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Jay S. Coggins

Name of Faculty Adviser

Jay S. Coggins

Signature of Faculty Adviser

Nov. 3, 2000

Date

GRADUATE SCHOOL

POINT-NONPOINT EMISSIONS TRADING FOR MINNESOTA RIVER PHOSPHORUS

A Thesis
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Robert Charles Johansson

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ABSTRACT

Excessive nutrients from agricultural production emitted into rivers, lakes, and coastal waters have increasingly attracted the attention of policymakers concerned with the degradation of U.S. water resources. In particular, excessive phosphorus emissions from agricultural runoff and from wastewater treatment facilities have been linked to eutrophication problems in the Upper-Mississippi and Minnesota Rivers.

This thesis addresses the question of how Minnesota regulators might best meet federal water quality standards in the context of the current levels of phosphorus emissions. In order to answer this question it is first necessary to develop an integrated biophysical and economic methodology to determine the costs of investing in abatement efforts. For nonpoint, agricultural sources this methodology entails the use of the water-quality management model, ADAPT, to simulate phosphorus best management practices, and of stochastic frontier analysis to estimate the representative abatement cost functions.

Using these abatement cost functions this thesis examines the use of tradable emissions permits for the simultaneous regulation of point and nonpoint source pollution. This policy is compared to one that uses effluent fees to achieve identical levels of phosphorus abatement and one that uses non-tradable quotas. It is shown for a sub-basin of the Minnesota River, the Sand Creek, that tradable permits provide significant efficiency gains (54%) when compared to a non-targeted policy requiring uniform phosphorus abatement. Furthermore, in an environment of uncertainty, tradable emissions permits are found to be superior to effluent fees in regulating phosphorus emissions. Also, it is shown that if nonpoint sources are subject to moral hazard due to asymmetric information, a 5.6% loss in efficiency is observed. When this analysis is extended to a dynamic framework the conclusions are not found to change substantially.

Given recent federal water quality legislation that require states to develop comprehensive programs to address impaired waters, this thesis provides a methodological and empirical example for Minnesota's policymakers to use as they begin to examine the problem of eutrophication in the Minnesota River. Furthermore, the comparison of costs to farmers should prove useful when soliciting their input on how best to affect changes in nonpoint emissions.

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To Siobhan, Liam, and Olivia Mairéad

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Chapter 1

Introduction

1.1 Point and Nonpoint Pollution Regulation

The environmental movement began in the United States in the mid-19th Century. It was based initially on an appreciation of the large endowment of natural resources in this country and a rejection of the popular materialist, industrial, and Calvinist views of life. Termed "transcendentalism", this movement gained popularity through the efforts and writings of those such as Ralph Waldo Emmerson (*Nature* was published in 1836), Henry David Thoreau (*Walden; or, Life in the Woods* was published in 1854), and John Muir (first president of the Sierra Club formed in 1892). Many of the tenets of modern day *environmentalism* became visible in the popular culture of the late 19th Century (e.g., the first National Park, Yellowstone, was created in 1872). In fact, one can note the appreciation of such considerations as market failure, environmental externalities, and sustainability in much of the Bureau of Reclamation discussion over water development projects in the Western United States dating back to 1902 (Reisner, 1993). However, public concern regarding environmental problems was typically localized and due to specific confined events. One example is the 1948 smog in Donora, Pennsylvania that killed 20 and caused 43% of the resident population to fall ill (Council on Environmental Quality, 1996).

The public awareness and concern over environmental issues became galvanized in the 1960's due to several well-publicized incidents such as the Cuyahoga River in Cleveland erupting in flame, a severe oil spill along the Santa Barbara coast, and the publication of *Silent Spring* (Carson, 1962), which documented the unintended consequences of DDT on wildlife populations (Council on Environmental Quality, 1996). Explicit regulation of the U.S. environment and its uses arrived during the Nixon administration in 1970 with the passage of the National Environmental Protection Act (NEPA), the formation of the United States Environmental Protection Agency (USEPA), and the formation of the Council on Environmental Quality (CEQ). Prior to this date, natural resource use and environmental issues were regulated via a hodgepodge of federal departments, councils, and commissions: Departments of the Interior, Health, Education and Welfare, and Agriculture, Atomic Energy Commission, and the Federal Radiation Council (Portney, 1993).

The prevailing economic wisdom in the early 1960's was that environmental externalities required only "appropriate" prices to provide the proper incentives for pollution abatement (Baumol and Oates, 1989). These prices, the familiar Pigouvian taxes, are an extension of microeconomic theory and seek to equate the marginal damage from an additional unit of abatement to the marginal cost of achieving that reduction. This form of regulation still forms the basis for much of today's policy and theoretical discussions of environmental regulation. However, the complexities of accurately calculating the marginal costs and benefits, coupled with political pragmatism, have limited the actual application of Pigouvian taxes for regulating pollution. To a large extent, the regulation of pollution in the United States has mostly been of the command-and-control form: explicit limits on the quantity of pollutant allowed or the processes and technology involved in production.

This form of regulation has been moderately successful in regulating air and water quality: between 1970 and 1994 the combined emissions of six principle pollutants[1] declined 24% (CEQ, 1996); a 30% reduction in biochemical oxygen demand (BOD) and total suspended solids (TSS) since the passage of the Clean Water Act in 1972 (CEQ, 1996). Typically, these reductions have come about by regulating point sources of pollution, those that discharge pollution at a specific location (e.g., pipe or smokestack). However, one place where command-and-control regulation has failed is in addressing the rising levels of environmental damages resulting from agricultural, nonpoint pollution. Nonpoint pollution, such as soil erosion from croplands or seepage from malfunctioning septic tanks, enters the environment in a disperse manner making accurate observations costly and control difficult.

Indeed, the regulation of nonpoint agricultural pollution has only recently been acknowledged as necessary under federal legislation (Boyd, 2000). Many current and former agricultural policies in fact serve to exacerbate the nonpoint pollution problem via their unintended environmental consequences. Examples include the former pesticide policies (as detailed in *Silent*) as well as seemingly benign crop deficiency payment policies (Peterson, 1995). Furthermore, since 1960 agricultural intensity has increased substantially in the United States (wetland areas have decreased by 50+% and the use of industrial fertilizers and pesticides have increased by approximately 200%) resulting in a 26% increase in output per unit input (CEQ, 1996). It should come as no surprise then, that agricultural, nonpoint pollution contributes to 72% of impaired river areas, 57% of impaired lake areas, and 43% of the impaired estuarine areas assessed (USEPA, 1990 and 1994).

The full extent of the damage done to public waters by ignoring this source of water pollution is difficult to estimate. However, any future water quality standards or cleanup policies that target inland or coastal waters for such pollutants as pesticide, sediment, dissolved oxygen, or nutrients will have to account for agricultural contributions. The potential to reach current water quality goals by regulating point

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[1] These include carbon monoxide (CO), lead (Pb), nitrogen oxides (Nox), ozone, particulate matter (PM), and sulfur dioxide (SO_2).

sources alone is infeasible or is prohibitively expensive. The question remains of how to regulate *all* sources of pollution efficiently. Hitherto, studies on environmental regulation and their costs have focused on point sources (e.g., electrical utilities – Swinton (1998), Coggins and Swinton (1996) and paper mills - O'Neil et al. (1983)) or nonpoint sources (e.g., nutrient emissions – Westra (1999), Morgan (1999), Fleming (1995)). The literature addressing simultaneous regulation of both point sources and nonpoint sources and its cost and is quite thin. Notable exceptions include examinations of the National Pollution Discharge Elimination System (NPDES), Dillon Reservoir, and Tar-Pamlico point/nonpoint trading programs (MPCA, 1996; Apogee Research, 1992; Harding, 1990; Elmore et al., 1985); and the literature on point/nonpoint trading ratios (Malik et al., 1993; Letson et al., 1993; Letson, 1992; Shortle, 1990). This thesis seeks to add to the theory and application of regulating point and nonpoint sources simultaneously.[2]

1.2 Minnesota River Phosphorus

Nonpoint agricultural pollution is an important issue in the current TMDL (Total Maximum Daily Load) discussions for U.S. surface waters, and in particular the Minnesota River (Boyd, 2000). The Minnesota River Basin encompasses approximately 10 million acres and hosts a population of approximately 700,000 in Central and Southern Minnesota before joining the Mississippi River in Saint Paul, Minnesota. Pleistocene glacial deposits cover almost the entire watershed, which contain the most widely used aquifers for domestic water supplies. Although glacial aquifers are widespread, less than a third of the wells in the watershed obtain water from them. The glacial deposits are predominantly till, an unstratified mixture of clay, silt, sand, and gravel. Beds of sand and gravel within the till are the most widely accessible and widely used shallow aquifers (MPCA, 2000). Approximately 92% of the region's area is

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[2] However, there is not a specific focus on the issues raised by Malik et al. (1993) regarding optimal trading ratios for point and nonpoint sources under uncertainty and enforcement. For the empirical applications found in Chapters 4 and 5, the marginal damage for point and nonpoint source emissions of phosphorus is assumed to be equal due the uniform, stock pollutant nature of phosphorus. Furthermore, the uncertain effects on nonpoint source pollution are deemed to be ex-ante and not ex-post due to the modeling methodology (Chapter 3). Because nonpoint emissions are known ex-post the primary question remains the ex-ante nonpoint source decisions under different policies (Chapter 5).

involved in agricultural, contributing about 50% of the state's corn and soybean production and hosting more than 20% and 40% of beef and hog production respectively. The Minnesota River has also been classified as one of America's most endangered rivers due to agricultural runoff (American Rivers, 2000). Contributions of sediment, nitrogen, and phosphorus by the Minnesota River to the Mississippi River have been linked to severe eutrophication and hypoxia problems downstream (USEPA, 1997).

Eutrophication results from excess nutrient inputs (nitrogen and phosphorus), which stimulate growth of algae and aquatic plants. These degrade the water quality making it difficult to use of the river for recreational and industrial uses or as a source of drinking water. In addition, eutrophic conditions severely reduce biologically available oxygen necessary for aquatic species. It has been estimated that the phosphorus levels need to be reduced by 40% to provide a livable environment for aquatic plants and animals (MPCA, 1999). Current attempts to regulate the amount of phosphorus entering the Minnesota River concentrate on point sources via command-and-control regulation (CAC).[3] These sources include municipal water treatment facilities, town runoff, and industry. The total phosphorus load to the Minnesota River from these point sources is approximately 348 tons per year (Faeth, 1998). To achieve the desired goal of reaching a 40% reduction in organic loading in the Lower Minnesota by point source regulation alone would cost in the range of $400 million (McCann, 1998). As a result regulators are increasingly looking to agricultural, nonpoint abatement as a less costly alternative to increasing point source regulation (Boyd, 2000; MPCA, 1999).[4] Recently, the Minnesota Pollution Control Agency (MPCA) adopted the goal of reducing organic loading, or biochemical oxygen demanding substances, by 40% (MPCA, 2000), which would in theory enable the Minnesota River to meet state water quality standards. To accomplish this, aggregate nonpoint phosphorus emissions[5] have been targeted for more than a 40% reduction from current levels (MPCA, 2000).

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[3] In general CAC regulation of PS's require an effluent standard, such as a monthly average of 1 mg p-emission / l liter for discharge (Senjem, 1997) with daily maximum loading restrictions (MPCA, 2000).

[4] The aforementioned Minnesota River Water Quality Plan (MPCA, 2000) proposes to reach its phosphorus reduction by reducing nonpoint emissions by more than 47%.

[5] Nutrients generate biological productivity and sediment uptake of oxygen in the river. The nutrient loadings convert into BOD load as the biology takes in the nutrient, grows, and then dies extending the

Regulation of nonpoint phosphorus is facilitated by its uniform, stock pollutant nature, which lends itself well to alternative forms of regulatory policy (e.g., effluent fees or pollution permits). Phosphorus movement in runoff and erosion from agricultural land occurs in two forms: particulate phosphorus (PP) and dissolved phosphorus (DP). PP is attached to soil materials and reaches the water system primarily through erosion. DP enters the water system though surface or subsurface runoff waters. Particulate phosphate comprises between 75-90% of the total phosphorus (TP) entering a water system (Minnesota Extension Service, 1997). While PP is not immediately available to aquatic vegetation and algae as is DP, it does come into solution with time as DP levels decrease. Accumulated PP arriving from nonpoint sources during a high-flow period can be significant enough to maintain stable concentrations of DP during low-flow periods (Busman et al., 1997). Therefore, TP will be used as the measure of phosphorus emissions (i.e. PP + DP)[6] entering the water system for regulatory purposes. The damage caused by each unit of phosphorus entering the water is assumed to be equal within a defined region.

It should be noted that crop production depends upon sound phosphorus management. Judicious additions of inorganic and organic phosphorus are required where the ambient soil composition does not supply sufficient quantities of phosphorus for plant uptake. Average applications of commercial phosphorus on agricultural land in Minnesota are approximately 24 lbs/acre/year (Minnesota Agricultural Statistics, 1995).[7] This region also has seen increased use of agricultural land in conjunction with intensive livestock production, which also adds to the plant-available phosphorus in the soil. In fact, data adapted from the Potash and Phosphorus Institute indicate that Minnesota has 76% of soil samples testing "high" or "above" for phosphorus (second highest behind Illinois) indicating that much of these areas require little or no supplemental phosphorus (Sharpley, 1994).

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length downstream of a source's BOD impact. The impact of nutrient conversion increases when the river slows and deposits organic material in one area such as metropolitan areas. During low flow periods the river is overloaded with a BOD from upstream.

[6] An insignificant amount of phosphorus (less than 1% of TP) is also lost to ground water via deep seepage.

[7] This is equivalent to 51.7 lb./acre of P_2O_5. Average manure application rates are not included.

1.3 Thesis Objectives and Overview

This thesis discusses water quality and mechanisms for restricting agricultural, nonpoint phosphorus emissions. It is argued that regulating heterogenous point and nonpoint sources simultaneously via a system of pollution permits can reduce the cost of complying with environmental regulation. It is also shown that there are efficiency gains to such a mechanism when point and nonpoint sources are allowed to freely trade emissions permits across sources and across time due to the nature of phosphorus as a stochastic-stock pollutant. To illustrate these efficiency gains, a permit trading system is compared to a system employing both emissions taxes and one mandating source reductions. This comparison is made both theoretically and empirically for the case of phosphorus emissions in the Minnesota River. The empirical application seeks to offer policymakers one avenue to address recently adopted maximum loading restrictions (TMDLs).[8] A further extension considering the problem of asymmetric information and moral hazard is provided to examine conditions that may affect the attractiveness of point-nonpoint permit trading.

To this end the thesis is organized as follows. Relevant theory and literature of pollution regulation is discussed and presented in Chapter 2. Included are a discussion of and an argument for the use of tradable permits to regulate nutrient emissions. Chapter 3 describes the methodology used to integrate economic and biophysical analyses via the development of abatement cost functions for nonpoint source emissions. Used for the water quality modeling is the Agricultural Drainage and Pesticide Transport model. Its required input parameters and how they are used to simulate best management practices are discussed. Furthermore, the econometric methodology for estimating the abatement cost functions using the simulated observations is detailed in Chapter 3. A stylized model of phosphorus reduction policies, examining a sub-watershed of the Minnesota River is presented in Chapter 4. Here initial emission levels for point and nonpoint source are estimated as are relevant abatement cost functions. These estimates are used to evaluate

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[8] New USEPA water quality standards are being implemented under the rubric of total maximum daily loads (TMDLs). These require those water bodies not meeting current pollutant standards to develop comprehensive abatement practices for both point and nonpoint sources (Boyd, 2000; MPCA, 2000).

various policies for achieving phosphorus abatement in this sub-watershed. Chapter 5 examines more closely the problem of asymmetric information and possible moral hazard encountered when regulating nonpoint pollution. The argument that moral hazard will erode the efficiency of abatement regulation has been raised against possible permit trading mechanisms. This thesis examines the implications for static and dynamic policy in this context. The results of the analysis are summarized in Chapter 6, accompanied by concluding comments.

Chapter 2

Background and Literature

2.1 Prices vs. Quantities

In the Coasian tradition, excessive emissions of nutrients into a body of water can be viewed as a case of market failure. Because there are not clearly defined property rights for clean water, agricultural producers do not take into account the adverse social costs associated with the use of inputs, such as fertilizers and pesticides, and therefore use of these factors will exceed socially optimal levels. Specifically, when aggregate contributions of phosphorus to a river exceed certain parameters an environmental externality (eutrophication) results; the behavior of specific individuals adversely affects the utility of other individuals. However, as positive quantities of pollution (phosphorus emissions) may occur in a Pareto-efficient equilibrium (Coase, 1960; Arrow and Hahn, 1971), it is not necessary to force polluters to cease production activities resulting in the externality, but only to maximize the difference between total benefits resulting from cleaner waters and the total cost of achieving the environmental amelioration.

To correct such a market failure, the regulator has available policy mechanisms to induce the producers of the externality to incorporate the social costs of the pollution into their profit maximizing endeavors. These policies are typically of two varieties: price instruments or quantity instruments. Taxes and subsidies are the most common price instruments available to the regulator; quotas and their many derivatives are the quantity mechanisms available to the regulator.[9] A third type of regulation that is commonly used is design standards.

In this thesis, I will primarily constrain the choice of regulatory mechanism to effluent fees (Pigouvian taxes), tradable quotas (permits), and non-tradable quotas (command-and-control). For example, an effluent fee will charge polluters for each unit of pollution emitted equal to the marginal social damage caused by that unit. Such a fee will induce the polluters to internalize the marginal costs of emitting an additional unit of pollution, and it will be shown that the resulting level of pollution will maximize social welfare (total benefits of pollution reduction minus total costs of achieving those reductions). Returning to the Coasian tradition, if the rights to clean water (or alternatively to pollute) are properly defined, a similar Pareto-efficient equilibrium between the benefits to pollution reduction and costs of achieving that reduction can be obtained when these rights are tradable (as in the case of tradable pollution permits). Lastly, the regulator can simply mandate that each polluter reduce his/her pollution levels to that which will result in the same balance of costs and benefits achievable under the previous two systems.

Some of these measures are better suited to different policy, informational, and physical environments. Often times due to incomplete knowledge of the benefits and costs associated with pollution abatement and the marginal value of cleaner water, the regulator will simply choose a pollution standard and mandate that polluters uniformly reduce their emissions equal to that level. When there are many polluters with different costs of abatement this form of regulation will obviously be inefficient. Comparisons between regulatory policies are generally based on one of two measures: "cost effectiveness" when polluters' compliance costs are compared in achieving an

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[9] Taxes and quotas can be targeted or not depending on the type of externality, quotas are often tradable.

exogenously determined standard, or "efficiency" when deviations from a socially optimal level in abatement are represented by deadweight losses. This chapter seeks to review the theory behind these measurements that will be used in analysis of policy options evaluated for the reduction of phosphorus emissions in the Minnesota River.

2.1.1 Deterministic Regulation

In a deterministic world tradable emissions permits and Pigouvian pollution taxes, or a system of prices and quantities, are equivalent and can achieve first-best allocations by equating marginal costs of pollution abatement across sources. These policies are more efficient than simple command-and-control policies mandating uniform reductions in the absence of transaction costs when polluters are heterogeneous in abatement costs (Baumol and Oates, 1988; Tietenberg, 1985 and 1995).

The theory behind permit markets stems from the seminal work of Dales (1968) and Montgomery (1972). However, there are many types of marketable permit systems that have arisen from this work (Morgan, 1999). The type of permit system utilized in this thesis is referred to in the literature as an *emissions trading system* (ETS). Under this system permits are traded between sources on a 1:1 basis. Another type of permit system is an *ambient permit system* (APS). An APS allows for emissions to be weighted by their environmental impact and is appropriate when dealing with non-uniform pollutants, where the amount of discharge and its spatial distribution are important to consider (e.g., sulfur dioxide and acid rain). Other systems include the pollution-offset system, the non-degradation offset, and the modified pollution offset. Offset systems are hybrids of the ETS and APS allowing for different degrees of control over the timing, spacing, and quantities of emissions (Hanley, Shogren and White, 1997). For the purposes of this thesis, the ETS allows sufficient simplicity to examine the problem of river pollution due to point and nonpoint phosphorus emissions.

Consider an emissions trading system (ETS) where a permit represents the right to emit a specified quantity of pollutant into the environment. At the beginning of the control period a predetermined number of permits can be issued to sources via some established mechanism or auctioned off in a bid system. These permits can be bought, sold, and traded in established permit markets, similar to spot markets for other commodities. If a source is in compliance with the environmental standard it can pollute up to the level of permit holdings. Under this system the marginal cost of abatement will be equalized across sources such that the equilibrium cost will equal the lowest marginal abatement costs. Those sources having marginal abatement costs greater than the permit price will prefer to abate less and to purchase additional permits and vice versa.

This process will insure the lowest cost of compliance in achieving the predetermined level of abatement excluding transaction costs. Transaction costs include those required for monitoring of emissions (especially costly for NPSs), enforcement of the environmental standard, and information costs associated within a tradable market system. Stavins (1995) has shown that these transaction costs are not negligible for permit markets. However, he concludes that even if transaction costs prevent a permit system from realizing a high number of trades, the aggregate costs of compliance will likely be less costly than a CAC approach. Often a permit system where no trades occur is also likely to be less costly than a technology standard (O'Neil et al., 1983).

Example 2.1.1

The equivalence of regulatory policies employing taxes or tradable pollution permits can be illustrated with a simple example. Consider a situation similar to that of phosphorus emissions in the Minnesota River. For simplicity assume a wastewater treatment facility (m) with known abatement cost function, $C_m(a_m) = 0.05a_m^2$, and which emits 2000 lbs of phosphorus per year into the river. There is also a farm with 50,000 acres of land that is identical in all aspects (this might represent one decision maker for a minor watershed having homogonous soil qualities throughout). Due to soil erosion, this farm emits 1 lb of phosphorus per acre per year into the river. The known abatement cost function for each acre of agricultural land is given by: $C_n(a_n) = 10a_n^2$. Total emissions of phosphorus into the river equal 52,000 lbs per year. The regulator has decided that emissions should be reduced by 40%, i.e. to 31,200 lbs per year. For this example, an environmental standard is chosen exogenously by the regulator and does not necessary imply social welfare maximization.

- *Uniform Reduction Policy*

Suppose the regulator declares the environmental standard and mandates that each source must independently reduce emissions by 40%. With perfect monitoring and enforcement information, the environmental standard will be met: the point source will abate 800 lbs of phosphorus per year and the farm will abate 0.4 lbs per acre per year, or 20,000 lbs aggregate abatement. The individual and total costs to comply with a uniform reduction policy are:

$$C_m(800) = 0.05 * 800^2 = \$32{,}000,$$

$$50{,}000 * C_n(0.4) = 10 * 0.4^2 * 50{,}000 = \$80{,}000,$$

and

$$TC(20{,}800) = C_m(a_m) + 50{,}000 * C_n(a_n) = \$112{,}000.$$

- *Effluent Fees*

Suppose now that the regulator imposes a Pigouvian tax on each pound of phosphorus emitted into the river. The regulator will choose a tax (*t*) that will achieve the environmental standard and minimize total abatement costs. In order to do this the regulator will solve the series of equations:

- $\dfrac{\delta C_m(a_m)}{\delta a_m} = 0.1a_m = t^*$,
- $\dfrac{\delta C_n(a_n)}{\delta a_n} = 20a_n = t^*$, and
- $a_m + 50{,}000 * a_n \geq 20{,}800$.

These first two equations are the first-order conditions characterizing the cost-minimizing choices for the two polluters given an effluent tax. The third constrains aggregate abatement to be greater than or equal to the desired environmental standard.

Given these first-order conditions and the environmental standard the optimal tax chosen by the regulator will equal $8.286 per pound of phosphorus emitted into the river.

The resulting levels of abatement chosen by the polluters and compliance costs given this tax will be:

$$a_m = 82.86 \text{ lbs/year},$$
$$C_m(82.86) = 0.05 * 82.82^2 = \$343.29,$$
$$a_n = 0.414 \text{ lbs/acre / year},$$
$$50{,}000 * C_n(0.414) = 10 * 0.414^2 * 50{,}000 = \$85{,}698,$$
and
$$TC(20{,}800) = C_m(a_m) + 50{,}000 * C_n(a_n) = \$86{,}041.$$

When the effluent fees are chosen optimally there are significant compliance cost savings, 23% in this example. There are, however, distributional aspects that also must be considered. In this example, the farm will end up abating more phosphorus under a system of effluent fees as compared to a system of uniform reductions. Consequently, the abatement costs of the farm will increase by 7.12% with effluent fees, and the abatement costs of the wastewater treatment facility will fall by 98.9%. Furthermore, with effluent fees each source will be paying a tax on emissions in addition to incurring abatement costs, which significantly increases total compliance costs to the polluter.

- *Emission Trading System*

Now the regulator distributes 31,200 permits (perfectly divisible) to the wastewater treatment facility and to the farm, where each permit (l) represents the right to emit 1 pound of phosphorus into the river that year. Suppose that the regulator distributes these permits according to historic levels of pollution such that each polluter receives permits equivalent to 60% of their historic emissions levels: $l_m = 1{,}200$ and each acre of nonpoint land will be given $l_n = 0.6$. Given historic emissions levels, $\bar{e}_m = 2000$ lbs and $\bar{e}_n = 1.00$ lb/a, final abatement and emission levels following regulation can be defined by: $a_m = 2{,}000 - e_m$ and $a_n = 1.00 - e_n$. If the permit allotments are not tradable this is essentially the uniform reductions policy, however, when polluters can trade these permits a significant decrease in compliance costs can be achieved. Let the purchase or sale of a permit be denoted by s. Each polluter given a permit allotment will choose a^* and s^* to solve the following cost minimization problem:

$$\min_{a,s} TC_i = C_i(a_i) + P_l * s_i$$

$$\text{subject to :}$$

$$a_i \geq 0, \text{and}$$

$$s_i = \bar{e}_i - l_i - a_i.$$

Here the market clearing price of a permit, P_l, will be characterized by the first-order conditions:

$$\frac{\delta C_i(a_i)}{\delta a_i} = P_l.$$

Given the environmental constraint, $l_m + 50{,}000 * l_n = 31{,}200$, the identities $a_m = 2{,}000 - e_m$ and $a_n = 1.00 - e_n$, the market clearing conditions will be:

- $a_m = 10P_l$,
- $a_n = \frac{P_l}{20}$, and
- $a_m + 50{,}000 * a_n \geq 20{,}800$.

The equilibrium price for permits will equal \$8.286. Similarly, the cost-minimizing abatement levels for the two polluters will be: $a_m = 82.86$ lbs/year and $a_n = 0.414$ lbs/acre/year. The costs of compliance and efficiency gains over the uniform reductions policy are identical to that of effluent fees based on Pigouvian taxes.

- Policy Comparison

While it can be seen that the abatement levels resulting from the effluent fee and tradable permit policies are identical, there are substantive differences between the policies. For example, under effluent fees the cost to each polluter to comply with the environmental regulation will equal the abatement costs plus the fees paid out for emissions. Given the Pigouvian tax of \$8.29 per pound of phosphorus emitted, the wastewater treatment facility will pay $15,893 in fees and will incur $343 in abatement costs for a grand total of $16,236. The farm will pay $242,756 in fees and will incur an additional $85,698 in abatement costs for a grand total of $328,454. It is no wonder that farmers (and other polluters) are opposed to effluent fees, even though the tax revenues may be used to offset the abatement costs at the end of the period (McCann, 1997). When permits are distributed free of charge and traded between polluters the total costs to the wastewater treatment facility and farm are $6,287 and $79,754 respectively. This is because the farm sells 717 permits to the wastewater treatment facility at a price of $8.29. Politically this may seem more palatable to the polluters than the system based on effluent fees, with promises of refunded tax revenues. It should also be noted that a targeted reductions policy could be employed by the regulator, mandating the optimal abatement levels derived under the effluent tax and emissions trading systems. Were this the case the total abatement costs would also be $86,041.

There are also several other differences between these systems that require some discussion. If the regulator is unsure of the abatement cost functions, she will be unsure of the polluters' responses to a per unit effluent fee. If the fee is set too high, abatement will exceed the environmental standard; similarly if the fee is set too low, abatement will not achieve the desired level of environmental quality. If the regulator must adjust the fee over time there may be costly repercussions to the polluters as they re-evaluate their cost-minimization choices and abatement efforts (Baumol and Oates, 1988). Also where the social damages vary temporally or spatially, it may be very difficult to implement a system of taxes that reflect these variations. These drawbacks to regulation using price instruments are not so severe when regulating with quantity instruments such as a tradable permit system. However, the "Polluter Pays Principle" exemplified by an effluent tax does has a certain reform appeal in the political economy arena. Effluent fees can provide the regulator with a significant source of income, which may be desirable, although certainly not to the polluter. This is similar to the situation when tradable permits are auctioned instead of freely distributed. Effluent fees do however reward polluters that have taken measures in the past to become cleaner. For example, a farmer who has been utilizing no-till residue management policies will show significantly fewer phosphorus emissions than a neighbor using conventional tillage practices. If permits are distributed according to some generalized percentage based on historic emissions, the conventional tillage farmer will receive a greater endowment of permits, i.e. the clean farmer is being de facto penalized for prior abatement efforts.

One major drawback to a system of taxes or one of tradable permits is the transaction costs associated with their implementation. Under such second-best conditions, command-and-control mechanisms may result in the lowest overall cost of regulation (Stavins, 1995; Tsur and Dinar, 1997; McCann, 1997). A transaction cost central to this thesis is the cost associated with the regulator's uncertainty regarding the costs and benefits of pollution abatement. Touched on earlier, if regulators are uncertain of the cost structure, the potential response of polluters to an effluent fee is also unknown. If the regulator is not concerned with the benefits of pollution abatement, a targeted command-and-control policy or an emissions trading system will allow the regulator to meet the environmental standard at lowest cost. This advantage of quantity instruments does not always hold, for example when the regulator's goal is to maximize social welfare. The next section addresses this issue.

2.1.2 Uncertain Regulation

Many authors have built on the deterministic model to reflect real world complications and to facilitate policy comparisons (see for example Horan et al., 1998; Smith and Tomasi, 1995, 1999; Shortle, 1990; Shortle and Dunn, 1986). Often what distinguishes the effectiveness or efficiency of a particular policy in regulating pollution is the manner in which uncertainty enters the regulator's social-welfare maximization problem and polluters' abatement-cost minimization (or profit maximization) problems. This uncertainty, ex-ante, may inhibit such regulation as a permit trading system from operating efficiently (Taff and Senjem, 1996). Due to this uncertainty, it has been typical to treat point and nonpoint pollution problems separately (Horan et al., 1998; Segerson, 1988; O'Neil, 1983). However, there are several reasons to combine the regulation of point and nonpoint pollution. Institutional transaction costs may be less when regulating point and nonpoint sources simultaneously than if separate pollution policies are used, for example. Another reason is that the uncertain nature of nonpoint pollution may be smoothed by allowing interaction between point and nonpoint abatement over the period of regulation.

We can examine this further by reviewing the discussion of regulation under uncertainty found in Weitzman's (1974) seminal analysis concerning pricing and quantity instruments. Extensions of his arguments allow for a comparison of pricing and quantity instruments when point and nonpoint sources are regulated simultaneously. In Wietzman's model the planner can choose a price-instrument (e.g., emissions tax) that induces the producer (polluter) to supply an optimal level of the economic variable (pollution abatement), or the planner can use a quantity instrument to restrict the production of a pollutant at an optimal level. When the planner is uncertain about the benefits or costs as a function of the production of the economic variable there are conditions when the planner should choose one instrument over the other.

Command-and-Control vs. Taxes

Initially consider the case of one agent and one central planner. The agent (polluter) emits pollution into the environment. The planner has decided to restrict these emissions (or to induce abatement) to the socially optimal level. Let abatement, a, equal the reduction of emissions from historic levels, $\bar{e}$, to a restricted level, e. Assume abatement and emissions levels are constrained to be non-negative. Following Weitzman's analysis (W-A), the planner given costs of abatement, $C(a)$, and the benefits of abatement, $B(a)$,[10] will choose a^* to solve:

$$\max_a B(a) - C(a). \tag{2.1}$$

First-order necessary conditions for the solution imply:

$$B'(a^*) = C'(a^*). \tag{2.2}$$

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[10] Costs and benefits are assumed to have the traditional properties: $B''(a)<0$, $C''(a)>0$, $B'(0)>C'(0)$, and $B'(a)<C'(a)$ for sufficiently high levels of abatement.

To achieve a^* the planner can directly restrict production of abatement to this level and let the polluter achieve a^* at least cost, or she can choose an optimal tax rate, t^*, so that a^* solves the polluter's cost-minimization problem:

$$\min_a C(a) + t^*(\bar{e} - a). \tag{2.3}$$

From this and (2.2) the necessary condition for a solution (a^*) is:

$$t^* = B'(a^*) = C'(a^*). \tag{2.4}$$

Weitzman shows it makes no difference in terms of social welfare whether the planner uses t^* or a^* in an environment of perfect information.[11] The nature of uncertainty concerns the link between a stochastic process and the cost and benefits functions. Suppose that this stochastic process is a random weather variable, w, that does not affect benefits[12], but is unobserved and unknown at the present. Then we can describe costs as $C(a,w)$ and benefits as $B(a)$.

To maximize expected welfare the planner now has a target level of abatement in mind, $\hat{a}$, which solves:

$$E[B(\hat{a}) - C(\hat{a}, w)] = \max_a E[B(a) - C(a, w)], \tag{2.5}$$

where $E[\bullet]$ is the expectations operator. A first-order necessary condition for $\hat{a}$ to solve (2.5) is:

$$B'(\hat{a}) = E[C'(\hat{a}, w)]. \tag{2.6}$$

When an emissions tax rate is chosen under uncertainty, the polluter will minimize compliance costs by adjusting abatement according to a function of the tax and weather:

$$a = h(t, w). \tag{2.7}$$

As in Weitzman this conditions can be written:

$$C(h(t,w), w) + t(\bar{e} - h(t,w)) = \min_a C(a, w) + t(\bar{e} - a). \tag{2.8}$$

A first-order necessary condition for a solution is:

$$C'(h(t,w), w) = t. \tag{2.9}$$

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[11] This analysis does not include transaction costs or the cost to farmers of paying emissions taxes in addition to incurring abatement costs. Weitzman points out that these issues are concerned with the implementation of policies and not with the comparisons of the policies themselves.

[12] The stochastic process affecting benefits in Weitzman (1974) does not significantly enter into the analysis, and does not affect the measure of regulatory efficacy.

The rational planner will choose an emissions tax rate, $\tilde{t}$, such that:

$$E[B(h(\tilde{t},w))-C(h(\tilde{t},w),w)]=\max_{t} E[B(h(t,w))-C(h(t,w),w))]. \tag{2.10}$$

First-order conditions imply:

$$\tilde{t}=\frac{E[B'(h(\tilde{t},w))\cdot h'(\tilde{t},w)]}{E[h'(\tilde{t},w)]}. \tag{2.11}$$

Given $\tilde{t}$ and w, the polluter will produce $\tilde{a}(w)=h(\tilde{t},w)$ that minimizes the costs of producing abatement and paying taxes on pollution.

Due to the presence of uncertainty, Weitzman argues that it is likely that $B'(\hat{a})\neq C'(\hat{a},w)$ and that $B'(\tilde{a}(w))\neq C'(\tilde{a}(w),w)$, implying that neither instrument will yield an optimal ex-post abatement level, a^*, and therefore, the choice of $\tilde{t}$ and $\hat{a}$ will have welfare implications. The measure of the comparative advantage of price instruments over quantity instruments is given by:

$$\Delta\ =E[(B(\tilde{a}(w))-C(\tilde{a}(w),w))-(B(\hat{a})-C(\hat{a},w))]. \tag{2.12}$$

This then illustrates that when the slope of the marginal benefits function is greater than the marginal cost function, delta will be negative and quantity instruments will be preferable to price instruments for regulating the pollution *ceteris paribus*.

However, implicit in (2.12) is the assumption that polluters can actually achieve $\hat{a}$. Under this definition of ex-ante uncertainty, the costs of abatement (i.e., $C(\tilde{a}(w),w)$ and $C(\hat{a},w)$) are uncertain, as is the level of abatement under price instruments (i.e., $\tilde{a}(w)$), but the level of abatement under quantity instruments is certain (i.e., $\hat{a}$). A farmer given $\hat{a}$ and expected weather patterns, will choose abatement efforts that minimize costs of expected abatement, $E[a(w)]=\hat{a}$. Abatement efforts for agricultural production are typically fixed for the production period, and so actual abatement as a function of realized weather, $\hat{\hat{a}}(w)$, will generally not equal expected abatement, $\hat{a}$. Similarly, given $\tilde{t}$ farmers will choose abatement efforts that minimize costs of expected abatement and taxes on expected emissions, where $E[a(\tilde{t},w)]=h(\tilde{t},w)=\tilde{a}(\tilde{t},w)$. Actual abatement in this case, $\tilde{\tilde{a}}(\tilde{t},w)$, will also not equal the level expected at the beginning of the period. The planner's ex-ante expectations of abatement levels given expected weather patterns, $\overline{w}$, and optimal choice of $\widetilde{t}$ are:

$$\hat{a} = \widetilde{a}(\overline{w}) = h(\widetilde{t}, \overline{w}). \tag{2.13}$$

Given inflexibility in abatement efforts following the initial decision period, the realized abatement levels under the two programs will be equal, but will not be equal to (2.13) if weather deviates from the mean. The costs incurred at the beginning of the period to achieve the expected levels of abatement will similarly be equal; the function mapping actual abatement into actual costs will be shifted up or down depending on the realized weather. Of course in this scenario Δ = 0 trivially, which makes Weizman's analysis seem somewhat irrelevant for this case.

The Case For Point-Nonpoint Trading

A return to Wietzman's framework is facilitated, however, by including at least one other polluter that has a flexible productive capacity over the space of the decision period. In this case we constrain the problem to one with two polluters: one nonpoint source (*n*) and one point source (*p*). Benefits as a function of abatement remains, *B(A)*, where:

$$A = a_p + a_n(w). \tag{2.14}$$

Point source abatement is assumed to be unaffected by weather, with abatement costs given by $C_p(a_p)$. Nonpoint abatement is affected by weather and has costs, $C_n(a_n(w), w)$. At the end of the period the planner knows with certainty what the contributions of abatement and the cost function were for each source, but is unsure of these during the period. The point source knows with certainty its abatement levels and costs at all times, but the nonpoint source has its abatement levels and cost function revealed over the period as weather is observed.

Condition 1

Subject to non-negativity constraints on abatement and emissions' levels ex-post levels of total abatement are deterministic (i.e., we are not considering the case where severe weather occurs, such that the difference in expected and realized nonpoint abatement exceeds the potential for point source adjustments). If realized nonpoint abatement is lower (greater) than ex-ante expected levels, it is possible to achieve $A = a_p + a_n(w)$ by increasing (decreasing) deterministic and flexible point source abatement.

Given Condition 1, optimal emission taxes, $\tilde{t}$, can be chosen by the planner at the beginning of the period to induce optimal choices of $\tilde{a}_p = h_p(\tilde{t})$ and $\tilde{a}_n(w) = E[h_n(\tilde{t}, w)]$, or the planner can distribute permits (q) to the point and nonpoint source such that: $q_p = \bar{e}_p - \hat{a}_p$, $q_n = \bar{e}_n - E[\hat{a}_n(w)]$, where $\tilde{a}_p = \hat{a}_p$ and $E[\tilde{a}_n(w)] = E[\hat{a}_n(w)]$. If the emissions permits are tradable, as stochastic weather is revealed to the farmer, she will enter the market to buy or sell permits based on her observations. If there exists a severe penalty for emitting in excess of owned permits the farmer will endeavor to purchase permits in the event of inclement weather. Similarly, the point source can offset costly abatement towards the end of the period by purchasing unused permits from the farmer when weather has been favorable for nonpoint abatement.

Keeping Condition 1 in mind we can return to (2.12):

$$\Delta_{ets} = E[(B(\tilde{A}(w)) - C(\tilde{A}(w), w)) - (B(\hat{A}) - C(\hat{A}, w))]. \tag{2.15}$$

It can be seen that $\Delta = \Delta_{ets}$, where $\tilde{A}(w) = \tilde{a}_p + \tilde{\tilde{a}}_n(w)$, $\hat{A} = \hat{\hat{a}}_p + \hat{\hat{a}}_n(w)$, $C(\tilde{A}(w), w) = C_p(\tilde{a}_p) + C_n(\tilde{a}_n(w), w)$, and $C(\hat{A}, w) = C_p(\hat{a}_p) + C_n(\hat{a}_n(w), w)$. Assuming quadratic approximations of the cost and benefits, the fundamental result remains:

$$\Delta_{ets} \cong \frac{\sigma^2 B''}{2C''^2} + \frac{\sigma^2}{2C''}. \tag{2.16}$$

As mentioned, the implications for emissions taxes and trading revolve around the sign of Δ_{ets}. If $\Delta_{ets}<0$ then $B'' + C'' < 0$; i.e. the slope of the benefit function is greater than the slope of the cost function and tradable emissions permits will have a comparative advantage over emissions taxes. Effluent fees are preferable to tradable permits, all else equal and subject to Condition 1, the more steeply sloped the cost function is and the more linear the benefit function is within a neighborhood around the optimal abatement level (i.e. $\Delta_{ets}>0$). If $C_p(\bar{a}) > C_n(\bar{a})$ the effect of including a point source will be to mute the effect of weather on the total cost curve, *C(A)*, which will decrease σ^2 and therefore, the magnitude of Δ_{ets}.

2.2 Dynamic Regulation

There are circumstances that require planners to regulate the production of an economic variable over time. Perhaps investment decisions are irreversible in the short run or perhaps we are investigating the decomposition of and production of abatement for a stock pollutant. In such an instance it is appropriate to compare policies to regulate pollution and abatement efforts over more than just one planning period.

Consider the problem of phosphorus pollution in a river. When phosphorus enters the river it may accumulate on the river bottom attached to sediment, it may enter into solution and be carried downstream, or it may be incorporated into organic plant matter. Therefore, the phosphorus available for plant growth at any one point in time is a dynamic function of current emissions, the built up stock of phosphorus on the river bottom, and current plant consumption of dissolved phosphorus. As damages due to eutrophication are a function of plant levels, a dynamic model seems more appropriate for regulating emissions. Continuing from our earlier example, assume that a central planner has decided that there is currently too much phosphorus being emitted into the river and has decided to impose phosphorus regulations on the sources of this pollution. There are several papers examining intertemporal permit markets, which effectively argue for the increased efficiency of a permit system when banking (borrowing) of permits is allowed (Cronshaw and Kruse, 1996; Rubin, 1996; Kling and Rubin, 1997; Leiby and Rubin, 1998).

Rubin (1996) notes the absence of significant research into emission banking and borrowing. His paper allows firms to meet an intertemporal environmental standard by direct abatement or by purchasing, selling, banking, or borrowing permits in order to meet the standard taking advantage of speculative opportunities that may arise. The benefit of allowing the banking or borrowing option is to lower compliance costs by adjusting emission streams more flexibly through time. Rubin assumes that all the permits are issued at the beginning of the time horizon. As an alternative, to allow for increased regulator flexibility in times of environmental instability, each source can be issued a fixed endowment of permits at the beginning of each year (Cronshaw and Kruse, 1996). Under the Rubin system some permits are always banked until the last period. He shows that the permit price will rise at the rate of interest. The explicit solution for the time path of emissions is determined using an optimal control framework. This continuous-time treatment of emissions and abatement decisions is attractive as it allows the calculation of such analytical results as steady-state time paths. It is also possible to illustrate the effects of changing regulatory time frames, varying degrees of initial stock quantities, and the effects of time dependent technology using this type of analysis.

Cronshaw and Kruse (1996) determined equilibrium conditions for an intertemporal permit market. The main thrust of their paper was to examine how permit prices change over time with respect to banking decisions and the prevailing interest rate. In addition they allow for some or all firms to be public utilities with profit regulations as well as environmental regulations. They show that in an intertemporal equilibrium the permit prices can rise no faster than the interest rate if there exists at least one firm with unregulated profits.[13] If firms do not bank permits, permit prices will rise slower than the rate of interest. They conclude that treating the uncertainty of future emissions with bankable permits in effect can be considered as an option, which may allow firms to delay making costly abatement investments.

2.2.1 First-Best

A first-best solution to the dynamic emissions problem is one that would maximize the net present value of the benefits to reducing the stock of phosphorus in the river less the costs of achieving those reductions. In a deterministic setting, price instruments will achieve the same result as quantity instruments. Due to the positive discount rate, the present value of abatement costs will decline over time, indicating that with a system of intertemporal permits the optimal abatement rate will increase over time. This indicates

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[13] This would be the case for the empirical application forwarded in this thesis: there are a number of unregulated firms (i.e., farms) and several regulated firms.

that firms will borrow emissions in early periods (subject to a fixed endowment of permits in each period) and repay them at a later date.

As an illustration, consider the following example of an optimal control system for a watershed.

- Aggregate Cost of Abatement: $C(t) = \beta A(t)^2$,
- Aggregate Damage Function: $D(t) = \alpha \ln(S(t))$,
- Stock Equation: $\dot{S}(t) = e(t) - \gamma S(t)$, and
- Emissions Equation: $e(t) = \overline{E} - A(t)$.

Here *A(t)* represents aggregate abatement, *S(t)* represents the stock of phosphorus in the river, *e(t)* represent aggregate emissions, $\overline{E}$ represents historic emissions, and where the functional forms are chosen to be general enough to sufficiently illustrate the case of a stock pollutant with a positive decay rate (γ) with traditionally assumed damage and cost function characteristics: D'<0, D">0, C'>0, and C">0.

The regulator's problem (RP) is to choose aggregate abatement in each time period to minimize the cost of abatement plus the damages due to the stock level at that time. If the regulator can choose the time period of regulation and the terminal stock level, (RP^1) is:

$$\begin{gathered}\min_{A(t)} \int_0^T e^{-rt}[\beta A(t)^2 + \alpha \ln(S(t))]dt \\ \text{subject to :} \\ \dot{S}(t) = \overline{E} - A(t) - \gamma S(t), \\ S(0) = S_0, \\ \lambda(T) = 0.\end{gathered} \tag{RP^1}$$

Here, $\lambda(T)$ represents the shadow price for an optimally chosen terminal stock level. The current value Hamiltonian (H^1) for this system is:

$$H \equiv \beta A(t)^2 + \alpha \ln(S(t)) + \lambda(t)[\overline{E} - A(t) - \gamma S(t)]. \tag{H^1}$$

The first-order necessary conditions for an interior solution are:

- $\frac{\partial H}{\partial A} = 0$, which implies: $A^{*}(t) = \frac{\lambda(t)}{2\beta}$;
- $-\frac{\partial H}{\partial S} = \dot{\lambda}(t) - r\lambda(t) = \gamma\lambda(t) - \frac{\alpha}{S(t)}$, which implies: $\dot{\lambda}(t) = (r+\gamma)\lambda(t) - \frac{\alpha}{S(t)}$; and
- $\dot{S}(t) = \overline{E} - A(t) - \gamma S(t)$.

To find the steady-state equations for the stock of phosphorus and for the abatement levels, it is possible to manipulate these first-order conditions, such that:

- $\dot{S}(t) = \overline{E} - A(t) - \gamma S(t)$ and
- $\dot{A}(t) = (r+\gamma)A(t) - \frac{\alpha}{2\beta S(t)}$.

Setting these two differential equations equal to zero, the steady-state levels of S^{ss} and A^{ss} are:

- $S^{ss} = \frac{1}{\gamma}(\overline{E} - A^{ss})$ and
- $A^{ss} = \frac{\alpha}{2\beta(r+\gamma)S^{ss}}$.

Solving for the steady-state levels:

$$S^{ss} = \frac{\overline{E}}{2\gamma} \pm \sqrt{\overline{E}^{2} - \frac{2\gamma\alpha}{\beta(r+\gamma)}} \quad \text{, and} \tag{2.17}$$

$$A^{ss} = \frac{\overline{E}}{2} \pm \gamma\sqrt{\overline{E}^{2} - \frac{2\gamma\alpha}{\beta(r+\gamma)}} \quad . \tag{2.18}$$

Because abatement and stock levels are subject to non-negativity constraints there will be either one, two, or no steady-state values, depending on the value of the square root term in (2.17) and (2.18). This value will depend on the parameters found in the specific watershed, and are often difficult for regulators to estimate.

2.2.2 Second-Best

As illustrated there exist links between phosphorus emissions over time, the amount of phosphorus available for algae growth, and the phosphorus deposited and banked in the river bottom silt. When the regulator is unsure of the exact nature of these links and is the social benefits to cleaner waters (e.g., those attributable to recreational boating and fishing) she may choose instead some level of phosphorus emissions, deemed by biologists to be safe for aquatic life. This may or may not be the efficient level of phosphorus emissions, and therefore policies chosen to reach this standard, *S*, are considered second-best policies. To compare second-best policies, one measure the regulator can use to judge regulatory efficiency is cost effectiveness. In other words, to achieve the pollution reductions necessary to reach *S* the regulator has decided that she will choose the most cost-effective policy, where costs are defined as the net present value to risk-neutral polluters with a discount rate (*r*). Three policies that the regulator may choose are uniform reductions, Pigouvian taxes, and tradable emissions permits. In a competitive deterministic market, sources will buy and sell permits such that the market price of permits is equal to marginal abatement costs. Furthermore, when banking and borrowing of permits are allowed, the net present value of discounted marginal abatement costs are equalized across time periods.

More recently Leiby and Rubin (1998) have extended the Rubin (1996) system to account for differing types of pollutants. They tailor their intertemporal permit system to account for *stock* pollutants (i.e., those pollutants that accumulate in the environment and where damages depend on their accumulated stock). This type of pollutant differs from a *flow* pollutant (i.e., pollutants that harm the environment as a function of their flow rate). Their treatment of a pure stock pollutant is quite similar to the treatment of total phosphorous entering the river system found in Chapters 4 and 5. The regulator is concerned about the amount of phosphorous entering the river system. When phosphorous emissions exceed the assimilative capacity of the river eutrophication results. Leiby and Rubin developed their model to account for greenhouse gas emission reductions. Due to the similarities inherent in the treatment of these pollutants much of the notation for the remainder of this chapter are derived from the Leiby-Rubin (1998) permit system as well as the Rubin (1996) permit system.

As their model is used to calculate the effects of a pure stock pollutant, they are concerned with the assimilative capacity of the system and therefore use a stock state equation to account for emissions and the rate at which those emissions are assimilated. A simpler version of this stock equation is shown below, one where the assimilative capacity of the system is assumed to be zero and where the environmental standard is solely the reduction of total emissions to a lower level. They refer to this as a *terminal stock standard*, and explain that this type of standard is useful when a particular level of pollution cannot be exceeded without great damage (i.e., a very steep benefit function in a neighborhood around the optimal abatement level).

Dynamic Social Planner Problem

The social regulator, under the Leiby-Rubin framework, seeks to achieve the desired environmental standard at the lowest cost to society. Suppose that the environmental standard ($\overline{ES}(T)$) will be over a planning horizon (T) and constrains total ex-post emissions ($e(t)$) in the river system will average 60% of the ex-ante emissions ($\bar{E}(T)$).

$$ES(T) = \int_0^T e(t)dt \le \int_0^T 0.4T(\bar{E}(t)) = \overline{ES}(T) \quad , \tag{2.19}$$

where $e(t) = \sum_{i=1}^{n} e_i(t)$ for $t = 1,\ldots,T$, $\bar{E} = \sum_{i=1}^{n} \bar{E}_i$ for $t = 1,\ldots, T$, and subscripts refer to the individual polluters.

In each period the regulator issues an initial endowment of permits, $l_i(t)$, to each source such that: $\sum_{i=1}^{n} l_i(t) = 0.6\sum_{i=1}^{n} \bar{E}_i$ for $t = 1,\ldots,T$. These permits can be bought, sold, or banked. As banking is allowed each source will manage an account of permits, $B_i(t)$. The aggregate stock of banked permits in each time period is: $B(t) = \sum_{i=1}^{n} B_i(t)$. The rate of change of aggregate banked emissions, $\dot{B}$, will vary according to the state equation:

$\dot{B} = \sum_{i=1}^{n}(l_i(t) - e_i(t))$. It should be noted that for this deterministic treatment, this equation could be written: $\dot{B} = \sum_{i=1}^{n}(l_i(t) - \overline{E}_i + a_i(t))$.

The regulator's new problem (RP^2) is to choose abatement levels for all sources so as to minimize compliance costs over the planning horizon subject to the environmental standard:

$$\min_{a_i} \int_0^T e^{-rt} \sum_{i=1}^{n} C_i(a_i(t))dt \qquad (RP^2)$$

$$\text{subject to: } \dot{B} = \sum_{i=1}^{n}(l_i(t) - \overline{E}_i + a_i(t)),$$

$$B(0) = 0,\ B(t) \geq 0\ \ \forall t = 1,\dots,T,\text{[14] and}$$

$$a_i(t) \geq 0 \quad \forall t = 1,\dots,T;\ \forall i = 1,\dots,n.$$

This is essentially identical to Rubin (1996), but uses abatement as the control variable instead of emissions. Equation (RP^2) indicates that the social regulator chooses abatement to minimize discounted abatements over the planning horizon, where (T) is the terminal time period and (r) is the discount rate. The state equation indicates that the rate of change for aggregate banked permits equals the difference between yearly emissions and yearly endowments. Initially, banking is constrained to positive quantities, i.e., there is no borrowing option. Lastly, are the non-negativity constraints on abatement levels.

Use of optimal-control theory will generate the analytical results describing the least cost solution. The co-state variable for the state equation, $\lambda(t)$, represents the shadow cost of additional units banked. The new current value Hamiltonian (H^2) will then be:

$$H \equiv \sum_{i=1}^{n} C_i(a_i(t)) + \lambda(t)[\sum_{i=1}^{n}(l_i(t) - \overline{E}_i + a_i(t))] \qquad (H^2)$$

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[14] Should borrowing be allowed this equation would be instead: $B(T) \geq 0$.

The first-order necessary conditions for an interior solution are:

- $\frac{\partial H}{\partial a_i} = \frac{\partial C_i(a_i(t))}{\partial a_i(t)} + \lambda(t) = 0$,
- $-\frac{\partial H}{\partial B} = \dot{\lambda}(t) - r\lambda(t)$, and
- $\dot{B} = \sum_{i=1}^{n} (l_i(t) - \overline{E}_i + a_i(t))$.

These simply state that for any given time period, the optimal level of abatement for each source will be one where marginal abatement costs are equalized across sources. Furthermore, the marginal abatement costs will be equal to the marginal value of banking an additional permit.

Dynamic Source Level Optimization

Each source given the price of permits in each time period ($P_l(t)$) will choose abatement levels (a_i) and sales of permits (x_i) to solve the optimization problem (J*):

$$\min_{a_i, x_i} \int_0^T e^{-rt} [C_i(a_i(t)) + P_l(t) x_i(t)] dt \quad , \qquad \text{(J*)}$$

$$\text{subject to: } \dot{B}_i = l_i(t) - E_i(t) + a_i(t) - x_i(t),$$

$$B_i(0) = 0, B_i(t) \geq 0 \quad \forall t = 1, \ldots, T\ ^{15} \text{ and}$$

$$a_i(t) > 0 \quad \forall t = 1, \ldots, T; \ \forall i = 1, \ldots, n.$$

Following Rubin (1996), but using abatement as the control variable instead of emissions, (J*) indicates that each source ($\forall i = 1, \ldots, n$) will choose abatement and permit sales (or purchases) to minimize discounted abatement costs plus permit purchases (sales) over the planning horizon, where (T) is the terminal time period and (r) is the discount rate. The state equation indicates that the rate of change for aggregate banked permits equals the difference between yearly emissions and yearly endowments plus permit purchases.

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[15] If borrowing were to be allowed, this equation would be instead: $B_i(T) \geq 0$.

Initially, banking is constrained to positive quantities, i.e., there is no borrowing option. Lastly, abatement levels are constrained to be non-negative.

Similarly, the co-state variable for the state equation, $\lambda_i(t)$, represents the shadow cost of additional units banked. The current value Hamiltonian (H$_i$) will then be:

$$H_i \equiv C_i(a_i(t)) + P_l(t)x_i(t) + \lambda_i(t)[l_i(t) - \overline{E}_i + a_i(t) + x_i(t)] \quad \cdot \qquad (\mathrm{H_i})$$

The necessary conditions for an interior solution are:

- $\dfrac{\partial H_i}{\partial a_i} = \dfrac{\partial C_i(a_i(t))}{\partial a_i(t)} + \lambda_i(t) = 0$,
- $\dfrac{\partial H_i}{\partial x_i} = P_l(t) + \lambda_i(t) = 0$,
- $-\dfrac{\partial H_i}{\partial B_i} = \dot{\lambda}(t) - r\lambda(t)$,
- $\dot{B} = \sum_{i=1}^{n}(l_i(t) - \overline{E}_i + a_i(t))$, and
- $B_i(T) \geq 0, \lambda_i(T) \geq 0,$ and $B_i(T)\lambda_i(T) = 0$.

These simply state that for any given time period, the optimal level of abatement for each source will be one where marginal abatement costs are equalized across sources. Furthermore, the marginal abatement costs will be equal to the marginal value of banking an additional permit. Also as $\lambda_i(t)$ represents the marginal present value of a unit of banked emissions for each firm, the third condition states that the marginal present value of a banked emission is constant for an interior solution; i.e., the number of permits banked and sold will be such that the present value price of permits will equal the present discounted shadow value of banked emissions.

From these conditions: $\dfrac{\partial C_i(a_i(t))}{\partial a_i(t)} = P_l(t)\,\forall t$, and for a non-bounded solution: $\dfrac{\dot{P}_l(t)}{P_l(t)} = r$. That is, the price of permits will grow at the rate of interest according to Hotelling's rule.

Totally differentiating the first-order necessary conditions with respect to time, it is possible to determine that:

$$\dot{a}(t) = \frac{rC'_a(a_i(t)) - C''_{at}(a_i(t))}{C''_{aa}(a_i(t))} \cdot \tag{2.20}$$

If we assume that the cost function is stationary over time (i.e. no technological innovations), then it is evident that (2.20) will be positive due to the concavity of costs as a function of abatement. Similar to Kling and Rubin (1997) this result shows that abatement will be increasing with time, and that there is an incentive to borrow early and repay later. Banking will never occur and borrowing will always occur unless the interest rate is equal to zero. Kling and Rubin (1997) illustrate how this result deviates from the social optimum when the cost and benefit functions are not changing over time.

Banking will occur in this scenario only when $rC'_a(a_i(t)) < C''_{at}(a_i(t))$. One means to achieve this result is to charge interest on borrowed permits or to reward banked emissions as in Leiby and Rubin (1998). This serves to alter the state equation for individual bank accounts such that: $\dot{B}_i(t) = l_i(t) + a_i(t) + x_i(t) - \overline{E}_i + \gamma B_i(t)$, where γ represents the interest payment to banked emissions. The same optimality results can be obtained for the time path of abatement:

$$\dot{a}(t) = \frac{(r-\gamma)C'_a(a_i(t)) - C''_{at}(a_i(t))}{C''_{aa}(a_i(t))} \cdot \tag{2.21}$$

Now it is possible to have banking when the interest rate charged to emissions (γ) is greater than the discount factor interest rate component (r). Ideally, assuming constant costs and damage functions, the regulator would choose gamma to equal the social interest rate (r), in which case the abatement levels in each period would remain constant.

As before, when information is perfect without stochastic shocks to the emissions function, the regulator can either choose a price instrument or a quantity instrument to regulate the emissions of phosphorus. In the above scenarios, the appropriate Pigouvian taxes would equal the equilibrium price of permits for all time periods.

2.3 Regulation Under Uncertainty and Market Imperfection

To conclude the discussion of regulating stock pollutants it is important to note several recent extensions to include stochastic uncertainty and market imperfection in dynamic regulation. Extending the W-A treatment of uncertainty to a dynamic environment offers a method by which pricing and quantity instruments can be compared over time. This has been accomplished for the case of stock pollutants (Hoel and Karp, 1999), where uncertainty enters the cost and benefits functions. They allow this uncertainty to enter both additively and multiplicatively. That is to say, the cost and benefits functions not only shift up and down (i.e. additively, as in Weitzman (1974)), but also may have slope changes (i.e. multiplicatively). The conclusions drawn in this analysis are quite similar to Weitzman; whether taxes dominate quotas will primarily depend on the slopes of the cost and benefits functions.

Also, given the uncertain environment in which regulatory agencies must operate, it is important to consider more than just static or dynamic policies, with or without uncertainty. It is also important to not view the agents under the regulation with a simple naïve, cost-minimizing or profit-maximizing lens. Groups affected by reform (e.g., legislation restricting farm practices or taxing inputs such as fertilizers and pesticides) will often lobby government policymakers to repeal such legislation. This form of political economy is often coupled with rent seeking or other political constraints to reaching first-best allocations.

In the simple case of one or two polluters operating under a one- or two-period policy, the assumption of perfect competition often does not hold and the resulting market equilibria will deviate from first-best allocations into the realm of second- or third-best. The effects of market imperfection on price and quantity instruments for pollution control has been documented for market power with tradable property rights (Hahn, 1984), for market power in dynamic permit markets (Hagem and Westskog, 1998), and for strategic pollution in dynamic systems (Moledina et al., 2000; Rubio and Escriche, 1999).

How regulated firms optimally choose abatement levels depends on the type of market imperfection. We have mentioned a few types of these related to market power, but another way in which markets may be imperfect is when regulators have imperfect monitoring abilities; i.e., the typical nonpoint source pollution problem. Under imperfect information there may be moral hazard present, such that farmers may have incentives to misrepresent abatement efforts (Xepapadeas, 1992a, 1991). One method to induce polluters subject to moral hazard to fully endogenized their marginal contribution to environmental damage is penalize (or reward) them based on ambient environmental quality measurements. Segerson (1988) discusses the problem of assigning responsibility to NPS when only observations of the ambient environmental quality are known. She discusses how a range of expected emissions could be modeled using a probability density function, which is conditioned on the adopted abatement practice. This analysis is generalized in Horan et al. (1998) when farmers have multiple abatement strategies available to them.

With these considerations in mind, it seems most appropriate to further examine the problem of regulating the emissions of phosphorus into the Minnesota River forwarded in Chapter 1 using an empirical example. First, an appropriate methodology for determining the nonpoint source cost functions will be described. Following this the cost functions for agricultural, nonpoint sources are estimated for a small watershed in Southeastern Minnesota. The implications for permit trading both in a static environment with and without point sources are then evaluated. The issue of dynamic regulation and imperfect information is then examined at some length in Chapter 5, where sources act strategically and misrepresent their actual abatement efforts.

Chapter 3

Models and Methodology

3.1 Integrating Economic & Biophysical Analyses

That agricultural lands contribute significant amounts of nonpoint source phosphorus pollution to domestic water resources has been noted. Presumably these contributions can be curtailed at a lower marginal cost than further point source reductions. For these reasons regulators are increasingly looking to agricultural, nonpoint abatement as an alternative to increased point source regulation. However, for a system to achieve an efficient solution the marginal costs of abatement should be equalized across polluters (i.e., the equi-marginal principle – Speir et al., 2000). In order for policymakers to choose appropriate mechanisms to regulate water pollution it is necessary to analyze point and nonpoint abatement costs.

Many environmental protection agencies such as the USEPA and state agencies have begun to adopt a geographical approach for water quality analysis, known as the "Watershed Protection Approach" (WPA). WPA implicitly acknowledges that water quality problems can be best solved at the watershed level in a holistic framework, where all factors contributing to a water quality problem are considered (USEPA, 1998). However, as recent as 1993, economists have noted the dearth of economics methodology incorporating agricultural modeling for nonpoint source pollution (Antle and Capalbo, 1993). Integrated economic and biophysical analyses have since been facilitated with advances in available computing technology and data cataloging (such as GIS spatial modeling), which allow researchers the ability to optimize several choice variables in a dynamic environment. Such is the case with analysis of the abatement efforts necessary to achieve a given goal of emission reductions. These are often termed "alternative management practices" or "best management practices" (BMPs) and have the focus of recent biophysical (Soranno et al., 1996; Gowda et al., 1998; Dalzell et al., 1999) and economic (Weinberg et al., 1993; Flemming, 1996; Flemming and Adams, 1997; Morgan, 1999; and Westra, 1999) research.

Combining economic values for biophysical model input and output parameters with optimization techniques, researchers are able to address problems such as nonpoint pollution. One means to accomplish the synthesis of complex economic and environmental effects for policy use is through the development of abatement cost functions. These functions map the costs associated with adopting abatement technologies and their resulting levels of pollution reduction. In Chapter 2 the importance of accurately describing these functions for the various sources was noted. It is also important to determine how uncertainty or stochastic processes affect these functions. The purpose of this chapter is to describe a methodology for evaluating the costs of adopting best management practices aimed at reducing agricultural, nonpoint phosphorus emissions.

In order to develop accurate abatement cost functions for nutrient reduction it is necessary to make a believable connection between abatement efforts (BMPs) on a particular piece of land and the resulting reduction in nutrient emissions from that land. If it is possible to determine the cost of adopting various BMPs, either from foregone crop revenue or from increased input investments, it is possible to estimate the relationship between those costs and the resulting abatement levels. Unlike previous studies focusing on changes in abatement costs due to changes in extensive or intensive parameters, this thesis explicitly models the marginal changes in abatement and abatement costs from both intensive and extensive abatement efforts. This is accomplished combining input/output analysis of the economic costs of alternative farming practices and subsequent nutrient reductions by using a water-table management model and by using stochastic frontier analysis to estimate the convex sets describing the abatement cost functions for each soil map unit.

3.2 Modeling Nonpoint Phosphorus: ADAPT

Approaches to nonpoint pollution analysis, as when developing abatement cost functions, are enhanced by the use of biophysical spatial models. These spatial models can be classified as either distributed or field-scale models. Both types of models can yield accurate predictions of water quality (Dalzell et al., 1999), however the advantage to using a field-scale model is that it can account for the variability of more than one parameter (e.g., land cover, soil, tillage, and drainage practices), which is generally necessary for simulating sediment and agrochemicals flows (Gowda et al., 1996). Dosi and Moretto (1993) discuss the uses of mathematical models to model nutrient flows for regulatory purposes. They note that such models are preferred when the cost of acquiring information about loading is prohibitively high for private economic agents. In addition, as the accuracy of watershed and field-level modeling programs advance and the costs of collecting information decrease (e.g., LandSat imagery – Gowda, 1999) this preference will increase substantially.

Because of its ability to account for subsoil drainage systems, the field-scale, water table management model that is most useful for tile-drained soils of the Upper Midwest is the Agricultural Drainage and Pesticide Transport model (ADAPT). It was developed as an extension of the GLEAMS model (Leonard et al., 1987) to incorporate subsurface drainage, subsurface irrigation, and deep seepage algorithms. The model estimates edge-of-field nutrient and pesticide loads in addition to crop yields (Desmond et al., 1996).[16] The use of ADAPT to predict dynamic nitrogen and pesticide emissions for a watershed was developed by Gowda et al. (1998) and is used in this thesis for dynamic phosphorus emissions. This methodology consists of identifying Hyrdrologic Response Unit (HRU) clusters by using several GIS "coverages" (e.g., land uses, slopes, tillage practices, and soil groups) to separate the region into clusters of distinct representative farm areas. These clusters are aggregated into Transformed Hydrologic Response Units (THRUs). THRUs can be used to run ADAPT simulations to develop a hydrograph, which estimate the nutrient movements in the watershed. These aggregated units can then be thought of as representative farms on a per hectare basis. ADAPT can then be used for two purposes: to model current farming practices and generate estimates of initial nonpoint source loadings; and to model alternative farming practices and consequent changes in nonpoint loadings.

3.2.1 Input Data for ADAPT

To estimate current levels of nonpoint source loadings, ADAPT requires a variety of data: weather, soil, slope, and parameters which characterize farming practices. These data sources are used to develop the four ADAPT parameter files: hydrology, erosion, nutrient and pesticide.[17] The parameter files are used in conjunction with historic weather (daily temperature and rainfall) observations to estimate nutrient, sediment, and pesticide emissions from each of the representative farm units on a daily, monthly, or annual basis.

The soil data used to develop hydrology and erosion parameter files can be derived from a soil database such as the STATSGO (State Soil Geographic) soil database (NRCS, 1993). The soil characteristics required include: the number and depths of the soil horizons; the percentage of clay, silt and organic content in each horizon; vertical and horizontal hydraulic conductivity; porosity, wilting point, and water content in the soil horizons at different matric suction and upflux levels. In order to complete the input parameter files it is necessary to input land use, tillage practice, and fertilization

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[16] Complete details of the model, and studies with the model, are presented by Chung et al. (1992), Ward et al. (1993), and Desmond et al. (1996).

[17] See appendix for examples of input parameter files.

parameters.[18] For initial loading estimates, the parameters files are developed using the region's representative farming practices.

3.3.2 Generating Observations for Estimation

Each ADAPT simulation of a management practice generates estimated average phosphorus emissions per acre, which can then be linked to the average costs per acre of adopting that practice given input and output prices. To achieve varying degrees of phosphorus abatement a farm can choose between extensive (e.g., crop choice and tillage practice) and intensive (e.g., method and rate of fertilizer application) management practices. The sources of variation in the costs and loading due to abatement efforts on the intensive and extensive margins are noted below.

Table 3.1: Sources of Variation for ADAPT Simulations

PARAMETER	MARGIN	SOURCE OF VARIATION
Soil Type	Extensive	Variation in phosphorus loads and yields
Crop Rotation	Extensive	Variation in phosphorus loads and farm revenue
Tillage Practice	Extensive	Variation in phosphorus loads and yields
		Variation in labor and machinery costs
Method of Application	Intensive	Variation in phosphorus loads and yields
		Variation in labor and machinery costs
Fertilizer Rates	Intensive	Variation in phosphorus loads and yields
		Variation in labor and machinery costs

These extensive and intensive practices can be combined to generate different abatement regimes resulting in different levels of yield and emissions. For example, in Southeastern Minnesota, where the predominant farming practice involves a corn-

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[18] These include: crops and number of years in the rotation cycle; crop residue left on the field per crop; nitrogen concentration in the rainfall (and irrigation water); nitrogen and phosphorus in the soil horizons; Julian planting, harvesting, fertilization, and tillage dates; method and type of fertilizer applications; and method and type of tillage operation.

soybean rotation, fourteen representative farming regimes can be developed using realistic combinations of extensive and intensive management practices (Table 3.2). ADAPT can then simulate these regimes under various weather conditions and soil types to provide estimates of varying yield and phosphorus emissions. For example, simulation (0) in Table 2 may represent the baseline practice (predominant farming practice in the region), a corn-soybean rotation with conventional tillage and high rates of broadcast fertilizer. The cost ($/a) and abatement levels (lbs/a) for simulations 1-14 are then normalized by the values estimated for this baseline practice.

Table 3.2: Representative Abatement Regimes for Southeastern Minnesota.

SIMULATION	ROTATION	TILLAGE	APPLICATION	RATE
(0)	Corn-Soybean	Conventional	Broadcast	High
(1)	Corn-Soybean	Conventional	Broadcast	Medium
(2)	Corn-Soybean	Conventional	Broadcast	Low
(3)	Corn-Soybean	Conventional	Incorporated	High
(4)	Corn-Soybean	Conventional	Incorporated	Medium
(5)	Corn-Soybean	Conventional	Incorporated	Low
(6)	Corn-Soybean	Conservation	Broadcast	High
(7)	Corn-Soybean	Conservation	Broadcast	Medium
(8)	Corn-Soybean	Conservation	Broadcast	Low
(9)	Corn-Soybean	Conservation	Incorporated	High
(10)	Corn-Soybean	Conservation	Incorporated	Medium
(11)	Corn-Soybean	Conservation	Incorporated	Low
(12)	Pasture	N/A	N/A	N/A
(13)	Continuous Corn	Conventional	Broadcast	High
(14)	No Production	N/A	N/A	N/A

3.3 Abatement Costs

For any particular soil type, then, ADAPT will generate observations of yield and emissions based on a set of intensive and extensive farming parameters. The cost of adopting a particular abatement strategy can be mapped as a function of the resulting level of abatement. The abatement cost function in dollars per pound of phosphorus abated is given by $C(a_i(t))$, where *i* represents a particular farm. This function maps the cost-minimizing choice of abatement effort for each soil map unit necessary to achieve any desired abatement level, *a*. Where abatement level, *a*, represents the reduction in pounds of nitrogen or phosphorus emissions from historic emissions levels.[19] The cost-minimizing choice of effort assumes each farmer has perfect information about abatement efforts, weather expectations, and soil map units.

This follows Montgomery's (1972) general framework for examining cost functions under regulation. Similar empirical examples include: Weinberg et al. (1993) for salination, Yiridoe and Weersink (1998) for groundwater nitrogen, and Westra (1999) for phosphorus. Similar to Yiridoe and Weersink (1998), the abatement effort to achieve the required level of phosphorus reduction can be described by abatement effort on the extensive margin and abatement effort on the intensive margin. Abatement effort on the extensive margin includes practices such as crop choice and tillage practice. Abatement effort on the intensive margin refers to method and rate of fertilizer application.

Although the assumption that the farmer has perfect knowledge of abatement levels and costs resulting from different choices of management regimes may in fact not be the case, it is possible for the regulator to make such information freely available to the farmer for efficient decision-making. For example, one could imagine an internet-based algorithm or process for farmers to calculate potential costs and abatement levels for various farming regimes. Such a system is currently available for a sample trading system in Kalamazoo, Michigan (World Resources Institute, 2000). Dosi and Moretto (1993) argue that even when the polluters' knowledge regarding emissions and abatement

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[19] I refer to historical levels of emissions as pre-control or ex-ante levels and conversely, ex-post levels will refer to emissions levels following abatement.

costs is no better than the regulator's, an "indirect approach" of regulation based on biophysical modeling techniques is superior to alternative regulatory approaches, such as an ambient-based system (e.g., Horan et al., 1998).

3.3.1 Abatement Cost Model

More formally, we consider the problem of phosphorus pollution caused by agricultural production. The sources are assumed to be perfectly competitive and risk neutral. Expected phosphorus emissions per hectare are given by:

$$e_i(t) = E_i(r_i(t), z_i(t)), \tag{3.1}$$

where $e_i(t)$ is the emissions rate per hectare, $r_i(t)$ represents farming practices on the extensive margin, and $z_i(t)$ represents farming practices on the intensive margin. Similarly, expected abatement per hectare is:

$$a_i(t) = A_i(r_i(t), z_i(t)). \tag{3.2}$$

Production of agricultural output (y) is given by:

$$y_i(t) = f_i(r_i(t), z_i(t)). \tag{3.3}$$

Variable costs of production (w) as a function of r and z is:

$$w_i(t) = W_i(r_i(t), z_i(t)). \tag{3.4}$$

Expected profit per hectare for the ith farm in the absence of phosphorus abatement, given competitive prices (P) and input costs (W), and averaged across crop rotations as a function of extensive and intensive farming practices can be written:

$$\pi_i(r_i^*(t), z_i^*(t)) = Pf_i(r_i^*(t), z_i^*(t)) - W(r_i^*(t), z_i^*(t)). \tag{3.5}$$

When emissions are reduced to some level, $\bar{e}_i(t)$, the farm's restricted profit function is:

$$\pi_i(\bar{r}_i(t), \bar{z}_i(t)) = Pf_i(\bar{r}_i(t), \bar{z}_i(t)) - W(\bar{r}_i(t), \bar{z}_i(t)), \tag{3.6}$$

subject to:

$$E_i(\bar{r}_i(t), \bar{z}_i(t)) \leq \bar{e}_i(t), \tag{3.7}$$

where $\bar{r}_i(t)$ and $\bar{z}_i(t)$ represent profit-maximizing choices of extensive-margin and intensive-margin practices given the phosphorus emissions constraint.

Average abatement costs per acre under phosphorus reductions ($\overline{a}_i$) can then be denoted:

$$C_i(\overline{a}_i(t)) = \pi_i(r_i^*(t), z_i^*(t)) - \pi_i(\overline{r}_i(t), \overline{z}_i(t)), \tag{3.8}$$

where abatement levels per acre meet target reductions in phosphorus:

$$\overline{a}_i(t) \geq E_i(r_i^*(t), z_i^*(t)) - E_i(\overline{r}_i(t), \overline{z}_i(t)). \tag{3.9}$$

Abatement cost functions can then be written as $C_i(a_i(r_i(t), z_i(t)))$. When estimating this function it would seem reasonable to assume that abatement costs are increasing and convex: $C'_a(a_i(r(t), z(t))) > 0$ and $C''_{aa}(a_i(r(t), z(t))) \geq 0$. I also assume for the moment that $C'_t(a_i(r(t), z(t))) = 0$,[20] or that the abatement cost functions are not changing over time. This is consistent with previous functional form assumptions of abatement costs (Leiby and Rubin, 2000; McKitrick, 1999; Kling and Rubin, 1997).

Various quadratic fits can be compared using Ordinary Least Squares estimation, selecting that having the largest F-statistics across the majority of soil types. However, costs as a function of abatement may not actually fit a quadratic function well when using simulated data due to the speculative nature of the extensive and intensive farming practices combined to simulate the set of abatement choices. Due to the characteristics of a soil type some of the simulations may appear to be redundant. For example, a movement from simulation (5) to simulation (6) may yield an average increase in abatement by 0.05 lb/a, but actually cost on average \$40.423/a less. This indicates that simulation (5) is redundant and not representative of actual farmer choices. This may inflate estimates of the abatement cost function. It is for this reason that, in order to accurately represent the cost-minimizing frontier of abatement effort choices for policy analysis, a frontier-analysis methodology is superior to a one that estimates a deterministic function, such as ordinary least squares.

To correct for potential redundancies in simulated observations, the border of a convex set can be estimated to represent the lower bound of abatement costs for a particular soil type. This border describes the lowest possible cost of abatement (or the highest possible restricted profit given a binding emissions constraint) for each level of

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[20] Decreasing abatement cost functions over time might correspond to better seed varieties that respond better to conservation tillage or lower fertilizer applications.

abatement. To facilitate the estimation of this convex set, representing linear combinations of all possible management decisions given the ADAPT-parameter sets, a stochastic frontier analysis is utilized.

3.3.2 Estimation

There are a number of ways to estimate abatement cost functions for agricultural nonpoint pollution. I use ordinary least squares when mapping abatement costs to abatement levels to identify the appropriate functional form. I then use stochastic frontier analysis to estimate the actual cost function. This methodology is unique to the literature of integrated biophysical and economic analysis, but does have precedent. A similar methodology using data envelope analysis, or DEA, was recently used to model cost functions for sediment abatement in Indiana (Randhir et al., 2000). Stochastic frontier analysis provides a continuous function to policymakers, which is useful for determining marginal costs under various policy scenarios. A DEA provides an envelope describing the convex set of abatement choices available to farmers, but is generally not continuous and therefore, would not facilitate easy derivations of marginal cost values.

The use of frontier analysis has typically been confined to production frontiers and measures of efficiency (Battese and Corra, 1977; Melfi and Rogers, 1988; Seale, 1990). Battese (1992) surveys the use of frontier production functions to measure technical efficiency, and Coelli (1995) provides a non-technical description of the procedure and recent developments in applications (including DEA estimations). Essentially, this econometric methodology arose to address the estimation of production functions when actual firms are observed producing in the interior of the set of possible production decisions; i.e. they are inefficient and do not reach the production frontier (the maximum amount of output achievable from a given quantity of inputs). Then why use frontier analysis to estimate cost functions generated by simulated biophysical data?

Earlier integrations of biophysical and economic analyses have typically estimated production functions (e.g., Cobb-Douglas) based on field experiments using OLS estimation techniques. Given an environmental constraint, method of control (e.g., input or output taxes), and relevant exogenous prices the production function is optimized using a mathematical (often dynamic) programming routine to predict constrained profit maximizing (cost minimizing) choices of technology and input levels (Flemming, 1995; Morgan, 1999). This same methodology is applicable to the dual, cost minimization problem under an environmental constraint, and will predict the same levels of abatement and total cost of compliance for a given regulatory system. A convenient way to encapsulate the information contained in the constrained optimization of the production function is to map the reduction in emissions against the costs (in foregone revenue) under various levels of environmental constraints. This mapping can be used to estimate an abatement cost function (described earlier), which are more tractable for policy analysis than are reported observations of the costs and emissions levels associated with particular abatement practices for a particular field; i.e., the abatement cost function makes the leap-of-faith that if two abatement practices with different abatement levels are achievable than linear combinations of those two practices are also achievable (as in Just and Zilberman, 1988).

The production frontier models discussed in Battese (1992) and Coelli (1995) can be adapted to represent constrained profit frontiers or cost frontiers as in the case for pollution abatement costs. In fact, Coelli (1995) notes that one possible policy issue that lends itself well to stochastic frontier analysis is identifying the influence of pollution controls in feedlots and irrigation farms. I would argue that frontier analysis is also appropriate and justified when using simulated data to model biophysical and economic processes.

The three types of frontier models are deterministic, stochastic, and panel data models. The first two are most appropriate for use in this thesis and are discussed in this context below. From the above presentation of the constrained profit function (3.6) a deterministic frontier model for $i = 1, 2, \ldots n$. is defined by:

$$\pi_i(\bar{a}_i) = f(\bar{r}_i, \bar{z}_i; \beta)\exp(-U_i), \tag{3.10}$$

Here $\pi_i(\bar{a})$ represents the possible profit level for the i$^{\text{th}}$ THRU using combinations of intensive (z) and extensive (r) abatement efforts in order to achieve $\bar{a}$, $f(r_i, z_i; \beta)$ is some function of abatement efforts, β is a vector of unknown parameters, and U_i is a non-negative random variable associated with soil-specific factors which contribute to a combination of abatement efforts falling in the interior of the convex set of abatement technology choices. Therefore, the constrained profit frontier is bounded above by the deterministic function $f(r_i, z_i; \beta)$ and the constrained abatement cost frontier will be bounded by the deterministic function: $f(r_i^*, z_i^*; \beta) - f(\bar{r}_i, \bar{z}_i; \beta)$.

Estimates of β (i.e. $\hat{\beta}$) are either the maximum-likelihood estimators or the corrected ordinary least-squares (COLS) estimators. OLS estimators of β, except for the intercept, define the COLS estimators if the functional form of abatement efforts is linear when logarithms are taken. The intercept estimator is the OLS estimator plus the largest residual necessary to encompass all the observations within the convex set of abatement choices (Battese, 1992). If the U_i random variables are *iid* the COLS estimator is consistent, and only if the U_i random variables are also shown to be gamma random variables can large-sample inferences be made for the β parameters (Green, 1980); i.e. sufficient for regularity conditions to hold.

Coelli (1995) noted that a primary criticism of the deterministic frontier models is that there is no accounting for the effect of measurement error and noise on the estimates. This criticism is addressed by adding a symmetric error term (V_i) to the non-negative error term (U_i). This systematic error is associated with random factors not under control of the firm, whereas the non-negative error term represents technical inefficiency. Again following Battese (1992) and Coelli (1995) and using (3.10) a stochastic frontier model is defined for $i = 1, 2, \ldots n$ by:

$$\pi_i(\bar{a}_i) = f(\bar{r}_i, \bar{z}_i; \beta) \exp(V_i - U_i), \tag{3.11}$$

The constrained profit frontier is bounded above by the deterministic function $f(r_i, z_i; \beta)\exp(V_i)$ and the constrained abatement cost frontier will be bounded below by the deterministic function: $f(r_i^*, z_i^*; \beta)\exp(V_i) - f(\bar{r}_i, \bar{z}_i; \beta)\exp(V_i)$. This stochastic error term is assumed to be *iid* as $N(0, \sigma_v^2)$ random variables, independent of the U_i's, which are assumed to also be *iid* as non-negative truncations of the $N(0, \sigma^2)$ distribution or of the exponential distribution. These assumptions allow inferences about the maximum-likelihood β parameters, given the return to the standard regularity conditions (Aigner et al., 1977). The distributional assumptions necessary for the stochastic frontiers and the U_i's are the main criticism of this methodology. In finite samples the statistical inferences of the either the COLS approach or the Maximum-Likelihood approach are equivalent (Coelli, 1995).

Given a functional form, the stochastic frontier analysis determines the best fitting convex shell for the observations. The distances between the data points and the shell are indicative of the level of inefficiency that observation has in relationship to the frontier. However, assuming that agents are cost minimizing, we would expect to see some actual abatement regimes on the frontier. The simulated points in the interior will be useful for determining potential deviations from cost-minimization (e.g., as in moral hazard - Chapter 5). This is the strength in using a frontier analysis as opposed to other estimation techniques such as OLS. Although OLS will minimize the squared deviation of observations (simulated abatement cost and abatement levels under alternative management regimes) from the fit abatement cost function, it may be skewed due to redundant combinations of intensive and extensive abatement efforts, perhaps due to topographical features, that would not occur in actuality. However, these redundant simulations may yield important information important to policymakers when using this integrated biophysical and economic analysis, as will be illustrated in Chapter 5.

3.3.3 Spatial Calibration

Before using these estimates for policy analysis it is necessary to account for the spatial distribution of the nonpoint sources. Until this point agricultural nonpoint sources have been differentiated by extensive and intensive abatement efforts (e.g. Table 3.2) and by exogenous soil characteristics. Many authors (Goetz and Zilberman, 1998; Flemming, 1995; Xepapadeas, 1992b; Tietenberg, 1974) have noted the efficiency implications of spatially differentiating polluters. Specifically, in the case of nonpoint phosphorus emissions, the marginal damage of a pound of phosphorus emitted from a field that is distant from a stream will be less than that from a field adjacent to the stream. This is simply due to the fact that a smaller percentage of that pound of phosphorus emitted at the edge of a field far from a stream will enter that stream.

The spatial heterogeneity in phosphorus emissions, present in any watershed, can be accounted for by adjusting the appropriate sediment delivery ratio; i.e. based on distance, slopes, crop residue, and tile drains the edge-of-field emissions of phosphorus (explicitly linked to erosion via sediment) can be calibrated to actual conditions through differentiated sediment delivery ratios (SDRs). These SDRs describe the percentage of edge-of-field emissions that arrive via water-born transport channels to the watershed outlet. Senjem (1997) notes that residue management will be most effective in reducing phosphorus emissions when fields have steep slopes (i.e., a higher potential for sediment deliveries) with high the sediment delivery ratios (which depends on field proximity to a water channel and the ability of phosphorus-laden sediment to remain in suspension). The effect of the delivery ratio will be to shift the abatement cost curves upwards; i.e., it will become more costly to reduce a given level of phosphorus in pounds per acre as the sediment delivery ratio decreases. Intuitively, the further from a water-channel a particular field is the greater the phosphorus emissions must be to deposit the same quantity of instream phosphorus that a field adjacent to the stream would deposit. Conversely, the further from a water-channel a field is the more pounds of abatement are required to achieve the same the same amount of instream reductions provided by abatement from a closer field.

There are many ways to calculate this ratio depending on the time frame and topographical features that are being examined. One simple methodology gives sediment delivery ratios as a function of drainage area. For example, the Sand Creek drains 160,000 acres, which would correspond to a sediment delivery ratio of approximately 7% (Haan, 1994). Applying this methodology to Sand Creek THRUs would result in SDR values ranging between 10% and 60% depending on the number of acres representing each THRU. The effects of these are illustrated in the following example.

Example 3.3.3

Consider three homogeneous acres of cropland having identical intensive and extensive farming regimes. Each acre emits phosphorus, which finds its way into a nearby stream. Differentiating these acres are their respective sediment delivery ratios. Based on empirical observations, these are found to be 10%, 60%, and 100% respectively. A researcher uses ADAPT and stochastic frontier analysis to estimate the abatement cost functions for each of these acres. The estimation results in the following cost function (in \$/lb) for i = 10%, 60%, and 100%:

$$C_i(a_i) = 10a_i^2, \tag{3.12}$$

However, abatement in this case corresponds to edge-of-field abatement (lbs/acre). The regulator is concerned with instream emissions and abatement, which are linked to edge-of-field emissions and abatement by the respective sediment delivery ratios. For policy analysis, then, the relevant cost functions will be:

$$\begin{aligned} C_{10\%}(a_{10\%}) &= 10(\frac{a}{.10})^2 = 1000a^2, \\ C_{60\%}(a_{60\%}) &= 10(\frac{a}{.60})^2 = 27.78a^2, \text{ and} \\ C_{100\%}(a_{100\%}) &= 10(\frac{a}{1.0})^2 = 10a^2. \end{aligned} \tag{3.13}$$

Here, the cost functions correspond to instream abatement. It should be noted that the original (edge-of-field) estimated cost function (3.12) is sufficient for policy analysis examining the costs per acre to farmers to reduce phosphorus emissions by a certain percentage. That is due to the fact that when incorporating this spatial attribute of specific fields, the actual contribution of phosphorus for distant fields will be reduced to the same extent as its abatement cost function is adjusted upwards. An explicit example of the effects of SDRs on abatement costs and phosphorus loads is presented in the next chapter.

Chapter 4

Sand Creek Application

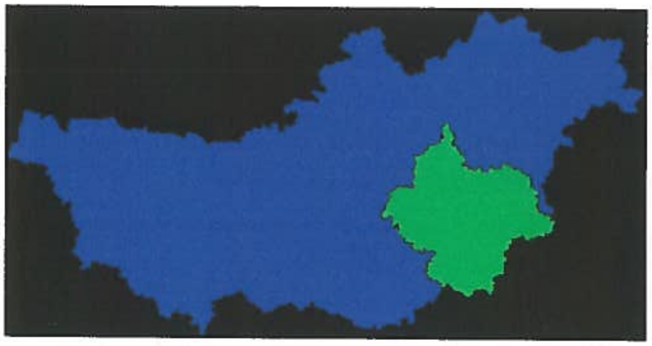
4.1 Sand Creek Phosphorus

For this section a stylized model will be developed using data gathered from the Sand Creek sub-watershed of the Lower Minnesota Basin (see Figures 4.1 and 4.2). This region was chosen for several reasons. First, the Lower Minnesota is the largest contributor of phosphorus to the Minnesota River. This contribution has been estimated to be between 17.2 % and 32.5% (Faeth, 1998; Mulla, 1998). Furthermore, the Sand Creek is one of the largest sub-basins of the Lower Minnesota Basin . It drains 14% of the Lower Minnesota watershed, or approximately 65,000 hectares (MPCA, 1998). Its average phosphorus contribution is 115,000 lbs/year or 11% of the Lower Minnesota total load (MPCA, 1994).

Figure 4.1: Minnesota River Basin

Source: MPCA (2000)

Figure 4.2: Location of the Sand Creek Sub-Watershed



Source: Dalzell (2000).

4.1.1 Nonpoint Sources

Dalzell et al. (1999) used the ADAPT model to calibrate estimates of sediment and nitrogen emissions for a three-year period in the Sand Creek watershed in the Minnesota River Valley. Although the focus of this thesis was different (i.e., phosphorus emissions over many periods) the geographic area was the same. For this reason much of the soil input data and slope values required for the ADAPT parameter files were synthesized from Dalzell et al. (1999). The soil data used to develop the hydrology and erosion parameter files was derived from the STATSGO (State Soil Geographic) soil database (NRCS, 1993). Specifically, a weighted average of soil characteristics from the three major soil categories within each soil map unit were taken from the Map Unit Use File (MUUF), a PC-based soil database (Baumer et al., 1984). These soil characteristics include: the number and depths of the soil horizons; the percentage of clay, silt and organic content in each horizon; vertical and horizontal hydraulic conductivity; porosity, wilting point, and water content in the soil horizons at different matric suction and upflux levels (Dalzell et al., 1999). In this manner Sand Creek can be first divided into 9 basic THRUs (see Chapter 3) corresponding to soil map units. These initial THRUs can then be differentiated spatially according to relevant sediment delivery ratios. A distance of approximately 300 feet to any perennial stream, intermittent stream, or drainage ditch was chosen as a representative buffer distance (Sharpley et al., 1999). This then yields 18 THRUs,[21] each of which will be considered a representative farm.

Initial Emissions

To estimate current phosphorus emissions for each THRU, combinations of extensive and intensive abatement practices representative of current farming practices in Sand Creek were modeled using ADAPT. For estimations of initial emissions these choices were: corn-soybean rotation, high rates of broadcast fertilizer use (approximately 180 lbs of Nitrogen and 70 lbs of Phosphorus per acre per two-years), and conventional tillage regimes.[22] These practices were simulated for fifty years (1947 – 1996) using weather data (daily temperature and precipitation) from the Waseca weather station. The mean

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[21] Sharpley et al. (1999) provide 5 buffer values corresponding to erosion loss potentials. For the purposes of exposition and brevity the medium buffer value of 300' was chosen. Obviously, this buffer could be chosen continuously, but the data requirements and simulation exercise would be daunting.

[22] These regimes were developed through conversations with extension agents in the region, conversations with researchers in the Department of Soils, Water & Climate, and by examining University of Minnesota extension bulletins (Olson and Senjem, 1998; UofMn Extension Service, 1998; Randall et al., 1996).

values for edge-of-field predictions and for instream emissions given the relevant sediment delivery ratios[23] are reported below in Table 4.1.

Table 4.1: Sand Creek Emissions.

THRU	Acres	Edge-of-Field Emissions		Instream Emissions (lbs/year)
		Total Emissions	Per Acre	
MN079a	59,014.11	67202.32	1.14	20,160.70
MN080a	11,673.41	15921.70	1.36	4,776.51
MN081a	8,476.38	11506.69	1.36	3,452.01
MN163a	8,300.38	7267.28	0.88	2,180.18
MN165a	2,524.88	10233.45	4.05	3,070.03
MN169a	1,432.91	5617.00	3.92	1,685.10
MN171a	507.53	810.15	1.60	243.05
MN178a	549.11	517.05	0.94	155.11
MN196a	34,952.74	55493.71	1.59	16,648.11
MN079b	9,218.94	10498.06	1.14	8188.49
MN080b	1,806.33	2463.71	1.36	1921.69
MN081b	1,372.59	1863.29	1.36	1453.36
MN163b	1,928.40	1688.38	0.88	1316.94
MN165b	499.50	2024.47	4.05	1579.09
MN169b	365.59	1433.12	3.92	1117.84
MN171b	32.61	52.05	1.60	40.60
MN178b	72.90	68.64	0.94	53.54
MN196b	5,665.42	8994.87	1.59	7016.00
TOTALS	**148,394**	**203,656**		**75,058**

MN--- a = aggregate acreage per soil group outside of 300 feet buffer with SDR = 0.30; MN---b = aggregate acreage per soil group within 300 feet of a streambed or drainage ditch with SDR = 0.78.

Recent calibrations of the ADAPT model include subsurface drainage for poorly drained Webster clay loam soil using no-till, continuous corn rotations (Davis, 1998), nitrogen and sediment emissions for the Sand Creek (Dalzell et al., 1999) and phosphorus emissions in the LeSueur Watershed (Westra, 2000). Once ADAPT has generated an estimate of the potential nutrient loadings from each of the THRUs, the values are compared to other estimates of potential loadings from similar regions and to actual

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[23] Sediment delivery ratios for the Sand Creek are calculated below in the sub-section: *Spatial Heterogeneity*.

observations. As mentioned earlier, ADAPT was calibrated for Sand Creek nitrogen and sediment emissions on a monthly basis (Dalzell et al., 1999), albeit for fewer years (21 months over a three-year period). However, because phosphorus emissions are closely related to sediment emissions the statistical fit of the ADAPT simulations for prevalent farming practices is of interest for this thesis.

For this previous study, root mean squared error (*RMSE)* was used to index actual error produced by the model:

$$RMSE = \left\{ \sum_{i=1}^{N} \frac{1}{N} (P_i - O_i)^2 \right\}^{0.5},$$

where N is the number of cases, P_i is the predicted value, and O_i is the corresponding observed value. Also used to measure the accuracy of the model's predictions were the coefficient of determination, R^2, and the index of agreement (d):

$$d = 1 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} (|P_i'| + |O_i'|)^2},$$

where $O_i' = O_i - O$ and $P_i' = P_i - O$. Ideally *RMSE* should approach zero and R^2 and d should approach one. Dalzell et al. report final statistics for sediment predictions as having a *RMSE* equal to 1491 tons and 0.66, and 0.89 respectively for R^2 and d. The authors conclude that these values are comparable to similar studies using other biophysical models to predict sediment loads in other watersheds. These results suggest that using the calibrated ADAPT model for Sand Creek will also accurately predict phosphorus emissions as well.

Abatement Costs

As discussed in Chapter 3, the cost function is derived from the restricted profit function following Montgomery's (1972) general framework for examining cost functions under regulation. Extensive and intensive practices are combined to generate different farming regimes resulting in different levels of abatement. ADAPT was used to simulate 14 farming regimes to provide estimates of yield and phosphorus emissions variation across soil type. Changes in variable costs across the 15 simulations were developed using University of Minnesota Extension reports.[24] These practices and area weighted average costs and phosphorus loads are noted in Table 4.2.[25] These simulations provide dynamic estimates of yield and phosphorus emissions across the 18 THRUs in the Sand Creek.

Table 4.2: Simulations for Abatement Management Practices

Simulation	Crop Rotation	Tillage	Method of Application	Fertilizer Rates
(0)	Corn-Bean	Conventional	Broadcast	High
(1)	Corn-Bean	Conventional	Broadcast	Medium
(2)	Corn-Bean	Conventional	Broadcast	Low
(3)	Corn-Bean	Conventional	Incorporated	High
(4)	Corn-Bean	Conventional	Incorporated	Medium
(5)	Corn-Bean	Conventional	Incorporated	Low
(6)	Corn-Bean	Conservation	Broadcast	High
(7)	Corn-Bean	Conservation	Broadcast	Medium
(8)	Corn-Bean	Conservation	Broadcast	Low
(9)	Corn-Bean	Conservation	Incorporated	High
(10)	Corn-Bean	Conservation	Incorporated	Medium
(11)	Corn-Bean	Conservation	Incorporated	Low
(12)	Pasture	N/A	N/A	N/A
(13)	Cont. Corn	Conventional	Broadcast	High
(14)	None	N/A	N/A	N/A

Each 50-year simulation in Table 4.2 generates estimated phosphorus loads per acre, which can then be linked to average costs per acre of adopting that practice given input and output prices. Simulation (0) represents the baseline practice and is the predominant farming practice in the region. From Table (4.2) we can see that this represents a corn-soybean rotation with conventional tillage and high rates of broadcast fertilizer. The cost (\$/acre) and abatement levels (lbs/acre) for simulations 1-14 are then normalized by the values estimated for the baseline practice. Descriptive statistics for these simulations weighted by the acreage in each soil association are reported in Table 4.3.

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[24] See University of Minnesota (1995-1998) and University of Minnesota Extension Service (1998).

[25] A detailed description of each simulation is given in the appendix.

Table 4.3: Area Weighted Average Abatement Costs and Levels across all THRUs

Simulation	Lbs/Acre & $/Acre	Mean	Std. Dev.	Min	Max
(0)	Abatement	0	0	0	0
	Cost	0	0	0	0
(1)	Abatement	0.27	0.42	0.11	2.74
	Cost	7.90	2.83	-3.39	15.00
(2)	Abatement	0.41	0.49	0.20	2.94
	Cost	20.78	6.12	-4.67	36.44
(3)	Abatement	0.34	0.43	0.15	2.54
	Cost	2.45	1.27	-1.92	3.67
(4)	Abatement	0.37	0.47	0.17	2.86
	Cost	12.58	2.29	1.50	16.76
(5)	Abatement	0.41	0.49	0.20	2.94
	Cost	19.80	5.80	-4.05	34.72
(6)	Abatement	0.46	0.26	0.32	1.79
	Cost	3.44	2.68	0.91	13.06
(7)	Abatement	0.63	0.41	0.43	2.75
	Cost	10.64	3.89	-2.10	15.13
(8)	Abatement	0.82	0.51	0.50	3.41
	Cost	22.77	6.57	-4.01	35.47
(9)	Abatement	0.77	0.47	0.47	3.18
	Cost	5.90	3.36	-1.79	16.59
(10)	Abatement	0.78	0.48	0.47	3.28
	Cost	15.38	3.75	2.79	20.02
(11)	Abatement	0.82	0.51	0.50	3.41
	Cost	21.88	6.28	-3.31	33.81
(12)	Abatement	0.98	0.52	0.60	3.58
	Cost	289.50	23.68	147.40	316.14
(13)	Abatement	-0.02	0.47	-3.62	0.37
	Cost	21.90	14.83	-11.56	52.43
(14)	Abatement	1.37	0.56	0.88	4.05
	Cost	344.02	26.31	178.48	377.90

For the most part the area weighted means reveal that with increasing abatement efforts (i.e. movement from simulation (0) to simulation (14)) abatement costs are also increasing. However, there are several apparent anomalies or redundancies attributable to individual soil characteristics. For example, the area weighted mean abatement (lbs/acre) for a continuous corn rotation (simulation (13)) is negative, indicating that a uniform movement from the baseline farming regime to one of continuous corn rotations across the watershed would result in revenue losses and would increase emissions.

By fitting various quadratic functions to individual observations, the functional form having the largest F-statistics across the majority of soil map units was $C(a_i) = \beta_i(a_i)^2$.

Table 4.4: Abatement Cost Functions for Sand Creek Soil Map Units

THRU	Margin[26]	β_i $C(a_i) = \beta_i(a_i)^2$	Std. Error	P > |t|[27]	R2
MN079	All	231.5933	35.91971	0.000	0.7481
	Intensive	40.09968	9.321852	0.001	0.6272
MN080	All*	161.7421	27.30574	0.000	0.7297
	Intensive	36.07894	7.111803	0.000	0.7006
MN081	All	146.7176	25.17659	0.000	0.7081
	Intensive	21.11286	4.866382	0.001	0.6312
MN163	All*	396.6775	62.70528	0.000	0.7548
	Intensive	120.7814	35.38587	0.008	0.5642
MN165	All	7.27235	2.413111	0.010	0.4113
	Intensive	1.144934	.1227221	0.000	0.8878
MN169	All*	4.421493	1.640745	0.018	0.3584
	Intensive	- 0.088503	.1410608	0.543	0.0345
MN171	All*	147.0914	22.35036	0.000	0.7691
	Intensive	37.87594	8.133271	0.001	0.6635
MN178	All*	266.8115	42.33948	0.000	0.7534
	Intensive	62.64929	3.835997	0.000	0.9604
MN196	All	128.3502	18.50382	0.000	0.7746
	Intensive	29.25226	5.236446	0.000	0.7394

* Simulations with negative abatement were removed from consideration.[28]

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[26] To maintain consistency the simulations chosen to bound the "Intensive" margin include corn-soybean rotations with conventional and conservation tillage practices with high rates of incorporated and broadcast fertilizer. The simulations bounding "All" also include pasture and no production regimes.

[27] $P \leq 0.05$ indicates that the coefficient is significant at the 95% level or greater.

[28] These observations were removed due to a violation of the original assumptions (i.e., non-negative abatement levels). For these THRUs adopting a continuous corn rotation would decrease revenues, but also increase phosphorus emissions. It is possible to account for the 2nd quadrant with the simple functional form employed, however it serves to detract from the analysis (as abatement strategies under phosphorus regulation is the theme of this thesis). University of Minnesota extension agents in the region note that there are very few farmers employing a continuous corn rotation. These farms are involved in dairy farming. Unfortunately the analysis conducted did not specifically model livestock production integrated with various crop rotations. This might be an avenue for further analysis.

This is consistent with previous functional form assumptions of strict convexity for abatement costs (e.g., Leiby and Rubin, 2000; McKitrick, 1999; Kling and Rubin, 1997). Only the fit of soil map unit MN169 to the simple quadratic functional form is quite poor (see Table 4.4). In this case, results indicate it is possible for farmers to actually increase profit by adopting abatement practices on the intensive margin. This result is not unexpected due to this soil's low crop productivity and high phosphorus loading potential. In fact many agronomists and agricultural economists have predicted that farmers might earn more per acre by adopting conservation tillage practices (Rehm et al., 1998; Olson and Senjem, 1996).

As noted in Chapter 3, the fit of a simple quadratic functional form has several potential problems. For example, on average a movement from simulation (11) to simulation (12) nets an average of only 0.16 lbs/acre in abatement at an increased cost of \$267.62/acre. A similar level of abatement (0.17 lbs/acre) can be gained by moving from simulation (6) to simulation (7) at only a fraction of the cost (\$7.30/acre). Note also that the same level of abatement can be achieved under either simulation (2) or (5), but at different cost. As mentioned due to the characteristics of the soil map units some of the simulations appear to be redundant. For example, a movement from simulation (4) to simulation (6) yields an average increase in abatement by 0.09 lbs/acre at a decreased cost of \$9.14 per acre. This indicates that simulation (4) may be redundant (i.e., not representative of actual farmer choices) and may only inflate estimates of the abatement cost function. To correct for potential redundancies in simulated observations, the border of a convex set was estimated to represent the abatement cost function for a particular soil map unit. This border describes the lowest possible cost of abatement for a particular level of abatement. The set bounded by the abatement cost frontier and the y-axis (cost in \$/acre) contains the management practice observations described above.

Following the initial estimation using ordinary least squares, the stochastic frontier estimation was performed for each soil group. Two abatement cost functions were estimated for each soil map unit: one representing abatement efforts on both

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[28] "All" abatement costs better represent the cost function over this range than "Extensive" abatement costs.

margins and one allowing abatement efforts only on the intensive margin. The results of the stochastic frontier estimation are reported below in Table 4.5.

Table 4.5: Frontier Estimations

THRU	Margin[29]	Maximum Abatement Achievable	β_i $C(a_i) = \beta_i (a_i)^2$	Std. Error	P > $\lvert t \rvert$[30]	Log Likelihood
MN079	All	1.13875	203.5509476	60.759626	.0008	-78.25044
	Intensive	0.6475	12.28997978	18.108599	.4973	-36.61010
MN080	All*	1.363929	151.2912228	43.384180	.0005	-73.17895
	Intensive	0.778393	20.78105100	8.7929258	.0181	-37.07555
MN081	All	1.3575	124.1666248	38.569014	.0013	-77.54826
	Intensive	0.775179	7.896549576	5.7295132	.1681	-32.76046
MN163	All*	0.875536	373.7953055	114.84738	.0011	-75.00794
	Intensive	0.498393	31.56886008	50.027072	.5280	-48.99095
MN165	All	4.053036	6.974407410	9.2860279	.4526	-79.35386
	Intensive	3.41125	1.336707678	.32770534	.0000	**
MN169	All*	3.92	11.53206245	4.8174079	.0167	**
	Intensive	3.183571	-0.2423460181	.72330329	.7376	-28.22726
MN171	All*	1.59625	152.4416515	50.268612	.0024	-72.68986
	Intensive	0.768571	14.01253792	9.4160940	.1367	-39.44827
MN178	All*	0.941607	251.5000359	64.914097	.0001	-68.21594
	Intensive	0.518214	53.41195075	4.9055312	.0000	**
MN196	All	1.587679	127.6030987	32.512767	.0001	-78.10483
	Intensive	0.924464	11.85667843	11.459295	.3008	-38.89232

* Observations with negative abatement were removed from consideration.[31]
** Residuals have wrong skew. OLS is MLE.

There are several anomalies in these results. The first is that the on the intensive margin (i.e. holding the crop rotation constant as corn-soybean) it would appear that farmers having MN169 acreage could actually earn positive revenues by adopting abatement strategies, which violates the assumption that costs are increasing in abatement. As discussed above, this is not entirely unexpected. That abatement costs are convex for MN169 when both margins are included indicates that for this soil one would

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[29] To maintain consistency the simulations chosen to bound the "Intensive" margin include corn-soybean rotations with conventional and conservation tillage practices with high rates of incorporated and broadcast fertilizer. The simulations bounding "All" also include pasture and no production regimes.

[30] $P \leq 0.05$ indicates coefficient is significant at the 95% level or greater.

[31] See Table 4.4 annotations.

expect farmers to adopt maximum abatement efforts on the intensive margin, but not to completely cease production (which is what is found in the results below). The other anomaly concerns the frontier analysis procedure for MN165 and MN178. For both of these soil types on the intensive margin, the assumptions regarding the error components required for the frontier analysis are not valid, and that the OLS estimation of the frontier is the maximum-likelihood estimator for these frontiers.

Spline Function

The difference between the "All" and "Intensive" cost functions is substantial. This is because changing extensive practices (e.g., moving from a corn-soybean rotation to alfalfa production or to no production) entails much greater costs than do changes in intensive practices. To more accurately represent abatement costs under these ranges a spline-type function can be used, where "Intensive" abatement costs are used for abatement levels achievable for corn-soybean rotations and "All" abatement costs for abatement levels achievable with both extensive and intensive abatement effort.[32] In other words, if the environmental constraint faced by a farmer falls within the range achievable using intensive abatement practices holding the extensive regime constant in a corn-soybean rotation, the appropriate cost function to use is the "Intensive" cost function. However, if the environmental constraint requires the farmer to abate phosphorus emissions at a level greater than that achievable with a corn-soybean rotation, it is more appropriate to use the lower cost function for the initial abatement, but to revert to the "All" cost function for the remaining abatement costs. The limit chosen for these levels is the maximum abatement achievable on the intensive margin. The effect of this is to shift the continuous abatement cost function at this limit as can be noted for MN079 in the example provided (Figure 4.3).

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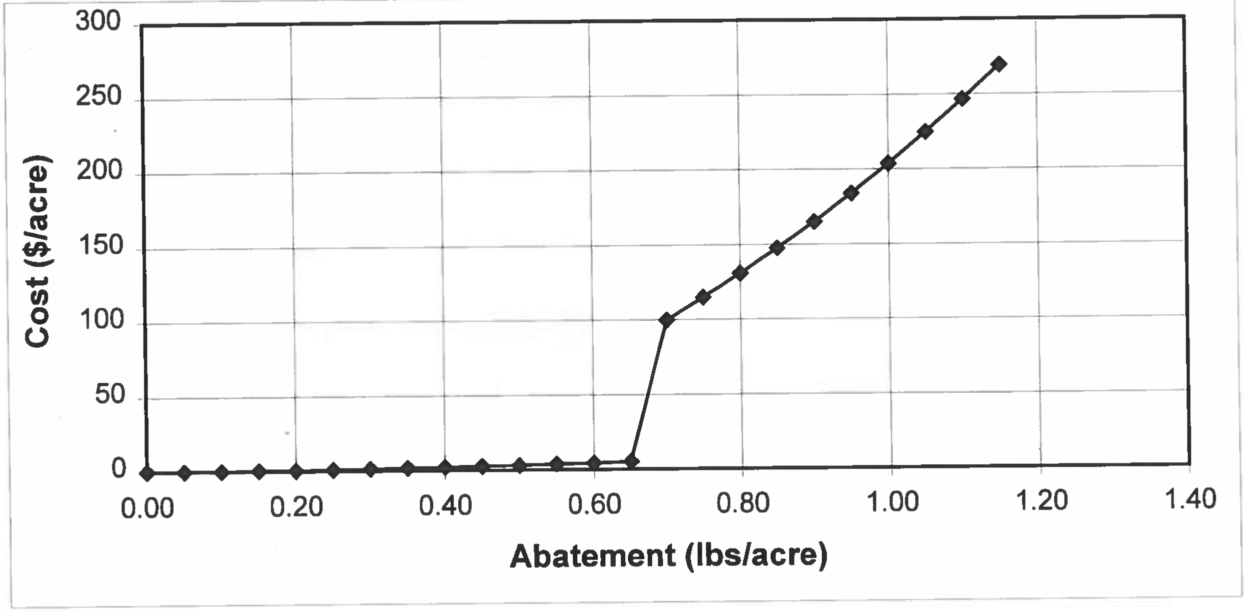
[32] "All" abatement costs better represent the cost function over this range than do "Extensive" abatement costs assuming linear combination of observations are achievable (see Just and Zilberman, 1988).

Figure 4.3: Abatement Cost Function-Spline (MN079)[33]



Spatial Heterogeneity

The abatement levels for the above analysis describe edge-of-field emissions. However, because the large majority of phosphorus entering the Minnesota River arrives as particulate phosphate in sediment loads, the abatement cost functions must be calibrated using the appropriate sediment delivery ratio (SDR). These describe the percentage of edge-of-field sediment emissions that arrive via water-born transport channels to the watershed outlet.

Calibrating the ADAPT simulations for Sand Creek aggregating soil map units to observed data yields a sediment delivery ratio of 36.8%. Albeit somewhat greater than previous estimates, this level probably reflects the smaller area and greater potential for sediment delivery noted for this region (University of Minnesota, 2000) as opposed to estimates for the entire watershed. This sediment delivery ratio (SDR) can be disaggregated by distance to water channel (perennial stream, intermittent stream or drainage ditch) as in Senjem (1997). A distance of approximately 300 feet was chosen as a representative buffer distance (Sharpley et al., 1999). Acres falling within this buffer

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[33] The abatement cost curves for the other soil map units are provided in the appendix.

(approximately 13% of the region) were assigned a SDR of 78%. The remaining 87% of the region was given a SDR of 30% to maintain the watershed average SDR of 36.8%.[34] The effect of the delivery ratio will be to shift the abatement curves upwards; i.e., it will become more costly to reduce a given level of phosphorus in pounds per acre as the sediment delivery ratio decreases. This is reflected in the adjusted abatement cost functions for the THRUs (Table 4.6).

Table 4.6: Spatially Calibrated Abatement Costs

THRU	Distance from Streambed or Drainage Ditch	Sediment Delivery Ratio	Abatement Cost Function (Intensive Margin)
MN079a	> 300 feet	0.30	$136.56 (a)^2$
MN080a	> 300 feet	0.30	$230.90 (a)^2$
MN081a	> 300 feet	0.30	$87.73 (a)^2$
MN163a	> 300 feet	0.30	$350.76 (a)^2$
MN165a	> 300 feet	0.30	$14.85 (a)^2$
MN169a	> 300 feet	0.30	$-2.69 (a)^2$
MN171a	> 300 feet	0.30	$155.69 (a)^2$
MN178a	> 300 feet	0.30	$593.47 (a)^2$
MN196a	> 300 feet	0.30	$131.74 (a)^2$
MN079b	< 300 feet	0.78	$20.20 (a)^2$
MN080b	< 300 feet	0.78	$34.16 (a)^2$
MN081b	< 300 feet	0.78	$12.98 (a)^2$
MN163b	< 300 feet	0.78	$51.89 (a)^2$
MN165b	< 300 feet	0.78	$2.20 (a)^2$
MN169b	< 300 feet	0.78	$-0.40 (a)^2$
MN171b	< 300 feet	0.78	$23.03 (a)^2$
MN178b	< 300 feet	0.78	$87.97 (a)^2$
MN196b	< 300 feet	0.78	$19.49 (a)^2$

The cost to abate phosphorus emissions increases the further one moves from a drainage ditch or streambed, compared to otherwise equivalent acreage. The effect on the abatement cost function for MN079 is shown below (Figure 4.4).

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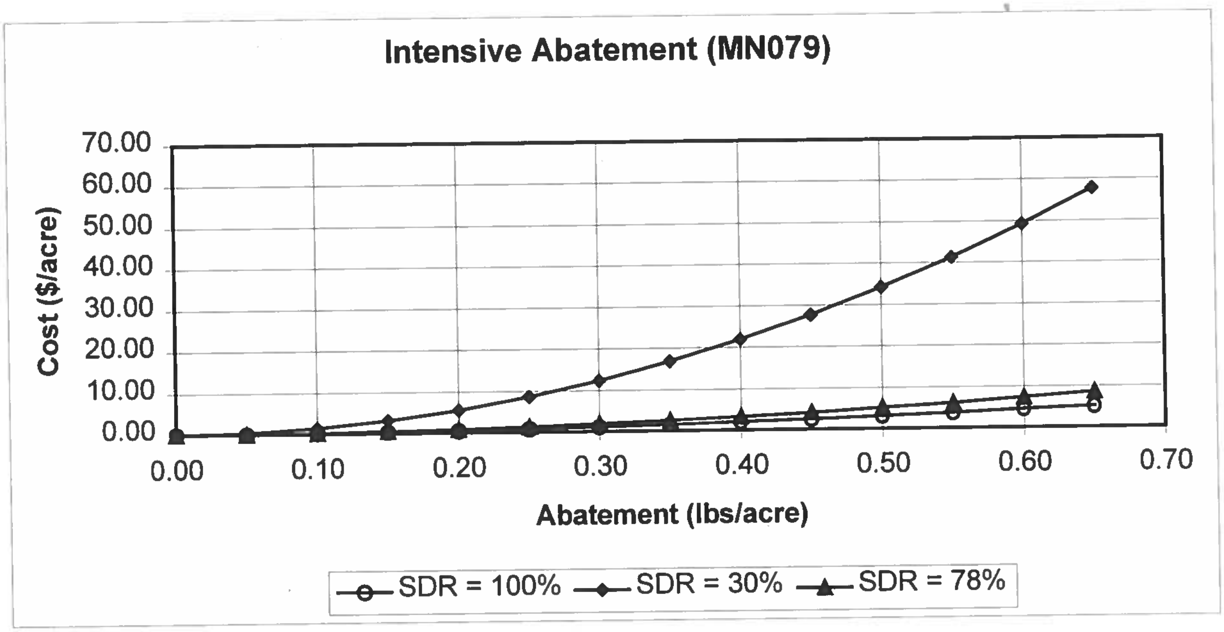
[34] Given Faeth's (1999) estimation of 15.5% for the Lower Minnesota Watershed and the relative sizes of the areas buffered for the Sand Creek, these estimates are consistent in Hahn (1981).

Figure 4.4: Spatially Calibrated Abatement Costs



Examining Figure 4.4, it can be seen that at the maximum abatement achievable on the intensive margin (holding the extensive margin choice of crop rotation constant) the cost per acre for acreage within the 300 foot buffer will be approximately $8.50 and for acreage outside of the 300 foot buffer will equal approximately $57.50. That is, to abate 0.65 lbs/acre the cost for MN079a will be $57.50 or $88.50 per pound and the cost for MN079b will be $8.50 or $13.00 per pound of abatement.

4.1.2 Point Sources

The main point source contributors of phosphorus to the Sand Creek are the wastewater treatment facilities and feedlots. Denote the wastewater facilities as WWTF-J and WWTF-N, for the facility in Jordan and New Prague, respectively.

Initial Emissions

There are reliable sources documenting the annual contributions of these two facilities (MPCA, 2000; MPCA, 1994; Metropolitan Waste Control Commission, 1993). Documenting feedlot contributions is more difficult, calling into question categorizing feedlot contributions as point sources. Livestock production in this region is fairly substantial (MPCA, 1999; USDA and Minnesota Department of Agriculture (MDA): 1992-1998) resulting in significant production of animal manure. Livestock manure varies in its levels of N, P, and K (MPCA, 1999) resulting in differential phosphorus loading potential. Further complicating the issue is the difficulty in determining the mode by which the manure enters the waterway. Manure may occasionally enter the water directly via feedlot seepage or lagoon overflow. Manure also is spread on row croplands as organic fertilizer, and suffers the same erosive fate as inorganic fertilizers.

Several simplifying assumption are made to separate these complicated links between crop and livestock production. First, feedlots are considered point source contributors of phosphorus. A set lower bound on the percentage of stored manure that annually enters the watershed is taken exogenously (5% of feedlot production – MPCA, 1999). The Minnesota Pollution Control Agency has been compiling a list of licensed feedlots for Minnesota. The most current database lists 92 reported feedlots in the Sand Creek (MPCA, 1998), which contain approximately 14,903 animal units (1000 lb animal). Using generic conversion ratios for beef cattle, this corresponds to an annual production of 583,601 pounds of phosphorus. At the 5% lower bound estimate, the initial point source contributions by feedlots are approximately 29,180 pounds per year.

If the number of animals found on feedlots is compared to the total number of animals found in the Sand Creek (USDA and MDA, 1992-1998) one finds that only 40% of the estimated animal units in the Sand Creek are located on a licensed feedlot. For lack of better data, it is assumed that the remaining animals are free-range. These free-range manure contributions and those, which are spread on cropland as fertilizer, enter the watershed as a nonpoint source. For this reason it is assumed that phosphorus contributions from nonpoint livestock serve to drive medium levels of phosphorus application rates to the high application rate. This second assumption incorporates manure production and dissemination from livestock not found on registered feedlots. While these simplifying assumptions may be debatable, when choosing limits for both assumptions, care was taken to choose lower bounds; i.e., a 5% lagoon or feedlot contribution rate was reported to be extremely conservative by MPCA analysts.

Similarly, when examining fertilizer application rates for this region, the upper bound chosen for application rates in the ADAPT simulations safely incorporates the potential manure applications on average. As these assumptions also are consistent across the various policy regimes, they should not qualitatively affect the results.

The initial point source emissions sum to approximately 40,000 lbs/year, or 35% of the total Sand Creek load (Table 4.7). This is consistent with earlier watershed estimates (MPCA, 2000).

Table 4.7: Sand Creek Point Source Emissions

Sources	Acres/Units	Emissions (lbs/year)
WWTF-J	1	2,285
WWTF-N	1	8,649
Feedlots	92	29,180
Total		**40,114**

Abatement Costs: Wastewater Treatment Facilities

For point sources, the abatement cost function is given by $C_i(a_i(t))$ where a represents the number of pounds abated by the source. This function maps the cost of adopting management activities required to achieve a lbs of abatement in time, t. This cost is given as the difference between unconstrained profits and constrained profits (Montgomery, 1972; Just and Zilberman, 1988; Malik et al., 1993). Using observations from 10 comparable wastewater facilities (Senjem, 1997) having different flow rates and influent concentrations, the marginal effects of these variables on average abatement costs ($/lb) were estimated using ordinary least squares (Table 4.8).

Table 4.8: Regression Estimates for Wastewater Abatement Costs

Variable	Coefficient	Standard Error	P-Value
Intercept	22.245	4.0254	3.7E-05
Flow Rate (MGD)	-0.096	0.255	0.713
Phosphorus Influent (mg/l)	-1.664	0.498	0.004
R-Squared	0.400		

WWTF-J has flow of 0.375 MGD and WWTF-N has flow of 0.683 MGD. The abatement cost function for each facility is dependent upon current levels of abatement efforts and flow quantities (i.e. the greater the flow the more phosphorus is removed for a given technological cost). Therefore, the coefficients from Table 4.2 were used to simulate various levels of abatement and costs at different levels of influent concentrations. For example, it is fairly inexpensive to reduce phosphorus effluent to a 1mg/l level. However, it is much more expensive to achieve .5 mg/l or .01 mg/l. The respective observations for abatement (lbs) can be squared and mapped against costs ($/lb) generated by varying the influent concentrations to estimate an abatement cost function for each of the wastewater treatment facilities. Note however that WWTF-J has phosphorus effluent levels of 0.2 mg/l and WWTF-N has phosphorus effluent levels of .4 mg/l, indicating that they are currently operating at different levels of abatement efforts. This will then shift the respective abatement functions up corresponding to the level of current operation. The ordinary least squares regression results for WWTF-J and WWTF-N are given below, given the functional form: $C_i(a_i(t)) = \beta_i(a_i^2)$. This simple quadratic form had superior F-statistics to those including an intercept and/or linear component.[35]

Table 4.9: WWTF Abatement Cost Functions

Source	Coefficient	Standard Error	P-Value	R-Squared
WWTF-J	0.033166	0.003761	0.012615	.942
WWTF-N	0.004903	0.0007	0.019782	.915

Abatement Costs: *Feedlots*

To develop an abatement cost function for these feedlots it was necessary to compare willingness-to-accept contracts for livestock producers in this region under a Minnesota Institute of Sustainable Agriculture (MISA) program, "Payment for Pounds" (Tiffany,

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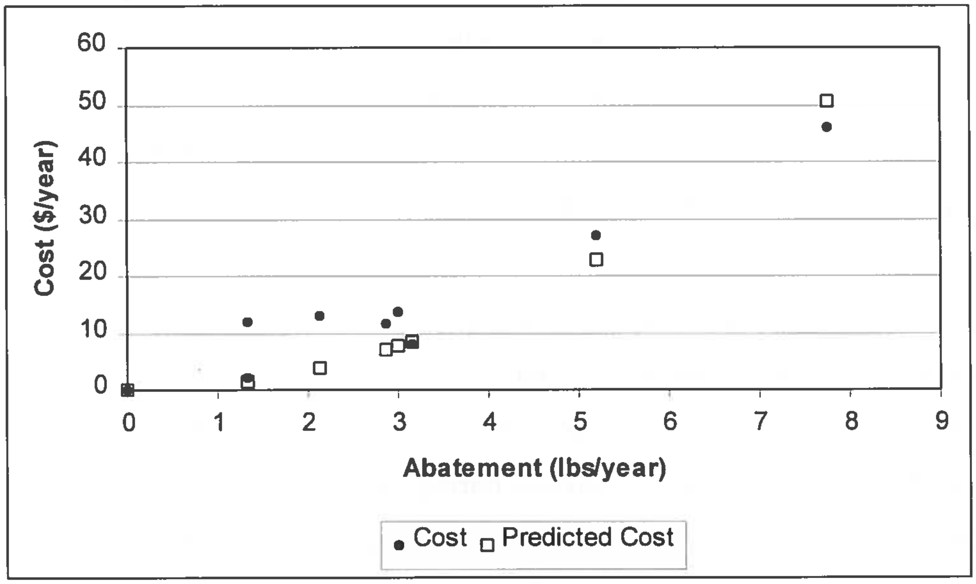
[35] Constraining these abatement cost functions to pass through the origin is not problematic. This is due to fact that they are already operating at positive levels of abatement. The observations used for the estimation do not include initial fixed investments, which might affect the analysis if the construction of new facilities was an option. In this region there already exists significant excess capacity due to the recent construction of two large wastewater facilities in Blue Lake and Seneca, and therefore the aforementioned option was not examined.

1999). Under this program livestock producers applied for financial assistance when adopting better phosphorus management practices. The application required a detailed explanation of costs and benefits resulting from the adoption of these practices. A mapping of the willingness-to-accept payment indicates that abatement costs are quadratic in nature (see Figure 4.5).

Figure 4.5: Feedlot Abatement Costs



The ordinary least squares regression results for feedlot abatement costs are given below, given the functional form: $C_i(a_i(t)) = \beta_i(a_i^2)$. This simple quadratic form had superior F-statistics to those including an intercept and/or linear component.

Table 4.10: Feedlot Abatement Cost Functions

Source	Coefficient	Standard Error	P-Value	R-Squared
Feedlot	0.839657	0.0840562	.0000129	.8144

4.2 Static-Deterministic Regulation

As mentioned, an emission permit represents the right to emit a specified quantity of pollutant into the environment. At the beginning of the control period permits can be issued to sources via some established mechanism or auctioned off to the highest bidders. They can be traded in established permit markets, similar to spot markets for other commodities (e.g., Morgan, 2000). If a source is in compliance with the environmental standard it can pollute up to the level of permit holdings. Under a permit system the marginal cost of abatement will be equalized across sources such that the equilibrium cost will equal the lowest marginal abatement costs. Those sources having marginal abatement costs greater than the permit price will prefer to abate less and to purchase additional permits and vice versa. This process will insure the lowest cost of compliance excluding transaction costs.

Transaction costs include those required for monitoring of emissions (especially costly for NPSs), enforcement of the environmental standard, and information costs associated within a tradable market system. Stavins (1995) has shown that these transaction costs are not negligible for permit markets. However, he concludes that even if transaction costs prevent a permit system from realizing a high number of trades, the aggregate costs of compliance will likely be less costly than a CAC approach. Indeed a permit system where no trades occur is also likely to be less costly than a technology standard. Hahn and Noll (1990) have identified several criteria for an efficient permit system. The first of these is that the number of permits should be limited and well defined. This will allow sources to accurately estimate a value for the permits and weigh it against their abatement costs. The permit market should also be fairly unrestricted so as to minimize transaction costs. They include a banking option as another mechanism to insure efficiency over time. Penalties for noncompliance should be greater than the cost of the permits. Finally, only in times of extreme environmental instability should permits be expropriated.

That these criteria are potentially satisfied in the case of nutrient trading in the Minnesota River has been examined in three recent studies. Taff and Senjem (1996) examined the issue of regulatory and participatory uncertainty when changes in institutional methods are encountered. In particular, they acknowledge that although in theory point-nonpoint trading schemes are attractive in practice few schemes are ever instituted and if they are, result in few trades (David and Joeres, 1983). However, when there exist substantial differences in abatement costs between point and nonpoint sources there should exist sufficient incentives for trades. This is the case of smaller wastewater treatment plants (<1 MGD flow) and farmers with high sediment delivery (>3 t/a/year) on riparian fields (Senjem, 1997).

Currently the MPCA is employing a modified-offset system for permit trading in the Minnesota River Valley. This has proven to be unwieldy and has resulted in relatively few trades (MPCA, 1996) for a number of reasons. Senjem (1997) provides a comprehensive study of the costs of alternative abatement strategies for point and nonpoint sources and details the requirements necessary to develop a more efficient, comprehensive pollutant trading system. It closely resembles that which is developed in this chapter. Senjem touches upon many of the issues already addressed: the need to determine the degree of equivalence between point and nonpoint sources taking into account time and place of discharge; the need to refine the accuracy of watershed models predicting nonpoint source loadings; the need to enhance predictability of BMP abatements; the need to determine appropriate penalties for noncompliance to cover damages and administrative costs; the need to ensure maximum accountability by nonpoint sources; and to develop institutional infrastructure to accommodate a comprehensive trading scheme.

Recently the World Resources Institute conducted several nutrient trading feasibility studies. One focused on the Minnesota River Valley (Faeth, 1998). This region was chosen due to the chronic nutrient pollution problem in the river. In addition the region had a history of PS-NPS examinations via the MPCA as well as several nutrient offset trades as part of current regulatory practice. This study modeled the entire Minnesota Valley watershed by allowing each source and sub-basin to optimally choose its abatement strategy. The economic simulations examined the varying costs of nutrient reduction as a percentage of total current emissions. They conclude that differing programs will allow reductions to be met at significantly lower costs than a point source standard. The approach used by Faeth is attractive as it compares several trading systems and illustrates how such a regulatory mechanism can be made more palatable to a NPS community that does not favor increased regulation

4.2.1 Cost-Effective Regulation

As discussed earlier, when the regulator is unsure of the actual cost and damage functions, she will often choose a standard based on other criteria (e.g., reductions to keep BOD levels safely within the range necessary for aquatic life – MPCA, 2000).

To provide a baseline comparison for the policy options available to the regulator, it is useful to generate a table representing the costs to achieve several levels of phosphorus abatement when the regulator employs a uniform reductions policy (i.e. mandating a uniform abatement percentage).

Table 4.11: Per Acre Cost of Uniform Phosphorus Reduction

THRU	Cost for Uniform Abatement ($/Acre)				
	10%	20%	30%	40%	50%
MN079a	0.16	0.64	1.43	2.55	3.98
MN080a	0.39	1.55	3.48	6.19	9.66
MN081a	0.15	0.58	1.31	2.33	3.64
MN163a	0.24	0.97	2.18	3.87	6.05
MN165a	0.22	0.88	1.98	3.51	5.49
MN169a	-0.04	-0.15	-0.34	-0.60	-0.93
MN171a	0.36	1.43	3.21	5.71	8.93
MN178a	0.47	1.89	4.26	7.58	11.84
MN196a	0.30	1.20	2.69	4.78	7.47
MN079b	0.16	0.64	1.43	2.55	3.98
MN080b	0.39	1.55	3.48	6.19	9.66
MN081b	0.15	0.58	1.31	2.33	3.64
MN163b	0.24	0.97	2.18	3.87	6.05
MN165b	0.22	0.88	1.98	3.51	5.49
MN169b	-0.04	-0.15	-0.34	-0.60	-0.93
MN171b	0.36	1.43	3.21	5.71	8.93
MN178b	0.47	1.89	4.26	7.58	11.84
MN196b	0.30	1.20	2.69	4.78	7.47

For nonpoint source in the Sand Creek, intensive abatement practices with a corn-soybean rotation can achieve abatement levels up to 50%. Using the abatement cost functions the costs of abatement per acre at various levels can be determined (see below). Using the cost per acre values from Table 4.11 and the acreage for each THRU from Table 4.1, the total costs for each THRU and for the entire region can be calculated (Table 4.12).

Table 4.12: Total Cost of Uniform Phosphorus Reduction

THRU	**Total Cost for Uniform Abatement ($/THRU)**				
	10%	**20%**	**30%**	**40%**	**50%**
MN079a	9405	37620	84646	150482	235128
MN080a	4513	18051	40615	72205	112821
MN081a	1233	4934	11101	19735	30837
MN163a	2009	8035	18078	32138	50216
MN165a	554	2218	4990	8871	13860
MN169a	-53	-213	-480	-854	-1334
MN171a	181	725	1631	2899	4530
MN178a	260	1040	2340	4161	6501
MN196a	10446	41786	94018	167143	261162
MN079b	1469	5877	13223	23508	36731
MN080b	698	2793	6285	11173	17458
MN081b	200	799	1798	3196	4993
MN163b	467	1867	4200	7467	11667
MN165b	110	439	987	1755	2742
MN169b	-14	-54	-123	-218	-340
MN171b	12	47	105	186	291
MN178b	35	138	311	552	863
MN196b	1693	6773	15239	27092	42331
TOTALS	**33,218**	**132,873**	**298,964**	**531,492**	**830,456**

We can use this table to examine a policy requiring farms to uniformly reduce phosphorus emissions at different levels. For a typical 343-acre farm in Southeastern Minnesota, the cost to attain 40% and 50% phosphorus abatement levels would be approximately $1,228.50 and $1,919 respectively (or $3.50 and $5.50 per acre). This is equivalent to 6.25% and 9.80% of expected farm profits in 1999 for a typical corn-soybean operation.[36] Another means to compare environmental policy is to compare the costs per pound of abated phosphorus.

Table 4.13: Uniform Phosphorus Reduction: Cost per Pound

THRU	Abatement Cost per Pound for Uniform Abatement ($/LBS)				
	10%	20%	30%	40%	50%
MN079a	4.67	9.33	14.00	18.66	23.33
MN080a	9.45	18.90	28.34	37.79	47.24
MN081a	3.57	7.15	10.72	14.29	17.87
MN163a	9.21	18.43	27.64	36.85	46.07
MN165a	1.81	3.61	5.42	7.22	9.03
MN169a	-0.32	-0.63	-0.95	-1.27	-1.58
MN171a	7.46	14.91	22.37	29.82	37.28
MN178a	16.76	33.53	50.29	67.06	83.82
MN196a	6.27	12.55	18.82	25.10	31.37
MN079b	1.79	3.59	5.38	7.18	8.97
MN080b	3.63	7.27	10.90	14.54	18.17
MN081b	1.37	2.75	4.12	5.50	6.87
MN163b	3.54	7.09	10.63	14.17	17.72
MN165b	0.69	1.39	2.08	2.78	3.47
MN169b	-0.12	-0.24	-0.37	-0.49	-0.61
MN171b	2.87	5.74	8.60	11.47	14.34
MN178b	6.45	12.90	19.34	25.79	32.24
MN196b	2.41	4.83	7.24	9.65	12.07
Aggregate	4.43	8.85	13.28	17.70	22.13

Aggregate costs of abatement range from $4.43 to $22.13 per pound of phosphorus abated for policies requiring 10% and 50% reductions, respectively. It is apparent, however, that targeted abatement strategies could focus first on emissions arriving from the acreage within the 300-foot buffer first. More specifically, abatement arriving from MN169b, MN169a, and MN165b are achieved at low cost even at high abatement levels. However, these THRUs do not constitute a large percentage of the watershed. Were these three THRUs to abate at the 50% level a total of 2,192 lbs of phosphorus could be abated at the low cost of $0.49 per pound. Conversely, it would be relatively expensive to abate on MN080, MN171, and MN178 soils.

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[36] Reported to be approximately $19,578 over labor and management (Southeastern Minnesota Farm Business Management Association, 1999).

Taxes and Permits

Under deterministic regulation an effluent fee (or Pigouvian tax) has been shown to result in equivalent abatement cost to a system of tradable emissions permits. Using the estimated abatement cost functions from above, the use of taxes and permits to regulate phosphorus regulation can be compared. First, a system considering nonpoint sources separately will be evaluated. Before estimating the most efficient (i.e. that which maximizes social welfare) level of abatement for the watershed, a goal of reducing phosphorus emissions by 40% will be evaluated using permits and taxes. This is the benchmark level set by many phosphorus reduction strategies including the Chesapeake Bay program and that of the MPCA for the Minnesota River.

Table 4.14: Regulation of Nonpoint Phosphorus Emissions

THRU	Acres	Emissions (lbs/year)	Uniform Reduction Abatement	Abatement Costs ($)	Tradable Permit Abatement	Abatement Costs ($)
MN079A	59,014	20,161	8,064	150,482	6,421	95,394
MN080A	11,673	4,777	1,911	72,205	751	11,159
MN081A	8,476	3,452	1,381	19,735	1,435	21,323
MN163A	8,300	2,180	872	32,138	352	5,223
MN165A	2,525	3,070	1,228	8,871	2,526	37,528
MN169A	1,433	1,685	674	-854	1,369	-3,520
MN171A	508	243	97	2,899	48	721
MN178A	549	155	62	4,161	14	204
MN196A	34,953	16,648	6,659	167,143	3,931	58,231
MN079B	9,219	8,188	3,275	23,508	4,656	47,503
MN080B	1,806	1,922	769	11,173	786	11,669
MN081B	1,373	1,453	581	3,196	830	6,517
MN163B	1,928	1,317	527	7,467	552	8,200
MN165B	499	1,579	632	1,755	1,328	7,754
MN169B	366	1,118	447	-218	909	-900
MN171B	33	41	16	186	20	276
MN178B	73	54	21	552	12	184
MN196B	5,665	7,016	2,806	27,092	4,085	57,400
TOTALS	**148,394**	**75,058**	**30,023**	**$531,492**	**30,023**	**$364,865**

Under a system of regulation using tradable permits or effluent fees a savings of \$166,627 or 31% over a system of uniform reductions would be realized. Similar abatement costs would be realized if the regulator mandated that each source abate by the efficient quantity found in the 6th column. Although the permit system and the system charging effluent fees result in similar abatement costs, the cost to the polluter is different due to the added permit costs (or revenues) and the pollution fees paid. The price per permit will equal the efficient choice of effluent fee in this case as shown in Chapter 2. The resulting price for this system equals \$29.71 and is approximately equal to the marginal costs of the polluters.[37]

Suppose that the regulator issues non-tradable emissions quotas to each source equal to the efficient quantity.[38] Alternatively suppose that a tradable permit endowment of 60% of initial emissions is distributed to each source. Lastly, suppose that the regulator simply charges \$29.71 per pound of phosphorus emitted by each source. It is apparent from Table 4.15 below, that under this type of permit system utilizing a uniform distribution (of tradable permits) policy, the sources with the lowest cost of abatement will benefit as compared to the command-and-control policy. When sources are mandated to abate at the efficient level, the aggregate costs are the same as with tradable permits, but it should be noted that those sources with low (high) abatement costs (i.e. those that would sell (buy) permits) end up paying more (less). It should also be noted that the tax revenues collected using effluent fees could be redistributed to the sources in such as way as to have the end result equal the total costs in columns 1 or 2.

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[37] It should be noted that the marginal costs of all producers are not realized due to boundary constraints on abatement levels, i.e. abatement must be greater than zero, but less than ex-ante emissions.

[38] If the quota amounts were distributed such that each source receives the efficient allotment then there would actually be no incentive to trade.

Table 4.15: Regulation Costs of Nonpoint Phosphorus Emissions

THRU	Emissions (lbs/year)	(1) Costs with Non-tradable Quotas	(2) Costs with Permits	(3) Costs with an Effluent Fee
MN079A	20,161	95,394	144,231	503,609
MN080A	4,777	11,159	45,613	130,754
MN081A	3,452	21,323	19,705	81,240
MN163A	2,180	5,223	20,690	59,551
MN165A	3,070	37,528	-1,035	53,697
MN169A	1,685	-3,520	-24,159	5,883
MN171A	243	721	2,169	6,502
MN178A	155	204	1,639	4,404
MN196A	16,648	58,231	139,311	436,069
MN079B	8,188	47,503	6,477	152,451
MN080B	1,922	11,669	11,167	45,424
MN081B	1,453	6,517	-877	25,032
MN163B	1,317	8,200	7,449	30,925
MN165B	1,579	7,754	-12,930	15,222
MN169B	1,118	-900	-14,619	5,309
MN171B	41	276	171	895
MN178B	54	184	453	1,407
MN196B	7,016	57,400	19,409	144,482
TOTALS	**75,058**	**$364,865**	**$364,865**	**$1,702,855**

Earlier it was estimated that achieving a 40% phosphorus abatement level for the Minnesota River focusing only on point sources would cost approximately $400 million (McCann and Easter, 1998). When nonpoint sources are included in this regulation it can be shown that a small amount of abatement effort per acre would generate significant savings when complying with the 40% reduction goal. Conversely, when point sources are included in the above analysis, the permit price should increase, the abatement costs for nonpoint sources should increase (because they will increase abatement and sell more permits), but the total costs due to sale of permits should decrease for nonpoint sources.

Table 4.16: Regulation of Point and Nonpoint Phosphorus Emissions

Source	Emissions (lbs/year)	Uniform Reduction Abatement	Abatement Costs ($)	Tradable Permit Abatement	Abatement Costs ($)
WWTF-J	2,285	914	27,706	711	16,752
WWTF-N	8,445	3,378	55,952	4,807	113,318
Feedlots	29,180	11,672	1,243,896	2,582	60,853
MN079A	20,161	8,064	150,482	10,187	240,115
MN080A	4,777	1,911	72,205	1,192	28,088
MN081A	3,452	1,381	19,735	1,971	40,217
MN163A	2,180	872	32,138	558	13,147
MN165A	3,070	1,228	8,871	2,584	39,278
MN169A	1,685	674	-854	1,369	-3,520
MN171A	243	97	2,899	77	1,815
MN178A	155	62	4,161	22	514
MN196A	16,648	6,659	167,143	6,236	146,573
MN079B	8,188	3,275	23,508	4,656	47,503
MN080B	1,922	769	11,173	1,097	22,735
MN081B	1,453	581	3,196	830	6,517
MN163B	1,317	527	7,467	750	15,115
MN165B	1,579	632	1,755	1,328	7,754
MN169B	1,118	447	-218	909	-900
MN171B	41	16	186	20	276
MN178B	54	21	552	20	463
MN196B	7,016	2,806	27,092	4,085	57,400
TOTALS	**114,968**	**45,987**	**$1,859,046**	**45,987**	**$854,012**

When point sources are included in the regulation, the increased abatement costs shown in Table 4.16, mainly stem from the high cost to livestock producers in achieving the uniform 40% reduction. It can be seen that under a system of regulation using tradable permits or effluent fees a savings of approximately $1 million or 54% over a system of uniform reductions would be realized, most of which is attributable to abatement transfers from livestock producers to cropland (i.e. croplands abate more and livestock producers abate less). The cropland abatement increases by 7,864 (lbs/year) under a tax or permit system. Similar abatement costs savings would be realized if the regulator mandated that each source abate by the efficient quantity.

Although a permit system and effluent fees result in similar abatement costs, the cost to the polluter is different due to permit costs (or revenues) and pollution fees paid.

The permit price will equal the efficient choice of effluent fee in this case as shown in Chapter 2. The resulting price is $47.14, approximately equal to the marginal costs of the polluters.[39] Suppose that the regulator issues non-tradable emissions quotas to each source equal to the efficient quantity.[40] Alternatively suppose that a tradable permit endowment of 60% of initial emissions is distributed to each source. Lastly, suppose that the regulator simply charges $47.14 per pound of phosphorus emitted by each source. A comparison of the total costs under these systems is found in Table 4.17.

Table 4.17: Regulation Costs of Point and Nonpoint Phosphorus Emissions

Source	**Emissions (lbs/year)**	**(1) Costs with Non-tradable Quotas**	**(2) Costs with Permits**	**(3) Costs with an Effluent Fee**
WWTF-J	2,285	16,752	26,336	90,964
WWTF-N	8,445	113,318	45,936	284,799
Feedlots	29,180	60,853	489,400	1,314,703
MN079A	20,161	240,115	140,058	710,289
MN080A	4,777	28,088	61,982	197,079
MN081A	3,452	40,217	12,388	110,026
MN163A	2,180	13,147	27,964	89,628
MN165A	3,070	39,278	-24,649	62,188
MN169A	1,685	-3,520	-36,264	11,399
MN171A	243	1,815	2,772	9,646
MN178A	155	514	2,411	6,798
MN196A	16,648	146,573	166,525	637,399
MN079B	8,188	47,503	-17,586	214,021
MN080B	1,922	22,735	7,281	61,635
MN081B	1,453	6,517	-5,213	35,894
MN163B	1,317	15,115	4,615	41,864
MN165B	1,579	7,754	-25,062	19,603
MN169B	1,118	-900	-22,666	8,952
MN171B	41	276	109	1,258
MN178B	54	463	548	2,063
MN196B	7,016	57,400	-2,874	195,570
TOTALS	**114,968**	**$854,012**	**$854,012**	**$4,105,779**
Tax Revenues		**0**	**0**	**$3,251,767**

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[39] It should be noted that the marginal costs of all producers are not equalized due to boundary constraints on abatement levels, i.e. abatement must be greater than zero, but less that ex-ante emissions.

[40] If the quota amounts were distributed such that each source receives the efficient allotment then there would actually be no incentive to trade anyways.

Notice the high tax revenues generated under the tax system, most of which are collected from livestock producers. As noted before, these revenues could be used to compensate sources in some manner similar to the tradable permit system or to the non-tradable quota system, or the revenues could be used for such things as monitoring and enforcement.

Policy Comparison

While it can be seen the abatement levels resulting from the effluent fee, non-tradable quota, and tradable permit policies are identical, there are substantive differences between the policies. Tables 4.14 – 4.17 can be used to examine which type of regulation would be preferable to the various sources given the 40% reduction standard.

Table 4.18: Cost-Effectiveness Comparisons

Source	Cost			
	343-Acre Farm	WWTF-J	WWTF-N	Feedlot
Uniform Reduction (NPS only)	$1,228			
Uniform Reduction (PS & NPS)	$1,228	$27,206	$55,952	$13,521
Non-Tradable Quota (NPS only)	$843			
Non-Tradable Quota (PS & NPS)	$1,673	$16,752	$113,318	$661
Tradable Permit (NPS only)	$843			
Tradable Permit (PS & NPS)	$676	$26,336	$45,936	$5320
Effluent Fee (NPS only)	$3,936			
Effluent Fee (PS and NPS)	$5,583	$90,964	$284,799	$14,290

Examining Table 4.18 it is clear that a typical corn-soybean farm in Southeastern Minnesota would prefer a phosphorus regulation, which allowed trading of uniformly distributed permits. Under such a system the farmer would expect to pay only $2.00 per acre or 3.5% of expected profits.[41] A small wastewater treatment facility that has already invested in some phosphorus reduction technology (such as that found in Jordan, MN) would prefer to be issued directly the efficient level of emissions permits (tradable or not). A larger facility with relatively little abatement investments also prefer to be issued uniformly distributed tradable permits. Lastly, the feedlot numbers indicate that an

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[41] Reported to be approximately $19,578 over labor and management (Southeastern Minnesota Farm Business Management Association, 1999).

efficient distribution of emissions quotas (tradable or not) would be much preferred to any other system of regulation. This is because of the added cost in purchasing permits. Note also that nonpoint sources would prefer a system that includes point sources when permits are tradable and uniformly distributed, however, if emissions quotas are distributed in an efficient manner farmers prefer to be regulated apart from point sources.

This policy comparison has several caveats. It should be remembered that the system of effluent fees results in the highest costs to all sources, but the tax revenues to the regulator can compensate the sources in whichever manner the regulator chooses. One might expect farmers to be leery of such compensation schemes, which may seem to further complicate the environmental regulation. Such behavior and dislike of additional taxes to regulate pollution has been reported in the literature (McCann and Easter, 1998). It is also interesting to compare the cost of compliance under these policies to current Conservation Reserve Program contracts paid to farmers in this region. For a typical 343-acre farm in this region the cost per year to comply with the different regulation policies ranges from $2.00 per acre to $16.00 per acre. In 1988, farmers in this region were willing to accept $70 per acre for CRP contracts. Currently CRP contracts range between $73 and $109 per acre for this area. The estimated area in this region under CRP contracts is approximately 2,500 acres per year (Taff, 1999). Assuming that this area represents marginal production acres, the resulting abatement will be 4,500 lbs/year at a cost of $53 per pound (assuming $100 per acre CRP contract). By comparison a similar level of uniform abatement for nonpoint sources would cost $1.77 per pound.

4.2.2 Efficient Regulation

If the regulator knows the cost functions for abatement and the damage function for stock levels it is possible to determine what the most efficient level of abatement per year should be chosen for proposed phosphorus regulation. Alternatively, instead of minimizing the sum of abatement costs and stock damages, it is possible to maximize the difference between the benefits to lowering the stock level and the costs of abatement to achieve the lower level. This will allow comparison of deadweight loss values associated with inefficient regulation policies.

Total Benefits

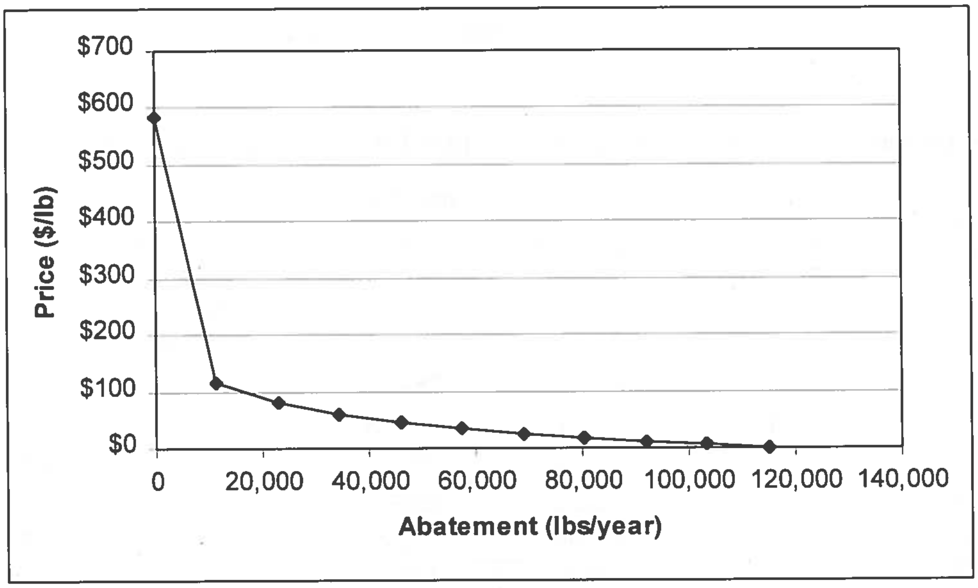
An *efficient* policy would maximize the net present benefits to society of reducing pollution. This entails maximizing the discounted distance between the total benefit function and the total cost function for the appropriate years. This will occur with well-behaved total benefits and total cost functions when the discounted marginal benefits of pollution reduction are equal to the discounted marginal cost of reducing an extra unit of pollution. For a static system this is simply the intersection of the demand curve for pollution reduction with the supply curve for pollution reduction (i.e., when the slope of the total benefit function equals the slope of total cost function). As mentioned earlier, if the marginal benefit function is known (the inverse demand function for environmental amelioration) and the marginal cost function is known (the supply function for environmental amelioration) it is possible to determine the efficient level of pollution abatement and the deadweight loss due to deviations from that standard (i.e. when the marginal benefits of abatement is equal to the marginal cost of abatement).

For deadweight loss calculations an estimate of the marginal benefit function for phosphorus abatement in the Sand Creek is required. Fortunately, a recent study has looked at this issue for the Minnesota River Valley (Mathews et al., 2000). Combining revealed and stated preferences, Mathews et al. (2000) estimate random-effects probit model for phosphorus abatement in the Minnesota River similar to Loomis (1997). Using these estimates it is possible to estimate the mean willingness-to-pay for a 40% phosphorus abatement level and the marginal effect of water quality on willingness-to-pay. Calibrating these results to the Sand Creek (i.e., 3.5% of the total phosphorus load in the Minnesota River) it is possible to determine the total benefits to 3.5% of the regional population for a 40% reduction in Sand Creek emissions.

Assume first that the marginal willingness-to-pay approaches zero as abatement approaches 100%. That is to say, that the benefits to abatement level off as 100% abatement is realized, consistent with the traditional assumptions of the benefits function. Also assume the form of the inverse demand function is semi-log, which approximates the estimate of total benefits and has a slope that approaches zero as abatement approaches 100%.[42] Under these assumptions, the marginal benefit function can be derived (Figure 4.6) from Mathews et al. (2000) to be:

$$MB = 585 - 50.2024 * \ln(\sum_{i=1}^{n} a_i). \tag{4.1}$$

Figure 4.6: Demand for Phosphorus Abatement



Then, by integrating this marginal benefits function, it can be shown where $A = \sum_{i=1}^{n} a_i$ and *B(0)* is assumed to be zero, that benefits as a function of abatement, *B(A)*, are:

$$B(A) = 635.2024A - 50.2024(A * \ln A) \quad , \tag{4.2}$$

Total Costs

The aggregate abatement cost function for the Sand Creek can be calculated by adjusting the levels of abatement required under the water quality regulation. The resulting abatement levels and aggregate costs can be used to estimate the standard cost function, $C_i(a_i(t)) = \beta_i(a_i^2)$ via ordinary least squares.

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[42] See Deaton and Muellbauer (1980) for a discussion of functional forms for demand functions.

Table 4.19: Aggregate Abatement Cost Function for the Sand Creek

Source	Coefficient	Standard Error	P-Value	R-Squared
Tradable Permits	0.000441	0.0000192	0.0000029	0.983
Uniform Reductions	0.0007218	0.0000529	0.0000379	0.940

Equating marginal cost to marginal benefits, the efficient level of abatement occurs when yearly abatement equals approximately 48,800 lbs, or 42.45%.[43]

Table 4.20: Efficient Regulation of Point and Nonpoint Phosphorus Emissions

Source	Emissions (lbs/year)	Uniform Reduction Abatement	Abatement Costs ($)	Tradable Permit Abatement	Abatement Costs ($)
WWTF-J	2,285	970	31,204	787	20,519
WWTF-N	8,445	3,585	63,016	5,321	138,811
Feedlots	29,180	12,387	1,400,940	2,857	74,535
MN079A	20,161	8,558	169,480	11,274	294,102
MN080A	4,777	2,028	81,321	1,319	34,403
MN081A	3,452	1,465	22,227	1,971	40,217
MN163A	2,180	925	36,196	617	16,103
MN165A	3,070	1,303	9,991	2,584	39,278
MN169A	1,685	715	-962	1,369	-3,520
MN171A	243	103	3,265	85	2,222
MN178A	155	66	4,686	24	629
MN196A	16,648	7,067	188,246	6,902	179,527
MN079B	8,188	3,476	26,475	4,656	47,503
MN080B	1,922	816	12,584	1,097	22,735
MN081B	1,453	617	3,599	830	6,517
MN163B	1,317	559	8,409	750	15,115
MN165B	1,579	670	1,976	1,328	7,754
MN169B	1,118	475	-245	909	-900
MN171B	41	17	210	20	276
MN178B	54	23	622	22	567
MN196B	7,016	2,978	30,512	4,085	57,400
TOTALS	**114,968**	**48,804**	**$2,093,754**	**48,804**	**$993,794**

To achieve this level of abatement the regulator could distribute 68,981 tradable emissions permits, which would result in an equilibrium price of $52.17 per permit, or

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[43] Were the regulator to use a system of uniform reductions, the most efficient level of abatement would be 38,269 lbs/year (given the higher aggregate abatement cost).

she could charge an effluent fee of \$52.17 per pound of phosphorus emitted into the river (cost savings are illustrated in Table 4.20). The deadweight loss resulting from choosing a 40% reductions standard given the estimates of the marginal abatement and cost curves is given by the area bounded by the marginal cost curve, the marginal benefits curve and the abatement levels of 45,987 lbs/year and 48,804 lbs/year, which equals \$7,768.[44]

4.2.2 Uncertainty

Although uncertainty has not been the focus of this chapter, it is interesting to utilize the theory of regulation under uncertainty from Chapter 2 to differentiate price and quantity instruments for Sand Creek phosphorus abatement. Recall that the key insight from Weitzman (1974) was that the sign of (2.16) determines the regulator's preference of policy instrument. That is to say, if the assumption of quadratic approximations for the cost and benefit functions, the fundamental W-A result is again:

$$\Delta_{ets} \cong \frac{\sigma^2 B''}{2C''^2} + \frac{\sigma^2}{2C''}. \tag{2.16}$$

The implications for emissions taxes and trading *ceteris paribus* revolve around the sign of Δ_{ets}. If $\Delta_{ets}<0$ then $B''+C''<0$; i.e. if the slope of the benefit function is greater than the slope of the cost function then tradable emissions permits will have a comparative advantage over emissions taxes. Effluent fees are preferable to tradable permits, all else equal and subject to Condition 1, the more steeply sloped the cost function is and the more linear the benefit function is within a neighborhood around the optimal abatement level (i.e. $\Delta_{ets}>0$). If $C_p(\bar{a}) > C_n(\bar{a})$ the effect of including a point source will be to mute the effect of weather on the total cost curve, *C(A)*, which will decrease σ^2 and therefore, the magnitude of Δ_{ets}.

In the case of Sand Creek, it can be shown that for the efficiently chosen abatement level of 48,800 lbs/year that $\Delta_{ets}<0$. This implies that given the slope of the

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[44] Given that it took a research assistant roughly 6 months to figure this out at a cost of approximately \$7,000 it would appear that the ballpark figure chosen by the MPCA of 40% is quite good.

estimated benefit and cost functions a regulator, all else equal, would prefer to regulate phosphorus in a stochastic environment using a quantity instrument, such as tradable emission permits. Whether this result will hold in a dynamic environment will be determined in Chapter 5.

4.3 Summary Comments

The comparisons of static-deterministic policies reveal several important features that are important for policymakers to consider when developing strategies for regulating point and nonpoint phosphorus emissions in this region. First, it can be seen that agricultural sources of phosphorus significantly outweigh non-agricultural sources. Furthermore, nonpoint emissions from agricultural cropland comprise on average approximately 65% of total emissions. For the Minnesota Pollution Control Agency to achieve its goal of 40% reductions of phosphorus emissions in the Minnesota River it will be necessary to include nonpoint sources of phosphorus.

From Table 4.19 it can be seen that abatement costs for cropland sources are lower under an equi-marginal cost system to a simple non-targeted uniform reductions policy. This could be achieved under a targeted reductions, tradable permit, or Pigouvian tax system. Furthermore, agricultural, nonpoint sources would prefer the inclusion of point sources only under certain conditions: when tradable permits are distributed using a uniform "grandfather" system[45] or when there is a compensation mechanism coupled with effluent fees equal such that they are at least as well off as under a system of without the inclusion of point sources. Point and nonpoint sources that have not invested in previous abatement efforts prefer a system that is based on historic emissions (e.g., tradable permit system discussed above); those sources that have already invested in abatement efforts prefer systems such as effluent fees or targeted emissions quotas that are based on current emissions. Whether these preferences hold when emissions are regulated in a stochastic, dynamic environment will be investigated in the next chapter.

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[45] This refers to a uniform distribution of permits based on a uniform percentage of historic emissions.

Chapter 5

Dynamics and Asymmetric Information

5.1 Dynamic Regulation

In a competitive, deterministic market, sources will buy and sell permits such that the market price of permits is equal to marginal abatement costs (for all firms, assuming no binding constraints on optimal abatement levels). Furthermore, when banking and borrowing of permits are allowed, the net present value of marginal abatement costs is equalized across time periods (Kling and Rubin, 1997; Hagem and Westskog, 1998). In the absence of transaction costs it can be shown that an emissions trading system using intertemporal permits can achieve first-best solutions (Leiby and Rubin, 1998). The examination of price and quantity policies under uncertainty (Weitzman, 1974) and extensions (Hoel and Karp, 1999) are briefly discussed in Chapter 2. Here, dynamic policies and the problem of asymmetric information and associated moral hazard (e.g., cheating) are considered.

First, an extension of the dynamic examples in Chapter 2 is provided for the Sand Creek. As with static policies it is possible to generate comparisons of uniform reductions and policies employing either emissions quotas (tradable and non-tradable permits) or effluent fees. These comparisons use *cost effectiveness* as a measure of regulatory efficiency when the environmental standard is exogenously determined (i.e.

second-best policies) or they use *social welfare* when the benefits (or damages) function is known.

5.1.1 First-Best

To determine the optimal abatement strategy for the regulator given the aggregate abatement costs for the watershed it is necessary to have estimates of the phosphorus stock parameters: the damage function, initial phosphorus stock, and the decay rate. For example, with eutrophication and BOD loading, phosphorus is washed down stream and/or deposited, depending on the rate of the river flow and topography. Many of the empirical and theoretical estimations of phosphorus have been conducted for lakes and wetlands (e.g., Naevdal, 1999; Wagner et al., 1996) making it difficult to determine appropriate parameters for the Sand Creek or Minnesota River. However, to illustrate why regulators have hitherto exogenously chosen to adopt water quality standards (that in general do not seek to optimize social welfare), a "back-of-the-envelope" calculation for Sand Creek will be developed.

First, an estimate of the damage function will be determined given the public's willingness-to-pay for phosphorus abatement. When estimating the benefits to abatement (Chapter 4), it is difficult to infer the benefit function for dynamic changes in the stock level, as this was not the specific question asked in the valuation survey (Mathews, 1998). Be that as it may, it is possible to make several simplifying assumptions to illustrate how the dynamic analysis may differ from the static results. The benefits to abatement function was estimated earlier (4.2): $B(t) = 635.2024*A(t)-50.2024(A(t)*lnA(t))$. This does not explicitly consider the stock damages due to the accumulation of phosphorus in the system. However, it is inversely related to stock levels in a linear fashion. Assume then that damages as a function of stock levels in each period for this example are simply: $D(S) = -B(t) = 50.2024(S(t)*lnS(t))-635.2024S(t)$.

The natural decay rate for phosphorus in a river's system depends on a number of things: the timing of sediment deposits, the flow volume and rate of the river at different time periods, and the underlying phosphorus content in the water. Phosphorus is a conservative pollutant, which implies it does not actually decay. For this reason daily load values calculated for phosphorus typically limit the load per volume of water (USEPA, 1994). However, a more appropriate way to think of phosphorus leaving the system is in one of two ways. Phosphorus attached to sediment can be deposited on the floor of the river, generally where the river broadens and slows (e.g., Lake Pepin). A small percentage of this phosphorus is retained in the soil bottom of the river. The remainder of the particulate phosphorus can enter solution as bio-available phosphorus over time and especially when the ambient phosphorus level is low enough. The percentage of phosphorus entering the system can be compared to the percentage of phosphorus that becomes bio-available from organic manure applications on a field; i.e. manure slurry is commonly assumed to yield about half of its nutrient content in a time decay fashion (0.5^t) each year (George, 2000). This phosphorus, as well as the bio-available phosphorus directly deposited into the river, is used by aquatic plants for growth. When these plants die and decompose they will release the phosphorus into the river once again further downstream.

The initial phosphorus stock in the Sand Creek can be calculated using the estimated loading values and watershed size from Chapter 4. First the phosphorus retention rate calculation can be determined using the formula developed in Florida (Wagner et al., 1996). The equation relating these parameters is:

$$P_a = 0.67 P_1^{.86},$$

where P_a is the phosphorus retention rate (g m^{-2} year^{-1}) and P_l is the phosphorus-loading rate (g m^{-2} year^{-1}). Using these values indicates that of the 115,000 lbs/year deposited into the Sand Creek from the 148,394 acres approximately 108,477 lbs/year are retained (P_l). However, this is dependent on the detention time of the body of water examined. In a lake the detention time would obviously be much longer than in a wetland or river. Wagner et al. (1996) offer the following relationship to estimate the effects of detention time on retention rates:

$$P_d = P_a(1 - e^{-kt}).$$

Here, P_d is the adjusted phosphorus retention rate as a function of the detention time (t) and the detention coefficient (k). Given the flow rate of the Sand Creek (Dalzell et al.,

1999) and the length of the Sand Creek, P_d can be estimated to be 3.04% of the total load. Therefore over a number of years given the decay rate above (0.5^t) and phosphorus retention rate of 3.04%, an initial phosphorus load in the Sand Creek (in the spring before significant emissions have occurred) can be determined to be:

$$S(0) = S_0 = \sum_{t=1}^{\infty} 103{,}500 * (0.4696)^t.$$

This converges to a value of 91,635 pounds.[46]

Now following from Chapter 2, using the above results and those from Chapter 4, consider the following optimal control system for a watershed.

- Aggregate Cost of Abatement: $C(t) = 0.000441*A^2$,
- Aggregate Damage Function: $D(S) = 50.2024(S(t)*\ln S(t))-635.2024S(t)$,
- Stock Equation: $\dot{S}(t) = e(t) - 0.5S(t)$,
- Initial Stock Level: $S_0 = 91{,}635$ lbs.,
- Emissions Equation: $e(t) = 115{,}000 - A(t)$,
- Discount rate: r = 0.06, and
- Discount factor: e^{-rt}.

The regulator's problem (RP^3) is to choose aggregate abatement in each time period to minimize the cost of abatement plus the damages due to the stock level at that time. If the regulator chooses the time period of regulation and the terminal stock level, RP^3 is:

$$\begin{gathered}\min_{A(t)} \int_0^T e^{-rt}[C(t) + D(t))]dt \\ \text{subject to :} \\ \dot{S}(t) = \overline{E} - A(t) - \gamma S(t), \\ S(0) = S_0, \\ \lambda(T) = 0.\end{gathered} \qquad (RP^3)$$

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[46] This assumes that 90% of the phosphorus deposited into the river is attached to sediment and that 10% enters as dissolved phosphorus (see Chapter 1 discussion).

Here, $\lambda(T)$ represents the shadow price for an optimally chosen terminal stock level. The current-value Hamiltonian (H^3) for this system is:

$$H \equiv A(t) + D(t) + \lambda(t)[\overline{E} - A(t) - \gamma S(t)]. \qquad (H^3)$$

The first-order necessary conditions for an interior solution are:

- $\frac{\partial H}{\partial A} = 0$, which implies: $A^{*}(t) = \frac{\lambda(t)}{0.000882}$;
- $-\frac{\partial H}{\partial S} = \dot{\lambda}(t) - .06\lambda(t) = 0.5\lambda(t) - \frac{\partial D(t)}{\partial S(t)}$,
  which implies: $\dot{\lambda}(t) = (.56)\lambda(t) - \frac{\partial D(t)}{\partial S(t)}$, and
- $\dot{S}(t) = e(t) - 0.5S(t)$.

Optimal abatement and stock levels can be determined from these first-order conditions. From the first condition, it can be seen that the marginal abatement cost will equal the shadow price of banked emissions. Similarly the marginal damages will also equal the discounted shadow value decayed at rate γ.[47] This implies that the regulator should choose optimally the abatement level such that the marginal abatement costs are equal to the discounted damage due to an additional unit of pollution.

To find the steady-state equations for the stock of phosphorus and for the abatement levels, it is possible to manipulate these first-order conditions, such that:

- $\dot{S}(t) = 115{,}000 - A(t) - .5S(t)$ and
- $\dot{A}(t) = (.56)A(t) - (\frac{50.2024 \ln S(t) - 585}{.000882})$.

Setting these two differential equations equal to zero, the steady-state levels of S^{ss} and A^{ss} are:

- $S^{ss} = 2(115{,}000 - A^{ss})$ and
- $A^{ss} = 101{,}640.8 * \ln S^{ss} - 1{,}184{,}402.7$.

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[47] For non-bounded solutions the marginal present value of a unit of emissions in the bank is constant and the time derivative will be zero (Kling and Rubin, 1996).

Solving for the steady-state levels: S^{ss} = 161,279 and A^{ss} = -92,558. As abatement cannot be negative, this system does not result in a steady state stock or abatement level.

5.1.2 Second-Best

As illustrated, the links between phosphorus emissions over time, the amount of phosphorus available for algae growth, and the phosphorus deposited and accumulated in the river bottom silt are often unknown. When the regulator is unsure of the exact nature of these links and of the social benefits to cleaner waters (e.g., those attributable to recreational boating and fishing) she may choose instead some level of phosphorus emissions, deemed by biologists to be safe for aquatic life. Using the permit models found in Leiby and Rubin (1998), Kling and Rubin (1996), and Rubin, 1996 a *terminal stock standard* of 40% emissions reductions can be evaluated for the Sand Creek (as shown earlier this is approximately equal to the efficient level of emissions reductions in a static environment). This type of standard is useful when a particular level of pollution cannot be exceeded without great damage (i.e., a very steep benefit function in a neighborhood around the optimal abatement level) or when the regulator is unsure of the damage and cost functions.

Dynamic Social Planner Problem

Following from Chapter 2, the environmental standard over a planning horizon (T) is such that total ex-post emissions in the river system will average 60% of the ex-ante emissions. In each period the regulator issues an initial endowment of permits, $l_i(t)$, to each source such that: $\sum_{i=1}^{n} l_i(t) = 0.6\sum_{i=1}^{n} \overline{E}_i$. These permits can be bought, sold, or banked. Because banking is allowed each source will manage an account of permits, $B_i(t)$. The aggregate stock of banked permits in each time period is: $B(t) = \sum_{i=1}^{n} B_i(t)$.

The rate of change of aggregate banked emissions, $\dot{B}$, will vary according to the state equation: $\dot{B} = \sum_{i=1}^{n} (l_i(t) - \overline{E}_i + a_i(t))$.

The regulator's problem (RP^4) then is to choose abatement levels for all sources so as to minimize compliance costs over the planning horizon subject to the environmental standard:

$$\begin{aligned} &\min_{A(t)} \int_0^T e^{-rt} \sum_{i=1}^{n} C_i(a_i(t)dt \\ &\text{subject to :} \\ &\dot{B} = \sum_{i=1}^{n} (l_i(t) - 115{,}000 + a_i(t)), \\ &B(0) = 0, B(t) \geq 0 \\ &\sum_{i=1}^{n} l_i(t) = 69{,}000 \quad \text{and} \\ &a_i(t) \geq 0 \; \forall i = 1, \ldots, n. \end{aligned} \tag{RP^4}$$

The regulator will choose abatement to minimize discounted abatements over the planning horizon, where (T) is the terminal time period and (r) is the discount rate. The state equation indicates that the rate of change for aggregate banked permits equals the difference between yearly emissions and yearly endowments. Initially, banking is constrained to positive quantities, i.e., there is no borrowing option. Lastly, are the non-negativity constraints on abatement levels. The co-state variable for the state equation, $\lambda(t)$, represents the shadow cost of additional units banked. The current value Hamiltonian (H^4) will then be:

$$H^4 \equiv \sum_{i=1}^{n} C_i(a_i(t)) + \lambda(t)[\sum_{i=1}^{n} (l_i(t) - 115{,}000 + a_i(t))]. \tag{H^4}$$

The first order necessary conditions for an interior solution are:

- $\frac{\partial H}{\partial a_i} = \frac{\partial C_i(a_i(t))}{\partial a_i(t)} + \lambda(t) = 0$,
- $-\frac{\partial H}{\partial B} = \dot{\lambda}(t) - 0.06\lambda(t)$, and
- $\dot{B} = \sum_{i=1}^{n}(l_i(t) - 115{,}000 + a_i(t))$.

These conditions simply state that for any given time period, the optimal level of abatement for each source will be one where marginal abatement costs are equalized across sources. Furthermore, the marginal abatement costs will be equal to the marginal value of banking an additional permit.

Dynamic Source Level Optimization

Each source *i* given the price of permits in each time period ($P_l(t)$) will choose abatement levels (a_i) and sales of permits (x_i) to solve the optimization problem (J*):

$$\begin{gathered}\min_{A(t)} \int_0^T e^{-rt}[C_i(a_i(t) + P_l(t)x_i(t)]dt \\ \text{subject to :} \\ \dot{B}_i = l_i(t) - 115{,}000 + a_i(t) - x_i(t), \\ B_i(0) = 0,\ B_i(t) \geq 0 \quad \text{and} \\ a_i(t) \geq 0 \ \ \forall i = 1, \dots, n.\end{gathered} \tag{J*}$$

Here each source$_i$ will choose abatement and permit sales (or purchases) to minimize discounted abatement costs plus permit purchases (sales) over the planning horizon, where (T) is the terminal time period and (r) is the discount rate. The state equation indicates that the rate of change for aggregate banked permits equals the difference between yearly emissions and yearly endowments plus permit purchases. Initially, banking is constrained to positive quantities, i.e., there is no borrowing option. Lastly, are the non-negativity constraints on abatement levels.Similarly, the co-state variable for the state equation, $\lambda_i(t)$, represents the shadow cost of additional units banked.

The current value Hamiltonian (H$_i$) will then be:

$$H_i \equiv C_i(a_i(t) + P_l(t)x_i(t) + \lambda_i(t)[l_i(t) - \overline{E}_i + a_i(t) + x_i(t)] .$$

The first-order necessary conditions are:

- $\frac{\partial H_i}{\partial a_i} = \frac{\partial C_i(a_i(t))}{\partial a_i(t)} + \lambda_i(t) = 0$,
- $\frac{\partial H_i}{\partial x_i} = P_l(t) + \lambda_i(t) = 0$,
- $-\frac{\partial H_i}{\partial B_i} = \dot{\lambda}(t) - 0.06\lambda(t)$,
- $\dot{B} = \sum_{i=1}^{n}(l_i(t) - \overline{E}_i + a_i(t))$, and
- $B_i(T) \geq 0, \lambda_i(T) \geq 0,$ and $B_i(T)\lambda_i(T) = 0$.

These conditions imply that the optimal level of abatement for each source will be one where marginal abatement costs are equalized across sources. Furthermore, the marginal abatement costs will be equal to the marginal value of banking an additional permit. Also, because $\lambda_i(t)$ represents the marginal present value of a unit of banked emissions for source *i*, the third condition states that the marginal present value of a banked emission is constant for an interior solution; i.e., the number of permits banked and sold will be such that the present value price of permits will equal the present discounted shadow value of banked emissions.

As illustrated in Kling and Rubin (1996) these yield the following two relationships: $\frac{\partial C_i(a_i(t))}{\partial a_i(t)} = P_l(t)$ and $\frac{\dot{P}_l(t)}{P_l(t)} = 0.06$.[48] That is the price of permits will grow at the rate of interest according to Hotelling's rule. Totally differentiating the first-order necessary condition with respect to time, it is possible to determine that:

$$\dot{a}(t) = \frac{rC'_a(a_i(t)) - C''_{at}(a_i(t))}{C''_{aa}(a_i(t))} = 0.06a_i(t).$$

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[48] These assume a non-bounded solution (i.e. one that doe not have binding constraints on abatement levels).

These results can be illustrated using the Sand Creek abatement costs found in Chapter 4. For brevity a two-period model will be used to illustrate the changes in compliance costs and abatement levels (Table 5.1).

Table 5.1: Dynamic Edge-of-Field (EofF) and River Abatement (lbs)

Source	40% Uniform Abatement	Year 1 (EofF)	Year 2 (EofF)	Total River Abatement	$\frac{\dot{a}}{a(t)}$
		Abatement w/ Q or T	Abatement w/ Q or T		
WWTF-J	914	689	731	1,420	0.0600
WWTF-N	3,378	4,670	4,950	9,620	0.0600
Feedlots	11,672	2,506	2,657	5,163	0.0600
MN079A	26,881	32,964	34,941	20,371	0.0600
MN080A	6,369	3,856	4,087	2,383	0.0600
MN081A	4,603	6,570	6,570	3,942	0.0000
MN163A	2,907	1,805	1,913	1,115	0.0600
MN165A	4,093	8,613	8,613	5,168	0.0000
MN169A	2,247	4,562	4,562	2,737	0.0000
MN171A	324	249	264	154	0.0600
MN178A	207	71	75	44	0.0600
MN196A	22,197	20,179	21,390	12,471	0.0600
MN079B	4,199	5,969	5,969	9,312	0.0000
MN080B	985	1,406	1,406	2,193	0.0000
MN081B	745	1,064	1,064	1,660	0.0000
MN163B	675	961	961	1,499	0.0000
MN165B	810	1,702	1,702	2,655	0.0000
MN169B	573	1,165	1,165	1,818	0.0000
MN171B	21	25	25	40	0.0000
MN178B	27	24	26	39	0.0600
MN196B	3,598	5,237	5,237	8,170	0.0000
TOTALS	**97,426**	**104,289**	**108,310**	**91,975**	**0.0385**

This illustration highlights several important features. First, a baseline 40% uniform reduction standard (annual standard) is provided to emphasize the significant changes in abatement quantities at the edge-of-field when sources are allowed to shift abatement efficiently. Second, note that the time derivative of abatement divided by abatement ($\frac{\dot{a}}{a(t)}$) equals 0.06 for the sources that do not have binding abatement constraints. The reason that some of these time derivatives equal zero and that the aggregate $\frac{\dot{a}}{a(t)}$ for the watershed equals 0.04 is that several sources are abating at the maximum amount achievable holding the crop rotation to a corn-soybean rotation. The discrete jump in abatement costs (i.e. due to the non-continuous nature of the abatement cost function, Figure 4.3) once a source moves from the corn-soybean rotation serves as a corner solution when the source seeks to equate marginal abatement costs with permit prices. In this case the price per permit will equal approximately \$45.75 in period one and \$48.50 in period two, which reflects that the permit price is growing at the rate of interest as expected.

The savings in cost when sources are allowed to shift abatement across time are shown below in Table 5.2. The net present static values were calculated by averaging the costs of static regulation (Table 4.16) over two years. The net present dynamic values were calculated by averaging discounted abatement costs for two years under uniform reductions and under permit trading. It can be seen that while sources can reduce abatement costs by shifting abatement efforts into the future, the savings are quite minimal.[49] This indicates that the majority of the savings attributable to a cost-effective regulatory policy (either tradable pollution permits or Pigouvian taxes) derive from the shifting of abatement between sources and not across time. In this deterministic, second-best world it would then appear that there is a strong argument in favor of regulating via tradable pollution permits or effluent fees[50] as compared to a uniform reductions policy, but that the case for intertemporal permits is not as strong.

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[49] One reason for the limited savings earned by trading intertemporally is the fact that many of the nonpoint sources are essentially solving at the corner even in the static case, and therefore are not able to increase abatement in the following years. If the water quality standard were relaxed to 30% reductions, for example, the gains to dynamic regulation would increase.

[50] The efficient Pigouvian tax on emissions would be equal to the permit price in each period.

Table 5.2: Sand Creek Abatement Costs under Dynamic Regulation

Source	Static Cost per Year		Dynamic Cost per Year*		Savings	
	40% Reduction	ETS**	40% Reduction	ETS	40% Reduction	ETS
WWTF-J	26,922	16,278	26,922	16,228	0	50
WWTF-N	54,368	110,111	54,368	110,144	0	-33
Feedlots	1,208,691	59,131	1,208,692	59,070	0	61
MN079A	146,223	233,319	146,223	233,078	0	242
MN080A	70,161	27,293	70,162	27,264	0	29
MN081A	19,176	39,079	19,177	39,079	0	0
MN163A	31,228	12,775	31,229	12,761	0	14
MN165A	8,620	38,166	8,620	38,166	0	0
MN169A	-830	-3,420	-830	-3,420	0	0
MN171A	2,817	1,764	2,817	1,761	0	2
MN178A	4,043	499	4,043	499	0	1
MN196A	162,413	142,425	162,413	142,277	0	148
MN079B	22,843	46,159	22,842	46,158	0	0
MN080B	10,857	22,092	10,857	22,092	0	0
MN081B	3,106	6,333	3,105	6,332	0	0
MN163B	7,256	14,687	7,255	14,688	0	0
MN165B	1,705	7,535	1,705	7,535	0	0
MN169B	-212	-875	-212	-875	0	0
MN171B	181	268	181	269	0	0
MN178B	536	450	537	449	0	1
MN196B	26,325	55,775	26,325	55,775	0	0
TOTALS	**$1,806,431**	**$829,842**	**$1,806,432**	**$829,330**	**$0**	**$512**

* Note that these are net present values and represent the average of two years' abatement costs using a discount rate of 0.06.

** ETS = Emissions Trading System

5.2 Asymmetric Information and Moral Hazard

One criticism of nonpoint permit markets is that emissions and abatement are difficult to monitor and enforce due to the very disperse nature of the nonpoint pollution. This asymmetric information problem can lead to a moral hazard; i.e., farmers may over-report actual abatement efforts (Shortle and Dunn, 1986; Smith and Tomasi, 1995, 1999). It has also been argued that this same difficulty would be manifest in typical command-and-control regulation (Xepapadeas, 1992) and many have examined methods of monitoring and enforcement to deal with this problem (Xepapadeas, 1991; Van Egteren and Weber, 1996; Stranlaund and Dhanda, 1999). It is the objective of this section to examine the effects of cheating when both point and nonpoint phosphorus sources are required to invest in abatement effort.

The cost effectiveness and efficiency in complying with a water quality standard are compared analytically and empirically for an emissions trading system (ETS) and for a uniform reduction mechanism (UR). When polluters do not cheat and abatement costs are heterogeneous, an emissions trading system was shown in Chapter 4 to have a higher cost effectiveness than a standard command-and-control regulatory approach that mandates uniform phosphorus reductions across sources. These gains in cost-effectiveness gains (measured in average costs of abatement) are shown to increase for the Sand Creek when cheating is incorporated. Furthermore, using the estimate of the benefits to pollution abatement from Chapter 4, the welfare implications of cheating will be assessed. It is shown that under certain general conditions the deadweight loss of regulating emissions by uniform reductions also increases with cheating.

Cheating by nonpoint sources shifts the abatement burden onto point sources, which increases total costs of regulation. In addition, the potential to cheat is shown to decrease at higher abatement levels. As a result both cost-effectiveness and net benefits decrease to a greater degree under uniform reductions than under emissions trading. The percentage difference then between the two policies describing the efficiency gains to regulating with emissions trading are 1.5 times greater for cost-effectiveness and more than 3 times greater when measuring deadweight losses. These results indicate that a system of tradable emissions permits to achieve abatement goals for this region should not be discounted based on the argument that asymmetric information will erode the efficiency of such a policy.

5.2.1 Model Setting

This section uses both a static and a two-period model (t = 1, 2) to illustrate the gains to trading and the potential losses associated with asymmetric information. There are n sources ($i = 1, \ldots, n$) that emit phosphorus into a river. Of those sources there are m point sources ($i = 1, \ldots, m$) and n-m nonpoint sources ($i = m+1, \ldots, n$). The regulator has observed historical emissions by sources and given expected weather patterns and can assume that total emissions in the absence of regulation are: $\overline{E} = \sum_{i=1}^{n} \overline{E}_i$. The regulator chooses an environmental standard (*S*) that is a function of historical emissions. The environmental standard can therefore be written as: $S = \alpha T \overline{E}$, where α represents the proportion of historical emissions allowable under the environmental standard and *T* represents the number of years of regulation. To reach this standard the regulator either issues tradable permits (*L*) representing the right to emit phosphorus into the river that are equal in quantity to *S*, or she requires each source to reduce emissions by (1-α)% over the period of regulation.

For point sources, the abatement cost function is given by $C_i(a_i(t))$ where *a* represents the number of pounds (lbs) abated by the source. This function maps the cost of adopting management activities required to achieve *a* lbs of abatement in time, *t*. We assume that emission monitors are already installed on these sources or could be at low cost. The regulator is therefore well aware of point source emissions. For a two-period model we can describe the abatement cost functions for point sources as $C_i(a_i(t))$ for *i* = *1,…,m*. Assume that abatement costs are increasing in abatement at an increasing rate: $C'_a(a_i(t)) > 0$ and $C''_{aa}(a_i(t)) > 0$. Assume also $C'_t(a_i(t)) = 0$,[51] or that the abatement cost functions are not changing over time.

Similarly, for nonpoint sources, the abatement cost function is given by $C_i(a_i(t))$. However, here abatement is a function of two parameters: abatement effort on the extensive margin (*r*) and abatement effort on the intensive margin (*z*).[52] The abatement levels as a function of extensive and intensive efforts can be written as $a_i(t) = f_i(r_i(t), z_i(t))$. Abatement effort on the extensive margin includes practices such as crop choice and tillage practice, and method of fertilizer application. Abatement effort on the intensive margin primarily refers to rate of fertilizer application. The regulator has

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[51] Increasing marginal abatement cost functions over time might correspond to growing populations serviced by wastewater treatment facilities.

[52] See Yiridoe and Weersink (1998) for an empirical discussion of abatement costs on the intensive and extensive margins.

observed (via surveys or direct observation) mean levels of r and z in the past and has mapped emission levels and profits as a function of weather, soil characteristics, r and z for nonpoint sources using a biophysical soils model. Furthermore, given observable data (i.e., weather and soil characteristics) and reported data (i.e., r and z) the regulator can accurately estimate emissions from nonpoint sources. In fact, the regulator can readily observe actual r-abatement efforts. The only parameter that the regulator cannot observe is the farm choice of z. For a two-period model we can describe the abatement cost functions for nonpoint sources as $C_i(a_i(r(t),z(t))$ for $i = m+1, \ldots, n$. Abatement costs are also increasing in abatement at an increasing rate: $C'_a(a_i(r(t),z(t)) > 0$ and $C''_{aa}(a_i(r(t),z(t)) > 0$. Assume also $C'_t(a_i(r(t),z(t)) = 0$[53] or that the abatement cost functions are not changing over time. As shown in Chapter 4, nonpoint abatement is increasing in abatement effort: $a'_r > 0$, $a'_z > 0$ for $i = m+1, \ldots, n$. This implies: $\frac{\partial C_i(a_i(r(t),z(t))}{\partial r} = \frac{\partial C}{\partial a}\frac{\partial a}{\partial r} > 0$ and $\frac{\partial C_i(a_i(r(t),z(t))}{\partial z} = \frac{\partial C}{\partial a}\frac{\partial a}{\partial z} > 0$. Furthermore, because abatement costs are strictly convex it must be that the net effect of increasing levels of intensive and extensive abatement efforts on abatement levels is decreasing. This implies concavity of the abatement production function: $a''_{rr} \leq 0$, $a''_{zz} \leq 0$, and $a''_{rr}a''_{zz} - a''^{2}_{rz} \geq 0$.[54]

5.2.2 Full Information

When sources truthfully report their abatement efforts, it is to say that they do not engage in cheating, i.e., sources will correctly report levels of abatement effort.

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[53] Decreasing marginal abatement cost functions over time might correspond to better seed varieties that respond better to conservation tillage or lower fertilizer applications.

[54] However, to discern the signs of the second derivatives of abatement with respect to intensive and extensive efforts, it is necessary to develop the specific functional form for nonpoint abatement, which may vary depending on the discrete combinations of management practices and soil type. Whether the abatement production function is strictly concave will be investigated below (section 5.2.4).

Two-Period Emission Trading

Under the permit system sources are allowed to bank, borrow, and trade permits subject to the non-negativity constraint on the bank account in the terminal period. Formally, given an endowment of permits, $l_i(t)$, each source will choose abatement levels, $a_i(t)$, permit purchases/sales, $x_i(t)$, in each period to solve the following cost-minimization problem, ($J^{ETS/F}$), where superscript ETS/F indicates an emissions trading system with full information:

$$J^{ETS/F} \equiv \min_{a_i(t),\, x_i(t)} C_i(1) + P_l(1)x_i(1) + \delta C_i(2) + \delta P_l(2)x_i(2)$$

subject to :

(1) $2\overline{E}_i \le l_i(1) + l_i(2) + a_i(1) + a_i(2) + x_i(1) + x_i(2)$,

(2) $\sum_{i=1}^{n} (l_i(1) + l_i(2)) = 2\alpha\overline{E}$,

(3) $\sum_{i=1}^{n} x_i(t) = 0 \ \forall t = 1, 2$ and

(4) $a_i(t) \ge 0 \ \forall\, i = 1,\ldots n$ and $\forall\, t = 1, 2$.

Here $P(t)$ represents the equilibrium price in periods 1 and 2, and δ represents the discount factor. The first constraint (1) essentially requires each source to equate emissions over the two periods with their account of permits.[55] The second constraint (2) describes the water quality standard (i.e. a ($1-\alpha$) reduction in phosphorus emissions). The third constraint (3) constrains permit purchases to equal permit sales for each period, and the fourth constraint (4) constrains abatement to non-negative values.

Given the assumption about the convexity of the abatement cost function we know that the first order Lagrangian conditions for cost minimization are necessary and sufficient. These are:

$$\frac{\partial C_i(1)}{\partial a_i(1)} = \delta \frac{\partial C_i(2)}{\partial a_i(2)} \text{ and}$$

$$P_l(1) = \delta P_l(2).$$

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[55] This is trivially non-negative, but will hold with equality for positive marginal abatement costs (see also Hagem and Westskog, 1998).

The equilibrium price condition, $P_l(1) = \delta P_l(2) = P_l$, allows $J^{ETS/F}$ to be rewritten as ($J^{ETS/F'}$):

$$J^{ETS/F'} \equiv \min_{a_i(t),\,(x_i(1)+x_i(2))} C_i(1) + \delta C_i(2) + P_l(x_i(1) + x_i(2))$$

subject to :

(1) $2\overline{E}_i \leq l_i(1) + l_i(2) + a_i(1) + a_i(2) + (x_i(1) + x_i(2))$,

(2) $\sum_{i=1}^{n} (l_i(1) + l_i(2)) = 2\alpha\overline{E}$,

(3) $\sum_{i=1}^{n} x_i(t) = 0 \ \forall t = 1,2$ and

(4) $a_i(t) \geq 0 \ \forall$ i = 1,...n and $\forall$ t = 1, 2.

Given the assumption about the convexity of the abatement cost function we know that the Lagrangian conditions for cost minimization are necessary and sufficient. These are:

$$\frac{\partial C_i(1)}{\partial a_i(1)} = P_l \text{ and}$$

$$\delta \frac{\partial C_i(2)}{\partial a_i(2)} = P_l.$$

This is the traditional equi-marginal cost principle (Speir et al., 2000) that has been referred to earlier as the motivation for using tradable emission permits to efficiently regulate polluters.

Given that the sum of permit sales/purchases in each period equal zero and that the sum of permits is equal to the environmental standard, we can solve for the cost-minimizing values of $a_i^{ets/f}(t)$ and $x_i^{ets/f}(t)$. Total cost of compliance is the sum of point source costs and nonpoint source costs in each period:

$$TC^{ETS/F} = \sum_{i=1}^{m}[C_i(a_i^{ets/f}(1) + \delta(C_i(a_i^{ets/f}(2))] + \sum_{i=m+1}^{n}[C_i(a_i^{ets/f}(1) + \delta(C_i(a_i^{ets/f}(2))].$$

Uniform Reduction

Under regulation requiring a uniform reduction in emissions by some given percentage over a two-year period, naïve sources will simply solve the following cost-minimization problem, $J^{UR/F}$, where superscript *UR/F* indicates uniform reduction under full information:

$$J^{UR/F} \equiv \min_{\mathrm{a(t)}} (C_i(1) + \delta(C_i(2),$$

$$\text{subject to: } a_i^{ur/f}(1) + a_i^{ur/f}(2) \geq 2(1-\alpha)\overline{E}_i .$$

Given the assumption about the convexity of the abatement cost function we know that the Lagrangian conditions for cost minimization are necessary and sufficient. These are:

$$\frac{\partial C_i(1)}{\partial a_i(1)} = \delta \frac{\partial C_i(2)}{\partial a_i(2)} \text{ and}$$

$$a_i(1) + a_i(2) - 2(1-\alpha)\overline{E}_i = 0.$$

Total cost of compliance is the sum of point source costs and nonpoint source costs in each period:

$$TC^{UR/F} = \sum_{i=1}^{m} [C_i(a_i^{ur/f}(1) + \delta(C_i(a_i^{ur/f}(2))] + \sum_{i=m+1}^{n} [C_i(a_i^{ur/f}(1) + \delta(C_i(a_i^{ur/f}(2))]$$

5.2.3 Asymmetric Information

When we allow sources to behave strategically based on asymmetric information, there is a range of options available to them. It is assumed that point sources do not cheat, because it is too easy for the regulator to catch them and impose punishment. For the same reasons, it is assumed that nonpoint sources do not cheat on the extensive margin. However, the nonpoint sources can cheat on the intensive margin without fear of regulator observation and/or punishment. Solving the emissions trading system and the uniform reduction system allowing for strategic behavior may yield a different level of compliance efficiency as cheating on the intensive nonpoint margin will serve to shift the actual percentage of total abatement towards the point sources. When the point sources have higher abatement costs than the nonpoint sources, the result will be to increase the slope of the total cost (marginal cost) function.

Two-Period Emission Trading

Under the permit system sources are allowed to bank, borrow, and trade permits subject to the non-negativity constraint on the bank account in the terminal period. Formally, given an endowment of permits, $l_i(t)$, each *point* source will choose abatement levels, $a_i(t)$, permit purchases/sales, $x_i(t)$, in each period to solve the following cost-minimization problem, $J^{ETS/A} \equiv J^{ETS/F}$, where the superscript *ETS/A* indicates emissions trading with strategic polluters and asymmetric information.

Due to the strategic nature of *nonpoint* sources, they will not cheat on the extensive margin, but will cheat on the intensive margin. Because the regulator has accurate knowledge of nonpoint abatement cost functions, the strategic nonpoint source will not be able to deviate from full-information, cost-minimizing choices of permit sales/purchases.[56] If they did, the regulator would be able to specifically target those sources with scrutiny. This implies that the nonpoint sources will first solve $J^{ETS/A}$ as under full-information to determine the appropriate level of net permit purchases and sales. They will then report $a_i^{ets/f}(r_i^{ets/f}(t), z_i^{ets/f}(t))$ and $x_i^{ets/f}(t)$ to the regulator taking P_l as given. However, actual abatement levels will reflect cheating on the intensive margin.

A Note on Abatement Cost Functions

To setup the appropriate cost-minimizing problem for the emissions trading system and the uniform reduction system it is necessary to first develop the notion of abatement cost functions under cheating. When the regulator is unable to monitor intensive margin choices (fertilizer rates in the case of the Sand Creek) it essentially enables the polluter to falsely report high abatement efforts on the intensive margin. In essence the cost of investing in intensive abatement efforts falls to zero, while the cost of investing in extensive efforts remains the same. If there were no limit to the amount of abatement achievable under intensive abatement efforts only, it is obvious that the polluter would

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[56] In this case the regulator assumes that the strategic nonpoint source is capable of solving for cost-minimizing levels of abatement and permit transactions.

report $a_i^a(0, z_i^a(t))$, but actually adopt $a_i^a(0,0)$. In this simple case the regulator would be forced to require abatement efforts only on the extensive (observable) margin.[57] In actuality, as developed in Chapter 4, as nonpoint source abatement levels increase it is necessary to combine both intensive and extensive abatement efforts and that extremely high levels of abatement are achievable only with extensive abatement efforts. Therefore the region that is of concern is that corresponding to corn-soybean rotations, when the polluter can choose tillage practice, fertilizer application rate and method.

It is, however, possible to describe how the optimization problem will change under strategic behavior. Let extensive abatement efforts $r \in (0, 4)$, where r = 0 indicates no effort and r = 4 indicates high levels of extensive abatement effort (i.e. simulation (12) and (14)). Similarly, let intensive abatement efforts $z \in (0, 2)$, where z = 0 indicates high levels of fertilizer application and z = 2 indicates low levels of fertilizer application. The amount of abatement achievable under extensive abatement efforts is limited by $a_i(t) \le \overline{E}_i$, i.e. any level of abatement is achievable using only extensive efforts. However, the amount of abatement achievable under intensive efforts is limited by the level of extensive abatement. Let these abatement limits be denoted as follows:

$$0 < a(0, z) < M1$$
$$M1 < a(1, z) < M2$$
$$M2 < a(2, z) < M3$$
$$M3 < a(3, z) < M4$$
$$M4 < a(4, z) < \overline{E}_i$$

Therefore, for abatement levels greater than *M2*, the polluter must choose some combination of abatement practices where extensive efforts are at least as great as r = 2.

Let the cost to adopt one unit of extensive abatement effort be C_r and the cost to adopt one unit of intensive abatement efforts be C_z. To achieve a given level of abatement, $\hat{a}_i$, the nonpoint source will choose some combination of intensive and

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[57] The choice of intensive abatement effort would be free to the polluter, but would not be considered by the regulator in achieving the water quality standard.

extensive abatement efforts in order to minimize costs. Given that $a_i(t) = a_i(r_i(t), z_i(t))$ the relevant cost minimization problem will be:

$$\min_{R(t),z(t)} C_i(r_i(t), z_i(t))$$
$$\text{subject to : } a_i(r_i(t), z_i(t)) \geq \hat{a}_i(t).$$

The Lagrangian for each nonpoint source$_i$ for this cost-minimization problem is:

$$L_i(r_i(t), z_i(t), \lambda) = C_i(r_i(t), z_i(t)) - \lambda_i(a_i(r_i(t), z_i(t)) - \hat{a}_i(t)).$$

The first-order conditions that characterize a solution are:

- $C'_r(r_i(t), z_i(t)) \leq \lambda_i^* \dfrac{\partial a_i(r_i(t), z_i(t))}{\partial r_i(t)}$ and $r_i^*(t)[C'_r(r_i(t), z_i(t)) - \lambda_i^* \dfrac{\partial a_i(r_i(t), z_i(t))}{\partial r_i(t)}] = 0.$

- $C'_z(r_i(t), z_i(t)) \leq \lambda_i^* \dfrac{\partial a_i(r_i(t), z_i(t))}{\partial z_i(t)}$ and $z_i^*(t)[C'_z(r_i(t), z_i(t)) - \lambda_i^* \dfrac{\partial a_i(r_i(t), z_i(t))}{\partial z_i(t)}] = 0.$

- $a_i(r_i^*(t), z_i^*(t)) - \hat{a}_i(t) \geq 0$ and $\lambda_i^*[a_i(r_i^*(t), z_i^*(t)) - \hat{a}_i(t)] = 0.$

Given that cheating on the extensive margin implies that the effectively $C_z=0$. Assuming perfect competition, the derivative of the abatement production function with respect to abatement efforts each margin will be equal to the price of the input divided by the price of the output, which will now equal zero. Given the above first-order conditions, the marginal effect of extensive abatement effort on cost will now be zero. Each source will choose then the maximum $z_i(t)$ possible and the minimum $r_i(t)$ possible to achieve $\hat{a}_i$.

Returning to Two-Period Emission Trading

The nonpoint source will then seek to achieve $a_i^{ets/f}(r_i^{ets/f}(t), z_i^{ets/f}(t))$ using the maximum amount of intensive abatement effort as possible as the cost of adopting these efforts is essentially zero, and similarly the minimum amount of extensive abatement effort as possible, having positive costs. This may result in non-optimal choices of abatement efforts and therefore may not fall on the abatement cost frontier described in

Chapter 3. The nonpoint source will thus report $a_i^{ets/f}(r_i^{ets/a}(t), z_i^{ets/a}(t))$, but will actually adopt $a_i^{ets/a}(r_i^{ets/a}(t), 0)$.

From the discussion of abatement effort margins above, it is clear that this abatement strategy will result in

$r_i^a(t) = 0$ and $z_i^a(t) = 0$ if $0 < a_i^f(r_i^f(t), z_i^f(t)) < M1$,

$r_i^a(t) = 1$ and $z_i^a(t) = 0$ if $M1 < a_i^f(r_i^f(t), z_i^f(t)) < M2$,

$r_i^a(t) = 2$ and $z_i^a(t) = 0$ if $M2 < a_i^f(r_i^f(t), z_i^f(t)) < M3$,

$r_i^a(t) = 3$ and $z_i^a(t) = 0$ if $M3 < a_i^f(r_i^f(t), z_i^f(t)) < M4$, and

$r_i^a(t) = 4$ and $z_i^a(t) = 0$ if $M4 < a_i^f(r_i^f(t), z_i^f(t)) < \overline{E}_i$.

Given this definition of cheating[58] the permit transactions and resulting price in both periods will be identical to the perfect information scenario. Total cost of compliance is given by:

$$TC^{ETS/A} = \sum_{i=1}^{m}[C_i(a_i^{ets/f}(1) + \delta(C_i(a_i^{ets/f}(2))] + \sum_{i=m+1}^{n}[C_i(a_i^{ets/a}(1) + \delta(C_i(a_i^{ets/a}(2))]$$

Uniform Reduction

Under command-and-control regulation requiring a reduction in emissions by some given percentage over a two-year period, sources will solve as before the cost-minimization problem, $J^{UR/A} \equiv J^{UR/F}$. As before, strategic nonpoint sources will[59] seek to achieve $a_i^{ur/f}(r_i^{ur/f}(t), z_i^{ur/f}(t))$ using the maximum amount of intensive abatement effort as possible and the minimum amount of extensive abatement effort as possible. Once again this may result in non-optimal choices of abatement efforts and therefore may not fall on the abatement cost frontier. The nonpoint source will thus report $a_i^{ur/f}(r_i^{ur/a}(t), z_i^{ur/a}(t))$,

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[58] Cheating under this definition assumes that the regulator and polluters can determine ex-ante what the optimal, naïve solution is. This implies that if a nonpoint source proposes abatement efforts or permit transactions that stray from the naïve levels, the regulator will impose some sort of sanction. This sanction could involve stringent monitoring and penalties for violating reported abatement levels. If this were not the case the sources could also cheat on permit purchases and sales.

[59] I think it appropriate here to note that "will" does not imply that these farmers would cheat in reality; it just implies that they have incentives to cheat when behaving optimally given these assumptions.

but will actually adopt $a_i^{ur/a}(r_i^{ur/a}(t),0)$. Similarly, from the discussion of abatement effort margins above, it is clear that this abatement strategy will result in

$$
\begin{array}{lll}
r_i^a(t) = 0 \text{ and } z_i^a(t) = 0 & \text{if} & 0 < a_i^f(r_i^f(t), z_i^f(t)) < M1, \\
r_i^a(t) = 1 \text{ and } z_i^a(t) = 0 & \text{if} & M1 < a_i^f(r_i^f(t), z_i^f(t)) < M2, \\
r_i^a(t) = 2 \text{ and } z_i^a(t) = 0 & \text{if} & M2 < a_i^f(r_i^f(t), z_i^f(t)) < M3, \\
r_i^a(t) = 3 \text{ and } z_i^a(t) = 0 & \text{if} & M3 < a_i^f(r_i^f(t), z_i^f(t)) < M4, \text{ and} \\
r_i^a(t) = 4 \text{ and } z_i^a(t) = 0 & \text{if} & M4 < a_i^f(r_i^f(t), z_i^f(t)) < \overline{E}_i .
\end{array}
$$

Total cost of compliance is given by:

$$TC^{UR/A} = \sum_{i=1}^{m}[C_i(a_i^{ur/f}(1) + \delta(C_i(a_i^{ur/f}(2))] + \sum_{i=m+1}^{n}[C_i(a_i^{ur/a}(1) + \delta(C_i(a_i^{ur/a}(2))].$$

5.2.4. Efficiency Comparisons

As discussed in Chapter 4, when examining policies aimed at achieving an environmental standard it is important to define concepts, which enable comparisons amongst these policies. An *efficient* policy would maximize the net present benefits to society of reducing pollution. This entails maximizing the discounted distance between the total benefit function and the total cost function for the appropriate years. This will occur with well-behaved total benefits and total cost functions when the discounted marginal benefits of pollution reduction are equal to the discounted marginal cost of reducing an extra unit of pollution. For one period this is simply the intersection of the demand curve for pollution reduction with the supply curve for pollution reduction (i.e., when the slope of the total benefit function equals the slope of total cost function).

It is difficult for a regulatory agency to correctly assess the actual benefits to pollution reduction or to assess the cost to reduce pollution, making the task of choosing an efficient environmental standard nearly impossible. An environmental standard is often chosen based on factors such as the health of the affected human, animal and resource populations to determine a minimum standard for the pollutant (Lake Standards

Subcommittee, 1992). Once the standard has been chosen the generally accepted method for comparing policy alternatives is *cost effectiveness.*

Cost Effectiveness

One means to compare the cost effectiveness of regulation is to examine the average cost per pound of abatement under a particular regulation. Consider first a single period, a single point source (*m*) with convex abatement cost function, $C_m(a_m)$, and a single nonpoint source (*n*) with convex abatement cost function, $C_n(a_n)$. The regulator either mandates a uniform reduction of $S_i = \alpha(E_i)$ for $i = m$ and n or distributes permits to each source equal to S_i and allows trading of these permits. Furthermore, assume that the point source is a net buyer of permits and the nonpoint source is net seller of permits (see example in section 2.1.1). Given these definitions and assumptions the properties of the abatement efficiencies can be developed. Let average cost of abatement be given by: $ACA \equiv TC/TA$ (where TA represents total abatement). The gains (losses) in cost effectiveness due to emissions trading (*CE*) can then be defined as the percentage difference between average abatement costs: $CE^{F,A} \equiv (ACA^{UR/F,A} - ACA^{ETS/F,A})/ACA^{ETS/F,A}$, where F and A refer to full and asymmetric information respectively.

If sources have heterogeneous abatement costs (i.e., $C_m(a_m) \neq C_n(a_n)$) then regulation, which allows sources to shift emissions between sources and time periods, has compliance costs equal to or less than a uniform reduction policy (i.e., $CE^F \geq 0$). This follows directly from the intuitive reasoning behind permit markets in general: as long as there are heterogenous abatement cost functions, there will be incentives under a permit system to trade in order to minimize costs (Baumol and Oates, 1989). As stated earlier these trades will seek to equalize the net present value of marginal abatement costs across sources and periods.

When cheating occurs, it is much more difficult to determine analytic properties of cost effectiveness and potential gains to emissions trading. For example, it is difficult to know to what degree CE^F is greater/less than CE^A. A movement from $z^n(t) > 0$ to $z^a(t) = 0$ under cheating will cause TC and TA to fall deviating from the environmental standard. The effect on average abatement costs and efficiency depends on the relative magnitude of these changes. To explore this further it is illuminative to re-examine the shape of the abatement production function once again. Consider the three cases of interest: (A) $\frac{\partial^2 a_i(r(t), z(t))}{\partial z(t)^2} > 0$ (the marginal effect on abatement increases with intensive margin efforts at an increasing rate); (B) $\frac{\partial^2 a_i(r(t), z(t))}{\partial z(t)^2} = 0$ (the marginal effect on abatement increases with intensive margin efforts at constant rate); and (C) $\frac{\partial^2 a_i(r(t), z(t))}{\partial z(t)^2} < 0$ (the marginal effect on abatement increases with intensive margin efforts at a decreasing rate). These cases can be thought of in a Cobb-Douglas framework for the production of abatement given r and z as inputs, where case (A) corresponds to the coefficient of z being greater than one, case (B) corresponding to the coefficient of z being equal to one, and case (C) corresponding to the coefficient of z being less than one. It should be noted under the previous assumptions of convex abatement costs and concave abatement production that case (A) will not occur.[60]

Proposition 1

If the potential for cheating is not changing at different levels of abatement (i.e., $a_n^{ets/a}(r_n^a(t), z_n^a(t)) - a_n^{ets/f}(r_n^f(t), z_n^f(t)) = a_n^{ur/a}(r_n^a(t), z_n^a(t)) - a_n^{ur/f}(r_n^f(t), z_n^f(t))$) then the percentage difference between abatement costs under uniform reductions and permit trading increases with cheating, or $CE^F < CE^A$.

That is, if sources with typical convex abatement cost functions are engaged in permit trading given that at higher levels of abatement the amount of potential cheating is constant (i.e., case (B)), then the advantage due to employing a system of tradable

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[60] That said it should be noted that in Chapter 4, it was shown MN169 abatement costs on the intensive margin are not concave.

emissions permits compared to a uniform reductions policy will increase with strategic polluters.[61] One disappointing feature of this proposition stems from the definition of CE. There may exist some analytical relationship between CE^F and CE^A, but the fact remains that these measures are derived from differing levels of total abatement. Given the convex nature of abatement costs, a more meaningful comparison of abatement efficiencies would be to compare the average abatement costs for the regulatory mechanisms evaluated at a fixed level of abatement. Developing general analytical properties of these abatement efficiencies would require rather strict assumptions about the quantities of emissions and abatement cost functions. Therefore, an empirical analysis comparing cost effectiveness when total abatement is held constant will be developed for the Sand Creek.

Net Benefits

As mentioned earlier, if the marginal benefit function is known (the inverse demand function for environmental amelioration) and the marginal cost function is known (the supply function for environmental amelioration) it is possible to determine the efficient level of pollution abatement and the deadweight loss due to deviations from that standard. For the above case, assume that the standard ($S^{F,A}$) is chosen such that the marginal benefits of abatement equal the marginal cost of abatement for the emissions trading system (under full or asymmetric information). Net benefits under a regulatory mechanism are defined as the sum of consumer surplus and producer surplus bounded by the environmental standard (S). As is shown above the emissions trading system is more cost effective than a uniform reduction system and therefore, the gain in efficiency due to emissions trading can then be defined as the difference between net benefits under a uniform reductions and emissions trading. This difference is simply the deadweight loss (DWL) of choosing S for the uniform reductions system (see Figure 5.1). The relationship of interest for this section is then whether the measure of deadweight loss increases or decreases when polluters act in a strategic manner.

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[61] This relationship is further developed in the proof found in the appendix.

Proposition 2

Let the total benefit function and the total cost function as a function be denoted:

$$TB = TB(a) \text{ and } TC = TC(a).$$

Assume that $TB' > 0$, TB'' is a negative constant, $TC' > 0$, and TC'' is a positive constant. Assume also that $\frac{\partial^2 a_i^{f,a}(r(t), z(t))}{\partial z(t)^2} = 0$. A sufficient condition for $DWL^F < DWL^A$ is

$$(\frac{\partial^2 TC^{ETS/A}}{\partial a^2})^{-1} - (\frac{\partial^2 TC^{UR/A}}{\partial a^2})^{-1} \geq (\frac{\partial^2 TC^{ETS/F}}{\partial a^2})^{-1} - (\frac{\partial^2 TC^{UR/F}}{\partial a^2})^{-1}.$$

This proposition restates that the advantage to regulating with tradable emissions permits compared to uniform reductions will increase with cheating when the difference in the inverse slopes of the supply functions is greater with strategic behavior than with naïve behavior.[62]

5.2.5 Application to Sand Creek

For this section a stylized model will be developed using data gathered from the Sand Creek sub-watershed of the Lower Minnesota River Basin. As detailed earlier abatement cost functions for the point and nonpoint sources were estimated using stochastic frontier analysis. Abatement costs were found to be heterogeneous and convex in abatement, however the second derivative of nonpoint abatement with respect to intensive marginal efforts was found to be discontinuous between discrete management choices and soils. A weighted average of soils for the watershed reveals that case (B) best describes the effect of intensive margin changes. This indicates that both the cost effectiveness and the deadweight-loss measure of gains to emissions trading should increase with cheating.

The aggregate total cost and marginal cost functions for the four scenarios are presented in Table 5.3. The lowest total and marginal costs for a given abatement levels are found under an emissions trading system with naïve polluters, the highest costs are under uniform reductions with strategic polluters.

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[62] This will hold under certain conditions (see proof in the appendix).

Table 5.3: Estimated Cost Functions for Sand Creek Abatement[63]

Mechanism / Behavior*	Total Cost Function	Marginal Costs
UR/F	$TC^{UR/N} = 0.000721(a)^2$	$MC^{UR/N} = 0.001442(a)$
ETS/F	$TC^{ETS/N} = 0.000441(a)^2$	$MC^{ETS/N} = 0.000882(a)$
UR/A	$TC^{UR/S} = 0.001725(a)^2$	$MC^{UR/S} = 0.003450(a)$
ETS/A	$TC^{ETS/S} = 0.000611(a)^2$	$MC^{ETS/S} = 0.001222(a)$

* UR = uniform reductions; ETS = emissions trading system; F = full information; A = asymmetric information.

Cost Effectiveness

An environmental standard of 40% was chosen and the average cost of abatement was calculated using the values from Table 5.3. From these, values for CE^F and CE^A were determined holding the standard constant, showing that with strategic behavior efficiency gains attributable to using an emissions trading system increase from 63% to 238% (see Table 5.4).

Table 5.4: Cost Effectiveness Measures

Mechanism – Behavior*	Average Cost of Abatement ($/lb)	Cost Effectiveness Gains to Emissions Trading	Total Cost of Abating 46,000 lbs of Phosphorus
UR/F	33.17	0.634921	$1,525,636
ETS/F	20.29		$933,156
UR/A	79.35	2.382353	$3,650,100
ETS/A	23.46		$1,079,160

* UR = uniform reductions; ETS = emissions trading system; F = full information; A = asymmetric information.

For a typical 343-acre farm in this region the cost per year per acre to comply with the 40% phosphorus abatement regulation would be $3.58 and $1.97 respectively for

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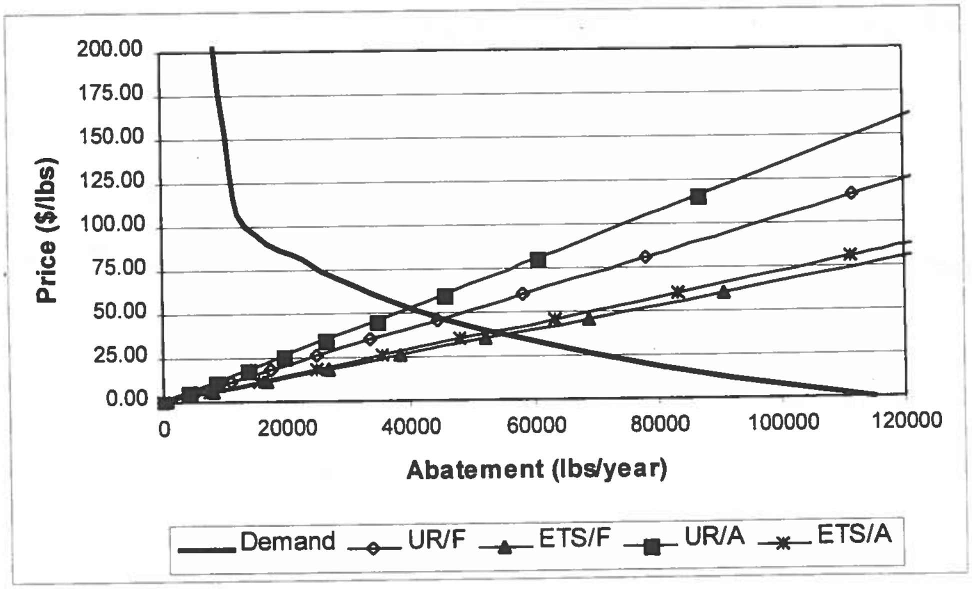
[63] These functions represent OLS estimates of varying levels of required abatement. Actual aggregate costs may deviate slightly from the predicted aggregate costs..

uniform reduction and emissions trading with naïve polluters.[64] However, because nonpoint sources maintain trade at naïve levels and will abate at strategic levels, the cost per year per acre to comply with the 40% phosphorus abatement regulation for a typical farm will be $0.24 and $3.12 assuming strategic behavior. The large difference is due to the fact that at high levels of abatement (i.e. when nonpoint sources trade with point sources) the ability to cheat decreases. At relatively low levels of abatement (i.e. under a policy of uniform reductions) nonpoint sources are able misrepresent abatement choices to a greater extent resulting in substantially low abatement costs.

Efficiency

Using the estimate of benefits to abatement (Chapter 4), developed from Mathews et al. (2000), it is possible to illustrate efficient levels of abatement given the total cost functions estimated above. Below can be seen how the efficient level of abatement will change depending on the relevant regulatory regime.

Figure 5.1: Marginal Benefits and Costs for Phosphorus Abatement



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[64] It should be noted that these values have been calculated assuming that the 40% abatement level is reached. To reach this level with strategic polluters it would be necessary for the regulator to increase the stated water quality standard so that after cheating occurs, the net total abatement would effectively achieve a 40% emissions reductions level.

The efficient level of abatement and associated costs given the aforementioned regulatory scenarios are presented below.

Table 5.5: Efficient Level of Phosphorus Abatement

Mechanism / Behavior*	Efficient Level of Abatement (lbs/year)	Total Cost of Abatement
UR/F	38,290.98	$1,057,130
ETS/F	48,799.54	$1,050,195
UR/A	23,258.83	$933,179
ETS/A	41,690.35	$1,061,970

* UR = uniform reductions; ETS = emissions trading system; F = full information; A = asymmetric information.

Using the slopes of the marginal cost functions from Table 5.3, the sufficient condition for proposition 2 is satisfied (the difference of the inverse slopes for strategic polluters is 528.48 lbs/acre and is 440.31 lbs/acre for naïve polluters). The resulting deadweight losses should indicate that efficiency gains from emissions trading regulation increase when polluters behave in a strategic manner. In fact the deadweight loss values are five times greater for strategic polluters (Table 5.6).

Table 5.6: Measures of Abatement Efficiency

Mechanism / Behavior*	Efficient Level of Abatement	Environmental Standard (*S*)	Deadweight Loss	Difference
UR/F	38,291 (33.3%)	48,800 lbs/year	$146,170	503%
ETS/F	48,800 (42.4%)			
UR/A	23,259 (20.2%)	41,690 lbs/year	$882,129	
ETS/A	41,690 (36.3%)			

* UR = uniform reductions; ETS = emissions trading system; F = full information; A = asymmetric information.

Therefore, the moral hazard problem marginally affects the cost-effective and efficient solutions when sources were allowed to trade emissions permits. The decrease in cost effectiveness due to cheating is \$3.17 per pound of abatement, or a 15% decrease in cost-effectiveness. The deadweight loss due to cheating was \$59,700, or 5.6%. The gains to regulating phosphorus emissions by using tradable emissions permits compared to a uniform reductions policy was 63% and 238% in cost effectiveness (under naïve and strategic behavior, respectively) and 13.9% and 83% in efficiency (under naïve and strategic behavior, respectively).

The following rubric (Table 5.7) compares deadweight losses under the four scenarios. The first-best efficient solution results in total abatement costs of \$1,050,195 (see Table 5.5). Table 5.7 reveals that the losses due to cheating under a system of tradable permits are 5.7% of the first-best efficient abatement costs, which are much less than either outcome using uniform reductions.

Table 5.7: Deadweight Loss Summary

	Uniform Reductions	**Emission Trading System**
Full Information	\$146,170 (13.9%)	-
Asymmetric Information	\$704,566 (67%)	\$59,700 (5.7%)

One question remaining is whether effluent fees and non-tradable quotas result in the same abatement levels and aggregate costs as do those found under the emission trading scenarios. The effluent fee set by the regulator will be such that the marginal cost of abatement is equal to the marginal benefit to abatement. This will be equivalent to the permit price. Faced with this price sources will equate the marginal cost of abatement with the permit price, given that the effective price of extensive abatement effort under cheating is zero. As before each nonpoint source will minimize extensive abatement efforts and will maximize intensive abatement efforts to report the efficient level of abatement, on which the regulator will charge the fee. Similarly with non-tradable quotas the nonpoint source given a mandated level of abatement will report efforts that achieve this level, but will not adopt the reported intensive abatement efforts. In both cases the resulting aggregate abatement costs will be equivalent to that found under a tradable permits.

Second-Best Behavior

Given these losses it is logical that the regulatory agency would assume that nonpoint sources would behave strategically. While it is not the intention of this thesis to forward mechanism-design solutions that might enable the regulator to induce first-best behavior, it is interesting to look at two simple alternative permit trading systems.

- *No Fertilizer (NF)*

The first system does not allow credit to nonpoint sources for adopting fertilizer abatement practices. That is to say, nonpoint sources are given their endowment of permits as before; they can buy or sell their permits; but they can only claim abatement efforts on the extensive margin[65] (i.e., practices observable to the regulator) when reporting to the regulator that their permit holdings equal their expected emissions.

- *No Intensive Management (NIM)*

The second system does not allow credit to nonpoint sources for adopting any intensive abatement practices. That is to say, nonpoint sources can only report extensive management practices when meeting permit and emissions obligations under the regulation.

These two systems can be compared to the full-information trading system discussed earlier (ETS/F) for the efficient level of abatement, 42.45%. These costs are noted below in Table 5.8.

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[65] Also includes the ability to choose some intensive management practices, such as the use of broadcast or incorporated fertilizer application.

Table 5.8: Abatement Costs Under Different Trading Systems

SOURCE	ETS/N	ETS/NF	ETS/NIM
WWTF-J	$20,519	$24,543	$173,165
WWTF-N	$138,811	$166,034	$349,699
Feedlots	$74,535	$89,153	$1,579,714
MN079A	$294,102	$272,715	$72,424
MN080A	$34,403	$41,150	$89,627
MN081A	$40,217	$35,928	$9,930
MN163A	$16,103	$19,260	$35,146
MN165A	$39,278	$34,190	$10,847
MN169A	-$3,520	-$3,058	-$704
MN171A	$2,222	$2,658	$2,082
MN178A	$629	$753	$4,354
MN196A	$179,527	$214,736	$117,942
MN079B	$47,503	$42,603	$11,314
MN080B	$22,735	$20,479	$13,865
MN081B	$6,517	$5,822	$1,609
MN163B	$15,115	$13,627	$8,163
MN165B	$7,754	$6,750	$2,141
MN169B	-$900	-$782	-$180
MN171B	$276	$244	$137
MN178B	$567	$678	$580
MN196B	$57,400	$47,976	$19,224
TOTALS	**$993,794**	**$1,035,459**	**$2,501,076**

By employing "Second-Best" emissions trading systems, Table 5.8 shows that the burden to abate falls more heavily on point sources. The intermediate system (ETS/NF), which does not give farmers credit for reducing fertilizer applications, has aggregate abatement costs that are 4.2% greater than the full-information scenario (ETS/F), but is still 32% cheaper than a full-information uniform reductions policy (UR/F). Aggregate costs do rise significantly under the more restrictive ETS/NIP system, which does not credit farmers for fertilizer rate or application method abatement practices. The total cost to achieve a 42.45% reduction in phosphorus emissions using an ETS/NIP is more than twice the cost of the full-information emissions trading system.

The aggregate costs under the two alternative trading systems can be determined for various levels of desired abatement. These aggregate cost observations can then be used as before to determine aggregate watershed abatement cost functions. The aggregate cost functions can then be used to develop welfare measures that reflect the benefits function derived in Chapter 4.

Table 5.9: Estimated Cost Functions for Emissions Trading Systems

Mechanism / Behavior*	Total Cost Function	Marginal Cost Function	Deadweight Losses
ETS/F	$0.000441(a)^2$	$0.000882(a)$	-
ETS/NF	$0.000461(a)^2$	$0.000922(a)$	$47,629
ETS/NIM	$0.001242(a)^2$	$0.002484(a)$	$1,907,533

* ETS = emissions trading system; F = full information; NF = no fertilizer; NIM = no intensive management.

The welfare losses to a slightly more restrictive trading system (i.e., one that does not give credit to farmers for adopting a lower rate of fertilizer) are quite modest, being less than 4.8% of total abatement costs. The reason for this result is simply that in general the most efficient choice of abatement management practices concerns the method of fertilizer application and the choice of tillage regime. The gains to fertilizer rate abatement efforts are marginal in abatement levels, but costly in foregone revenues. The welfare losses when emissions trading exclude intensive management choices are quite dramatic. This indicates that if the method of fertilizer application is not known, losses in welfare due to cheating may be severe, but also that the gains to regulators in knowing this information are quite large.

Dynamic Efficiency

Up to this point the empirical application has focused on static measures of efficiency. There are some interesting features of the dynamic model that should be explained as well. First, abatement effort with naïve polluters will be shifted to later periods such that the discounted abatement costs are equalized across time, abatement constraints permitting. The analysis of the above scenarios will only change marginally. When polluters are constrained to maintain permit trading levels and prices to avoid detection by the regulator as in the above analysis, the cheating involved is somewhat passive. As sources can shift abatement (in either uniform reductions or emissions trading) to later periods, the effect of this passive form of cheating will be to decrease cheating potential in later periods when case C holds (i.e., $\frac{\partial^2 a_i^{n,s}(r(t),z(t))}{\partial z(t)^2} < 0$) and to increase cheating potential in earlier. The marginal cost of abatement will change accordingly; i.e. in case C, marginal costs of abatement will approach naïve marginal costs over time.

Chapter 6

Summary and Conclusions

6.1 Thesis Objectives

This thesis investigates water quality and mechanisms for restricting agricultural, nonpoint phosphorus emissions. Phosphorus hitherto has not been commonly considered as a regulated pollutant in rivers (North American Lake Management Society, 1992), however a return to certain provisions in the Clean Water Act in recent water quality legislation has necessitated a re-examination of phosphorus emissions (MPCA, 2000). Phosphorus is the limiting nutrient for aquatic plant growth (Sutcliffe and Jones, 1992). High levels of phosphorus in rivers and lakes can generate excessive blue-green algae growth, which is called eutrophication (see graphics below). Eutrophication reduces water clarity, makes water unsuitable for swimming or other recreational activities (Mathews, 1998; McCann, 1998); it can significantly increase drinking water production costs and water cooling costs (Vandevelde and Molo, 1992); and it can severely affect the biologically available oxygen necessary for other aquatic species (MPCA, 2000; Reynolds, 1992).

Figure 6.1: Minnesota River Blue-Green Algae (Eutrophication)

Source: MPCA (2000).

This water quality aberration has been noted in both the Mississippi River (most notably in Lake Pepin, a popular water recreation area on the Mississippi River) and the Minnesota River, a tributary. The Minnesota River Basin encompasses approximately 10 million acres and hosts a population of approximately 700,000 in Central and Southern Minnesota before joining and depositing its phosphorus load into the Mississippi River in Saint Paul, Minnesota. The majority of the region is involved with agriculture, contributing about 50% of the state's corn and soybean production and hosting more than 20% and 40% of beef and hog production respectively. The Minnesota River has also been classified as one of America's most endangered rivers due to agricultural runoff (American Rivers, 2000). Contributions of sediment, nitrogen, and phosphorus by the Minnesota River to the Mississippi River have been linked to severe eutrophication and hypoxia problems downstream (USEPA, 1997). It should come as not surprise then that the poor water quality standards found in the Minnesota River, classified as one of America's most polluted rivers, have been linked to anthropogenic inputs of phosphorus into the river. Principally, these inputs include discharges from wastewater facilities and those arising from crop and livestock production in the region.

The question facing Minnesota's policymakers, then, is "What is the best way to regulate phosphorus emissions into the Minnesota River?" Implicit in this question are the related questions: "How much will it cost to reduce phosphorus emissions into the

Minnesota River?" and "How much damage do phosphorus emissions actually cause?" This thesis investigates the theoretical and empirical issues that surround how one might answer these questions. An empirical example is developed for the Sand Creek, a sub-watershed of the Minnesota River to illustrate how one might estimate phosphorus abatement and benefit functions and how one might compare different regulatory mechanisms to achieve the desired level of abatement.

As noted by many authors in this field, the importance of using multi-disciplinary analysis to investigate these issues should not be discounted. In doing so this thesis provides several additions to the literature examining agricultural nonpoint pollution. This thesis uses the most appropriate biophysical, water table management model to estimate the effects of phosphorus best management practices. This model is relatively new, and has not been used expressly for the purpose of accounting for phosphorus. This thesis provides a timely and relevant application of the Agricultural Drainage and Pesticide Transport (ADAPT) model. These results generated from the modeling exercise are then used to develop spatially heterogeneous, abatement cost functions for agricultural nonpoint sources of phosphorus. These cost functions are particularly useful tools for policymakers for comparing the economic effects of targeting pollution reduction on agricultural lands. Empirical estimates of phosphorus best management practices and their costs have previously focused on either the intensive margin or extensive margin. This thesis explicitly models both margins and incorporates the marginal effects into an abatement cost function. By considering management practices on both margins, this thesis provides a relatively new means to examine how different policies and nonpoint behavior may result in sub-optimal abatement practices due to the related problems of asymmetric information and moral hazard. Furthermore, the econometric estimation of these functions account for potential modeling bias in the analysis via the use of frontier analysis. This is a new application of frontier analysis techniques, which helps to avoid the possibility of upwardly biasing the abatement cost functions through the inclusion of redundant simulations. Lastly, in light of recently passed federal water-quality legislation[66] and the adverse water quality in the Minnesota River, the methodology and empirical examples in this thesis may assist Minnesota water-quality policymakers as they begin to grapple with the daunting task of reducing phosphorus emissions in the Minnesota River by more than 40% (MPCA, 2000).

6.2 Summary of Methodology: Integrated Analysis

In order to address the questions raised above, it was necessary to develop an integrated biophysical and economic methodology that would enable meaningful analysis of the target region, the Sand Creek. This methodology linked a water table management model to an econometric estimation technique in order to generate the relevant abatement cost functions for nonpoint, agricultural sources of phosphorus emissions. The field-scale model that is most useful for tile-drained soils of the Upper Midwest is the Agricultural Drainage and Pesticide Transport model (ADAPT) due to its ability to account for subsoil drainage systems.

To estimate current levels of nonpoint source loadings ADAPT requires a variety of data: weather, soil, slope, and parameters which characterize farming practices. These data sources are used to develop the four ADAPT parameter files: hydrology, erosion, nutrient and pesticide. The parameter files are used in conjunction with historic weather (daily temperature and rainfall) observations to estimate nutrient, sediment, and pesticide emissions from each of the representative farm units on a daily, monthly, or annual basis. Each ADAPT simulation generates estimated average phosphorus emissions per acre, which can then be linked to the average costs per acre of adopting that practice given input and output prices. To achieve varying degrees of phosphorus abatement a farm can choose between extensive and intensive management practices: crop rotation, amount of nutrients applied as fertilizer, manner by which that fertilizer is applied, or residue management practices.

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[66] The proposed total maximum daily load (TMDL) rules require states to develop water quality implementation plans for impaired waters. These must include a means to achieve target TMDLs, which include contributions from point and nonpoint sources and a timeline to reach the target goals.

These simulated observations can be used to estimate an abatement cost function in dollars per pound of phosphorus abated. This function maps the cost-minimizing choice of abatement effort for each soil map unit necessary to achieve any desired abatement level. This follows Montgomery's (1972) general framework for examining cost functions under regulation. Similar empirical examples include: Weinberg et al. (1993) for salination, Yiridoe and Weersink (1998) for groundwater nitrogen, and Westra (1999) for phosphorus. Similar to Yiridoe and Weersink (1998), the abatement effort to achieve the required level of phosphorus reduction can be described by abatement effort on the extensive margin and abatement effort on the intensive margin. Abatement effort on the extensive margin includes practices such as crop choice and tillage practice. Abatement effort on the intensive margin refers to method and rate of fertilizer application.

As noted earlier, given a functional form, the stochastic frontier analysis determines the best fitting convex shell for the observations. The distance between the data points and the shell are indicative of the level of inefficiency that observation has in relationship to the frontier. However, making the assumption of cost-minimizing agents, we would expect to see actual abatement regimes on the frontier. The simulated points in the interior will be useful for determining potential deviations from cost-minimization (e.g., as in moral hazard - Chapter 5). This is the strength in using a frontier analysis as opposed to other estimation techniques such as OLS. Although OLS will minimize the squared deviation of observations (simulated abatement cost and abatement levels under alternative management regimes) from the fit abatement cost function, it may be skewed due to redundant combinations of intensive and extensive abatement efforts, perhaps due to topographical features, that would not occur in actuality. To avoid this possible pitfall when using simulated data, a frontier analysis can estimate a convex production (or abatement) set that will describe the most efficient border for the function.

Before using these estimations for policy analysis it is necessary to account for the spatial distribution of the nonpoint sources. The marginal damage of a pound of phosphorus emitted from a field that is distant from a stream will be less than that from a field adjacent to the stream. This thesis incorporates spatial heterogeneity in phosphorus emissions by calibrating the appropriate sediment delivery ratio, based on distance, slopes, crop residue, and tile drains, to actual water quality observations. These sediment delivery ratios describe the percentage of edge-of-field emissions that arrive via water-born transport channels to the watershed outlet. The effect of the delivery ratio will be to shift the abatement cost curves upwards.

6.3 Summary of Regulatory Mechanisms

In Chapter 2, a discussion of mechanisms for regulating pollution was provided to illustrate how efficient levels and methods of regulation are determined and compared. Specifically, this thesis examined the use of tradable emissions permits to regulate phosphorus emissions in a sub-watershed of the Minnesota River. Tradable emissions permits allow the regulator to simultaneously control point and nonpoint sources of phosphorus emissions. In addition tradable emissions permits can be tailored to both spatial and temporal qualities particular to a given region. This is one advantage that permits have over the use of effluent fees, which prove somewhat unwieldy with hetrogenous spatial and temporal dimensions (Flemming, 1996).

Both the tradable permit mechanism and the effluent fee mechanism for regulating phosphorus emissions forwarded in this thesis was shown to exhibit significant efficiency gains over traditional command-and-control (uniform reduction) policies for phosphorus abatement. When comparing the costs of restricting emissions to 60% of current levels, it was shown in Chapter 4 that targeted nonpoint regulation (whether is be price or quantity based) is 31% more efficient than non-targeted (i.e. uniform reductions) nonpoint regulation. The inclusion of point sources in this comparison reveals that abatement is 54% less costly with targeted regulation when compared to non-targeted regulation. This indicates that there are efficiency gains to regulating both point and nonpoint sources simultaneously.

It was also shown that although similar abatement levels can be reached at identical aggregate abatement costs under a targeted, command-and-control policy with mandated abatement levels, or with tradable pollution permits, or with an effluent fee, phosphorus polluters will have a preference for one or the other of these mechanisms. Therefore, in a deterministic world, the regulator has no preference (all else equal) to which policy mechanism to use in the pursuit of reducing phosphorus emissions. However, in the absence of the redistribution of tax proceeds to polluters, a regulatory system employing an effluent fee equal to the marginal cost of abatement will cost polluters more than a targeted command-and-control policy or one that uniformly distributes tradable permits based on historic emissions. Those polluters with relatively high costs of abatement (i.e. those that would purchase tradable permits) will prefer a system of mandated targeted reductions, and those polluters with relatively low costs of abatement (i.e. those that would sell tradable permits) would prefer a policy of tradable emissions permits.

The effects of uncertainty, asymmetric information and moral hazard may affect the regulator's choice of policy. Following the seminal price and quantity mechanism analysis by Weitzman (1974) it can be shown that the regulator will prefer to utilize a phosphorus emissions tax over a tradable permit system (or targeted command-and-control reductions policy) when the slope of the benefits to abatement function is less than the slope of the abatement cost function. Using the estimates of aggregate watershed abatement costs (Chapter 4) and adapting a willingness-to-pay for water quality improvement study (Mathews, 1998) it is shown that the slope of the aggregate abatement cost function is less than the benefits to abatement function at the efficient level of abatement. This indicates that all else equal (i.e. not taking into account transaction costs) a regulator should prefer to utilize a quantity instrument for regulating phosphorus emissions in the Sand Creek.

As is shown in Chapter 5, this result may not hold for dynamic phosphorus regulation, which may be more appropriate due to the stock pollutant nature of phosphorus. Because the damages of phosphorus emissions and of the stock of phosphorus found in the Minnesota River are not known it is difficult to estimate what the optimal level of abatement and steady-state values of the phosphorus stock are. When the optimal level of abatement is determined exogenously (e.g., the optimal static abatement level or that which maintains water quality at a level necessary for safe recreational use) the use of intertemporal emissions may result in inefficient levels of abatement. Because sources discount future abatement costs, it was shown that when there is not a binding constraint on abatement levels, sources will borrow in earlier periods and pay them back in the future. This may be unacceptable to regulators. In which case mandated abatement levels at the cost-effective rate or effluent fees that induce identical abatement behavior may be preferred. The gains in abatement cost reduction due to allowing permits to be traded across sources and time was shown to be minimal. This result is important and tempers the last statement made about unacceptable banking and borrowing of permits.

Because nonpoint sources will typically abate up to an intensive margin (i.e. they will not change crop rotation or stop production due to high revenue losses), there is no significant intertemporal banking effect because the marginal value to borrowing an additional permit (i.e. shifting abatement into the future) is not as great as that gained from abating today and selling a permit to a high abatement cost source, such as a wastewater treatment facility. In addition, if the intertemporal shifting of abatement is shown to be a significant problem the regulator could make use of charging an interest rate on borrowed permits (or reward for banked permits) similar to that discussed in Chapter 2.

Lastly, the effect of nonpoint source cheating on reported abatement practices was examined. This analysis was motivated by the argument that the regulation of nonpoint nutrient emissions could be undermined by asymmetric information and possible noncompliant behavior by nonpoint polluters. However, in order to achieve the substantial nutrient reductions necessary to meet federal water standards it is now necessary to include agricultural nonpoint pollution in any meaningful abatement strategy. There are potential cost savings by regulating point and nonpoint sources using an emissions trading system. The question answered in this section was whether the efficiency gains to point-nonpoint emissions trading when compared to a command-and-control approach increase or decrease when farmers misrepresent their abatement efforts.

The implication of proposition 1 is that the cost effectiveness of an emissions trading system as compared to uniform reductions may become greater in magnitude when polluters have the incentive to cheat due to asymmetric information about their abatement efforts. If the ability to cheat is constant as abatement effort increases this condition will always hold. This implies that if the regulator can hold the cheating of polluters to a bounded range, the attractiveness of an emission permit trading system increases when compared to a command-and-control approach. Finally, proposition 2 describes sufficient conditions that generalize the cost effectiveness relationships from propositions 1 to welfare measures of efficiency.

These propositions can be considered extensions to the relationships found by Shortle and Dunn (1986) and Smith and Tomasi (1995, 1999), who find that with asymmetric information estimated runoff incentives (i.e., permits) are superior to runoff standards (i.e., uniform reductions), but do not examine the magnitude this superiority in a second-best world with observable point sources. Specifically in the case of phosphorus pollution in the Minnesota River Valley, where the extensive margin is observable and the intensive margin is not, an emissions trading system should not be discounted solely on the basis of possible moral hazard. First, abatement costs under uniform reduction or emissions trading are much less costly than current programs that target marginal lands for abatement practices (e.g., CRP or RIM – Taff, 1999). Second, proposition 1 is shown to hold for phosphorus reductions in the Sand Creek: when farmers do not (do) cheat the percentage difference between cost effectiveness is 63.5% (238%). Using an estimated marginal benefit and marginal cost functions for phosphorus abatement proposition 2 also holds for the Sand Creek illustrating that the gains to regulating with emissions trading increase when polluters misrepresent abatement efforts as compared to regulating with uniform reductions: when farmers do not (do) cheat the DWL associated with uniform reductions is $146,170 ($882,129).

This result illustrates that the manner in which sources manifest the problem of moral hazard is essential to understand when assessing the effects of the moral hazard problem. In the case of Sand Creek abatement levels, the moral hazard problem marginally affected the cost-effective and efficient solutions when sources were allowed to trade emissions permits (a 15% decrease in cost-effectiveness and a 5.6% deadweight loss in efficiency) when compared to the gains from regulating using such a mechanism. These deadweight losses for regulating phosphorus can be compared to those of two variants on the emissions trading system. One system allows the trading of permits, but does not credit farmers for unobservable fertilizer rate abatement efforts. The second system also allows permit trading, but only credits farmers for extensive abatement efforts. The deadweight loss from the "No Fertilizer" system is found to be 4.8%, less than that under unrestricted emissions trading. However, these losses increase significantly under the "No Intensive Management" system.

6.4 Avenues for Future Research

Due to the complex nature of the issues investigated in this thesis, there were many assumptions made to simplify the analysis, which may be relaxed for future research extensions. For example, advances in computing technology and multidisciplinary research methods will continue to facilitate the use of simulated data to estimate abatement cost functions for agricultural nonpoint pollution. One way in which this dissertation could be extended toward this end is by using the stochastic simulations for the estimation of abatement cost functions rather than utilizing 50-year mean values for BMP simulations. It should then be feasible to fully utilize the descriptive power of the stochastic frontier analysis by estimating a panel for each soil map unit based on the multi-year data set.

Another potential area for extending this thesis concerns variations of systems for achieving reductions in point and nonpoint nutrient loading. For example, what would happen if the sources were allowed to choose the type of regulation that they would face: price instruments or quantity instruments. Holding the cheating question aside for the moment, assume that the regulator has ex-post perfect monitoring information available and that the regulator offers the source a choice of whether to participate in an intertemporal trading regime or to pay effluent fees equal to the expected cost of a permit trade. Another interesting avenue for this type of research would be to allow the sources to trade the type of regulation they face, similar to the nutrient offset trading allowed under the NPDES. Under this type of regulation, a source could choose to trade the type of regulation they faced based on the possibility of potential loading or based on the probability of cheating.

Returning to the emissions trading system examined in this thesis, one could allow exogenous players to participate in the trading market. It could possible for outside participants to purchase permits and not use them. Call this group the "Environmentalists". It would also be possible for other watersheds to purchase emissions permits to increase their load at another location in the Minnesota River Valley. While it may be easier to set-up discrete trading blocks (in the form of water conservation districts, counties, watersheds, etc.) it may be too complicated to set-up an entire Minnesota River Basin system where the trading ratio between any two parties is based on the expected damage that the emission causes dependent on some distance or flow function. However, a watershed district may notice that permits are trading at a low cost down or up stream and want to purchase a number of emissions permits (especially if the system is intertemporal) for the sources inside their trading boundary. This would entail some sort of government player in the trading scenario that would seek to perform an arbitrage function for the trading of permits over large areas encompassing several trading regions.

Not dealt with in this thesis is the question of nitrogen emissions and sediment emissions that may or may not be positively affected by phosphorus BMPs. In some research it is noted that by increasing residue management through conservation or no-till strategies the amount of nitrogen emitted into the water increases. Also many researchers note that prolonged periods of conservation tillage strategies may increase the resident population of harmful pest organisms and therefore would require increased usage of pesticides and herbicides to maintain yields. This is somewhat accounted for in the development of abatement cost function by decreasing expected yield values for conservation tillage, however the environmental impacts of increased pesticide and herbicide usage may counter-balance the benefits from abatement of phosphorus. All these factors should enter the regulator problem in the form of multiple optimal control state equations (Hediger, 1999). As usual the welfare maximizing solution would seek to maximize the difference between the benefits to abating all these harmful pollutants and the cost to abate them given that some abatement strategies would increase the emissions of the other pollutants and vice versa.

One last area, but certainly not the only one, concerns the estimation of the type of cheating that may occur under moral hazard and its repercussions on the abatement levels and costs. As illustrated above, given the structure of abatement costs and assumptions about the nature of cheating, the loss in regulatory efficiency will be $59,714 if regulators assume naïve behavior, but cheating is observed. This deviation is a modest 5.6% of aggregate abatement costs under the ETS^S scenario. How might regulators develop regulation mechanisms to circumvent the moral hazard problem? One way that regulators could prevent cheating is to approve trades and proposed abatement efforts that are based solely on observable abatement practices.

6.5 Caveats and Concluding Comments

The question of appropriate trading ratios is one that opponents of tradable permit systems often raise, especially when examining empirical evidence from past trading systems. These systems have been noted for their lack of actual trades occurring. One reason suggested for this is that the differential affect of pollutant loading from different sources requires the need to alter trading ratios; hence there is too much complexity in a pollutant trading to warrant their use.

This argument is contrary to the finding of this thesis however. The appropriate trading ratios have been implicitly incorporated into the right to pollute, i.e. sources trade on a 1:1 ratio the right to emit one pound of phosphorus into the river. Obviously if permits allowed the source to emit one pound of phosphorus to the edge-of-field the trading ratios would not be 1:1. The trading ratio would be 1.28:1 between sources within the 300-foot buffer zone and point sources, 3.33:1 between sources outside the buffer and point sources, and 2.6:1 between sources outside the buffer and those within the buffer. Because trading concerns phosphorus emissions within a particular region (i.e. sub-watershed) the damage done by these emissions is approximately equal. Similarly due to the conservative nature of phosphorus and the ability to become stored in the river bottom sediment, the intertemporal nature of the phosphorus does not need to be explicitly incorporated into the permit.

More importantly, the analysis in this thesis for the most part assumes that the abatement levels for the nonpoint sources are deterministic. Of course stochastic weather variables are key components in determining what the resulting level of abatement will be given nonpoint best management practices, as illustrated in Chapter 3. It is for this reason that it is essential to determine how stochastic weather events might affect the choice of regulatory mechanism. From Chapter 2 it was shown that it is possible for quantity instruments to achieve the optimal level of abatement with stochastic nonpoint emissions when point sources are included in the regulation, subject to certain conditions. In other words during periods of lower than expected emissions, nonpoint sources can sell permits to point sources; in periods of higher than expected emissions, point sources can sell permits to nonpoint sources. Under a system of effluent fees, the same abatement choices will be made ex-ante, but the resulting level of abatement will not meet the water quality standard. In the static case, tradable permits are preferred to taxes when the slope of the benefit function is greater than the slope of the cost function, as in the case with estimated Sand Creek abatement costs and benefits.

In a dynamic system Hoel and Karp (1999) illustrate that quotas (tradable permits) are preferred to taxes when the slope of the benefits function is large relative to the cost function, when the future is not discounted heavily, when the variance of the stochastic variable is high, when the retention factor is high, and when the period for adjusting abatement efforts is large. Given the characteristics of nonpoint pollution, i.e. large variance in abatement levels, low abatement costs, and long period for adjusting abatement efforts, it would be expected that tradable permits would be preferred to effluent fees in the specialized case of point and nonpoint phosphorus abatement. This result is difficult to illustrate empirically without a believable estimation of the damage function. However, for second-best policy, Leiby and Rubin (1998) have illustrated how an intertemporal trading system with banking and borrowing can be systematically altered by the regulator (via aforementioned permit interest rate changes) following observations of stochastic influences. This same mechanism could be employed for phosphorus emissions permits and for ex-post observations of weather and resulting abatement levels.

To conclude I would like to summarize the motivation behind this thesis. Previous attempts at regulating the emissions of pollutants into water resources, such as the Minnesota River, focused on tightening levels of point source emissions. While this did reduce the amount of pollution entering these resources from point sources, it did not account for increasing levels of nonpoint nutrient emissions due to agricultural intensification. As a result many lakes, rivers, and coastal areas are continuing to degrade despite the clean-up efforts spawned after the passage of the Clean Water Act in 1972. It is therefore necessary to develop methods by which regulators can incorporate nonpoint source pollution when attempting to meet federal water quality standards.

One main reason for the omission of nonpoint source emissions in water quality regulation has been that it is too difficult to determine the polluter responsible for the nonpoint emissions. I argue that due to the development of accurate biophysical modeling techniques and increasing computing power, it is no longer sufficient to ignore nonpoint pollution based solely on this argument. Furthermore, it is possible in the absence of survey data, to now simulate the effects of different best management practices using new biophysical soils models for specific agricultural lands, due to the accumulation of detailed soils data for the majority of the United States. Once the yield and emissions information has been generated, it is possible to estimate abatement cost functions for soil groups based on distance and sediment delivery ratios. By employing frontier analysis in these estimations using simulated data, it is possible to account for biased results due to redundant simulations.

Given the structure of these abatement cost functions it is possible to identify the effects of both extensive management practices and intensive management practices. This is useful for regulators in comparing different regulatory mechanisms. In the case of

Sand Creek it was found that a static system of regulating point and nonpoint sources using tradable emissions permits is preferable to one using effluent fees. This is due to the slopes of the estimated costs and benefits curves for abatement. Furthermore, it was also found for the Sand Creek that the benefit to regulation using intertemporal permits is not that much greater (on average) than a static system. The potential efficiency losses due to asymmetric information and moral hazard was shown to be much higher for traditional regulatory policy as compared to targeted policies, such as permit trading systems.

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Appendix A: Proofs of Propositions

Proof Proposition 1

(1.1) $CE^{N} \equiv (ACA^{UR/N} - ACA^{ETS/N}) / ACA^{ETS/N}$

(1.2) $CE^{S} \equiv (ACA^{UR/S} - ACA^{ETS/S}) / ACA^{ETS/S}$

(1.3) $CE^{n} < CE^{S} \Rightarrow \frac{(TC^{UR/N} / TA^{ER/N})}{(TC^{ETS/N} / TA^{ETS/N)}} < \frac{(TC^{UR/S} / TA^{UR/S})}{(TC^{ETS/S} / TA^{ETS/S})}$

(1.4) $\Rightarrow \frac{TC^{UR/N}}{TC^{ETS/N}} < \frac{TC^{UR/S}}{TC^{ETS/S}} \times \frac{TA^{ETS/S}}{TA^{UR/S}}$

Let $a_n^{ets/s}(r_n^s(t), z_n^s(t)) - a_n^{ets/n}(r_n^n(t), z_n^n(t)) = a_1$ and $a_n^{ur/s}(r_n^s(t), z_n^s(t)) - a_n^{ur/n}(r_n^n(t), z_n^n(t)) = a_0$.

Let $TC^{ETS/N} - TC^{ETS/S} = c_1$ and $TC^{UR/N} - TC^{UR/S} = c_0$. Let $\frac{TC^{UR/N}}{TC^{ETS/N}} = k$.

Recall from Section 5 the discussion of the cross-derivatives of abatement effort on the extensive margins. Given convex abatement cost function Case A $\Rightarrow a_1 > a_0 \cap c_1 > c_0$. Similarly, Case B $\Rightarrow a_1 = a_0 \cap c_1 > c_0$ and Case C $\Rightarrow a_1 < a_0 \cap c_1 ? c_0$.

(1.5) $k = \dfrac{TC^{UR/S} + c_0}{TC^{ETS/S} + c_1}$, which yields the following conditions:

(1.5.1) $k > \dfrac{TC^{UR/S} + c_0}{TC^{ETS/S} + c_1}$ if $c_0 - kc_1 > 0$,

(1.5.2) $k = \dfrac{TC^{UR/S} + c_0}{TC^{ETS/S} + c_1}$ if $c_0 - kc_1 = 0$, and

(1.5.3) $k < \dfrac{TC^{UR/S} + c_0}{TC^{ETS/S} + c_1}$ if $c_0 - kc_1 < 0$.

(1.6) $\dfrac{TA^{ETS/S}}{TA^{UR/S}} = \dfrac{TA^{ETS/N} - a_1}{TA^{UR/N} - a_0}$.

Let A represent the *rhs* of (2.6), which yields the following conditions:

(1.6.1) A < 1 if $a_1 > a_0$,

(1.6.2) A = 1 if $a_1 = a_0$, and

(1.6.3) A > 1 if $a_1 < a_0$

(1.7) Then, $CE^N < CE^S$

(1.7.1) if (1.5.2) and (1.6.3) hold,

(1.7.2) if (1.5.3) and (1.6.2) hold, or

(1.7.3) if (1.5.3) and (1.6.3) hold;

(1.8) $CE^N ? CE^S$

(1.8.1) if (1.5.3) and (1.6.1) hold;

(1.8.2) if (1.5.3) and (1.6.1) hold;

(1.9) $CE^N = CE^S$

(1.9.1) if (1.5.2) and (1.6.2) hold; and

(1.10) $CE^N > CE^S$

(1.10.1) if (1.5.1) and (1.6.1) hold,

(1.10.2) if (1.5.1) and (1.6.2) hold, or

(1.10.3) if (1.5.2) and (1.6.1) hold.

(1.11) Case A implies condition (1.8.2) $\Rightarrow CE^N ? CE^S$;

Case B implies condition (1.7.2) $\Rightarrow CE^N < CE^S$; and

Case C implies (1.7.1) or (1.7.3)) $\Rightarrow CE^N < CE^S$, and

Case C implies (1.8.1) $\Rightarrow CE^N ? CE^S$.

Examining these conditions, (1.9) and (1.10) will never occur. The proposition holds under Case B always, and conditionally under Case A and C.

■

Proof Proposition 2

Deadweight loss is given by the expression, $DWL = \frac{1}{2} * (TA^{ETS} - TA^{UR})(MC^{ETS} - MC^{UR})$, where *TA* and *MC* correspond to the abatement and price level at the intersection of the emissions trading and uniform reduction marginal cost function with the marginal benefit function. $DWL^S > DWL^N$ implies

$$(TA^{ETS/S} - TA^{UR/S})(MC^{UR/S} - MC^{ETS/S}) > (TA^{ETS/N} - TA^{UR/N})(MC^{UR/N} - MC^{ETS/N}).$$

If $\frac{\partial^2 a_i^{n,s}(r(t),z(t))}{\partial z(t)^2} = 0$, then $\frac{(TC^{UR/N} / TA^{ER/N})}{(TC^{ETS/N} / TA^{ETS/N)}} \leq \frac{(TC^{UR/S} / TA^{UR/S})}{(TC^{ETS/S} / TA^{ETS/S})}$.

This implies

(2.1) $(MC^{UR/S} - MC^{ETS/S}) > (MC^{UR/N} - MC^{ETS/N})$. It remains only to show

(2.2) $(TA^{ETS/S} - TA^{UR/S}) > (TA^{ETS/N} - TA^{UR/N})$.

Let the marginal cost function be denoted: $MC(a) = \beta_i * a_i$, where *i = ur/s, ur/n, ets/s, or ets/n*, then (2.2) implies $(\beta_{ets/s}^{-1} - \beta_{ur/s}^{-1}) > (\beta_{ets/n}^{-1} - \beta_{ur/n}^{-1})$, which is the sufficient condition for *Proposition 2.* ■

Appendix B: ADAPT Calibrations

ADAPT Parameters

(1) *C Factor*
Adapt is very sensitive to the C-factor coefficients. The c-factor refers to the soil loss ratios for cropstage period and canopy cover, given consistent cropping, residue management, and tillage practices (USDA and Purdue, 1978).

(2) *P Factor*
Adapt is not very sensitive to the P-factor coefficients. These refer to the conservation practice coefficients, such as contour farming, strip cropping, subsurface drainage, and terracing. For example in the case of Sand Creek, we choose a p-factor of 0.5, which corresponds to a land slope of 3-8% with maximum slope length of 200-300 feet (Ward and Elliot, 1995).

(3) *N Factor*
Adapt is not very sensitive to the N-factor coefficients. These refer to the value of Manning's roughness coefficients and describe friction coefficients for runoff water. The values chosen for cultivated areas are 0.01 and 0.02 depending on the crop and tillage dates (Ward and Elliot, 1995).

Calibration values for Southeastern Minnesota

Parameter	Value	Source	Description
		ADAPT Parameters	
Soil Map units		USDA (2000)	Soil map units taken from the STATSGO soils database
THRUs and Runoff Curve Numbers		Dalzell et al. (1999)	Aggregate hydrological response units created for the Sand Creek
C Factor		USDA & Purdue Agricultural Experiment Station (1978)	Soil loss ratios for cropstage period and canopy cover, given consistent cropping, residue management, and tillage practices.
P Factor		Ward & Elliot (1995)	Conservation practice coefficients (e.g., contour farming, strip cropping, subsurface drainage, and terracing)
N Factor		As above	Manning's roughness coefficients, which describe friction coefficients for runoff water
		Sand Creek Parameters	
Sediment Delivery Ratio	0.368	ADAPT Simulations, and MPCA (1994, 1998)	The percentage of sediment load arriving at the edge of field arriving at the watershed outlet
Corn	2.057	USDA & MDA (1992-1998)	Calibration coefficients for crop production in Scott County, MN
Soybean	1.179		
Pasture	3.266		
Corn	0.98	Wu, et al. (1996), Randall, et al. (1996), Oplinger & Philbrook (1992)	Long-run conservation tillage reductions in yield
Soybeans	0.98		
Yield response to N / P rates	0.9 – 0.13	Webb, et al. (1992), Rehm, et al. (1995)	Positive response to increases in nitrogen and phosphorus rates
		Prices / Costs	
Corn	$2.51/bu	Minnesota Agricultural Statistics (1998), UofMn (1995-1999)	Mean from 1993-1997
Soybeans	$6.34/bu		Mean from 1993-1997
Pasture	$10/ton		Mean from 1997-1998
Nitrogen	$0.277/lb	USDA & NASS (1999)	Mean from 1995-1998
Phosphorus	$0.621/lb		
Cost to Incorporate	$4.89/acre	Lazarus (1999)	Combination Field Cultivator /Incorp.
Corn	($6.489)	Olson & Senjem (1996)	Conservation tillage variable costs
Soybeans	($4.2875)		

Simulation Descriptions

Simulations*	Implement	Date / Depth	Rate	N / P (Kg/Ha)
Tillage				
•Conventional	Moldboard Plow	Fall / 10 cm		
	Disk Harrow	Spring / 10 cm		
	Planter	Spring / 7.5 cm		
•Conservation	Chisel Plow	Fall / 10 cm		
	Planter	Spring / 7.5 cm		
Fertilizer				
•Broadcast		Fall / 0 cm	High	Corn: 180N / 50P Soybeans: 0N / 20P
			Medium	Corn: 140N / 20P Soybeans: 0N / 10P
			Low	Corn: 80N / 0P Soybeans: 0N / 0P
•Incorporated		Fall / 7.5 cm	As Above	

* Tillage, fertilizer, and cropping values are chosen to represent bounds on current practices occurring in this region. They are based on conversations with individuals in the Department of Soils, Water and Climate at the University of Minnesota, in the Department of Applied Economics at the University of Minnesota, and NRCS and Extension agents located in Scott County.

Input Parameter Files for ADAPT

MN079

```
ADAPT Erosion Parameter File:  Sand Creek Watershed   Created:  9/14/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN079
       47        96        3        0        1        0        0
1.67E-05     0.010    100.0   0.1092
     0.21      0.37     0.42    0.052    800.0      4.0     0.05   1000.0
   343.00     100.0      0.06      0.06      0.06      0.06         0       6.0
100.0      0.0
        1       1.0     0.28
        2
      001       100      120      135      150      165      225      300
      001       100      120      135      150      165      225      300
        1       1.0
     0.00      0.52     0.73     0.61     0.41     0.29     0.21     0.18
     0.50      0.50     0.50     0.50     0.50     0.50     0.50     0.50
     0.02      0.01     0.02     0.02     0.02     0.02     0.02     0.01
     0.00      0.53     0.81     0.65     0.51     0.40     0.30     0.25
     0.50      0.50     0.50     0.50     0.50     0.50     0.50     0.50
     0.01      0.01     0.01     0.01     0.01     0.01     0.01     0.01
```

```
ADAPT PESTICIDE Parameter File                        Created: 8/04/99
Generic Soybean Corn Rotation starting with Soybeans
Sand Creek Watershed for 1947 through 1996
    47001        1        0        0        0
        1    47001    96366
        1  ATRAZIN       33        5       60       100        0        0
0.45       0.0
     1121     2120        1
        1     0.00      1.0        0        1      0.1        0
     2121     3120        1
        1     1.80      1.0        0        1      0.1        0
...
    50121    50366        1
        1     1.80      1.0        0        1      0.1        0
        0
```

```
ADAPT  Hydrology  Parameter  File:   Sand  Creek  Watershed    Created:
7/23/99
Soybean Corn Rotation Conservation Tillage beginning with Soybean
Soil Map Unit - MN079
   47001  2  1  1  1  0  0  0  0  1  1  2  0  0 graphics=no
   343.00     3.47     24.0     4.00     75.0     0.06      1.0    45.00
   1100.0     44.0      2.0      7.0     98.0      6.0     1.75     0.00
10       17
        0     48.0        3      9.0     36.0    180.0
     0.45     0.40     0.38
     0.13     0.17     0.14
     3.00     0.80     0.30
    21.00    29.50    25.00
    37.40    36.80    36.50
```

```
    3.47    1.16    1.34   .0002
    3.47    1.16    1.34
    0.45     0.43     0.41     0.38     0.34     0.30     0.28     0.23
0.16    0.13
     5.0     20.0     40.0     80.0    150.0    300.0    400.0   1000.0
5000.0 15300.0
    0.40     0.40     0.39     0.38     0.36     0.33     0.32     0.27
0.20    0.17
     5.0     20.0     40.0     80.0    150.0    300.0    400.0   1000.0
5000.0 15300.0
    0.38     0.38     0.37     0.35     0.33     0.29     0.28     0.24
0.18    0.14
     5.0     20.0     40.0     80.0    150.0    300.0    400.0   1000.0
5000.0 15300.0
  0.2000   0.2000   0.2000   0.2000   0.1429   0.0895   0.0628   0.0449
0.0329  0.0245
  0.0191  0.0117  0.0080  0.0057  0.0031  0.0015  0.0000
     0.0     10.0     20.0     30.0     40.0     50.0     60.0     70.0
80.0    90.0
   100.0   120.0   140.0   160.0   200.0   250.0   550.0
   180.0     0.0    1440    48.0     0.5     1.0
     168      260      368      426      496      535      557      486
366     237
     146     124
      47      96      50
      58    1130     1275              35.00                 0        0
0     1.0
       0
      20    2120     2290              45.00                 0        0
0     1.0
       0
      ...
      ...
       0       0       1       0
      -1       0       0       0

ADAPT NUTRIENT Parameter File                                   Created:
10/13/99
Soybean Corn Rotation in the Sand Creek Watershed beginning with
Soybean
Soil Map unit = MN079 - Conventional/Broadcast Tillage
      47      96       1      50       1       0  0  0
   500.0     3.1

       2       2       2
   444.0   100.0     1.0

    0.06    0.06   0.061
      10       1     0.1

    1001
       1       3    1275
      58       1
    1305       0       0
```

```
 140.0     0.0     20.0     0.0
  0300      19     10.0
  1115      10     10.0
  1130      22      7.5
...
...
...
50001
     1       3    50290
    20       0
 50305       0        0
   0.0     0.0     10.0     0.0
 49300      19     10.0
 50115      10     10.0
 50120      22      7.5
     0
```

MN080

```
ADAPT Erosion Parameter File:  Sand Creek Watershed   Created:  8/02/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN080
       47       96        3        0        1        0        0
1.67E-05   0.010   100.0   0.1092
    0.32    0.30    0.38   0.035   800.0     4.0    0.05  1000.0
  343.00   100.0   0.069   0.069   0.069   0.069          0     6.9
100.0     0.0
       1     1.0    0.28
       2
     001     100     120     135     150     165     225     300
     001     100     120     135     150     165     225     300
       1     1.0
    0.00    0.52    0.73    0.61    0.41    0.29    0.21    0.18
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.02    0.01    0.02    0.02    0.02    0.02    0.02    0.01
    0.00    0.53    0.81    0.65    0.51    0.40    0.30    0.25
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.01
```

```
ADAPT  Hydrology  Parameter  File:    Sand  Creek  Watershed     Created:
8/06/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN080
  47001  2  1  1  1  0  0  0  0  1  1  2  0  0 graphics=no
  343.00    1.98    24.0    4.00    78.0   0.069     1.0   45.00
  1100.0     44.0      2.0       7.0     98.0       6.0     1.75     0.00
10       17
       0    48.0       3    9.00    36.0   180.0
    0.44    0.40    0.38
    0.17    0.17    0.14
    2.00    0.80    0.30
   31.50   29.50   25.00
   33.30   36.80   36.50
```

```
     1.98     1.10     1.34   .0002
     1.98     1.10     1.34
     0.44      0.43      0.42      0.40      0.38      0.34      0.32      0.27
0.21    0.17
      5.0      20.0      40.0      80.0     150.0     300.0     400.0   1000.0
5000.0 15300.0
     0.40      0.39      0.39      0.38      0.36      0.33      0.31      0.27
0.20    0.17
      5.0      20.0      40.0      80.0     150.0     300.0     400.0   1000.0
5000.0 15300.0
     0.38      0.38      0.37      0.35      0.33      0.29      0.28      0.24
0.18    0.14
      5.0      20.0      40.0      80.0     150.0     300.0     400.0   1000.0
5000.0 15300.0
  0.2000    0.2000    0.2000    0.2000    0.1396    0.0983    0.0722    0.0538
0.0406  0.0322
  0.0252  0.0168  0.0116  0.0085  0.0047  0.0024  0.0000
      0.0      10.0      20.0      30.0      40.0      50.0      60.0      70.0
80.0     90.0
    100.0   120.0   140.0   160.0   200.0   250.0   500.0
    180.0     0.0    1440    48.0     0.5     1.0
      168       260       368       426       496       535       557       486
366      237
      146     124
       47      96      50
       58     1130     1275              35.00                    0        0
0      1.0
        0
       20     2120     2290              45.00                    0        0
0      1.0
```

```
ADAPT NUTRIENT Parameter File                                       Created:
10/13/99
Soybean  Corn  Rotation  in  the  Sand  Creek  Watershed  beginning  with
Soybean
Soil Map unit = MN080 - Conventional/Broadcast Tillage
       47       96        1       50        1       0  0  0
    500.0      3.1

        2        2        2
    444.0    100.0      1.0

     0.06     0.06    0.061
       10        1      0.1

     1001
        1        3     1275
       58        1
     1305        0        0
    140.0      0.0     20.0      0.0
     0300       19     10.0
     1115       10     10.0
```

```
    1130      22     7.5
    2001
       1       3    2290
      20       0
    2305       0       0
     0.0     0.0    10.0      0.0
    1300      19    10.0
    2115      10    10.0
    2120      22     7.5
    3001

ADAPT PESTICIDE Parameter File                    Created: 8/04/99
Generic Soybean Corn Rotation starting with Soybeans
Sand Creek Watershed for 1947 through 1996
   47001        1       0       0       0
       1   47001   96366
       1 ATRAZIN        33         5        60       100          0         0
0.45     0.0
    1121    2120        1
       1    0.00      1.0       0       1     0.1       0
    2121    3120        1
       1    1.80      1.0       0       1     0.1       0
    3121    4120        1
```

MN081

```
ADAPT  Erosion  Parameter  File:   Sand  Creek  Watershed    Created:
10/11/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN081
      47       96        3       0        1       0       0
1.67E-05   0.010   100.0  0.1092
    0.21    0.37    0.42   0.052   800.0     4.0    0.05  1000.0
  343.00   100.0    0.072    0.072    0.072    0.072         0      7.2
100.0      0.0
       1     1.0    0.28
       2
     001     100     120     135     150     165     225     300
     001     100     120     135     150     165     225     300
       1     1.0
    0.00    0.52    0.73    0.61    0.41    0.29    0.21    0.18
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.02    0.01    0.02    0.02    0.02    0.02    0.02    0.01
    0.00    0.53    0.81    0.65    0.51    0.40    0.30    0.25
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.01
```

```
ADAPT  Hydrology  Parameter  File:   Sand  Creek  Watershed    Created:
7/23/99
Soybean Corn Rotation Conservation Tillage beginning with Soybean
Soil Map Unit - MN081
  47001  2  1  1  1  0  0  0  0  1  1  2  0  0 graphics=no
  343.00    3.47    24.0    4.00    75.0   0.072    1.0   45.00
```

```
   1100.0     44.0      2.0      7.0     98.0      6.0     1.75   0.00        10
17
        0     48.0        3      9.0     36.0    180.0
     0.45     0.40     0.38
     0.13     0.17     0.14
     3.00     0.80     0.30
    21.00    29.50    25.00
    37.40    36.80    36.50
     3.47     1.16     1.34    .0002
     3.47     1.16     1.34
     0.45       0.43       0.41       0.38       0.34       0.30       0.28       0.23
0.16     0.13
      5.0       20.0       40.0       80.0      150.0      300.0      400.0   1000.0
5000.0 15300.0
     0.40       0.40       0.39       0.38       0.36       0.33       0.32       0.27
0.20     0.17
      5.0       20.0       40.0       80.0      150.0      300.0      400.0   1000.0
5000.0 15300.0
     0.38       0.38       0.37       0.35       0.33       0.29       0.28       0.24
0.18     0.14
      5.0       20.0       40.0       80.0      150.0      300.0      400.0   1000.0
5000.0 15300.0
   0.2000    0.2000    0.2000    0.2000    0.1429    0.0895    0.0628    0.0449
0.0329   0.0245
   0.0191   0.0117   0.0080   0.0057   0.0031   0.0015   0.0000
      0.0       10.0       20.0       30.0       40.0       50.0       60.0       70.0
80.0     90.0
    100.0    120.0    140.0    160.0    200.0    250.0    550.0
    180.0      0.0     2160     48.0      0.5      1.0
      168        260        368        426        496        535        557        486
366       237
      146        124
       47         96        50
       58       1130      1275                 35.00                     0        0
0      1.0
```

```
ADAPT NUTRIENT Parameter File                                            Created:
10/13/99
Soybean  Corn  Rotation  in  the  Sand  Creek  Watershed  beginning  with
Soybean
Soil Map unit = MN081 - Conventional/Broadcast Tillage
       47       96        1       50        1       0  0  0
    500.0      3.1

        2        2        2
    444.0    100.0      1.0

     0.06     0.06    0.061
       10        1      0.1

     1001
        1        3     1275
       58        1
     1305        0        0
```

```
   140.0     0.0    20.0      0.0
    0300      19    10.0
    1115      10    10.0
    1130      22     7.5
    2001
       1       3    2290
      20       0
    2305       0       0
     0.0     0.0    10.0      0.0
    1300      19    10.0
    2115      10    10.0
    2120      22     7.5
    3001
```

MN163

```
ADAPT Erosion Parameter File:  Sand Creek Watershed   Created:  8/02/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN163
      47       96        3        0        1        0        0
1.67E-05   0.010   100.0  0.1092
    0.29    0.37    0.34   0.052   800.0      4.0    0.05  1000.0
  343.00    100.0    0.058     0.058     0.058     0.058          0       5.8
100.0       0.0
       1     1.0    0.28
       2
     001     100     120     135     150     165     225     300
     001     100     120     135     150     165     225     300
       1     1.0
    0.00    0.52    0.73    0.61    0.41    0.29    0.21    0.18
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.02    0.01    0.02    0.02    0.02    0.02    0.02    0.01
    0.00    0.53    0.81    0.65    0.51    0.40    0.30    0.25
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.01
```

```
ADAPT  Hydrology  Parameter  File:    Sand  Creek  Watershed     Created:
8/06/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN163
  47001  2  1  1  1  0  0  0  0  1  1  0  0  0 graphics=no
  343.00    0.71    24.0    4.00    78.0   0.058     1.0    45.00
  1100.0     44.0      2.0       7.0      98.0       6.0     1.75      0.00
10      17
       0    48.0       3   10.00    48.0   180.0
    0.46    0.43    0.39
    0.19    0.27    0.20
    3.00    1.00    0.30
   28.50   39.50   30.00
   37.30   31.30   36.50
    3.47    1.16    1.34     .02
    3.47    1.16    1.34
    0.46     0.46     0.45     0.44     0.42     0.39     0.37     0.31
 0.23    0.19
```

```
      5.0      20.0       40.0      80.0      150.0      300.0      400.0   1000.0
5000.0 15300.0
     0.43      0.43       0.43      0.43       0.43       0.43       0.43     0.41
0.34    0.27
      5.0      20.0       40.0      80.0      150.0      300.0      400.0   1000.0
5000.0 15300.0
     0.39      0.39       0.39      0.39       0.38       0.37       0.36     0.32
0.24    0.20
      5.0      20.0       40.0      80.0      150.0      300.0      400.0   1000.0
5000.0 15300.0
  0.2000    0.2000    0.2000    0.2000    0.2000    0.1677    0.1270    0.0996
0.0804  0.0665
  0.0558  0.0414  0.0326  0.0253  0.0166  0.0106  0.0000
      0.0      10.0       20.0      30.0       40.0       50.0       60.0     70.0
80.0     90.0
    100.0     120.0     140.0     160.0     200.0     250.0     500.0
    180.0       0.0      1440      48.0       0.5       1.0
      168       260        368       426        496        535        557      486
366      237
      146       124
       47        96         50
       58      1130       1275                35.00                     0        0
0       1.0
        0

ADAPT NUTRIENT Parameter File                                          Created:
10/13/99
Soybean  Corn  Rotation  in  the  Sand  Creek  Watershed  beginning  with
Soybean
Soil Map unit = MN163 - Conventional/Broadcast Tillage
       47        96          1        50          1        0  0  0
    500.0       3.1

        2         2          2
    444.0     100.0        1.0

     0.06      0.06      0.061
       10         1        0.1

     1001
        1         3       1275
       58         1
     1305         0          0
    140.0       0.0       20.0       0.0
     0300        19       10.0
     1115        10       10.0
     1130        22        7.5
     2001
        1         3       2290
       20         0
     2305         0          0
      0.0       0.0       10.0       0.0
     1300        19       10.0
     2115        10       10.0
```

```
    2120       22      7.5
    3001
       1        3     3275
```

MN165

```
ADAPT Erosion Parameter File:  Sand Creek Watershed   Created:  9/06/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN165
      47       96        3        0        1        0        0
1.67E-05   0.010   100.0  0.1092
    0.23    0.53    0.24   0.061   800.0      4.0     0.05  1000.0
  343.00    100.0    0.069    0.069    0.069    0.069        0      6.9
100.0     0.0
       1     1.0    0.28
       2
     001     100     120     135     150     165     225     300
     001     100     120     135     150     165     225     300
       1     1.0
    0.00    0.52    0.73    0.61    0.41    0.29    0.21    0.18
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.02    0.01    0.02    0.02    0.02    0.02    0.02    0.01
    0.00    0.53    0.81    0.65    0.51    0.40    0.30    0.25
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.01
```

```
ADAPT  Hydrology  Parameter  File:   Sand  Creek  Watershed     Created:
8/06/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN165
  47001  2  1  1  1  0  0  0  0  1  1  2  0  0 graphics=no
  343.00    1.01    24.0     4.00    78.0   0.069     1.0   45.00
  1100.0     44.0      2.0       7.0     98.0       6.0     1.75     0.00
10      17
       0    48.0       3    8.00    38.0   180.0
    0.48    0.44    0.24
    0.14    0.14    0.07
    3.50    2.00    0.50
   22.50   22.50    9.50
   52.70   52.70    0.80
    1.01    0.63   19.73   .0002
    1.01    0.63   19.73
    0.48     0.47     0.46     0.43     0.39     0.34     0.32     0.26
0.18    0.14
     5.0     20.0     40.0     80.0    150.0    300.0    400.0   1000.0
5000.0 15300.0
    0.44     0.43     0.42     0.41     0.38     0.34     0.32     0.26
0.18    0.14
     5.0     20.0     40.0     80.0    150.0    300.0    400.0   1000.0
5000.0 15300.0
    0.24     0.19     0.17     0.15     0.14     0.13     0.12     0.11
0.09    0.07
     5.0     20.0     40.0     80.0    150.0    300.0    400.0   1000.0
5000.0 15300.0
```

```
  0.2000   0.2000   0.2000   0.1835   0.1208   0.0844   0.0619   0.0088
0.0012  0.0005
  0.0004  0.0003  0.0002  0.0000  0.0000  0.0000  0.0000
     0.0      10.0      20.0      30.0      40.0      50.0      60.0      70.0
80.0    90.0
   100.0   120.0   140.0   160.0   200.0   250.0   500.0
   180.0     0.0     960    48.0     0.5     1.0
     168       260       368       426       496       535       557       486
366     237
     146     124
      47      96      50
      58    1130    1275             35.00                    0        0
0      1.0
       0
```

```
ADAPT NUTRIENT Parameter File                                    Created:
10/13/99
Soybean  Corn  Rotation  in  the  Sand  Creek  Watershed  beginning  with
Soybean
Soil Map unit = MN165 - Conventional/Broadcast Tillage
      47      96       1      50       1       0  0  0
   500.0     3.1

       2       2       2
   444.0   100.0     1.0

    0.06    0.06   0.061
      10       1     0.1

    1001
       1       3    1275
      58       1
    1305       0       0
   140.0     0.0    20.0     0.0
    0300      19    10.0
    1115      10    10.0
    1130      22     7.5
    2001
       1       3    2290
      20       0
    2305       0       0
     0.0     0.0    10.0     0.0
    1300      19    10.0
    2115      10    10.0
    2120      22     7.5
    3001
       1       3    3275
```

MN169

```
ADAPT Erosion Parameter File:  Sand Creek Watershed   Created:  8/02/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN169
      47      96       3       0       1       0       0
```

```
1.67E-05   0.010   100.0  0.1092
    0.23    0.68    0.09   0.061   800.0     4.0    0.05  1000.0
  343.00   100.0    0.092    0.092    0.092    0.092         0       9.2
100.0     0.0
       1     1.0    0.28
       2
     001     100     120     135     150     165     225     300
     001     100     120     135     150     165     225     300
       1     1.0
    0.00    0.52    0.73    0.61    0.41    0.29    0.21    0.18
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.02    0.01    0.02    0.02    0.02    0.02    0.02    0.01
    0.00    0.53    0.81    0.65    0.51    0.40    0.30    0.25
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.01
```

```
ADAPT  Hydrology  Parameter  File:   Sand  Creek  Watershed     Created:
8/06/99
Soybean Corn Rotation Conservation Tillage beginning with Soybean
Soil Map Unit - MN169
  47001  2  1  1  1  0  0  0  0  1  1  2  0  0 graphics=no
  343.00    0.12    24.0     4.00   64.0   0.092     1.0   45.00
  1100.0     44.0       2.0       7.0      98.0       6.0      1.75     0.00
10       17
       0    48.0       3   15.00    33.0   180.0
    0.48    0.42    0.14
    0.15    0.16    0.05
    3.50    1.20    0.40
   22.50   22.50    5.50
   68.00   44.20    3.80
    0.12    0.36   33.56   .0002
    0.12    0.36   33.56
    0.48      0.48      0.47      0.46      0.44      0.39      0.37      0.29
0.19    0.15
     5.0      20.0      40.0      80.0     150.0     300.0     400.0    1000.0
5000.0 15300.0
    0.42      0.41      0.41      0.40      0.39      0.35      0.34      0.28
0.20    0.16
     5.0      20.0      40.0      80.0     150.0     300.0     400.0    1000.0
5000.0 15300.0
    0.14      0.11      0.10      0.09      0.08      0.08      0.07      0.06
0.05    0.05
     5.0      20.0      40.0      80.0     150.0     300.0     400.0    1000.0
5000.0 15300.0
  0.2000    0.2000    0.1284    0.0798    0.0555    0.0411    0.0280    0.0044
0.0014  0.0011
  0.0004  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
     0.0      10.0      20.0      30.0      40.0      50.0      60.0      70.0
80.0    90.0
   100.0   120.0   140.0   160.0   200.0   250.0   500.0
   180.0     0.0    2160    48.0     0.5     1.0
     168       260       368       426       496       535       557       486
366      237
     146     124
```

```
       47      96      50
       58    1130     1275              35.00                0      0
0      1.0
        0

ADAPT NUTRIENT Parameter File                                 Created:
10/13/99
Soybean  Corn  Rotation  in  the  Sand  Creek  Watershed  beginning  with
Soybean
Soil Map unit = MN169 - Conventional/Broadcast Tillage
       47      96       1       50       1       0  0  0
   500.0     3.1

        2       2       2
   444.0   100.0     1.0

    0.06    0.06   0.061
      10       1     0.1

    1001
       1       3    1275
      58       1
    1305       0       0
   140.0     0.0    20.0     0.0
    0300      19    10.0
    1115      10    10.0
    1130      22     7.5
    2001
       1       3    2290
      20       0
    2305       0       0
     0.0     0.0    10.0     0.0
    1300      19    10.0
    2115      10    10.0
    2120      22     7.5
    3001
       1       3    3275
```

MN171

```
ADAPT Erosion Parameter File:  Sand Creek Watershed   Created:  8/02/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN171
       47      96       3       0       1       0       0
1.67E-05   0.010   100.0  0.1092
    0.21    0.37    0.42   0.052   800.0     4.0    0.05  1000.0
  343.00   100.0   0.120   0.120   0.120   0.120       0      12.0
100.0     0.0
       1     1.0    0.28
       2
     001     100     120     135     150     165     225     300
     001     100     120     135     150     165     225     300
       1     1.0
    0.00    0.52    0.73    0.61    0.41    0.29    0.21    0.18
```

```
      0.50      0.50      0.50      0.50      0.50      0.50      0.50      0.50
      0.02      0.01      0.02      0.02      0.02      0.02      0.02      0.01
      0.00      0.53      0.81      0.65      0.51      0.40      0.30      0.25
      0.50      0.50      0.50      0.50      0.50      0.50      0.50      0.50
      0.01      0.01      0.01      0.01      0.01      0.01      0.01      0.01
```

```
 ADAPT  Hydrology  Parameter  File:    Sand  Creek  Watershed     Created:
 7/23/99
 Soybean Corn Rotation Conservation Tillage beginning with Soybean
 Soil Map Unit - MN171
   47001  2  1  1  1  0  0  0  0  1  1  0  0  0 graphics=no
   343.00     3.47     24.0     4.00     75.0     0.12     1.0    45.00
   1100.0      44.0       2.0       7.0      98.0       6.0     1.75      0.00
10       17
        0     48.0       3      9.0     36.0    180.0
     0.45     0.40     0.38
     0.13     0.17     0.14
     3.00     0.80     0.30
    21.00    29.50    25.00
    37.40    36.80    36.50
     3.47     1.16     1.34     .002
     3.47     1.16     1.34
     0.45      0.43      0.41      0.38      0.34      0.30      0.28      0.23
0.16     0.13
      5.0      20.0      40.0      80.0     150.0     300.0     400.0    1000.0
5000.0 15300.0
     0.40      0.40      0.39      0.38      0.36      0.33      0.32      0.27
0.20     0.17
      5.0      20.0      40.0      80.0     150.0     300.0     400.0    1000.0
5000.0 15300.0
     0.38      0.38      0.37      0.35      0.33      0.29      0.28      0.24
0.18     0.14
      5.0      20.0      40.0      80.0     150.0     300.0     400.0    1000.0
5000.0 15300.0
   0.2000   0.2000   0.2000   0.2000   0.1429   0.0895   0.0628   0.0449
0.0329   0.0245
   0.0191   0.0117   0.0080   0.0057   0.0031   0.0015   0.0000
      0.0      10.0      20.0      30.0      40.0      50.0      60.0      70.0
80.0     90.0
    100.0    120.0    140.0    160.0    200.0    250.0    550.0
    180.0      0.0     2160     48.0      0.5      1.0
      168       260       368       426       496       535       557       486
366      237
      146       124
       47        96       50
       58      1130     1275              35.00              0         0
0       1.0
        0
```

```
ADAPT  NUTRIENT  Parameter  File                                   Created:
10/13/99
Soybean  Corn  Rotation  in  the  Sand  Creek  Watershed  beginning  with
Soybean
Soil Map unit = MN171 - Conventional/Broadcast Tillage
```

```
       47        96         1        50         1         0   0   0
    500.0       3.1

        2         2         2
    444.0     100.0       1.0

     0.06      0.06     0.061
       10         1       0.1

     1001
        1         3      1275
       58         1
     1305         0         0
    140.0       0.0      20.0       0.0
     0300        19      10.0
     1115        10      10.0
     1130        22       7.5
     2001
        1         3      2290
       20         0
     2305         0         0
      0.0       0.0      10.0       0.0
     1300        19      10.0
     2115        10      10.0
     2120        22       7.5
     3001
        1         3      3275
```

MN178

```
ADAPT Erosion Parameter File:  Sand Creek Watershed   Created:  8/02/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN178
       47        96         3         0         1         0         0
1.67E-05     0.010     100.0    0.1092
     0.13      0.20      0.67     0.026     800.0       4.0      0.05    1000.0
   343.00     100.0     0.071     0.071     0.071     0.071              0        7.1
100.0         0.0
        1       1.0      0.28
        2
      001       100       120       135       150       165       225       300
      001       100       120       135       150       165       225       300
        1       1.0
     0.00      0.52      0.73      0.61      0.41      0.29      0.21      0.18
     0.50      0.50      0.50      0.50      0.50      0.50      0.50      0.50
     0.02      0.01      0.02      0.02      0.02      0.02      0.02      0.01
     0.00      0.53      0.81      0.65      0.51      0.40      0.30      0.25
     0.50      0.50      0.50      0.50      0.50      0.50      0.50      0.50
     0.01      0.01      0.01      0.01      0.01      0.01      0.01      0.01
```

```
ADAPT  Hydrology  Parameter  File:    Sand  Creek  Watershed     Created:
8/06/99
Soybean Corn Rotation Conservation Tillage beginning with Soybean
Soil Map Unit - MN178
```

```
     47001  2  1  1  1  0  0  0  0  1  1  0  0  0 graphics=no
     343.00      6.72     24.0     4.00     75.0    0.071      1.0    45.00
     1100.0       44.0       2.0       7.0      98.0        6.0      1.75      0.00
  10        17
             0      48.0        3     8.00     29.0    180.0
         0.41      0.40      0.26
         0.10      0.10      0.05
         1.50      0.50      0.20
        13.00     14.00      6.00
        20.10     41.10      1.30
         6.72      1.71     25.85     .002
         6.72      1.71     25.85
         0.41       0.38       0.35       0.31       0.27       0.23       0.21       0.17
  0.12      0.10
          5.0       20.0       40.0       80.0      150.0      300.0      400.0     1000.0
  5000.0 15300.0
         0.40       0.39       0.38       0.35       0.31       0.26       0.25       0.19
  0.13      0.10
          5.0       20.0       40.0       80.0      150.0      300.0      400.0     1000.0
  5000.0 15300.0
         0.26       0.20       0.17       0.14       0.12       0.11       0.10       0.08
  0.06      0.05
          5.0       20.0       40.0       80.0      150.0      300.0      400.0     1000.0
  5000.0 15300.0
     0.2000     0.2000     0.2000     0.1738     0.0936     0.0562     0.0360     0.0212
  0.0105    0.0042
     0.0013   0.0002   0.0001   0.0001   0.0000   0.0000   0.0000
          0.0       10.0       20.0       30.0       40.0       50.0       60.0       70.0
  80.0      90.0
       100.0    120.0    140.0    160.0    200.0    250.0    500.0
       180.0      0.0     2160     48.0      0.5      1.0
          168        260        368        426        496        535        557        486
  366       237
          146        124
           47         96         50
           58       1130       1275                  35.00                    0          0
  0        1.0
            0

ADAPT  NUTRIENT  Parameter  File                                                Created:
10/13/99
Soybean  Corn  Rotation  in  the  Sand  Creek  Watershed  beginning  with
Soybean
Soil Map unit = MN178 - Conventional/Broadcast Tillage
           47        96         1        50         1        0  0  0
     500.0       3.1

            2         2         2
     444.0     100.0       1.0

      0.06      0.06     0.061
        10         1       0.1

      1001
```

```
       1       3    1275
      58       1
    1305       0       0
   140.0     0.0    20.0     0.0
    0300      19    10.0
    1115      10    10.0
    1130      22     7.5
    2001
       1       3    2290
      20       0
    2305       0       0
     0.0     0.0    10.0     0.0
    1300      19    10.0
    2115      10    10.0
    2120      22     7.5
    3001
       1       3    3275
      58       1
```

MN196

```
ADAPT Erosion Parameter File:  Sand Creek Watershed   Created:  8/02/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN196
      47      96       3       0       1       0       0
1.67E-05   0.010   100.0  0.1092
    0.24    0.37    0.39   0.104   800.0     4.0    0.05  1000.0
  343.00   100.0   0.069   0.069   0.069   0.069       0     6.9
100.0    0.0
       1     1.0    0.28
       2
     001     100     120     135     150     165     225     300
     001     100     120     135     150     165     225     300
       1     1.0
    0.00    0.52    0.73    0.61    0.41    0.29    0.21    0.18
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
    0.02    0.01    0.02    0.02    0.02    0.02    0.02    0.50
    0.00    0.53    0.81    0.65    0.51    0.40    0.30    0.01
    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.25
    0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.50
                                                            0.01
```

```
ADAPT  Hydrology  Parameter  File:   Sand  Creek  Watershed     Created:
8/06/99
Soybean Corn Rotation Conventional Tillage beginning with Soybean
Soil Map Unit - MN196
  47001  2  1  1  1  0  0  0  0  1  1  2  0  0 graphics=no
  343.00    2.04    24.0    4.00    78.0   0.069     1.0   45.00
  1100.0    44.0     2.0     7.0    98.0     6.0    1.75    0.00
10     17
       0    48.0       3   22.00    41.0   180.0
    0.52    0.44    0.40
    0.17    0.21    0.17
    6.00    2.00    0.70
   23.50   29.50   25.00
```

```
     37.20   36.80   36.50
      2.04    0.54    0.54   .0002
      2.04    0.54    0.54
      0.52     0.51     0.49     0.47     0.43     0.38     0.36     0.29
0.21    0.17
       5.0     20.0     40.0     80.0    150.0    300.0    400.0   1000.0
5000.0 15300.0
      0.44     0.44     0.44     0.43     0.43     0.40     0.39     0.34
0.25    0.21
       5.0     20.0     40.0     80.0    150.0    300.0    400.0   1000.0
5000.0 15300.0
      0.40     0.40     0.40     0.39     0.37     0.35     0.33     0.28
0.21    0.17
       5.0     20.0     40.0     80.0    150.0    300.0    400.0   1000.0
5000.0 15300.0
   0.2000    0.2000   0.2000   0.2000   0.2000   0.1876   0.1376   0.0996
0.0754  0.0577
   0.0472  0.0324  0.0234  0.0173  0.0106  0.0060  0.0000
       0.0     10.0     20.0     30.0     40.0     50.0     60.0     70.0
80.0    90.0
     100.0   120.0   140.0   160.0   200.0   250.0   500.0
     180.0     0.0     960    48.0     0.5     1.0
       168      260      368      426      496      535      557      486
366     237
       146      124
        47       96       50
        58     1130     1275               35.00                 0        0
0      1.0
         0

ADAPT NUTRIENT Parameter File                                  Created:
10/13/99
Soybean  Corn  Rotation  in  the  Sand  Creek  Watershed  beginning  with
Soybean
Soil Map unit = MN196 - Conventional/Broadcast Tillage
      47       96        1       50        1       0  0  0
   500.0      3.1

       2        2        2
   444.0    100.0      1.0

    0.06     0.06    0.061
      10        1      0.1

    1001
       1        3     1275
      58        1
    1305        0        0
   140.0      0.0     20.0      0.0
    0300       19     10.0
    1115       10     10.0
    1130       22      7.5
    2001
```

Appendix C: Nonpoint THRUs

Representative Farm Units

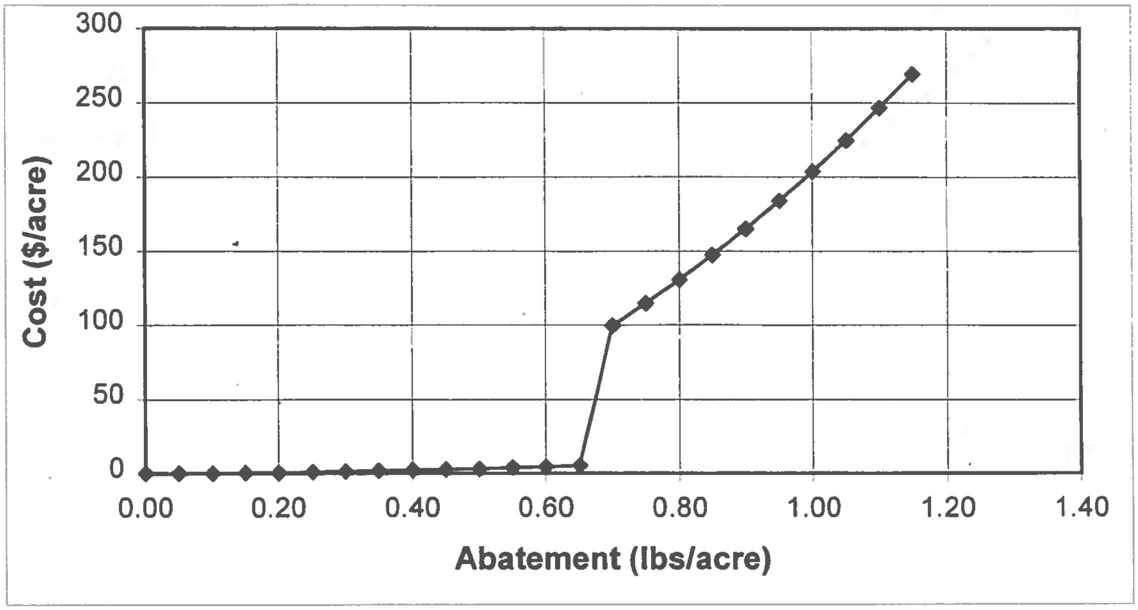
THRU	Acres	Soil Types	Slope	Drain Spacing	Distance to Water Channel
MN079a	59,014	Lester – 55% LeSueur – 12% Cordova – 10%	0.060	120 feet	> 300 feet
MN080a	11,673	Lester – 55% Hamel – 10% LeSueur – 9%	0.069	120 feet	> 300 feet
MN081a	8,476	Lester – 33% Muskego – 15% Hayden – 7%	0.072	180 feet	> 300 feet
MN163a	8,300	Kilkenny – 39% Caron – 15% Hamel – 8%	0.058	120 feet	> 300 feet
MN165a	2,525	Chaska – 24% Minneiska – 19% Colo – 14%	0.069	80 feet	> 300 feet
MN169a	1,433	Sparta – 23% Estherville – 13% Waukegan – 12%	0.092	180 feet	> 300 feet
MN171a	508	Lester – 25% Hawick – 17% Terril – 13%	0.12	180 feet	> 300 feet
MN178a	549	Etter – 18% Rockton – 17% Copaston – 16%	0.06	180 feet	> 300 feet
MN196a	34,953	Kilkenny – 34% Hamel – 26% Lerdal – 17%	0.06	80 feet	> 300 feet
MN079b	9,219	Lester – 55% LeSueur – 12% Cordova – 10%	0.060	120 feet	< 300 feet

MN080b	1,806	Lester – 55% Hamel – 10% LeSueur – 9%	0.069	120 feet	< 300 feet
MN081b	1,373	Lester – 33% Muskego – 15% Hayden – 7%	0.072	180 feet	< 300 feet
MN163b	1,928	Kilkenny – 39% Caron – 15% Hamel – 8%	0.058	120 feet	< 300 feet
MN165b	500	Chaska – 24% Minneiska – 19% Colo – 14%	0.069	80 feet	< 300 feet
MN169b	366	Sparta – 23% Estherville – 13% Waukegan – 12%	0.092	180 feet	< 300 feet
MN171b	33	Lester – 25% Hewick – 17% Terril – 13%	0.12	180 feet	< 300 feet
MN178b	73	Etta – 18% Rockton – 17% Copaston – 16%	0.06	180 feet	< 300 feet
MN196b	5,665	Kilkenny – 34% Hamel – 26% Lerdal – 17%	0.06	80 feet	< 300 feet

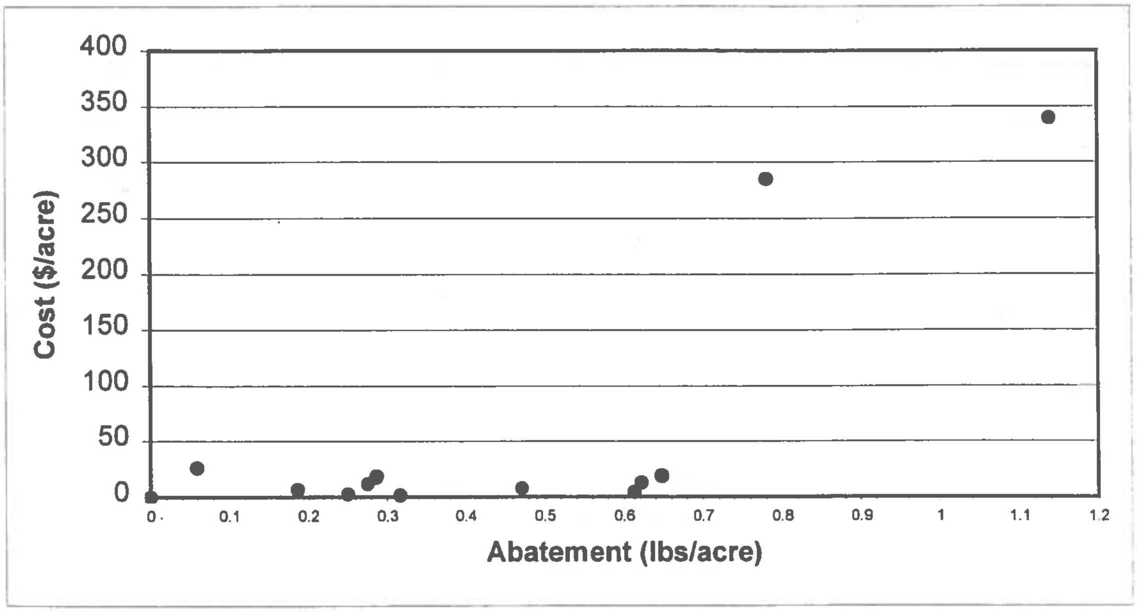
BMP Simulations by THRUs

MN079 (Edge-of-Field)

Abatement Cost Function-Spline

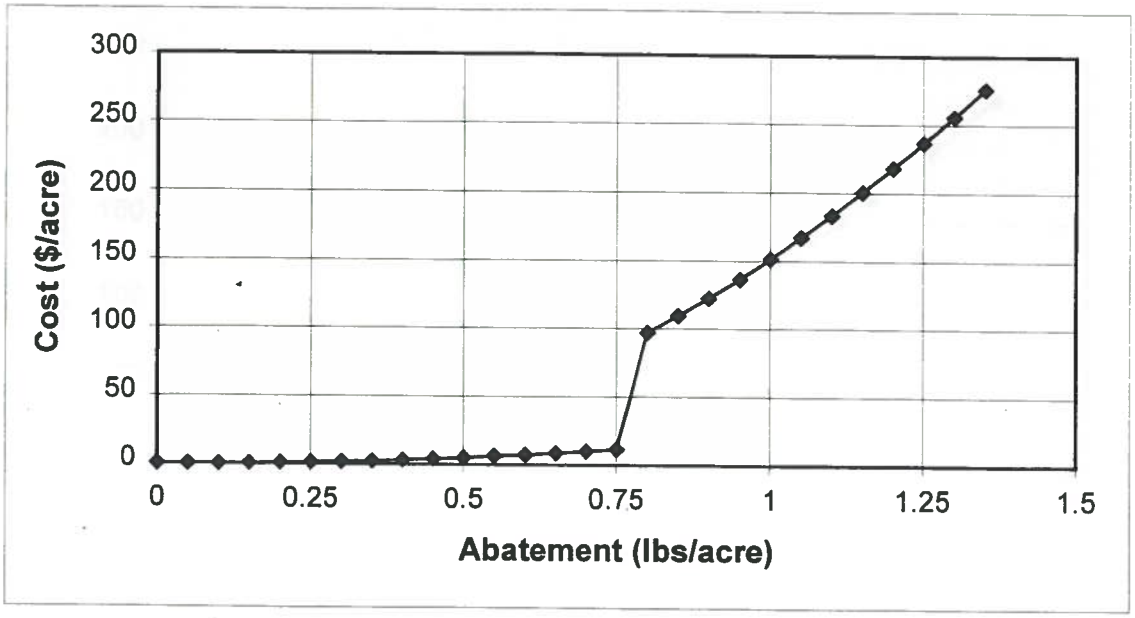


Simulated Observations

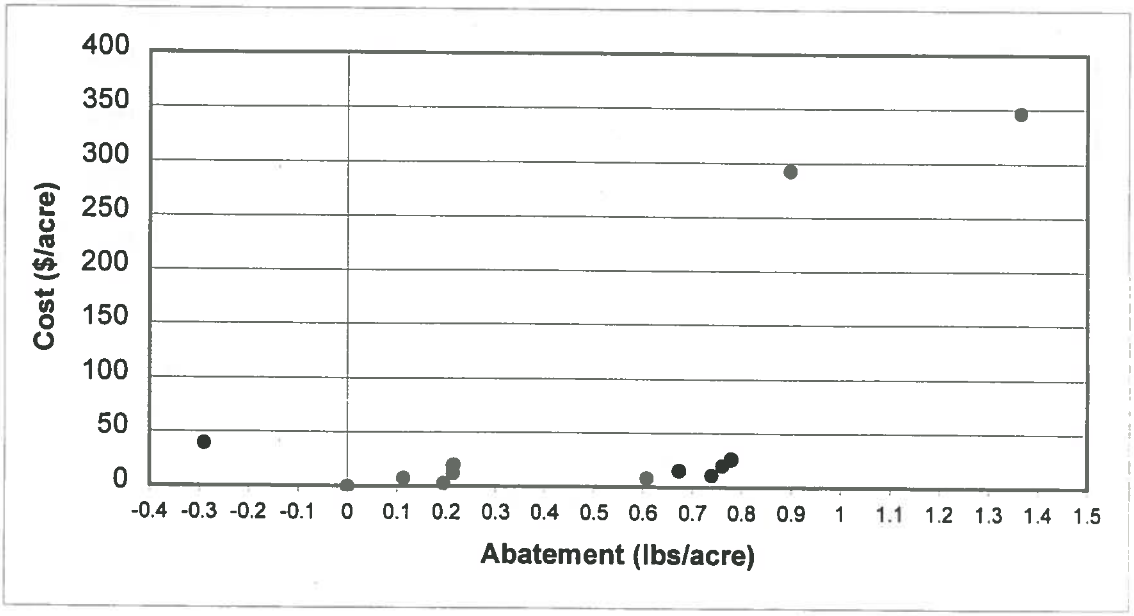


MN080 (Edge-of-Field)

Abatement Cost Function-Spline

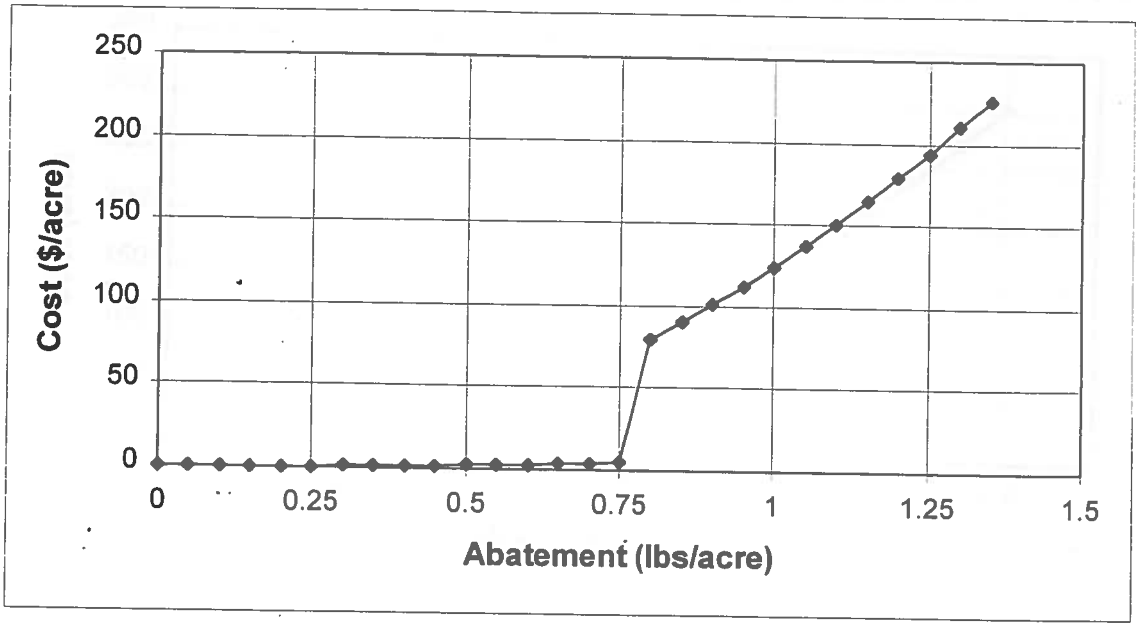


Simulated Observations

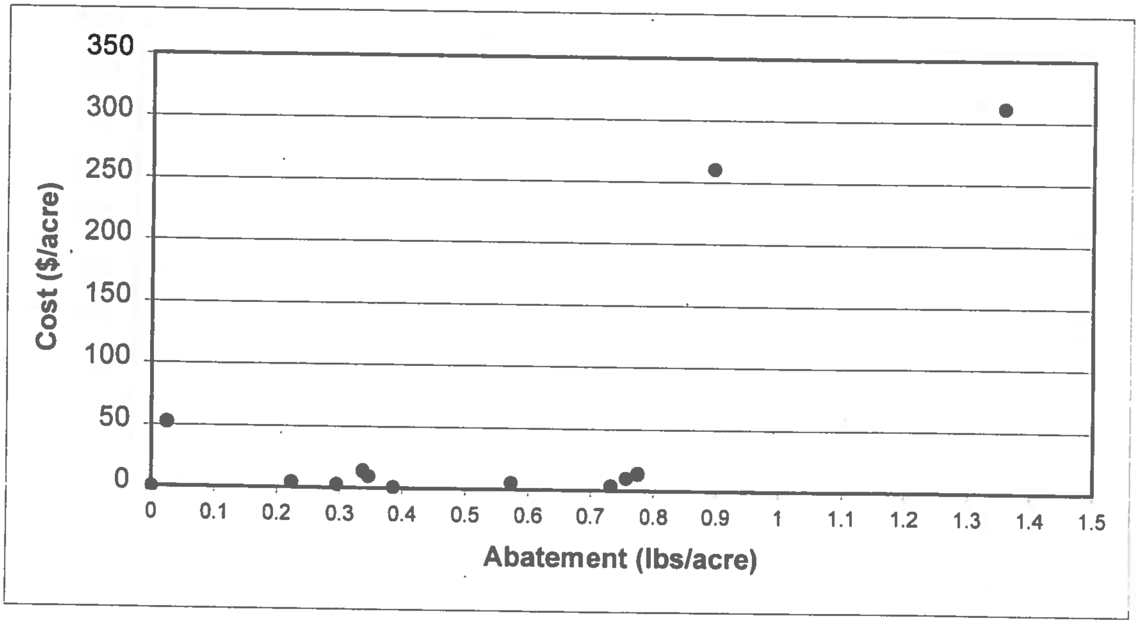


MN081 (Edge-of-Field)

Abatement Cost Function-Spline

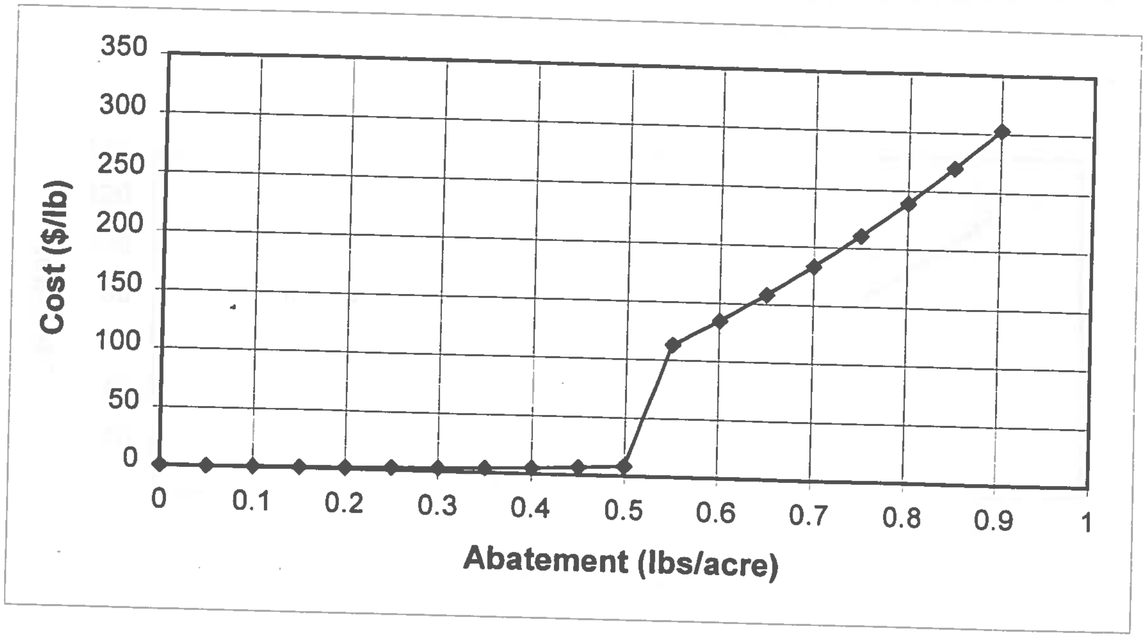


Simulated Observations

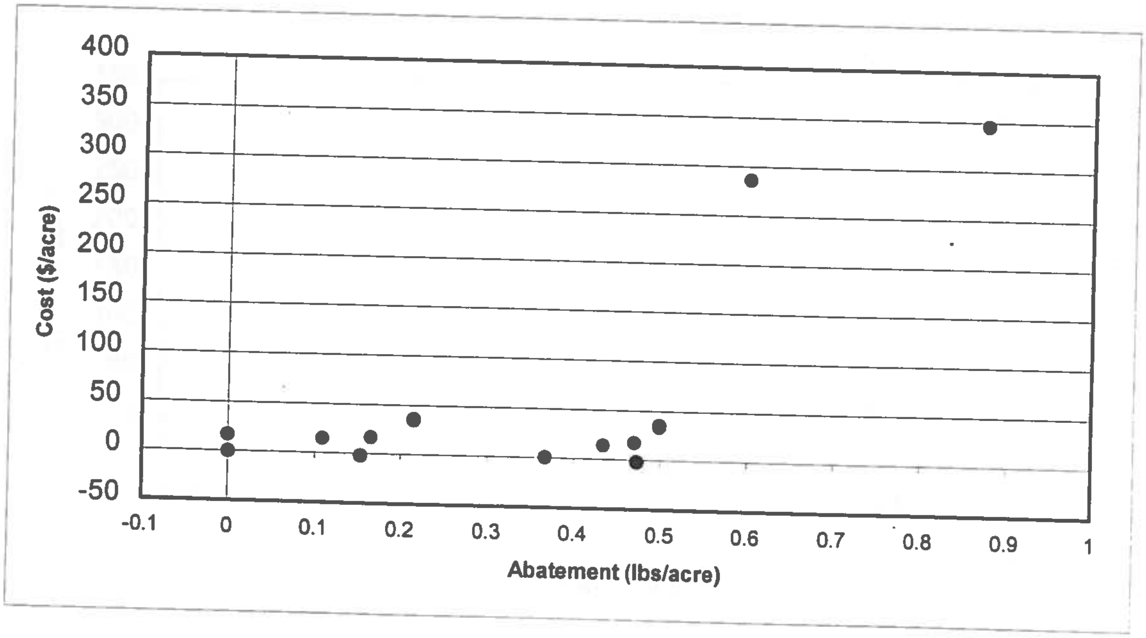


MN163 (Edge-of-Field)

Abatement Cost Function-Spline

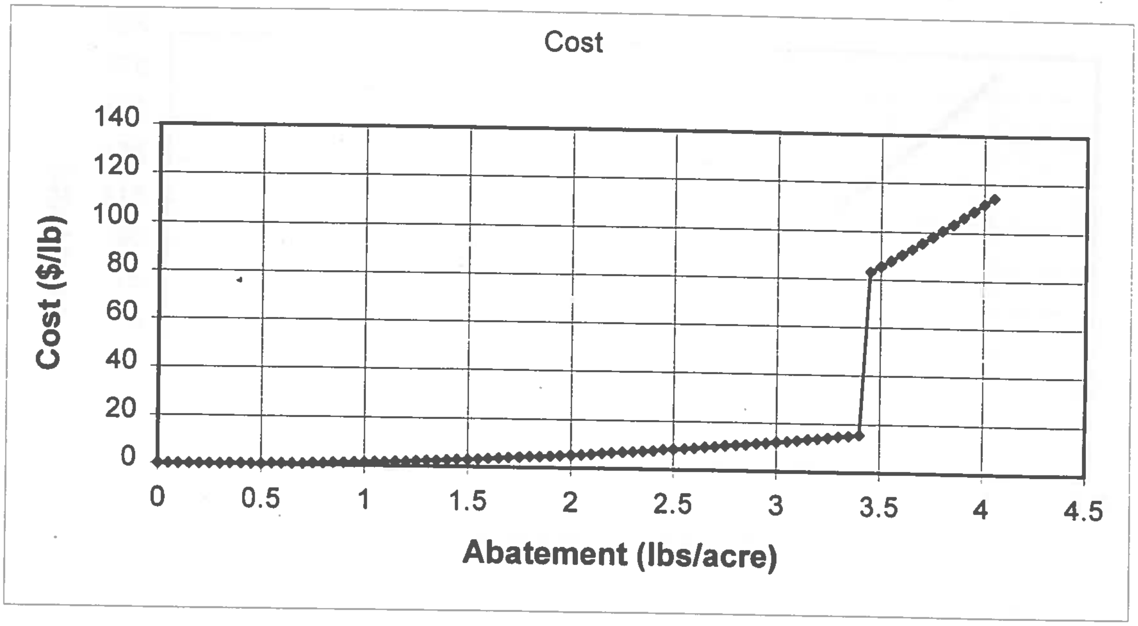


Simulated Observations

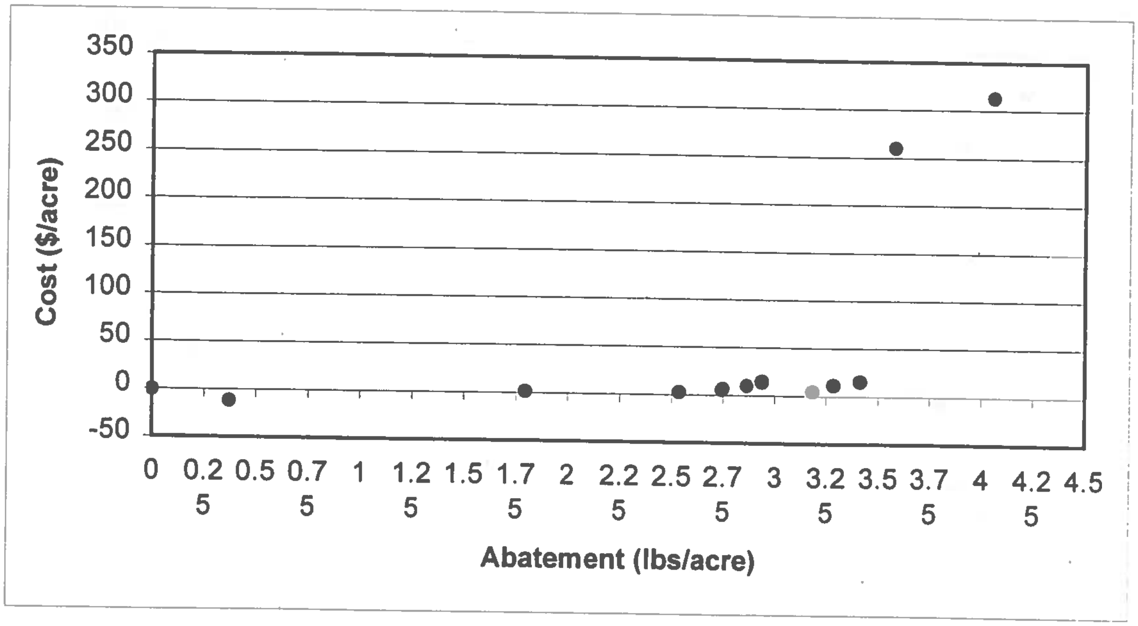


MN165 (Edge-of-Field)

Abatement Cost Function-Spline

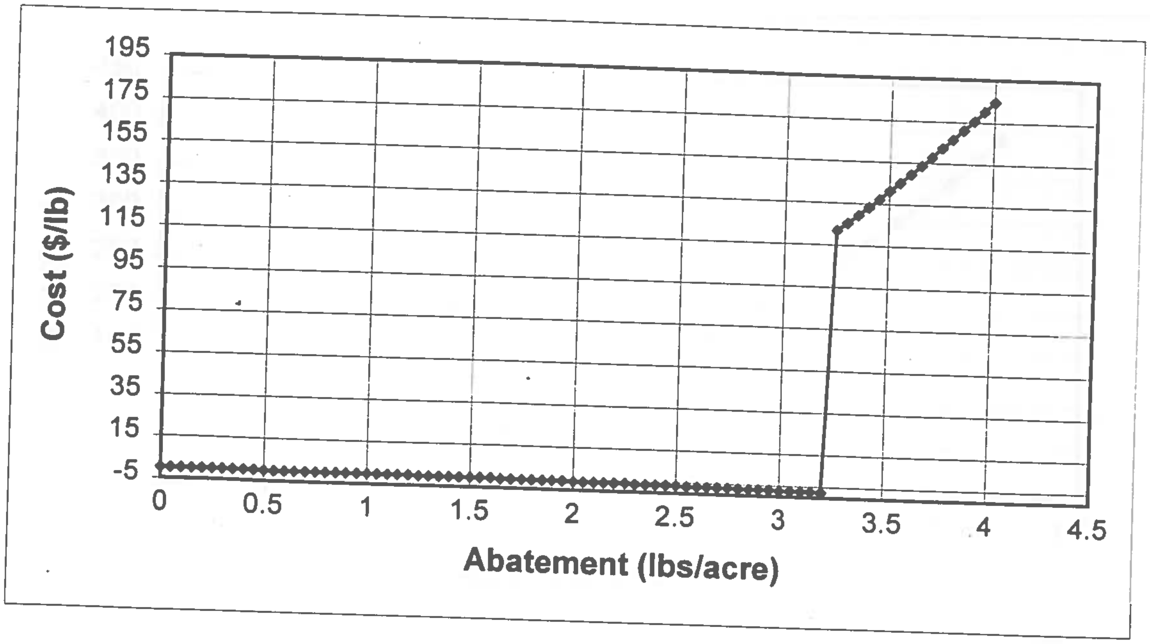


Simulated Observations

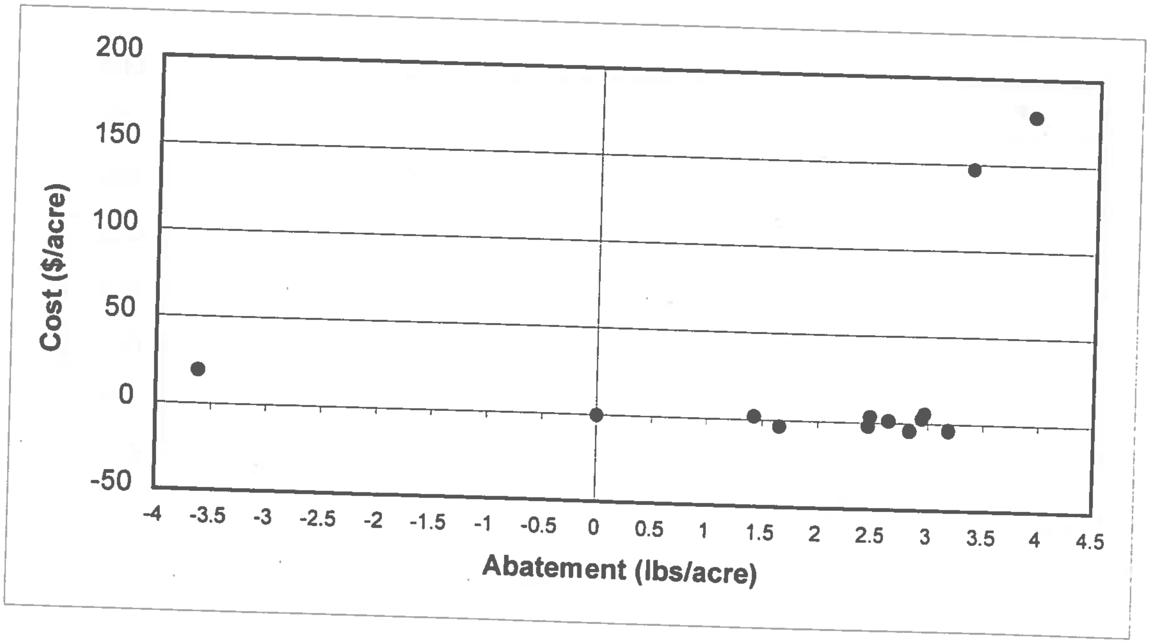


MN169 (Edge-of-Field)

Abatement Cost Function-Spline

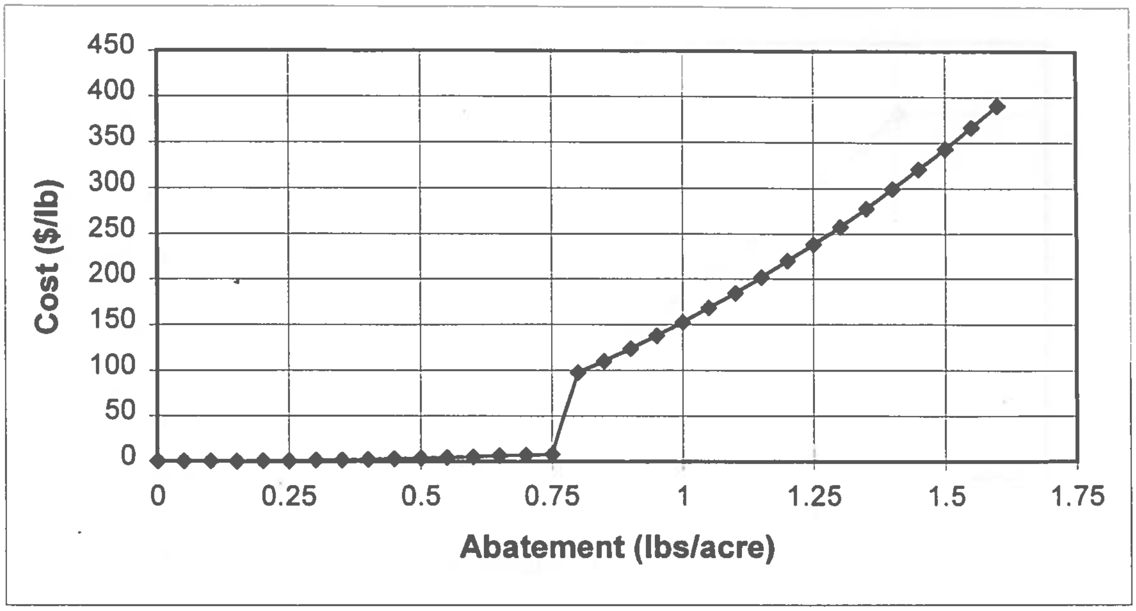


Simulated Observations

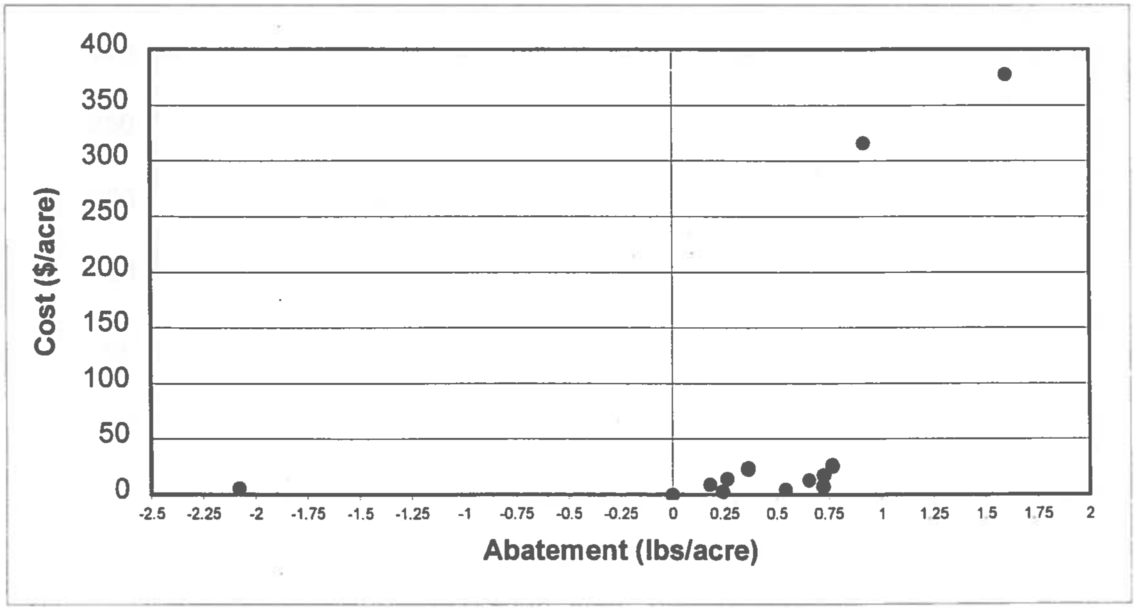


MN171 (Edge-of-Field)

Abatement Cost Function-Spline

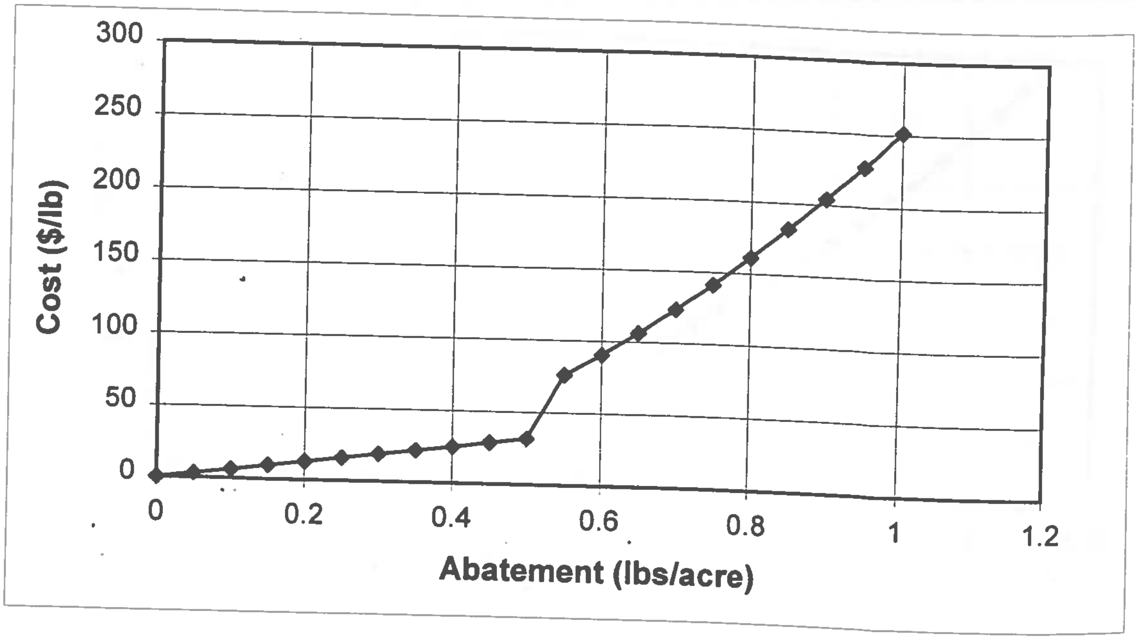


Simulated Observations

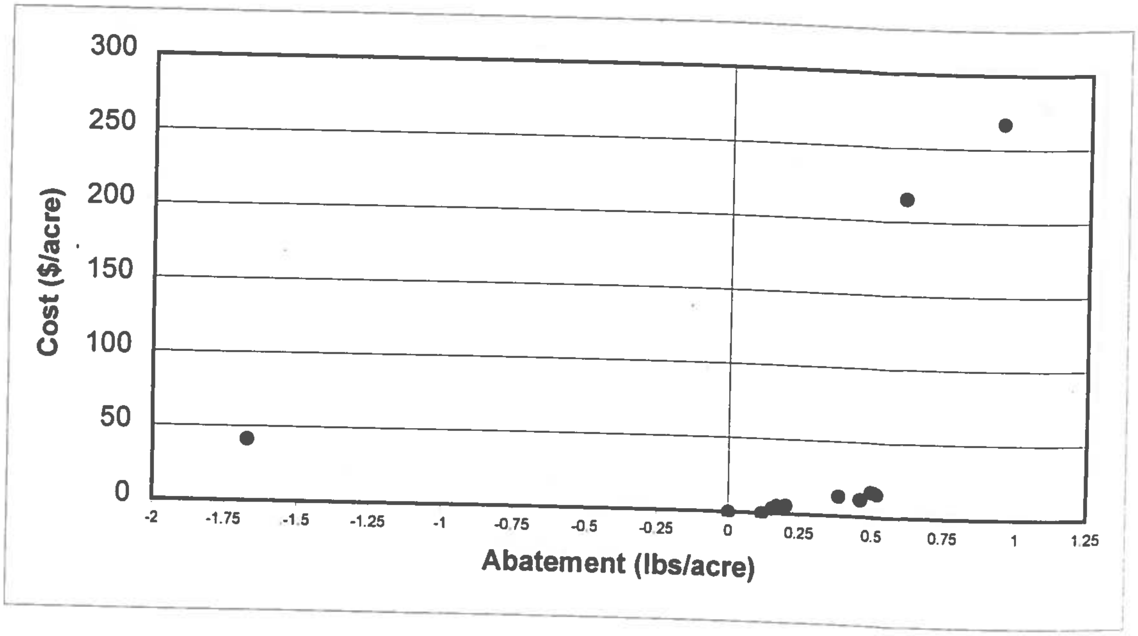


MN178 (Edge-of-Field)

Abatement Cost Function-Spline

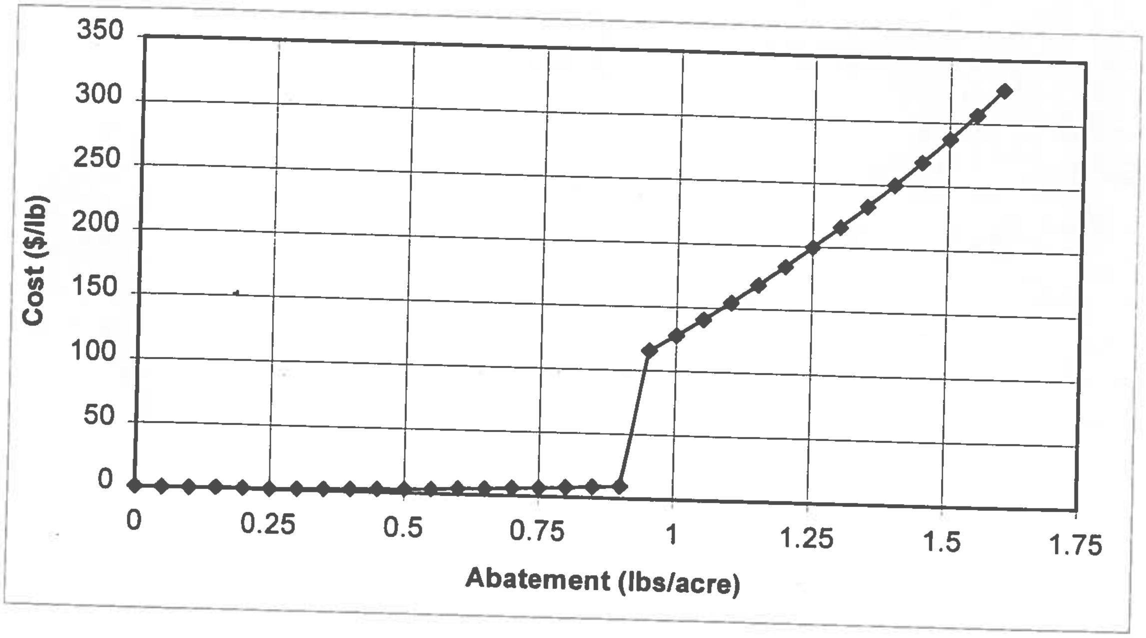


Simulated Observations



MN196 (Edge-of-Field)

Abatement Cost Function-Spline



Simulated Observations