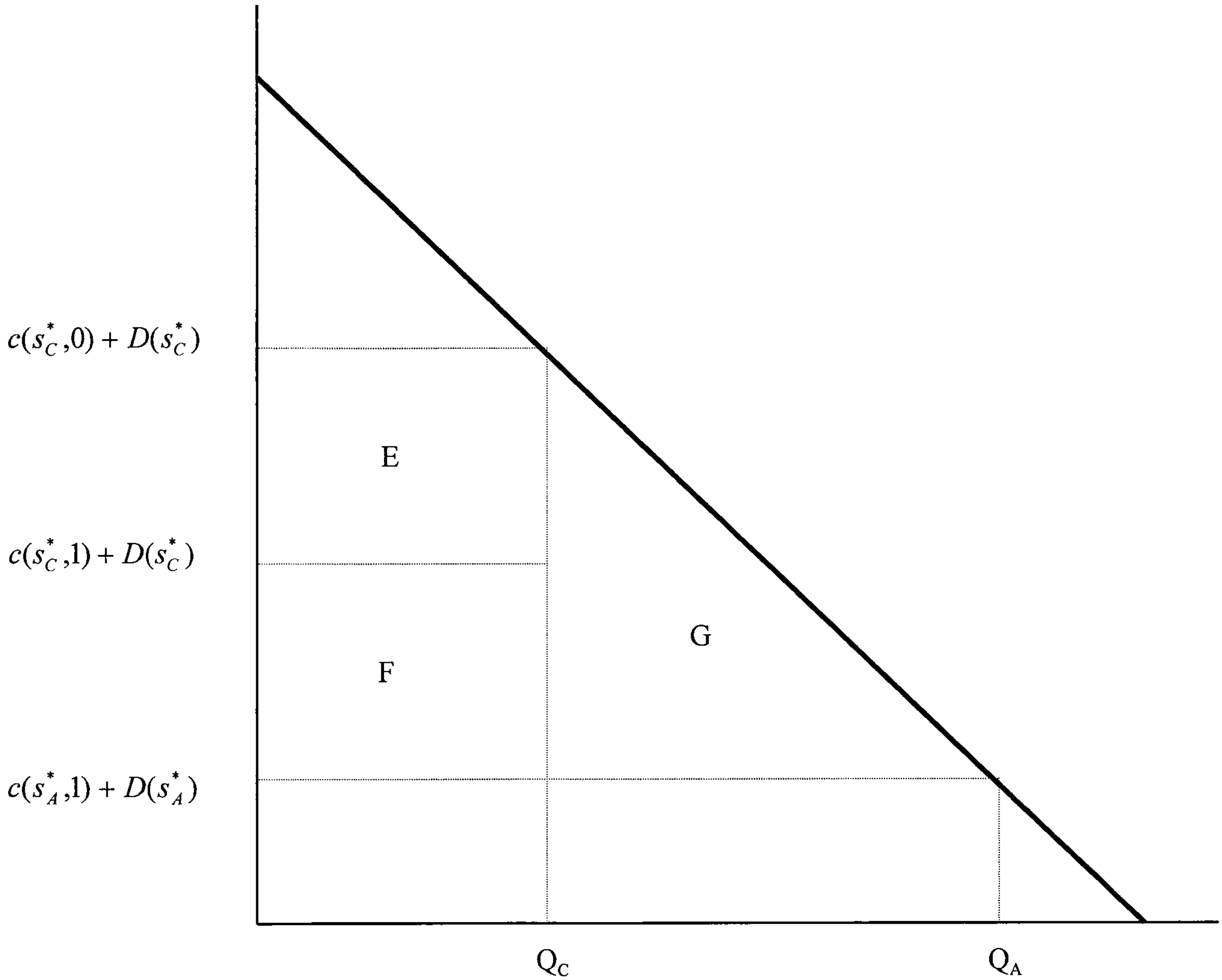


Figure 3.2

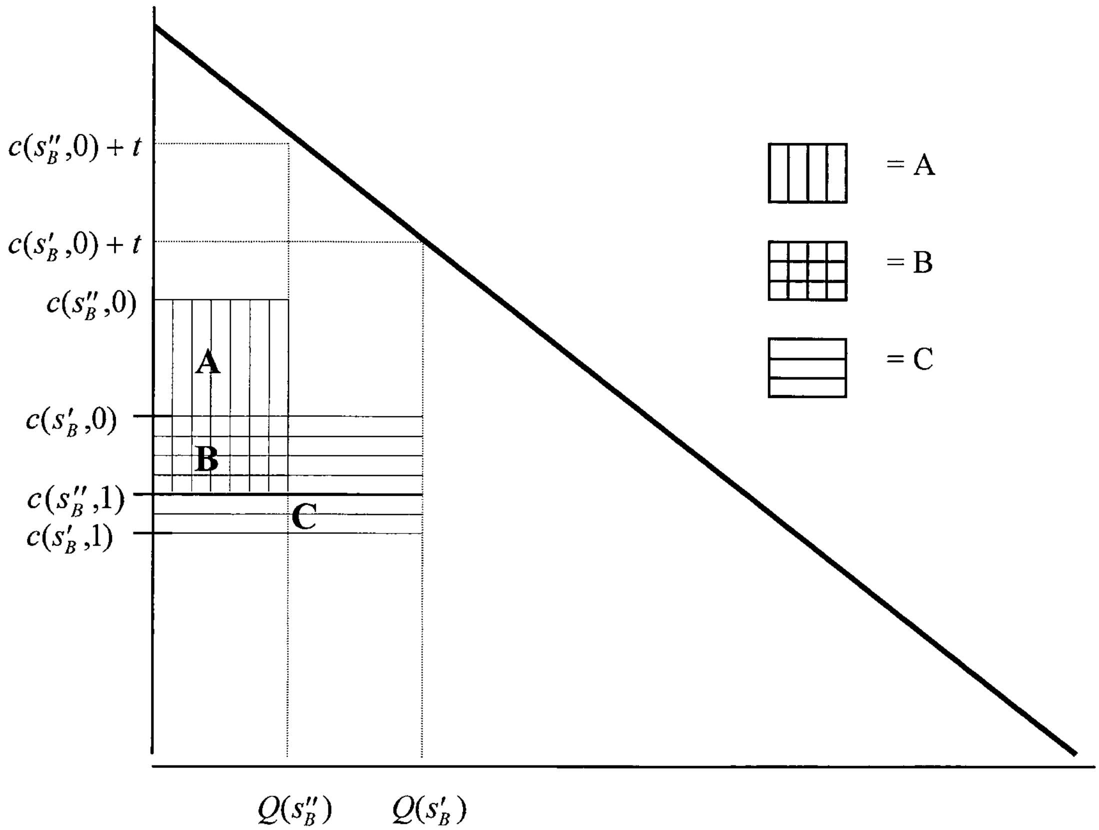


Figure 3.3

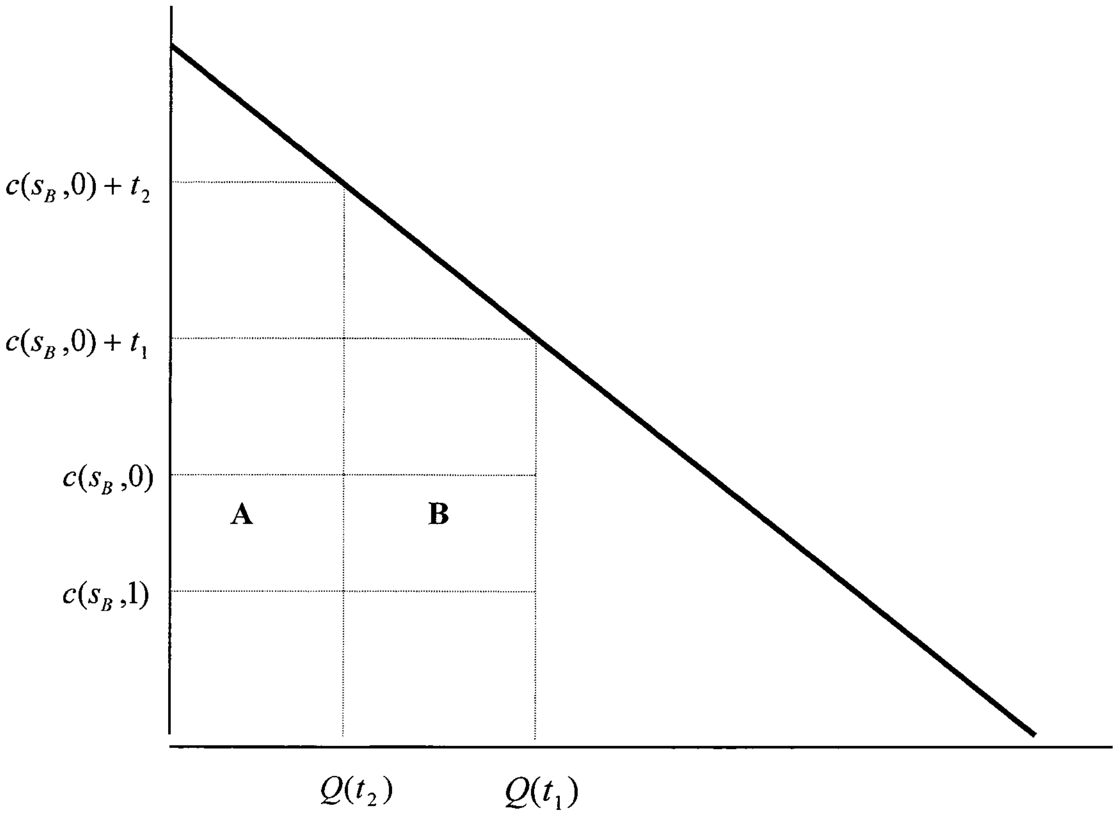
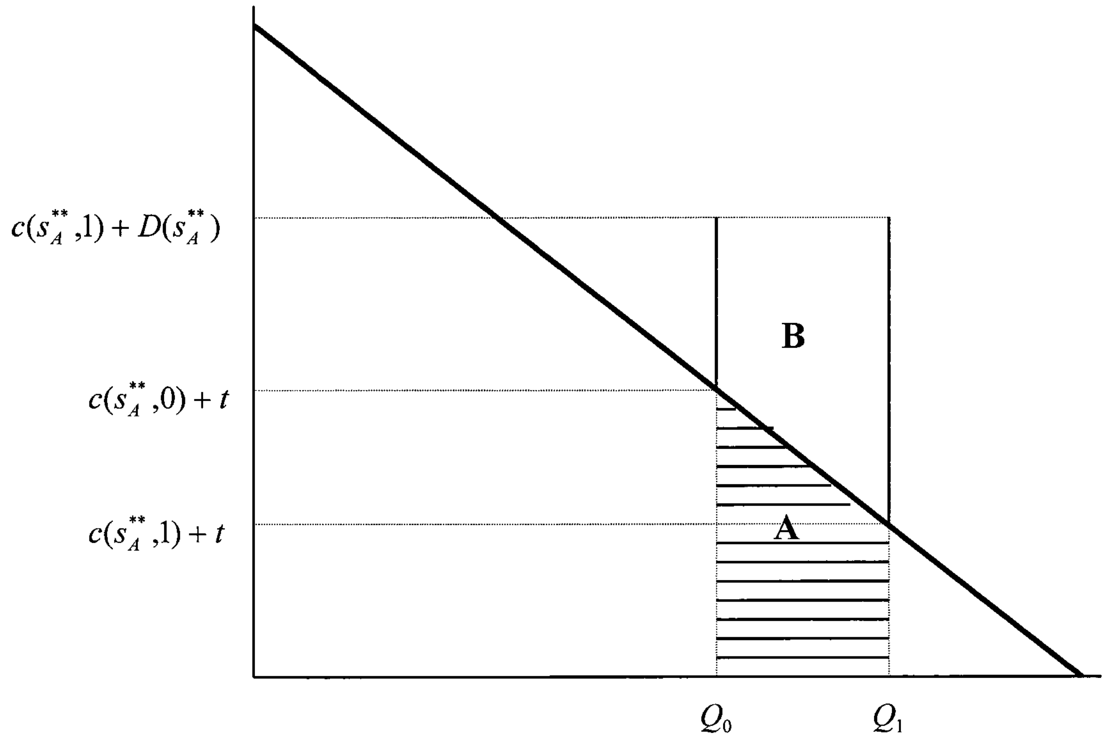


Figure 3.4



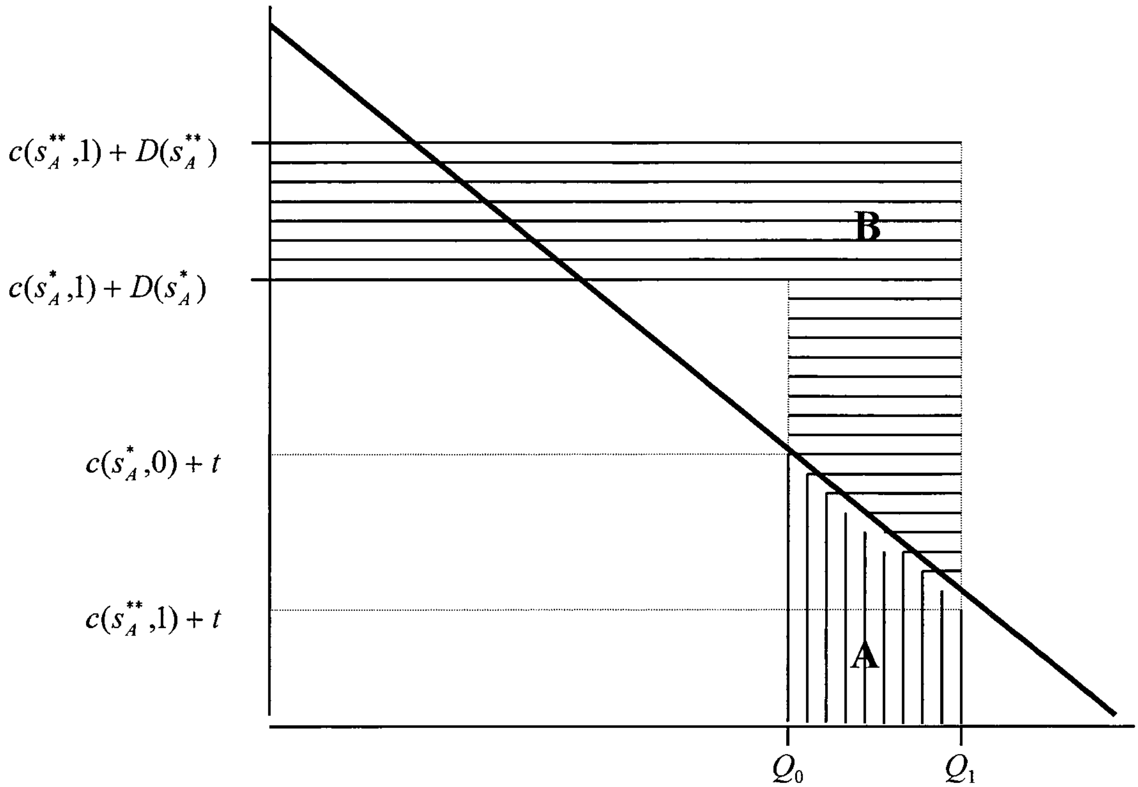
From (4.13):

$$\int_{Q(c(s_A^{**},0)+t)}^{Q(c(s_A^{**},1)+t)} P(z)dz = \text{A}$$

$$[c(s_A^{**},1)+D(s_A^{**})](Q_1 - Q_0) = \text{A} + \text{B}$$

Clearly, A+B > A

Figure 3.5



From (A.6.4),

$$\int_{Q(c(s_A^{*},0)+t)}^{Q(c(s_A^{**},1)+t)} P(z)dz \;=\; \text{A}$$

$$[c(s_A^{**},1) + D(s_A^{**})]Q(c(s_A^{**},1) + t) - [c(s_A^{*},1) + D(s_A^{*})]Q(c(s_A^{*},0) + t) \;=\; \text{A} + \text{B}$$

Clearly, A + B $>$ A

Figure 3.6

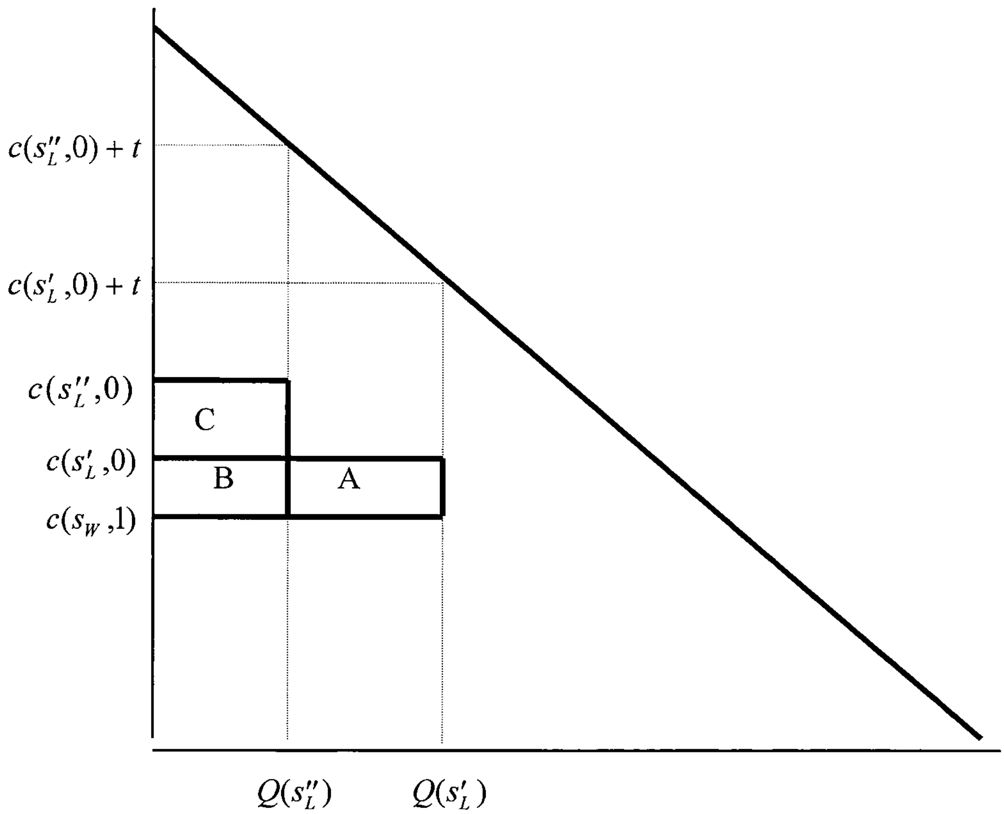
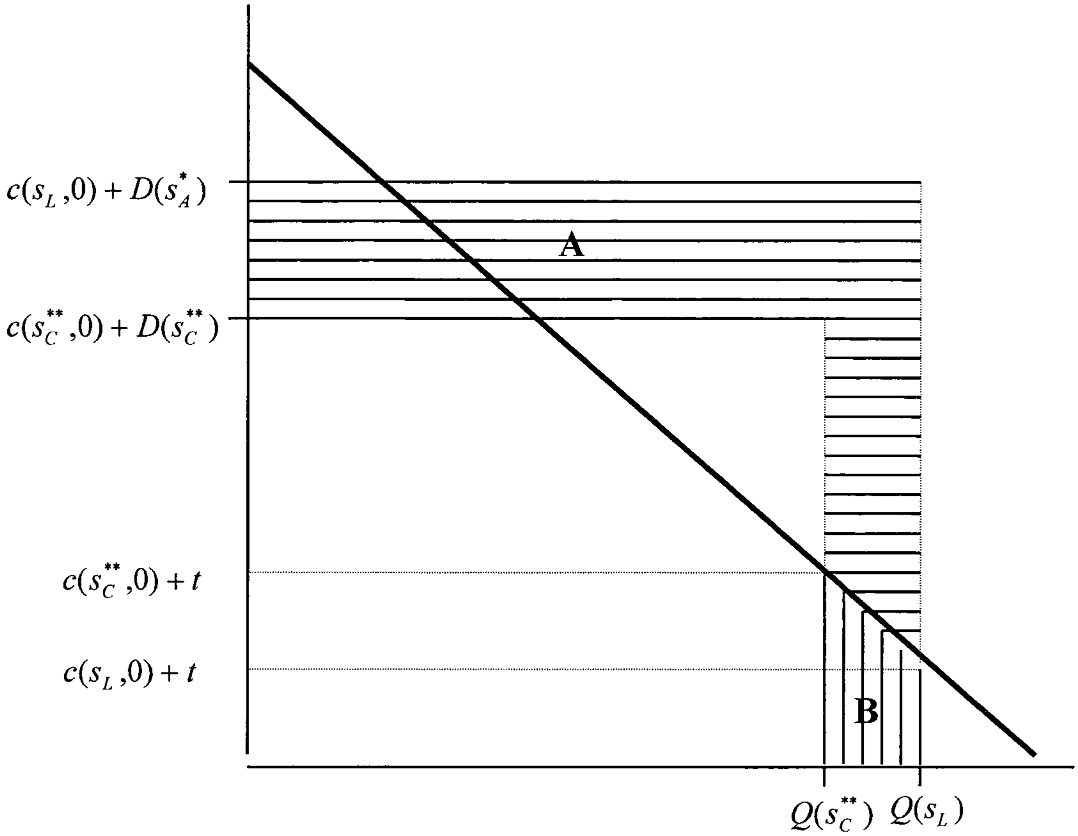
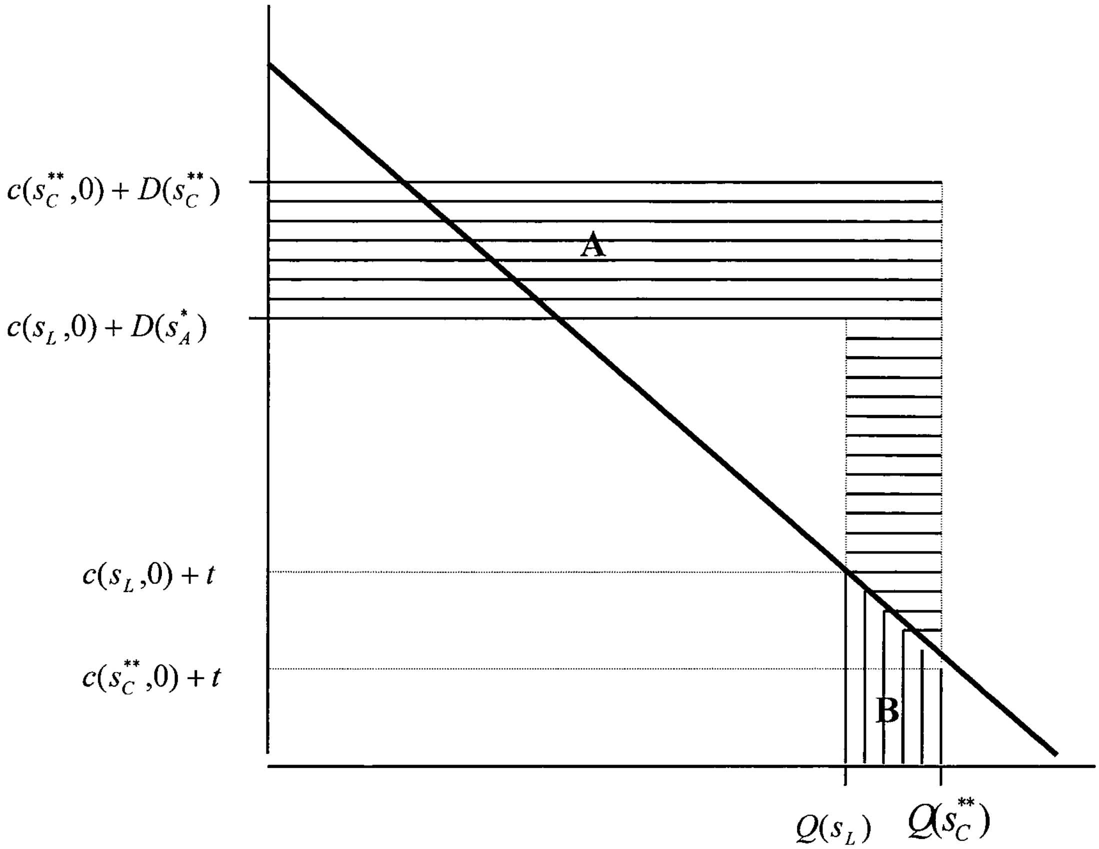


Figure 3.7



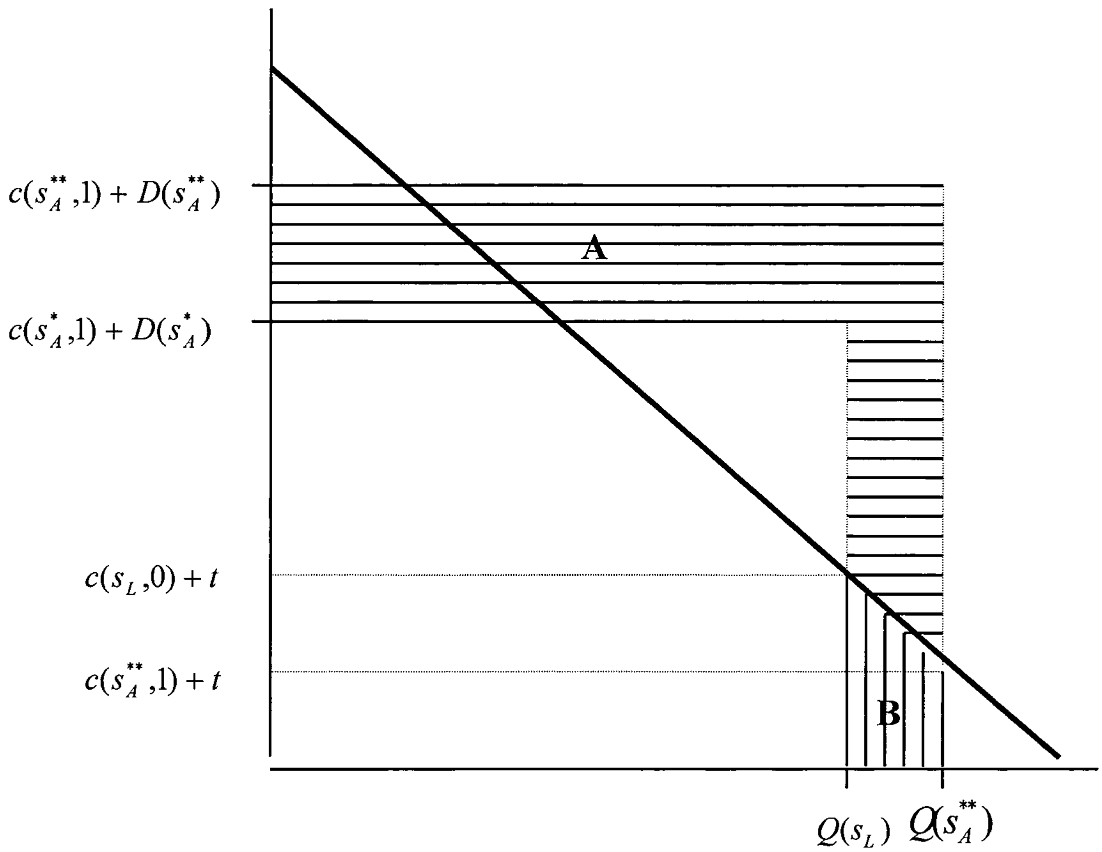
A + B > B

Figure 3.8



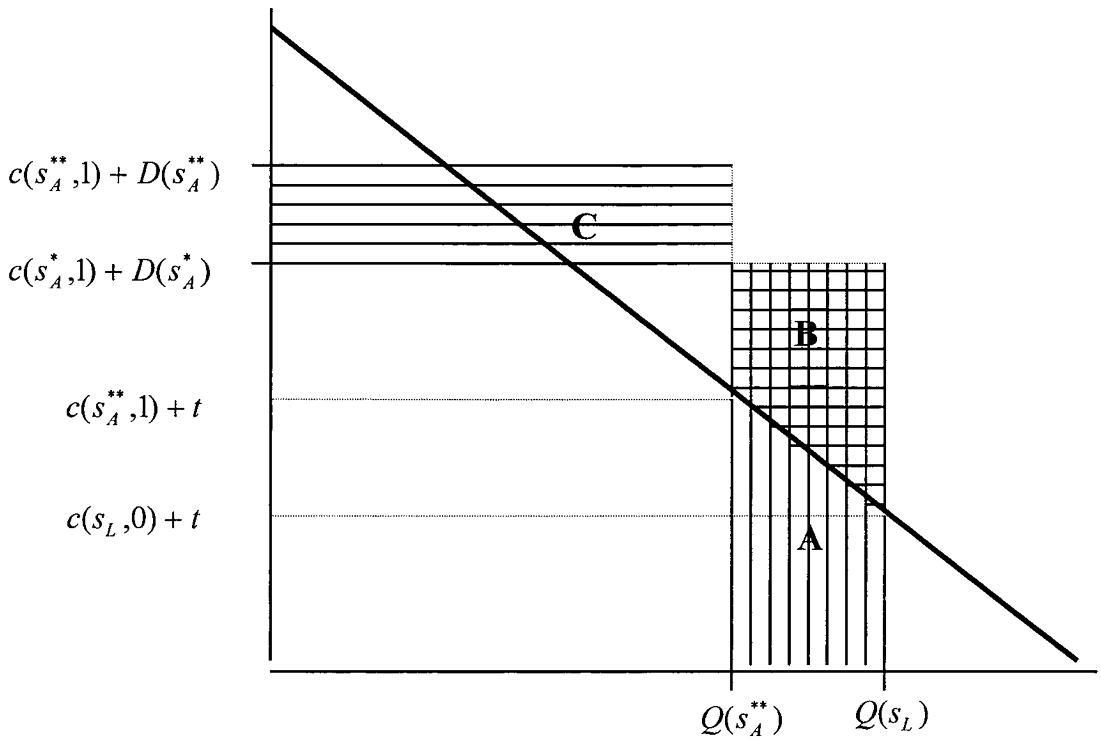
A + B > B

Figure 3.9



A + B > B

Figure 3.10



APPENDICES

Appendix A

Early judicial decisions involving pollution of streams settled upon a rule of reasonable use. This states, "A riparian owner may make reasonable use of his water for either natural or artificial wants. However, he may not so use his rights so as to affect the quantity or quality of water available to a lower riparian owner" (Black, 1991). The alternative to the reasonable use rule is the natural flow theory, which forbids riparian users from altering the quantity or quality of a stream flow. Under the natural flow theory, a riparian owner had little ability to utilize the stream's waters other than to watch them flow by his property. Realizing this, the courts allowed riparian users to access the stream even though their use might noticeably impair the water quality. The reasonable use rule was (and still is) applied in a variety of water pollution cases involving a broad spectrum of uses, including manufacturing and other industrial uses and agricultural uses.[i] For example, in *Packwood et ux.* v. *Mendota Coal and Coke Co. et al.*, 84 Wash. 47 (1915), the plaintiff owned a farm with a stream running through it. A coal company located upstream, washed recovered coal using stream water that flowed down to the complainant's property. The court held that the water returned to the stream after washing the coal was not the result of reasonable use and found in favor of the farmer for damages.[ii] In addition to awarding damages, the courts often issued injunctions against upstream users who had denied downstream users the right to water unimpaired by unreasonable use. These injunctions were costly to the upstream users because they forced them to utilize expensive methods of abatement.[iii] By the early 1900s, the reasonable use doctrine was a well established precedent in the common law.

The courts also established the rights of riparian users confronted with polluted water resulting from unreasonable use by upstream users. Unreasonable use was established when lower riparian users proved the pollution materially damaged them. For example, in *George Morgan* v. *City of Danbury* 67, Conn. 484 (1896), the plaintiff owned a cider mill downstream from the defendant city on the Still River. The City of Danbury, with a population of approximately 7000, discharged raw sewage into the river. The city attempted to abate this waste after complaints by the plaintiff, by installing a sewage system costing $139,000.[iv] The system was unsuccessful at adequately reducing the sewage waste, however, and the plaintiff was forced to cease cider mill operations. An injunction sought by the plaintiff was granted by the court. The estimated cost of a sewage system capable of properly abating the raw sewage was estimated to cost between $1.85 million and $2.3 million. Although the costs to the defendant were much larger than the resulting damages to the plaintiff, the decision to issue an injunction was upheld. This ruling was followed in similar decisions throughout the period.[v]

Many decisions rendered in cases prior to the advent of interstate compacts on water pollution involved multiple upstream polluters. Unfortunately, the precedents established in those cases were less consistent than cases involving one identifiable polluter. Given multiple upstream polluters, complainants often tried to sue a particular polluter for all the damage resulting from all the polluters. The claim was that it was impossible to separate the damages from each polluter and, therefore, each was responsible for all of the damage caused. But the common law held, in numerous decisions, that defendants could not be held solely responsible for damages when they had acted independently of one another. It is easy to conceive of evidentiary difficulties inherent in trying to separate polluters' effluent. For example, in *Chipman* v. *Palmer*, 77 N.Y. 51 (1879), the defendant owned a boarding house from which sewage ran into a stream that later reached the plaintiff's property. The sewage of the boarding house was joined by the sewage of several other boarding houses and hotels also upstream from the plaintiff. The acts of the defendant were clearly independent of the other upstream users. The court decided that the difficulty of separating the injury to the plaintiff was not a sufficient reason to join the defendant with the other polluters and hold him responsible for the full damages.

A similar decision was reached in *Witland* v. *Redbank*, 151 Ill. App. 433 (1909). The defendants, several oil producers on lands upstream from the plaintiff, discharged effluent into the valley of Big Creek, which flowed to the plaintiff's land. The acts of the defendants were clearly independent of each other, although their wastes were indistinguishable by the time they accumulated and subsequently harmed the plaintiff's property. The court held that, "while it is true it is difficult or impracticable to separate the injury, that is no reason why one of the defendants should be liable as a joint tort-feasor…[p. 439]." This decision was consistent with numerous other cases in the late

1800s and early 1900s.[vi] As the following cases illustrate, however, court refusal to join defendants was not unanimous.

The courts sometimes held that, because a sufferer would have little available action if he had to prove damages of a particular polluter, all defendants could be joined in a suit. For example, in *Lockwood Co.* v. *Lawrence*, 77 Me. 297 (1885), the court held that although the defendants could not be held jointly liable in a suit for damages, they could all be covered by an injunction. The court reasoned that, although the actions of the defendants were independent, there was co-operation in the production of the nuisance, and the acts of the respondents "in equity constitutes but one cause of action." In suits for damages, however, the court stated, "there must be concert of action and co-operation … where damages are sought to be recovered." Similarly, Indiana common law held that defendants could not generally be held jointly liable for damages, but they could be joined if the joint actions constituted a public nuisance.[vii]

Decisions in other cases of the late 1800s and early 1900s were not as explicit in distinguishing between suits for damages and suits for injunctions.[viii] In *Day* v. *Louisville Coal & Coke Co.*, 60 W. Va. 27 (1906), the defendant was a mining firm that deposited slag, cinders, and other waste into Flipping Creek, which flowed into the Blue Stone River. The plaintiff owned farm land downstream which was damaged by the activities of the upstream mine. The defendant contended that because its acts were independent of other operators in the area, it could not be joined in a suit for joint damages with those operators. The court did not agree, citing *Columbus & H. Coal & Iron Co.* v. *Tucker*, 48 O. St. 41 (1891).

A series of cases decided in California in the late 1800s further illustrate the courts' inconsistency in cases involving numerous polluters. Two cases involving numerous polluters were decided in the same court, with completely opposite results. In *Keyes* v. *Little York Gold Washing and Water Company*, 53 Cal. 724 (1879), the court decided that a polluter could not be held liable for the actions of others and could not, therefore, be joined with other polluters in a suit. Four years later the same court held that polluters could, in fact, be held jointly liable for damages in *Hillman* v. *Newington*, 57 Cal. 56. The indecisiveness of the California court is representative of the difficulty that common law courts throughout the country experienced in cases involving numerous polluters during the late nineteenth and early twentieth centuries.

Interstate Decisions

Although *Georgia* v. *Tennessee Copper Co.*, 206 U.S. 230 (1907) involved air pollution, the general precedent established by the decision could easily be applied to water pollution cases.[ix] The plaintiff maintained that pollution emitted from the defendants' copper smelters caused damage to the forests, orchards, and crops in Georgia as well as causing unknown harm to its citizens. The plaintiff first pursued action in the state of Tennessee, but a preliminary injunction was denied. The case was then remanded to the U.S. Supreme Court. Neither of the two defendants in the case, the Tennessee Copper Company and the Ducktown Company denied that its pollution reached Georgia. More importantly, neither objected to being joined in the injunction. The court held that the evidence before it left little doubt that both defendants were guilty of the stated offense.

> The proof requires but a few words. It is not denied that the defendants generate in their works near the Georgia line large quantities of sulphur dioxide which becomes sulphurous acid by its mixture with the air. … On the evidence the pollution of the air and the magnitude of that pollution are not open to dispute. … it is proper to add that we are satisfied, by a preponderance of evidence, that the sulphurous fumes cause and threaten damage …

While there were two polluters, the uncertainty regarding their pollution was absent in the case. Under the court's decision, both companies installed pollution control devices. In addition, the Tennessee Copper Company entered into an agreement with the state of Georgia to "supply a fund to compensate those injured by fumes from its works." The state was unable to agree with the Ducktown Company, however, and moved for another injunction in *Georgia* v. *Tennessee Copper Co.*, 237 U.S. 474 (1915).

In this second case, the court relied on evidence regarding emissions to a larger extent. The court heard testimony about what the average emissions of the two companies were. Interestingly, the Ducktown Co. used a different defense in the second case. It argued that "if any such damage is being done, the Tennessee Company alone is responsible therefor." Essentially, the Ducktown Co. was using the multiple polluter defense.[x] The evidence they presented, however, did not convince the court, and the injunction was upheld.

The *Georgia* cases involved only two polluters and action was taken to protect Georgia from pollution originating in Tennessee. Although the second case was still decided in favor of the plaintiff, the greater use of scientific evidence resulted in some disagreement between the judges. Unlike the first case where there were no dissents, three judges dissented in the second case, stating, "(we) do not think that the evidence justifies the decree limiting production as stated." Producing the standard of scientific evidence required by the courts was a costly method of establishing economic rights. Nowhere was this more true, as the following decisions show, than in the complex interstate pollution problems of the early 1900s.

The decision in *Missouri* v. *Illinois*, 200 U.S. 96 (1906), relied entirely on scientific evidence. The case set the standard for scientific evidence in multiple polluter cases. Chicago discharged raw sewage into a stream that eventually drained into the Mississippi River. St. Louis asserted that the sewage caused numerous cases of typhoid in St. Louis. Missouri tried to convince the court that the cases of typhoid in St. Louis resulted from the discharge of raw sewage into the Mississippi River basin by the Sanitary District of Chicago. Missouri presented expert testimony relying on scientific evidence showing that bacteria could survive a trip down the Mississippi to St. Louis. Illinois argued that the bacteria causing typhoid outbreaks in St. Louis could not travel from Chicago, and it was the cities along the Mississippi, particularly those in Missouri, that were responsible for the damages. The court agreed with Illinois, stating that the decision was based on the available scientific evidence, which it concluded indicated that Chicago could not be singled out as the culprit.

Not long after the *Missouri* case, a dispute in the Upper New York Bay took place. In *New York* v. *New Jersey*, 256 U.S. 296 (1921), New York sought an injunction against the state of New Jersey to enjoin discharge of sewage into Upper New York bay. New Jersey had built a sewage system that was to collect waste from the Passaic Valley and dispose it in the New York bay. Like the *Missouri* case, this case relied on scientific evidence. New York complained that the waste discharge would amount to a public nuisance for its citizens and should therefore be enjoined. New Jersey argued that the sewage already reached the bay through natural channels, and that the water was not suitable for drinking or bathing in its current state. They argued that the proposed sewage system would not significantly worsen the quality of the water. The court interpreted the evidence as follows:

> The evidence introduced (by the plaintiff), … , is much too meager and indefinite to be seriously considered as ground for an injunction, … Considering all of this evidence, and much more which we cannot detail, we must conclude that the complainants have failed to show by the convincing evidence which the law requires that the sewage which the defendants intend to discharge into Upper New York bay, … , would so corrupt the water … as to create a public nuisance.

Again, the scientific evidence provided by the plaintiff was not adequate. The decision in the case did not satisfy New York as pollution problems in the Upper New York bay continued to worsen.

Endnotes

[i] See *Mayor of Baltimore* v. *Warren Manufacturing Co.*, 59 Md. 96 (1882); *Honsee* v. *Hammond*, 39 Barb. (N.Y.) 89, *Strobel* v. *Kerr Salt Co.*, 164 N.Y. 303 (1900), *Wood* v. *Sutcliffe*, 2 Sim (N.S.) 163.

[ii] Other cases supporting this general principle include: *Parker* v. *American Woolen Co.*, 191 Mass. 591 (1907); *MacNamara* v. *Taft*, 196 Mass. 597 (1908); *Red River Roller Mills* v. *Wright* (1883), 30 Minn. 249 (1883); *Worthen & Aldrich* v. *White Spring Paper Co.*, 74 N.J. Eq. 647 (1908).

[iii] See *Indianapolis Water Co.* v. *American Strawboard Co.*, 57 Fed. Rep. 1000 (1893).

[iv] All damages reported in 1996 dollars.

[v] In the following year, a similar case was decided in the same court, *Patrick Nolan* v. *The City of New Britain*, 69 Conn. 668 (1897). While no injunction was issued, the plaintiff still collected damages amounting to $31,000. The complainant resided on a farm a short distance from New Britain. That the damages were a result of the untreated sewage discharged by the defendant was convincingly proven.

[vivi] *Little Shuylkill Navigation, Railroad and Coal Co.* v. *Richard's Administrator*, 57 Pa. 142 (1868); *Serley* v. *Alden*, 61 Pa. 302 (1869); *Bonte* v. *Postel*, 109 Ky. 64 (1900); *Bowman* v. *Humphrey*, 132 Iowa 234 (1906); *Lull* v. *Improvement Co.*, 19 Wis. 101.

[vii] Public nuisance is "a condition dangerous to health, offensive to community moral standards, or unlawfully obstructing the public in the free use of property." (Black, 1991) See also *West Muncie Strawboard Co.* v. *Slack*, 164 Ind. 21 (1904).

[viii] Cases other than those discussed include: *Blaisdell* v. *Stephens*, 14 Nev. 17 (1879); *Hillman* v. *Newington*, 57 Cal. 56.

[ix] Indeed, the case was cited in the argument for the plaintiff in *New York* v. *New Jersey* (1921), a water pollution case.

[x] By this, I mean that they were trying to convince the court that it was the other polluter's fault. This defense relies on the difficulty of proving where the pollution originated.

Appendix B

Price Index (Base Year = 1996)*

Year	Index	Year	Index	Year	Index
1890	7.2	1912	8.1	1934	8.5
1891	7.2	1913	6.3	1935	8.7
1892	6.9	1914	6.4	1936	8.8
1893	7.0	1915	6.5	1937	9.1
1894	6.6	1916	6.9	1938	9.0
1895	6.7	1917	8.2	1939	8.9
1896	6.5	1918	9.6	1940	8.9
1897	6.5	1919	11.0	1941	9.4
1898	6.7	1920	12.8	1942	10.4
1899	6.9	1921	11.4	1943	11.0
1900	7.2	1922	10.7	1944	11.2
1901	7.1	1923	10.9	1945	11.5
1902	7.4	1924	10.9	1946	12.4
1903	7.4	1925	11.2	1947	14.2
1904	7.5	1926	11.3	1948	15.3
1905	7.5	1927	11.1	1949	15.2
1906	7.6	1928	10.9	1950	15.3
1907	7.8	1929	10.9	1951	16.5
1908	7.7	1930	10.6	1952	16.9
1909	8.0	1931	9.7	1953	17.0
1910	8.2	1932	8.7		
1911	7.8	1933	8.2		

* 1913-1953: Consumer Price Index (CPI), Series E 113, *Historical Statistics of the United States* (1975). 1890-1912: Calculated from Wholesale Price Index (WPI), Series E 13, *Historical Statistics of the United States* (1975) and the Consumer Price Index, Series E 113, as follows: WPI regressed on CPI for the years: 1913-1953 where the two series overlapped. The OLS results were then used to "predict" the CPI back to 1890. Results: CPI = 21.97 + .47WPI, Adjusted R^2 = 0.76 and t-statistics: constant (4.75) and WPI (10.99).

Appendix C

The early 1900s was a period of heavy industrialization in the Ohio Valley. Industrial centers included Youngstown (Ohio), Pittsburgh (Pennsylvania), Ashland (Kentucky), and numerous other cities located in the region. Industrial activity led to discharges of waste into the Ohio and its tributaries. One of the more annoying discharges was phenol. Phenol is a by-product in the production of coke, a raw material used in making steel. It can travel large distances, making it difficult to identify the polluter discharging the waste.[i] Numerous complaints were registered with health departments in the Ohio Valley concerning the taste of water that had come into contact with phenol. Few regions, however, acted on these complaints until the Ohio River Interstate Stream Conservation Agreement in 1924.

The earliest reported lawsuit involving phenol took place in 1912. The suit was brought by New Castle Water Company (New Castle, Pennsylvania) against the Carnegie Steel Company of Farrel, Pennsylvania.[ii] New Castle is located about fifteen miles downstream from Farrel. The complainant's claim was that phenol discharged into the Shenango River by the steel company resulted in bad-tasting water in New Castle, even after treatment. In this case, Carnegie Steel was the *only* upstream producer with a by-product coke plant capable of producing phenol in the quantities found in New Castle. The case was settled out of court with a settlement paid to the complainant and an agreement that the steel company would prevent further disturbance. To accomplish this, the company installed a coke quenching plant designed to remove the objectionable wastes. While no cost for the plant installed in Farrel is reported, the cost of coke quenching plants were generally $600,000 and upwards.[iii]

Another instance similar to that experienced in New Castle took place in Johnstown, Pennsylvania in 1916. This time the Bethlehem Steel Co., located upstream from Johnstown on the Conemaugh River, was ordered to install a quenching system by the Pennsylvania Department of Health. Bethlehem Steel was the only upstream producer of phenol at the time, and it was clear that they were the only source capable of producing the objectionable discharge. In 1918, another case involving a Carnegie Steel plant located in Clairton, Pennsylvania resulted in an abatement order. Carnegie polluted the water supply of McKeesport, Pa., a city located less than ten miles downstream. McKeesport took its water from the Monongahela River upon which Carnegie was also located. Carnegie Steel was the only producer of phenol upstream from McKeesport. The steel company was forced to install a coke-quenching plant with reported operating expenses of over $625,000 annually.

While the steel producers in Pennsylvania were held to a high standard, they were not the only producers of phenol in the Ohio River valley. There were fifteen other producers in the basin, including some in Pennsylvania, that were not forced to install expensive pollution control facilities. This is not to say that downstream water users were not complaining. At the time, complaints were registered in Cincinnati (Ohio), Louisville (Kentucky), Youngstown (Ohio), Morgantown (West Virginia), Covington

(Kentucky), and other Ohio River cities (Waring, 1928). But these complaints did not lead to action as they did in the earlier Pennsylvania cases. The coke producers who were upstream from Youngstown, Cincinnati, Louisville, and the other cities mentioned were not entirely like their counterparts who were forced to install control systems. These coke producers were not the *only* upstream polluter. To complicate matters, the other producers often resided in neighboring states. Given the distance phenol is capable of traveling, it was difficult, in not impossible to isolate the source of the objectionable discharge of phenol. In addition, where many producers were located close together, it was impossible to determine exactly from where the foul waste was actually emitted. The costs of attempting to do so were prohibitive.

The complaints of Cincinnati in 1917 could be traced to three coke plants; two were in West Virginia, some three-hundred miles upstream on the Ohio River; another plant was in Ashland, Kentucky, two-hundred miles closer to Cincinnati (Calculated from Waring (1928) and the American Automobile Association *Road Map* (1995)). The Ohio board of health could not take action in this case for two reasons. First, under the Northwest Territory agreement, the Ohio River was entirely owned by West Virginia and Kentucky. Ohio did not have the right to force pollution abatement on the Ohio River (Cleary, 1967). Second, it would be difficult to prove which plant was responsible for how much of the phenol discharge. This was complicated by the multiple jurisdictions involved. Indeed, the same situation was repeated in various incidents on the Ohio River. By the time Cincinnati complained again in 1925, along with numerous other Ohio River cities, there were no fewer than seven by-product coke plants operating without pollution control systems. The distance between the seven plants ranged from three-hundred miles to only six miles.

Other cases in the Ohio River valley existed, most with the same characteristics of the Cincinnati experience. In Youngstown, residents complained of bad-tasting water in 1918 and 1919, but no action was taken. There were three producers of by-product phenol in Youngstown, all located within ten miles of each other on the Mahoning River. An additional producer was located approximately fifteen miles upstream on the Mahoning in Warren, Ohio. No injunctions were issued during this time period. Incidentally, Youngstown is no further than twenty miles from the Pennsylvania border. Municipalities located on the Beaver River in Pennsylvania, the drainage basin for the Mahoning, also complained about the poor tasting water originating in Ohio.

Endnotes

[i] Tastes and odors from phenolic waste have been detected in amounts of only one part of phenol to fifty million parts of water (Waring, 1928). As a comparison, bacteria is a problem only at much higher levels, approximately 2500 parts bacilli coli to 50 million parts water (Cleary, 1967). Phenolic wastes are more of a nuisance than a health concern. They impart a medicinal taste to water that may render it undrinkable.

[ii] The cases discussed here may be found in Waring (1928). Other information relating to the Ohio Valley during this time period is taken from Volume I of ORSANCO's historical archives (see References for complete citation).

[iii] The cost figures reported in this section are in 1996 dollars.

Appendix D

Due to its industrial importance, the Ohio Valley had long been the focus of many federal efforts to manage natural resources. For example, the first Flood Control Act (1936) included a comprehensive plan to control flood waters in the basin.[i] Much of the proposed work in the Ohio Valley remained undeveloped, though, and funding from the postwar bill was expected to bring additional projects into the region. The downstream states had an opportunity to secure Pennsylvania's cooperation by supporting the construction of certain postwar projects in Pennsylvania, particularly near Pittsburgh. Indeed, a variety of projects in the state that were authorized in the original act, but still not constructed, were finally initiated as postwar projects.

One of the worst floods in the history of the Ohio Valley took place in 1937. Although many flood control reservoirs and local protection structures were in place, damage throughout the valley was serious. The damage was estimated at over $4.4 billion (Water Resource Policy Commission, 1950).[ii] More flooding followed in 1942 and 1945, also with large damages. The reservoirs built under the previous Flood Control Acts reduced the damages by nearly $350 million in these floods (House Report No. 2165, 1946), but many reservoirs and other flood protection remained undeveloped. For example, Pittsburgh had long sought additional reservoirs to reduce flood damage in its city, but judging by the lack of progress on these reservoirs, other projects were deemed more important in the Ohio Valley. In a communication dated 1941, the Pittsburgh Chamber of Commerce acknowledged its desire for additional flood protection, specifically mentioning the Conemaugh Dam and Reservoir and the Upper Allegheny Reservoir.[iii] Both of these projects were among the most costly in the valley, though, and little progress had been made on either project.[iv]

Pennsylvania was well aware of its "key" position in the Ohio Valley in terms of pollution control. A Pennsylvania representative at the sixth, and final, conference to negotiate an Ohio Valley compact in December 7, 1944, observed, "We (Pennsylvania) are going to demonstrate a willingness to cooperate in the interest of our neighbors (on the compact), which, by the way, in my judgment, will *redound* to the benefit of the Keystone State in almost every direction (emphasis is mine)."[v] In other words, it appears that any action taken by Pennsylvania on the compact was expected to generate support on other issues from the downstream states. Indeed, shortly after the Pennsylvania representative made the above announcement at the December negotiations meeting, the Cincinnati Chamber of commerce issued a plea to the Pittsburgh Chamber of Commerce in January, 1945, asking for cooperation in the compact for support on flood control.[vi] The downstream states, led by Ohio, and particularly Cincinnati, could support the construction of reservoirs to the benefit of their upstream neighbor. Low flow reservoirs, for example, would help Pittsburgh in abating pollution by increasing stream flows during low flow periods. Flood control reservoirs, such as the Conemaugh, would minimize damages in Pittsburgh and smaller municipalities along the Conemaugh River and the Allegheny.[vii] Even with the downstream states' offer of cooperation on flood projects, however, Pittsburgh's Chamber of Commerce remained unconvinced that the compact was in the best interest of Pennsylvania. It argued that the recipients of the benefits still resided primarily downstream, while Pennsylvania would pay a large share of the costs (*Minutes*, Pittsburgh Chamber of Commerce, see ORSANCO Historical Archives, Vol. VII). By April, though, the situation had changed. The Rivers and Harbors Act,[viii] an omnibus bill approving postwar river development projects, had passed a month earlier. The measure did not include the Beaver-Mahoning shipping channel, an expensive construction project designed to link the Great Lakes to the Ohio River. The project was omitted because it did not generate enough support in Congress to be included in the bill. Pennsylvania, and Pittsburgh in particular, did not want to jeopardize any other postwar projects due to lack of support. The Conemaugh Dam and Reservoir, located just outside Pittsburgh, was a very expensive construction project that required continual support for the large federal appropriations necessary to insure its completion in a timely manner. In addition, low flow regulation was not a standard feature in the construction of reservoirs, and the design of new reservoirs near Pittsburgh required the support of Pennsylvania's downstream neighbors. But even with the support of the downstream states, there was still a cost to securing these projects. Because Congress limited appropriations for the development of the Ohio Valley, the region could only develop a certain number of projects at a time.[ix] For example, Congress authorized $625 million for the construction of authorized projects in the Ohio Valley in the Flood Control Act of 1944.[x] Projects were then developed according to a number of criteria including: need, cost-benefit ratios, and support for the project by affected regions (Leopold and Maddock, 1954).[xi] Because the downstream states were affected by projects built up stream, they played a significant role in securing upstream projects. For money to be sent upstream, the downstream states would require something in return. Pennsylvania's cooperation in the compact could secure this support.

Pennsylvania's General Assembly, which met every two years, would not meet again until 1947. By then, the fate of the largest postwar river development bills would have already been decided. As it turned out, Pennsylvania signed the compact April 2, 1945, soon after the Rivers and Harbors Bill passed. The projects that developed in the Ohio Valley in the period following Pennsylvania's cooperation in the compact indicate that Pennsylvania, and particularly Pittsburgh, faired quite well (see tables D.1, D.2, and D.3).

Under the Ohio Valley compact, Pittsburgh would be forced to install expensive pollution treatment facilities to control sewage discharges. Low flow regulation, which allowed for greater storage capacity in a given reservoir, was an option that allowed river flows to be increased during periods of low flow, normally the summer months, and could supplement pollution control. In its plea to Pittsburgh in 1945, Cincinnati stated that the downstream states would support the inclusion of low flow regulation in the design of reservoirs near Pittsburgh. Before the compact, there were six completed or planned reservoirs near Pittsburgh.[xii] Only one of these reservoirs, the Youghiogheny, included low flow regulation features. Following the compact, four reservoirs were either planned or being constructed on the Allegheny and Monongahela Rivers, both flowing into Pittsburgh. Of these four reservoirs, only one did not include low flow regulation.[xiii] In addition to low flow regulation on new reservoirs after the compact was signed, Pittsburgh also saw construction begin on its long anticipated Conemaugh Dam and Reservoir.

Construction was initiated for the Conemaugh Reservoir in 1946 (House Report No. 2165, 1946). The reservoir, authorized in 1939, provided flood protection of Pittsburgh from waters originating on the Conemaugh River and flowing into the Allegheny River. Although the project was similar in size to other reservoirs in the Ohio Valley, it was one of the most costly projects in the country (The American Yearbook, 1949). The estimated cost of $247 million (1996 dollars) made it the second most expensive project in the Ohio Valley at the time. The most expensive project was the Wolf Creek Reservoir in Kentucky. While the Conemaugh's storage capacity was only 4.5 percent that of Wolf Creek's capacity, its expected cost was over fifty percent of Wolf Creek's.[xiv] In addition, the Conemaugh Dam and Reservoir did not provide hydroelectric power like the other large projects being constructed. Table D.1 displays selected projects that received the largest appropriations in 1949; the estimated cost is for the completed project.

Table D.1: Selected Flood Control Projects with the Highest Federal Appropriations, 1949

Project	Location	Purposes[a]	Estimated Cost (*dollars*)	Storage Capacity (*Acre-feet*)	Cost per *Acre-foot* (*dollars*)
Garrison Reservoir	Missouri	F, H	1.2 billion	13,850,000	85.76
Fort Randall Reservoir	Missouri	F, H	976 million	6,200,000	157.41
Wolf Creek Reservoir	Kentucky	F, H	482 million	6,100,000	79.06
Conemaugh Reservoir	Pennsylvania	F	247 million	274,000	901.65

Source: Water Resource Policy Commission (1950) and *The American Yearbook* (1949). Figures reported in 1996 dollars.
[a] F = flood control; H = hydroelectric power.

While the Conemaugh project was always one of the most expensive projects in the Ohio Valley, its costs increased substantially during its construction. Whether these cost increases were anticipated is unclear, but the final project was nearly double the cost of the originally authorized plan. In either case, Pennsylvania clearly received some very expensive postwar projects. This is not to say that other regions in the Ohio Valley were not the recipients of expensive projects. Indeed, Kentucky had the most expensive project, the Wolf Creek Reservoir. Further examination of the distribution of projects in the Ohio Valley yields other interesting results.

By examining flood control spending by the federal government (in constant 1996 dollars) in the Ohio Valley, particularly in the upper region where pollution problems were worse, I find that spending in the region was consistent with the bargaining explanation set out in Section 2.3.

Although construction of sewage treatment facilities received some attention in postwar discussions on public works projects, the federal government appeared content with having the states handle pollution problems on their own.[xv] Flood control projects were different. Indeed, federal flood control spending more than doubled after the war (in constant 1996 dollars). Table D.2 reports spending by the federal government on flood control before and after 1945.

Table D.2: Flood Control Spending by the Federal Government in the Ohio Valley

State	1936-1944 (*Millions*)	1945-1953 (*Millions*)	Total (*Millions*)	Ratio: Post/Pre
United States	8653.8	20906.4	29560.2	2.42
Pennsylvania	370.6	377.7	748.3	1.02
Ohio	543.7	334.3	878.0	0.61
West Virginia[a]	342.5	240.6	583.1	0.70

Source: *Annual Report of the Chief Engineer of the United States* (1936-1953). Spending measured in 1996 dollars.
[a] Includes Bluestone Reservoir, joint with Virginia (see text for details).

That the Ohio Valley states did not receive increases commensurate with the United States as a whole was largely the result of the development of other river basins in the United States.[xvi] The Ohio Valley had long received federal funding for development of the region; these states continued to receive some of the largest federal appropriations after the war as well, but the distribution of funds changed significantly. Ohio and West Virginia, the only downstream states that withheld their involvement in the compact until Pennsylvania signed, saw their federal appropriations for flood control decreased, in real terms, by nearly forty-percent and thirty percent, respectively. Due to their proximity to Pennsylvania, these two states would have received the greatest benefits from Pennsylvania's membership. At the same time, Pennsylvania's flood control benefits were unchanged from the pre-war period and it actually experienced a slight increase in spending.

One possible explanation for this redistribution could be that most of the projects were complete in Ohio and West Virginia, but this was not the case. Indeed, West Virginia had at least ten authorized projects that had not yet been constructed. The gross storage capacity of the remaining reservoirs was over 1.2 million acre-feet.[xvii] This was more than the gross storage capacity of all pre-1945 projects and other projects under construction in West Virginia (not quite 1.2 million acre-feet). The situation in Ohio was similar. It had at least ten authorized projects with gross storage capacity of nearly 1.2 million acre-feet that had not yet been constructed. And while the storage capacity of the remaining projects was less than that of the pre-1945 projects and other projects under construction (2.2 million acre-feet), they represented a sizable portion of the projects not yet constructed in the Ohio Valley. For comparison, Pennsylvania had completed or initiated construction on seven projects with gross storage capacity of 1.0 million acre-feet. It had at least five authorized projects not yet started with gross storage capacity of approximately 1.5 million acre-feet. Most of this, though, came from the massive Allegheny Reservoir (1.1 million acre-feet), that was shared with New York. It seems that the states were relatively homogeneous on the amount of remaining projects to be built, but yet Pennsylvania received a larger share of federal appropriations than either of the other two states.[xviii]

While the aggregate flood control spending figures are consistent with the predictions of the bargaining model, perhaps the most striking differences between the states are seen when examining individual projects. Table D.3 reports per unit flood control spending by the federal government for Ohio, Pennsylvania, and West Virginia. Average unit cost is defined as the average of flood control expenditures divided by the gross storage capacity for each project that was funded either primarily before or after 1945 (see Appendix E for detailed explanation). Spending for local protection, which were smaller flood control measures such as increased river embankments, is not reported because the largest expenditures were associated with reservoirs. Each of the three states, however, had substantial expenditures on reservoirs during the time period examined.

Table D.3: Per Unit Flood Control Spending by the Federal Government in the Ohio Valley[1]

State	Average Storage Capacity (*Acre-feet*)		Average Unit Cost (*dollars per Acre-foot*)		Ratio: Post/Pre Average Capacity	Ratio: Post/Pre Unit Cost
	1936-44	1945-53	1936-44	1945-53		
Pennsylvania	130,160	179,150	549.6	810.0	1.37	1.47
Ohio	108,693	159,096	439.0	359.0	1.38	0.82
West Virginia[a]	289,600	448,150	672.0	179.0	1.55	0.27

Source: *Annual Report of the Chief Engineer of the United States* (1936-1953). Spending measured in 1996 dollars.
[1]Reservoir spending only (see text for details).
[a] Only one project constructed in pre period (1936-1944).

The average size of reservoirs constructed, at least for these three states, increased in the post-1945 period. The increase in Ohio and Pennsylvania, however, is relatively small. All of the projects built in these two states over the entire period from 1936-1953 were between 20,000 and 300,000 acre-feet, with most projects between 100,000 and 200,000 acre-feet. These moderately sized projects were not nearly as large as those built in West Virginia either before or after 1945. The large increase in size in West Virginia was due mainly to the 631,000 acre-feet Bluestone Reservoir, a project shared with

Virginia. There were other immense projects built in the Ohio Valley after 1945 such as the Wolf Creek Reservoir in Kentucky, which had a gross storage capacity of 6.1 million acre-feet. Judging by the average gross storage capacity of the projects in Ohio and Pennsylvania during the two periods, there appears to be little difference in size. This is further witnessed by the similar pre-1945 and post-1945 ratios of 1.37 and 1.38.

While the size of the projects constructed in Ohio and Pennsylvania were comparable, the expenditures on these projects were significantly different. Like other projects in the Ohio Valley, the projects in Ohio were, on average, larger and had lower unit costs. Indeed, there appear to be some scale economies in the construction of reservoirs in the Ohio Valley.[xix] This was not the case in Pennsylvania. Although the storage capacities and the increase in size of reservoir projects were similar in Pennsylvania to those in Ohio, Pennsylvania's average unit costs actually *increased* with the larger average capacity. Ohio's unit costs decreased by nearly twenty percent in the post-1945 (post/pre ratio of 0.82) while Pennsylvania's unit costs increased by nearly fifty percent (post/pre ratio of 1.47). Few explanations can reconcile the differences in these ratios, although they are fully consistent with the predicted bargaining outcome; Ohio may have encouraged expensive upstream projects at the expense of projects in its own state. It is difficult to say what was happening in West Virginia using the same argument because of the large difference in the size of pre-1945 and post-1945 reservoirs constructed there. The figures in Table D.2, however, indicate that West Virginia did not fare nearly as well in the post-1945 period as Pennsylvania.

Endnotes

[i] The Flood Control Act of 1936 was approved June 22, 1936 and it authorized numerous projects for flood control throughout the country. While a project may have been authorized, construction was not guaranteed. Most of the projects authorized in the various flood control bills were not constructed until years later, if at all. The Flood Control Acts 1f 1937 (50 Stat. 876), 1938 (52 Stat. 1215), 1941 (55 Stat. 638), and 1944 (58 Stat. 887) continued to authorize new projects and additional funding, but they did not guarantee construction either.

[ii] All of the damage and cost figures in this section are reported in 1996 dollars.

[iii] *Minutes* (1941), see ORSANCO Historical Archives, Vol. VI. The Conemaugh Dam is located forty-two miles east of Pittsburgh and was authorized in the 1939 plan for flood control in the Ohio Valley (*Hearings*, 1943). The Upper Allegheny Dam is located on the Allegheny River near New York.

[iv] Some planning had taken place during the war for the Conemaugh Dam and Reservoir, but no contracts for work had been awarded until 1946 (*Annual Report of the Chief Engineer*, 1946).

[v] *Sixth Conference to Draft an Ohio Valley Compact*, held in Pittsburgh, Pennsylvania, 1944.

[vi] The complete resolution, may be found in ORSANCO's Historical Archives, Vol. VI.

[vii] It is important to note that flood control and pollution control had a common link for a long period in the Ohio Valley. In the mid thirties, the Council of State Governments set up various interstate commissions to manage interstate resources. The Interstate Commission on the Ohio River Basin (INCOHIO) was an interstate agency set up in the Ohio Valley to address flood control concerns. The closeness of the two organizations was witnessed by an amendment to the Articles of INCOHIO that made members of ORSANCO ex officio members of INCOHIO, as well (Proposed Amendment No. 2, ORSANCO Historical Archives, Vol. 4, 1938). Although flood control was eventually turned over almost entirely to the federal government, the bond between ORSANCO and flood control in the Ohio Valley had already been forged.

[viii] PL-14, March 2, 1945.

[ix] The comprehensive plan in the Ohio basin authorized hundreds of projects, but appropriations allowed only a certain number to be constructed at any one time. A report by the Chief Engineer of the United States on the Flood Control Program (*Report of the Chief of Engineer, Part 1, Vol. 3*, 1951) states that these construction projects are subject

to changes relating to economic conditions and public interest: "Planning for flood control, and for any other Civil Works activity, cannot be static; it must be sufficiently flexible to recognize the impact of changing local conditions and economic developments."

[x] 58 Stat. 887.

[xi] Leopold and Maddock (1954) discuss the events that must take place before a flood control project may be initiated (see Chapter 7, in particular). For example, before a project is considered, it must first be brought to the attention of the area's Congressional representative. The project is then considered by the Public Works Committee. The Chief of Engineers makes a preliminary examination of the area and holds a public hearing to gauge the views of all interested parties. "Where there is intense interest on the part of local people or where large valleys are involved the report (final report of the Chief Engineer) may be completed promptly." This last step is required before any project is initiated. With the support of many individuals, a project receives a much higher probability of being constructed in a timely manner.

[xii] Tionesta Reservoir, Mahoning Creek Reservoir, Crooked Creek Reservoir, Loyalhanna Reservoir, Conemagh Reservoir, and Youghiogheny Reservoir.

[xiii] Allegheny Reservoir, French Creek Reservoir, Turtle Creek Reservoir, and East Branch Clarion Reservoir.

[xiv] Also, the Wolf Creek Reservoir was to include hydoelectric power. This was not a feature of the Conemaugh Reservoir (Water Resource Policy Commission, 1950).

[xv] Postwar water works construction was conducted mainly by the states during the mid 1940s. Federal aid was unlikely because local governments were considered, by the federal government, to be capable of building the necessary treatment works (The American Yearbook, 1944). In addition there was little promise for a postwar bill as witnessed by the failure of a 1946 antipollution bill to make it out of the House committee (The American Yearbook, 1946).

[xvi] The Ohio Valley did not "lose out" after the war as might be inferred when comparing the post/pre 1945 ratio. Ohio's share of the total appropriations had decreased steadily over the two time periods due to the development of other river basins such as the Missouri.

[xvii] The calculations reported here were compiled from Table 5, Table 6, and Table 7 found in Water Resource Policy Commission (1950).

[xviii] The situation in the other Ohio Valley states was different. Illinois and Indiana did not receive the large sums of money that the other states did. This was largely due to the relatively small size of the population involved. Kentucky had some very large projects in its state, but these were projects designed to address concerns further down river. These massive projects had been coordinated with the development of the Mississippi River and appear to be independent of the bargaining situation in the upper region of the Ohio Valley.

[xix] This seen perhaps most clearly with the Kentucky projects. The Dale Hollow Reservoir, with a capacity of 1.7 million acre-feet had a unit cost of approximately $127. The Wolf Creek Reservoir, with a capacity of over 6 million acre-feet had a much lower unit cost—approximately $85.

Appendix E

Pre-1945 and Post-1945 Flood Control Projects

It is difficult to label projects simply as pre-1945 or post-1945 because all of the projects were authorized under the comprehensive Ohio Valley plan in the flood control legislation of the mid to late 1930s. I proceeded by examining expenditures before and after 1945. I labeled a project as pre-1945 if post-1945 expenditures were less than or equal to twenty-percent of pre-1945 expenditures. That is, to be labeled as pre-1945, the pre-1945 expenditures had to be at least five times greater than post-1945 expenditures. To be labeled as a post-1945 project, post-1945 expenditures had to be at least five times greater than pre-1945 expenditures. Most projects were less than ten percent of either pre-1945 or post-1945 expenditures and many were less than five percent, which made labeling straightforward. The single exception was the Youghiogheny Reservoir, which had post-1945 expenditures that were twenty-one percent of its pre-1945 expenditures. I labeled this project as pre-1945. The only project that could not be labeled as pre-1945 or post-1945 using this method was the Mosquito Creek Reservoir in Ohio. Its post-1945 expenditures were fifty-six percent of its pre-1945 expenditures. Most of the spending was concentrated before and after 1945. I did not include this project in the calculations. The data was taken from *Annual Report of the Chief Engineer of the United States* from 1936-1953.

Appendix 1

Proposition: $I^* > I^{**}$

Proof:

$I^* >=< I^{**}$ as $W(1) - W(0) >=< R_N$ where $R_N = \{[c(s_C^*,0) + D(s_C^*)] - [c(s_A^*,1) + D(s_A^*)]\}Q_C^*$

$W(1) - W(0) =$

$$\left(\int_0^{Q_A^*} P(z)dz - [c(s_A^*,1) + D(s_A^*)]Q_A^*\right) - \left(\int_0^{Q_C^*} P(z)dz - [c(s_c^*,0) + D(s_C^*)]Q_C^*\right)$$

$$= \int_{Q_C^*}^{Q_A^*} P(z)dz - \left([c(s_A^*,1) + D(s_A^*)]Q_A^* - [c(s_C^*,0) + D(s_C^*)]Q_C^*\right)$$

$W(1) - W(0) - R_N =$

$$\int_{Q_C^*}^{Q_A^*} P(z)dz - [c(s_A^*,1) + D(s_A^*)]\,(Q_C^* - Q_A^*)$$

$$> 0$$

$I^* > I^{**}$

Appendix 2

Proposition: $I^* < I_S^{**}$

Proof:

$I^* >=< I_S^{**}$ as $W(1) - W(0) >=< R_S$ where $R_S = \{[c(s_C^*,0) + D(s_C^*)] - [c(s_A^*,1) + D(s_A^*)]\}Q_A^*$

$W(1) - W(0) =$

$$\int_0^{Q_A^*} P(z)dz - \int_0^{Q_C^*} P(z)dz - [c(s_A^*,1) + D(s_A^*)]Q_A^* - [c(s_C^*,0) + D(s_C^*)]Q_C^* + Q_A^* - Q_A^*$$

$$= \int_{Q_C^*}^{Q_A^*} P(z)dz + \{[c(s_C^*,0) + D(s_C^*)] - [c(s_A^*,1) + D(s_A^*)]\}Q_A^* - (Q_A^* - Q_C^*)[c(s_C^*,0) + D(s_C^*)]$$

$W(1) - W(0) - R_S =$

$$\int_{Q_C^*}^{Q_A^*} \{P(z) - [c(s_C^*,0) + D(s_C^*)]\}dz$$

< 0 because $P(Q_C^*) = c(s_C^*,0) + D(s_C^*)$ and demand is downward sloping ($P'(Q) < 0$).

$I^* < I_S^{**}$

Appendix 3

(4.2.1) $\frac{dW^{**}(\delta,t)}{d\delta} > 0$ if $t \geq D(s)$

Proof:

$$\frac{dW^{**}(\delta,t)}{d\delta} = \frac{\partial c(s,\delta)}{\partial \delta}\{Q'(c(s,\delta)+t)[t-D(s)] - Q(c(s,\delta)+t)\}$$

The first term on the RHS is negative. The term in the brackets is unambiguously negative only when $t \geq D(s)$ [sufficient condition only]. The term in the brackets may still be negative is this does not hold, but that would depend upon the elasticity of the demand curve.

(4.2.2) $\frac{dW^{**}(\delta,t)}{dt} >=< 0$ as $D(s) >=< t$

Proof:

$$\frac{dW^{**}(\delta,t)}{dt} = Q'(c(s,\delta)+t)[t-D(s)]$$

Because $Q'<0$, the sign of (4.2.2) depends only on the magnitude of the fixed tax as it relates to the corresponding damage arising from standard s.

(4.3.1) $\frac{ds^{**}(\delta,t)}{dt} < 0$ as $t \leq D(s)$

Proof:

Again, by (4.3) and the Implicit Function Theorem:

$$\frac{ds^{**}(\delta,t)}{dt} = \text{(in sign) } \frac{\partial c(\text{s},\delta)}{\partial \text{s}}\{Q''(c(s,\delta)+t)[t-D(s)] - D'(s)Q'(c(s,\delta)+t)\}$$

Because $Q'' \geq 0$, the sign of the above expression depends upon $[t - D(s)]$. If $t \leq D(s)$, the expression above is < 0.

Appendix 4

$(W_B(s_B,t)$ - $W^{**}(C)$ - $F_B)$ < 0 for $s_B \neq s_C^{**}$

Proof:

$$W(C) = \int_0^{Q(c(s_C,0)+t)} P(z)dz - [c(s_C,0) + D(s_C)]Q(c(s_C,) + t)$$

Maximizing *W*(*C*) with respect to s_C yields the following:

$$\max_{s_C} W(C) = W^{**}(C) = \int_0^{Q(c(s_C^{**},0)+t)} P(z)dz - [c(s_C^{**},0) + D(s_C^{**})]Q(c(s_C^{**},) + t)$$

$$W_B(s_B,t) = \int_0^{Q(c(s_B,0)+t)} P(z)dz - [c(s_B,1) + D(s_B)]Q(c(s_B,0) + t)$$

$$F_B = [c(s_B,0) - c(s_B,1)]Q(c(s_B,0) + t)$$

Now, $W_B(s_B,t) - F_B = \int_0^{Q(c(s_B,0)+t)} P(z)dz - [c(s_B,0) + D(s_B)]Q(c(s_B,0) + t)$ (A.4.1)

Clearly, s_C^{**} maximizes (A.4.1) so we have:

(A.4.1.a) $(W_B(s_B,t)$ - $W^{**}(C)$ - $F_B)$ = 0 for $s_B = s_C^{**}$

(A.4.1.b) $(W_B(s_B,t)$ - $W^{**}(C)$ - $F_B) < 0$ for $s_B \neq s_C^{**}$

Appendix 5

Proposition: $s_B^{**} < s_A^{**}$

Proof:

Let $W(s,\Delta) = \int_0^{Q(c(s,\Delta)+t)} P(z)dz - [c(s,1) + D(s)]\,Q(c(s,\Delta) + t$ (A.5.1)

Because all that changes from state B to state A in (A.5.1) is that Δ goes from 0 to 1, we would like to examine the effect that this change in Δ has on the resulting standard. Therefore, we seek $ds / d\Delta$, which we can obtain using the Implicit Function Theorem and (A.5.1).

(A.5.2) $$\frac{dW(s,\Delta)}{ds} = Q'(c(s,\Delta)+t)\frac{\partial c(s,\Delta)}{\partial s}\{[c(s,\Delta)+t] - [c(s,1) + D(s)]\}$$
$$- [c_s(s,1) + D'(s)]Q(c(s,\Delta)+t)$$

We make the same assumption here that we did earlier on the relationship between the loser's cost and the true social cost. I.e.,

(A.5.3) $c(s,0) + t \le c(s,1) + D(s) \quad \Rightarrow \quad [c(s,0)+t] - [c(s,1) + D(s)] \;\le\; 0$

Because (A.5.3) is true for c(s,δ) with δ = 0, then it must be true for all δ. Hence, the first term on the RHS of (A.5.2) is positive. The sign of the second term on the RHS depends upon the relationship between $c_s(s,1)$ and $D'(s)$. We know from deriving the first best standard in this case (Section 2, equation (2A)) that $c_s(s,1) + D'(s)$ is equal to zero for s_A^*. Given that $s_A^{**} > s_A^*$, if we evaluate (A.5.2) near s_A^{**} then $c_s(s,1) + D'(s) < 0$. Therefore, the second term on the RHS of (A.5.2) is also positive when evaluated near s_A^{**}. It is sufficient to restrict attention to this region because we are interested in how *s* changes from s_A^{**} with a change in Δ.

(A.5.4) $$\frac{dW(s,\Delta)}{d\Delta} = Q'(c(s,\Delta)+t)\frac{\partial c(s,\Delta)}{\partial \Delta}\{[c(s,\Delta)+t] - [c(s,1) + D(s)]\}$$

Each term on the RHS of (A.5.4) is negative—the final term is negative due to (A.5.3).

Given (A.5.2) and (A.5.4) we have the following:

(A.5.5) $$\frac{ds}{d\Delta} = -\frac{\partial W(s,\Delta)/\partial\Delta}{\partial W(s,\Delta)/\partial s} > 0 \quad \text{(evaluated near } s_A^{**}\text{)}$$

Appendix 6

Proposition: $\hat{s}_B < s_A^*$ if $\dfrac{\partial I(s_B,t)}{\partial s_B} < 0$

Proof:

The proof of this proposition involves evaluating (4.10) at s_A^*. It is easy to show that the second term on the RHS is negative. Expanding $\partial W_B / \partial s_B$, we get:

(A.6.1)

$$\frac{\partial c(s_B,0)}{\partial s_B} Q'(c(s_B,0)+t)\left\{[c(s_B,0)+t]-[c(s_B,1)+D(s_B)\right\} - \left[\frac{\partial c(s_B,1)}{\partial s_B} + D'(s_B)\right] Q(c(s_B,0)+t)$$

Evaluating (A.6.1) at $s_B = s_A^*$ we get that the bracketed term in the first term is negative given our earlier assumption about the per unit damage tax:

(A.6.2) $t \leq D(s_B) - [c(s_B,0) - c(s_B,1)] < D(s_B) \quad \Rightarrow \quad [c(s_B,0)+t] - [c(s_B,1)+D(s_B)] < 0$

Because the bracketed term is negative as well as Q', the first term in (A.6.1) is positive. The second term in (A.6.1) is zero at s_A^* by condition (2A) of Section 2. Given that (A.6.1) is positive, we have that the second term in (4.10) is positive.

Returning to the first term in (4.10), we make the additional assumption that:

(A.6.3) $c(s_A^*,0) > c(s_A^{**},1)$

(A.6.3) simply states that the increase in cost from not having a successful technological innovation outweighs the decrease in cost from the reduction in the standard from s_A^{**} to s_A^*. With (A.6.3) (sufficient condition, not necessary), $W_B(s_B,t)$ is greater than $W^{**}(A)$.

(A.6.4) $W_B(s_B,t)\big|_{s_B=s_A^*} - W^{**}(A)$

$$= \int_{Q(c(s_A^*,0)+t)}^{Q(c(s_A^{**},1)+t)} P(z)dz - \left\{[c(s_A^{**},1)+D(s_A^{**})]Q(c(s_A^{**},1)+t) - [c(s_A^*,1)+D(s_A^*)]Q(c(s_A^*,0)+t)\right\}$$

< 0

To show that (A.6.4) is negative, observe that:

(A.6.5) $[c(s_A^{**},1)+D(s_A^{**})]Q(c(s_A^{**},1)+t)-[c(s_A^{*},1)+D(s_A^{*})]Q(c(s_A^{*},0)+t)$
$> [c(s_A^{*},1)+D(s_A^{*})][Q(c(s_A^{**},1)+t)-Q(c(s_A^{*},0)+t)$

It is then easy to see that the second term in (A.6.5) is larger than the first term in (A.6.4) because $P(z)$ is downward sloping (see Figure 5). Finally, if the second term in (A.6.5) is larger than the first term in (A.6.4), then the second term in (A.6.4) is clearly larger than the first term in (A.6.4) by condition (A.6.5).

(A.6.6) $W^{**}(C)$ is greater than $W_B(s_B,t) - F_B$ whenever $s_A^{*} \neq s_C^{**}$, which is expected.

Given (A.6.4) and (A.6.6), we have that the bracketed term in the first term of (4.10) is negative. Finally, if $\frac{\partial I(s_B,t)}{\partial s_B} < 0$ (sufficient condition) then (4.10) is positive $\Rightarrow$ $\hat{s}_B < s_A^{*}$.

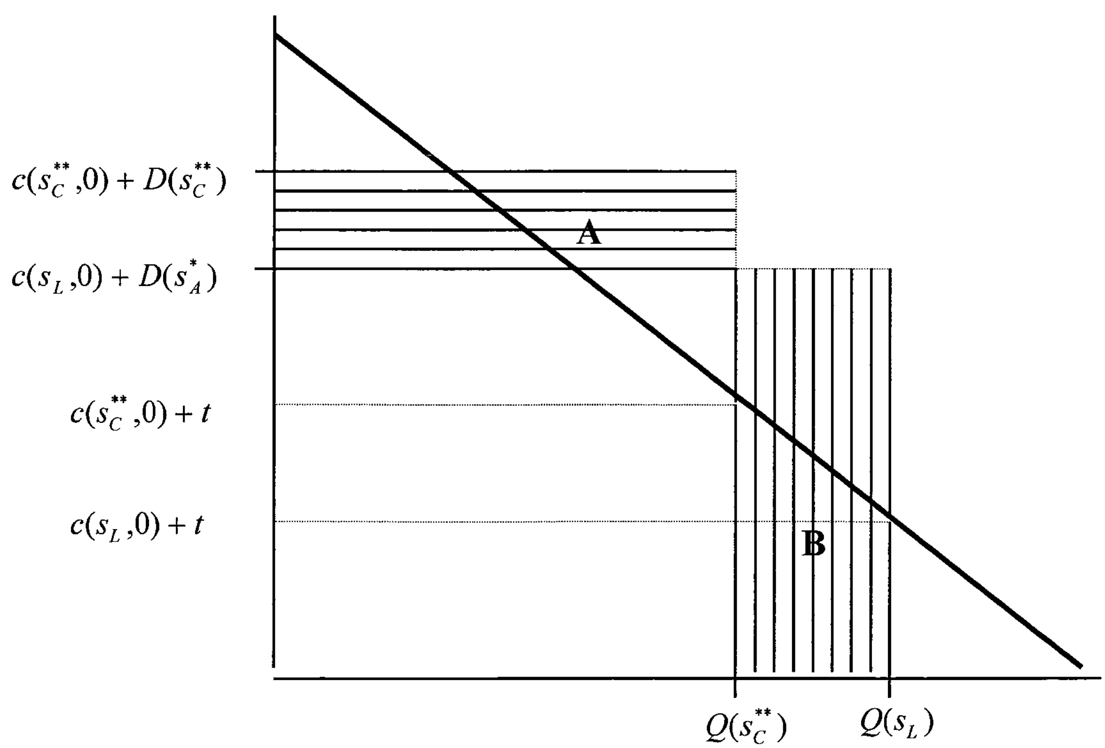
Appendix 7

Sufficient Condition for $(W_B - W^{**}(C) - F_{BB}) > 0$ when $s_W = s_A^*$ and $s_L < s_C^{**}$:

(A.7.1) $[c(s_L,0) + D(s_A^*)]Q(c(s_L,0)+t) < [c(s_C^{**},0) + D(s_C^{**})]Q(c(s_C^{**},0)+t)$

Note: the above sufficient condition is more likely to hold when $s_A^* > s_C^{**}$.

Figure A.7



Sufficient Condition: A > B

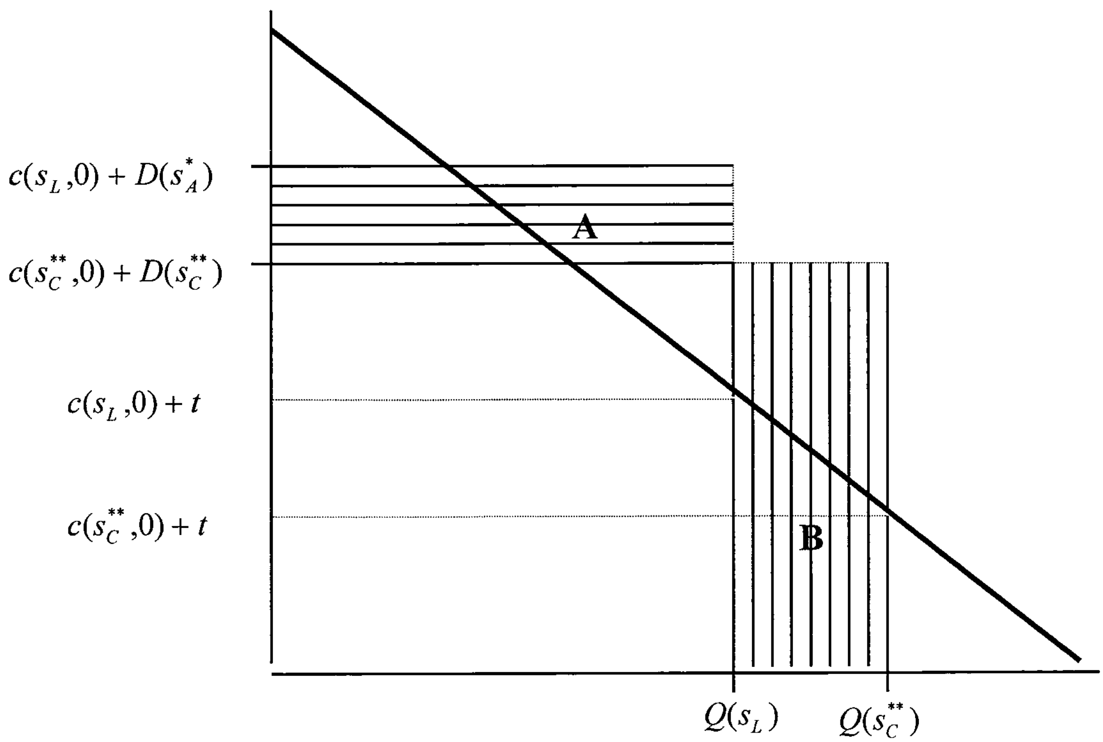
Appendix 8

Sufficient Condition for $(W_B - W^{**}(C) - F_{BB}) < 0$ when $s_W = s_A^*$ and $s_L > s_C^{**}$:

(A.7.1) $[c(s_L,0) + D(s_A^*)]Q(c(s_L,0)+t) > [c(s_C^{**},0) + D(s_C^{**})]Q(c(s_C^{**},0)+t)$

Note: the above sufficient condition is more likely to hold when $s_A^* < s_C^{**}$.

Figure A.8



Sufficient Condition: A > B

REFERENCES

Air Pollution Control Association, Proceedings: Dispersion Modeling from Complex Sources. St. Louis (1981).

________, Proceedings: Receptor Models Applied to Contemporary Pollution Problems. Publishers Choice Book Mfg. Co., Mars, PA. (1982).

Amacher, G.S. and A.S. Malik, "Bargaining in Environmental Regulation and the Ideal Regulator," *Journal of Environmental Economics and Management*, 30, 233-253 (1996).

American Auto Association, 1995 Road Atlas. Heathrow, Florida (1995).

Annual Report of the Chief of Engineers, U.S. Army, Part I, Vol. 1, G.P.O., Washington (1936-1953).

_____, Part I, Vol. 3, G.P.O., Washington (1951).

Archer, M.B. and R.O. Brooks, Buying the sky: acid rain controls in the U.S. under the 1990 Clean Air Act. "Acid Rain", ed. J. Rose, Amsterdam, 229-244 (1994).

Arora, Seema, and Timothy N. Cason, "A Voluntary Approach to Environmental Regulation: The 33/50 Program." *Resources*, 116, 6-10, Summer (1994).

_____, "An Experiment in Voluntary Environmental Regulation: Participation in the EPA's 33/50 Program," *Journal of Environmental Economics and Management*, 28(3), 271-286 (1995).

_____, "Why Do Firms Volunteer to Exceed Environmental Regulations? Understanding Participation in the EPA's 33/50 Program," *Land Economics*, 72(4), 413-432, November (1996).

Arora, Seema, and Shubhashis Gangopadhyay, "Toward a Theoretical Model of Voluntary Overcompliance," *Journal of Economic Behavior and Organization*, 28, 289-309, December (1995).

Atkinson, S.E. and T.H. Tietenberg, "The Empirical Properties of Two Classes of Designs for Transferable Discharge Permit Markets," *Journal of Environmental Economics and Management*, 9, 101-121 (1982).

Bartnicki, J.J., Air Pollution Modeling and Its Application IX, ed. H. Van Dop and G. Kallos, Plenum Press, New York (1992).

Barzel, Yoram, Economic Analysis of Property Rights. Second Edition, Cambridge University Press (1997).

Baumol, W. J., and W.E. Oates, The Theory of Environmental Policy. Second Edition, Cambridge University Press, Cambridge, UK (1988).

Biglaiser, G., and J.K. Horrowitz, "Pollution Regulation and Incentives for Pollution-Control Research," *Journal of Economics and Management Strategy*, 3, 663-684 (1995).

Black, Henry Campbell, Black's Law Dictionary. *Sixth Edition*, West Publishing Co., St. Paul, Minn. (1991).

Buchanan, James M., and Gordon Tullock, The Calculus of Consent. University of Michigan Press, Ann Arbor (1962).

_____ , "Polluters' Profits and Political Response: Direct Controls versus Taxes," *American Economics Review*, 65, 139-147, March (1975).

Butler, Henry H. and Jonathon R. Macey, Using Federalism to Improve Environmental Policy. The AEI Press, Washington, D.C. (1996).

Cason, T.N. and C.R. Plott, "EPA's New Emissions Trading Mechanism: a Laboratory Experiment," *Journal of Environmental Economics and Management*, 30, 133-160 (1996).

Cleary, Edward J., The ORSANCO Story: Water Quality Management in the Ohio River Valley under an Interstate Compact. Resources for the Future, John Hopkins Press (1967).

Coase, Ronald H., "The Problem of Social Cost," *Journal of Law and Economics*, 3, 1-44 (1960).

Coggins, J.S. and J.R. Swinton, "The Price of Pollution: A Duel Approach to Valuing SO_2 Allowances," *Journal of Environmental Economics and Management*, 58-72 (1996).

Cox, W.M. and J.A. Tikvart, "A statistical procedure for determining the best performing air quality simulation model, *Atmospheric Environment*, 24, 2387-2395 (1990).

Cumberland, John H., "Interregional Pollution Spillovers and Consistency of Environmental Policy," Regional Environmental Policy, ed. Horst Siebert, Ingo Walter, and Klaus Zimmerman, New York University Press, New York, 255-283 (1979).

______ , "Efficiency and Equity in Interregional Environmental Management," *Review of Regional Studies*, 2, 1-9 (1981).

Davis, L.E., and North, D.C., Institutional Change and American Economic Growth. Cambridge, England: Cambridge University Press (1971).

Demsetz, H., "Towards a Theory of Property Rights," *American Economic Review* 57 (1967).

Downing, Paul R., and Lawrence J. White, "Innovation in Pollution Control," *Journal of Environmental Economics and Management*, 13, 18-29 (1986).

Forster, B.A., "The Acid Rain Debate," Iowa State University Press, Ames (1993).

Goddard, H.C., Using Tradeable Permits to Achieve Sustainability in the World's Large Cities, *Environmental and Resource Economics*, forthcoming.

Haddock, David D., "Must Water Regulation be Centralized?" Water Marketing: the Next Generation. Edited by Terry L. Anderson and Peter J. Hill, Rowman & Littlefield Publishers (1997).

Hahn, R.W., "Market Power and Transferable Property Rights," *Quarterly Journal of Economics*, 99, 753-765, (1984).

________ and R.G. Noll, Reform of Environmental Regulation. "Designing a Market for Tradeable Emission Permits," ed. W.A. Magat, Ballinger, Cambridge Ma. (1982).

Hines, "Regulation of Water Quality," *Iowa Law Review*, Vol. 52, p. 802 (1967).

Innes, Robert, Catherine Kling, and Jonathon Rubin, "Emission Permits under Monopoly," *Natural Resource Modeling*, 5, 321-343 (1991).

Johnson, W.B., "Interregional Exchanges of Air Pollution: Model Types and Applications, *Journal of the Air Pollution and Control Association*, 33, 563-574 (1983).

Krupnick, A.J., W.E. Oates, and E. Van De Verg, "On Marketable Air-pollution Permits: the Case for a System of Pollution Offsets," *Journal of Environmental Economics and Management*, 10, 233-247 (1983).

Leach, Richard H. and Redding S. Sugg, Jr. The Administration of Interstate Compacts. Louisiana State University Press (1959).

Leopold, Luna B. and Thomas Maddock, Jr., The Flood Control Controversy: Big Dams, Little Dams, and Land Management. The Ronald Press Company, New York (1954).

Libecap, Gary D., Contracting for Property Rights. Cambridge University Press (1989).

_____, "The Conditions for Successful Collective Action," *Journal of Theoretical Politics*, 563 (1994).

_____, "Environmental Regulation and Federalism," *Arizona Law Review*, 38, 901-907 (1996).

Ludwig, F.L., H.S. Javitz, and A. Valdes, "How Many Stations are Required to Estimate the Design Value and the Expected Number of Exceedences of the Ozone Standard in an Urban Area?," Journal of the Air Pollution Control Association, 33, 963-967 (1983).

Maloney, Michael T., and Robert E. McCormick, "A Positive Theory of Environmental Regulation," *Journal of Law and Economics*, 25, 99-123 (1982).

Malueg, D.A., "Welfare Consequences of Emission Credit Trading Programs," *Journal of Environmental Economics and Management*, 18, 66-77 (1990).

Martin, D.O., "An Urban Diffusion Model for Estimating Long Term Average Values of Air Quality," *Journal of the Air Pollution Control Association*, 21, 16-19 (1971).

McHugh, Richard, "The Potential for Private Cost-Increasing Technological Innovation under a Tax-Based, Economic Incentive Pollution Control Policy," *Land Economics*, 61(1), 58-64, February (1985).

Misolek, W.S. and H.W. Elder, "Exclusionary Manipulation of Markets for Pollution Rights," *Journal of Environmental Economics and Management*, 16, 156-166 (1989).

McGartland, A.M., "A Comparison of Two Marketable Discharge Permit Systems," *Journal of Environmental Economics and Management*, 15, 35-44 (1988).

________, and W.E. Oates, "Marketable Permits for the Prevention of Environmental Deterioration," *Journal of Environmental Economics and Management*, 12, 207-228 (1985).

Meiners, Roger E. and Bruce Yandle, "Clean Water Legislation: Reauthorize or Repeal?" Taking the Environment Seriously, ed. Meiners and Yandle, 73-101 (1993).

Milliman, Scott R., and Raymond Prince, "Firm Incentives to Promote Technological Change in Pollution Control," *Journal of Environmental Economics and Management*, 17, 247-265 (1989).

Montgomery, Stanley D. and Earle B. Phelps, "Stream Pollution: A Digest of Judicial Decisions and a Compilation of Legislation Relating to the Subject," Public Health Bulleting, No. 87, U.S. Public Health Service, Washington (1917).

Montgomery, W.D., "Markets in Licenses and Efficient Pollution Control Programs," *Journal of Economic Theory* 5, 395-418 (1972).

Moroz, W.J., Atmospheric Pollution. "Air pollution concentration prediction models," ed. E.E. Picket, Springer-Verlag (1987).

Oates, Wallace E., and Robert M. Schwab, "Economic Competition among Jurisdictions: Efficiency Enhancing or Distortion Inducing?" *Journal of Public Economics*, 35, 333-354 (1988).

Ohio River Valley Sanitation Commission, *Historical Archives*, Volumes I - IX, Cincinnati, Ohio (1927-1949).

_____, *First Conference of Delegates Appointed to Draft an Ohio River Valley Sanitation Compact*, Cincinnati, Ohio (1936).

_____, *Second Conference of Delegates Appointed to Draft an Ohio River Valley Sanitation Compact*, Cincinnati, Ohio (1938).

_____, "Communication No. 42," *Historical Archives*, Cincinnati, Ohio (1939).

_____, *Sixth Conference of Delegates Appointed to Draft an Ohio River Valley Sanitation Compact*, Cincinnati, Ohio (1944).

_____, *Annual Report*, No. 2, Cincinnati, Ohio (1949).

_____, *Annual Report*, No. 5, Cincinnati, Ohio (1953).

_____, *Annual Report*, No. 6, Cincinnati, Ohio (1954).

_____, *Annual Report*, No. 7, Cincinnati, Ohio (1955).

Ostrom, Elinor, Governing the Common: The Evolution of Institutions for Collective Action. Cambridge: Cambridge University Press (1990).

Ostrom, Elinor, James Walker, and Roy Gardner, "Covenants With and Without a Sword: Self-Governance is Possible," *American Political Science Review*, Vol. 86, No. 2, June (1992).

Parry, Ian W. H., "Optimal Pollution Taxes and Endogenous Technological Progress," *Resource and Energy Economics*, 15, 99-116 (1995).

_____, "The Choice between Emissions Taxes and Tradable Permits When Technological Innovation is Endogenous," Resources for the Future, Discussion Paper 96-31 (1996).

Paumier, J.O., S.G. Perry, and D.J. Burns, "CTDMPLUS: a dispersion model for sources near complex topography. Part II: performance characteristics," *Journal of Applied Meteorology*, 31, 646-660 (1992).

Research And Education Association, Modern Pollution Control Technology. REA, New York, N.Y. (1978).

Revesz, Richard L., "Rehabilitating Interstate Competition: Rethinking the Race-to-the-Bottom Rationale for Federal Environmental Regulation," *New York University Law Review* 67(6), December, 1210-1254 (1992).

______, "The Control of Interstate Environmental Externalities in a Federal System," *Arizona Law Review*, 38, 883-899 (1996).

Reynolds, Stanley S., and R. Mark Isaac, "Stochastic Innovation and Product Market Organization," *Economic Theory*, 2, 525-545 (1992).

Rose, Carol M., "Energy and Efficiency in the Realignment of Common Law Water Rights," *Journal of Legal Studies*, 19(2), 261-296 (1990).

Salop, Steven, and David Scheffman, "Raising Rivals' Costs," *American Economic Review (Papers and Proceedings)*, 73, 267-271, May (1983).

Sah, Raaj Kumar, and Joseph E. Stiglitz, "The invariance of market innovation to the number of firms," *RAND Journal of Economics*, 18(1), 98-208, Spring (1987).

Scherer, F.M., Industrial Market Structure and Economic Performance. Second Edition, Rand McNally, Chicago (1980).

Segerson, K., "Uncertainty and Incentives for Nonpoint Pollution Control," *Journal of Environmental Economics and Management*, 15, 87-98 (1988).

Stavins, R. N., "Transaction Costs and Tradeable Permits," *Journal of Environmental Economics and Management* 29, 133-148 (1995).

Stewart, Richard, "Pyramids of Sacrifice? Problems of Federalism in Mandating State Implementation of National Environmental Policy," *Yale Law Journal*, 86, 1196-1212 (1977).

Ströbel, Wolfgang J., Environmental Scarcity: The International Dimension. "Institutional Arrangements for Transfrontier River Pollution," edited by Horst Siebert (1991).

Thursby, Vincent V., Interstate Cooperation: A Study of the Interstate Compact. Public Affairs Press, Washington D.C. (1953).

Tietenberg, T.H., "Emissions Trading: An Exercise in Reforming Pollution Policy," Resources for the Future, Washington D.C. (1985).

________, "Transferable Discharge Permits and the Control of Stationary Source Air Pollution: A Survey and Synthesis, *Land Economics* 56, 391-416 (1980).

Tirole, Jean. The Theory of Industrial Organization. MIT Press, Cambridge, Mass. (1988).

Touma, J.S., J.S. Irwin, J.A. Tikvart, and C.T. Coulter, "A Review of Procedures for Updating Air Quality Modeling Techniques for Regulatory Rrograms, *Journal of Applied Meteorology*, 34, 731-737 (1995).

Tullock, Gordon, "Which Rectangle?" forthcoming, *Public Choice* (1998).

United States, *Census of the Population*, Washington, (1930).

_____, "Pollution of Navigable Waters," *Hearings before the Committee on Rivers and Harbors*, House of Representatives, Washington, May 20 (1936).

_____, "Pollution of Navigable Waters," *Hearings before the Committee on Rivers and Harbors*, House of Representatives, Washington, March 3 and March 6 (1939).

_____, "Ohio River Pollution Control," House Document No. 266, Washington, 78th Congress, 1st Session (1943).

_____, "Flood Control Plans and New Projects," *Hearings before the Committee on Flood Control*, House of Representatives, H.R. 4485, 78th Congress, 1st Session (1943).

_____, "Pollution of Navigable Waters," *Hearings before the Committee on Rivers and Harbors*, House of Representatives, Washington, November 13-15 and November 20 (1945).

_____, "Authorizations for Reservoirs, Levees and Flood Walls for Flood Control," House Report No. 2165, 79th Congress, 2nd Session, May 29 (1946).

_____, "Table 5: Parts 35, 38, and 48," *Census of the Population*, Washington (1950).

_____, Historical Statistics of the United States: Colonial Times to 1970. Bureau of the Census, Washington, D.C. (1975).

_____, "Clear Act Amendments of 1990." P.L. 101-549, Washington D.C. (1990).

U.S. Environmental Protection Agency, "Guideline on Air Quality Planning and Standards," EPA-450/2-78-027 (1978).

U.S. General Accounting Office, "Air Pollution: Reliability and Adequacy of Air Quality Dispersion Models," RCED-88-192 (1988).

Waring, F.H., "Results Obtained in Phenolic Wastes Disposal under the Ohio River Basin Interstate Stream Conservation Agreement," presented at the Public Health Engineering Section of the American Public Health Association, 57th Annual Meeting, Chicago, October 18, 1928.

_____, "The Ohio Valley Water Sanitation Compact," Read before the committee meeting of Pennsylvania General Assembly, Harrisburg, Pennsylvania, March 26 (1941).

Yandle, Bruce, The Political Limits of Environmental Regulation: Tracking the Unicorn. Quorum Books, New York (1989).

_____, Common Sense and Common Law for the Environment: Creating Wealth in Hummingbird Economies. Rowan & Littlefield, Lanham, Maryland (forthcoming Fall 1997).

Zimmerman, Frederick L. and Mitchell Wendell, The Interstate Compact since 1925. The Council of State Governments, Chicago, Illinois (1951).