Chapter 2

Comparing Options for Addressing Nonpoint-Source Pollution

Water pollution is an externality to production that prevents an efficient allocation of resources. One role of public policy is to correct such externalities. To do so, an agency must take into account a number of considerations in selecting a policy instrument. Weighing on these considerations are the unique characteristics of agricultural nonpoint source pollution. Nonpoint source pollution cannot be easily traced back to individual sources, and its movement is a stochastic process related to weather, topography, and land use. However, limitations in information do not prevent the design of economically sound pollution control policies.

Introduction and Overview

In chapter 1, we showed the economic costs associated with nonpoint-source pollution to be significant. In this chapter, we formalize the nonpoint problem by first discussing the characteristics of nonpoint-source pollution and then examining why government intervention is necessary. Next, we focus on how the unique characteristics of nonpoint-source pollution influence policy design and limit the options for cost-effective control. Finally, issues related to the appropriate level of government (Federal, State, local) for carrying out nonpoint-source pollution policies are discussed.

Characteristics of Nonpoint-Source Pollution

Agricultural water pollution is described as "nonpoint source" (NPS) pollution because emissions (runoff) from each farm are diffuse. Runoff does not emanate from a single point, but leaves each field in so many places that accurate monitoring would be prohibitively expensive (Braden and Segerson, 1993; Shortle and Abler, 1997). The amount and quality of runoff leaving a field depend not only on factors that can be measured, such as the technology used and the use of variable inputs, but also on factors such as rainfall that vary daily and are difficult to predict (Braden and Segerson, 1993; Shortle and Abler, 1997).[1]

The relationship between agricultural production and damages from water pollution is complex, involving physical, biological, and economic links (fig. 2.1). How well a policy performs often depends on how well these links are understood. The first link (runoff) is between production practices and movement of pollutants off a field. Important variables include rainfall, soil characteristics, slope, crop management, chemical management, water management, and conservation practices. These factors combine to determine the amount of soil particles, nutrients, and pesticides that actually leave a field.

The second link consists of pollutants moving from the field to water resources, or the pollution transport process. Pollutants can travel in overland runoff and be discharged directly into the water resource, or enter small streams and waterways and be transported to larger rivers, lakes, and estuaries. The amount of pollutants that eventually reach a water resource depends on factors such as distance, rainfall, slope, vegetation, properties of agrichemicals, and intervening conservation practices such as riparian buffers and constructed wetlands.

The third link is between the agricultural pollutants discharged into water resources and water quality. Water quality is expressed in terms of physical and biological measures, including dissolved oxygen, temperature, turbidity, pH, ambient pollution concentrations, fish populations, algae levels, and zooplankton and bacterial concentrations. Changes in ambient pol-

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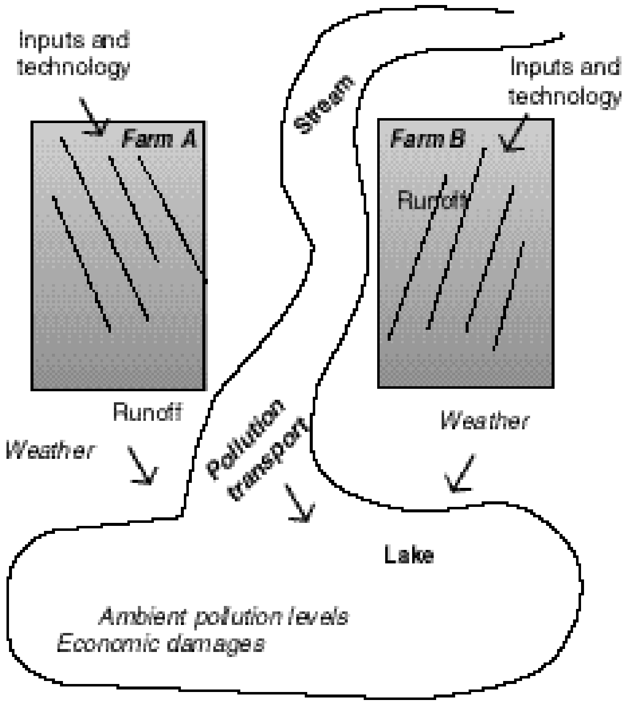
[1] Inputs are defined as those items used in production that can be applied in varying amounts (e.g., chemical fertilizers, pesticides, water for irrigation, etc.). Alternatively, technologies (or management practices) are defined as specific production techniques or methods used (e.g., conservation tillage, crop rotation, aerial pesticide applications, etc.).

Figure 2.1
Flow of agricultural pollution



lution concentrations may affect other measures of water quality (fish populations) as well.

The fourth link is how changes in ambient pollution levels (and hence water quality) affect the ability of the water resource to provide economic services. For example, the recreation potential for a water body can be affected by changes in its biological characteristics and physical appearance. Fewer fish, foul odors, algae blooms, and turbidity can all reduce the attractiveness of a potential recreation site. Suspended sediment, algae, and dissolved chemicals can increase the cost of providing water for municipal use.

The fifth link is between the services provided by the water resource and the economic (use and nonuse) value actually placed on those services. This is a function of demand by individuals, municipalities, or industry. The greater the demand for services such as recreation or industrial use, the greater their value and the greater the economic damages if impaired by pollution. Factors influencing the value of services include population, regional income, and treatment costs. The reduction in economic values due to ambient pollution levels is referred to as economic damages.

Nonpoint-Source Pollution Is an Externality

Nonpoint-source pollution (NPS) occurs at inefficiently high levels because farmers, when making their production decisions, have no incentive to consider the costs pollution imposes on others (Baumol and Oates, 1979). Economists refer to such costs as *externalities* because they are external to the production manager's decision framework. A decentralized, competitive economy will not maximize social welfare in the face of agricultural NPS pollution; farmers have no incentives to consider the social costs of pollution when making production decisions. Economic theory suggests several ways to design policies that provide the appropriate incentives for farmers to account for the costs of their pollution.

An *efficient solution* is one that maximizes expected net economic benefits—the private net benefits of production (aggregate farm profits) minus the expected economic cost of pollution.[2] Decisions must be made based on the **expectation** of what damages will be since it is impossible to accurately predict damages due to the varying nature of pollutant runoff and transport. Consequently, the efficient solution is often referred to as the ex ante efficient solution, meaning that it is the expected outcome as opposed to the actual or realized outcome.

Efficiency Conditions

The economically efficient solution is defined by three conditions (formally developed in Appendix 2A):

(1) **For each input and each site, the marginal net private benefits from the use of the input on the site equal the expected marginal external damages from the use of the input.** In other words, the last unit of the input used in production should provide an equal increase in net private benefits and expected damages. This condition is violated and the Pareto-efficient outcome forgone if farmers ignore external damages. Instead, the use of pollution-causing inputs will be too high, the use of pollution-mitigating inputs will be too low, and the resulting runoff levels will be too high.

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[2] Private net benefits from production may also include benefits to consumers and owners of factors of production. We discuss private net benefits in terms of aggregate profits for simplicity, but note that nonpoint policies may also impact consumers and factor owners by altering input and output prices.

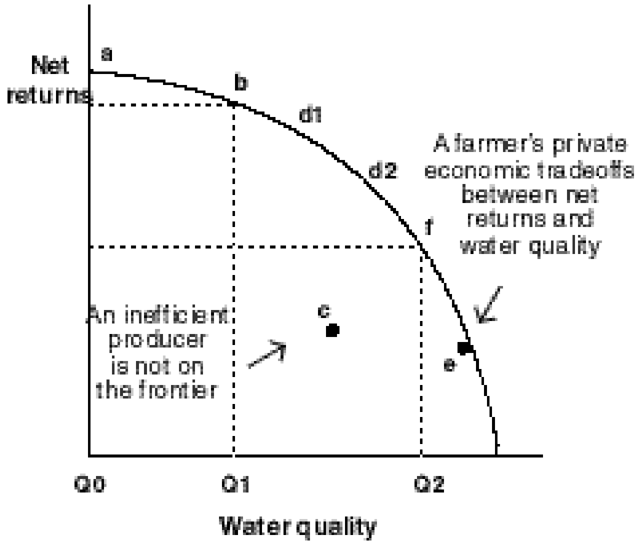
(2) **A site should be brought into production as long as profits on this site are larger than the resulting expected increase in external damage.** In other words, the benefits from allowing a site into production should exceed the expected social costs of doing so. This condition defines the optimal amount of land in production. *Marginal acreage* is defined as sites with profits equal to their expected contribution to damages in the efficient solution (or the sites with the smallest positive difference between profits and expected damage contribution). Sites with a positive (negative) difference between profits and its expected damage contribution are defined as *inframarginal (extramarginal)*. It is only efficient for the marginal and inframarginal sites to be in production. If external damages are ignored, the amount of land expected to produce profitably is greater than optimal, as is runoff and ambient pollution.

(3) **Technologies should be adopted on each site such that the incremental impact of each technology (relative to the next best alternative) on expected social net benefits is greater than or equal to the incremental impact on expected damages.**

The three efficiency conditions represent economic tradeoffs involving farm profitability (net returns) and water quality (fig. 2-2). Movement along the curve represents changes in inputs and technologies familiar to the farmer that achieve increasing levels of water quality. For instance, higher levels of water quality protection may necessitate a move away from conventional practices to ones using fewer chemical inputs, adding filter strips, and even retiring cropland. It is assumed here that higher levels of water quality can be achieved only with a loss of net returns, reflecting the fact that pollution control is typically costly.

Figure 2.2

Farmlevel tradeoff between net returns and water quality, given known technology



We assume here and throughout that a farmer's economic goal is to maximize net revenues, taking into consideration personal and family health. Suppose tradeoffs exist as in figure 2.2 and that the socially desirable level of water quality is *Q2*. With no external incentives to control pollution and no apparent personal health impacts from the pollution, a farmer's economic calculations would lead to production at point *a*. Point *a* maximizes net returns without consideration of water quality. Any movement away from *a* results in a profit loss. A farmer may have an incentive to pollute less if directly affected by onfarm practices, such as polluting a drinking water well. Such consideration, without any further incentives, may lead to the adoption of practices at point *b*, which corresponds to a water quality level of *Q1*. Essentially, the policy tools discussed in the following chapters aim to move farmers along the frontier toward *Q2*.

Nonpoint-Source Policy Goals: Cost-Effectiveness[3]

Environmental policies are cost-effective if they achieve some measurable objectives or goals at least cost. An overall strategy for water quality protection, therefore, depends on the choice of both policy goals and the instruments to achieve them. These choices are generally interdependent. Depending on the goals,

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[3] While we do not discuss this explicitly, existing market distortions that are outside of the regulatory agency's control must be taken into account when designing optimal incentives. Otherwise, the performance of incentives will be limited. A variety of agricultural policies, such as price floors, target prices, and deficiency payments, that are designed to support farm income also stimulate production. The resulting use of more chemical inputs and more intensive land use may lead to increases in nonpoint-source pollution (Miranowski, 1978; Reichelderfer, 1990; Ribaudo and Shoemaker, 1995). The 1996 Farm Act has phased out many of these policies, explicitly to reduce market distortions. Other programs, such as acreage retirement programs and paid land diversion, are supply control programs that may help to offset the effects of some support policies. Recently, some supply control programs and other agricultural conservation programs (e.g., Sodbuster, Swampbuster) have been targeted to environmentally sensitive land and linked to agricultural support policies.

it may not be possible to attain the least-cost solution with some types of policy instruments.

Water quality protection is costly to those who must pay for pollution reduction. Consequently, nonpoint policies can produce net social economic gains only if their impact is to reduce the expected damages from pollution. Reducing expected damages may not always constitute a measurable policy goal, however, because damages from NPS pollution often remain largely unquantified. In addition, the relationships among runoff, ambient pollution levels, and economic damages to society are often unknown or poorly understood (Shortle, Horan, and Abler, 1998; Baumol and Oates, 1988). Instead, it is necessary to adopt alternative goals that are measurable and that are believed to reduce expected damages—even when damages remain unknown. Potential alternatives include goals based on measurable physical (i.e., ambient water quality, expected runoff) or production-related (i.e., input use, technology) performance indicators.[4] For example, U.S. point-source policy goals are often defined in terms of ambient water quality (EPA, 1993). With nonpoint sources, ambient water quality or runoff goals must be defined in terms of a probability of occurrence (e.g., to attain a mean ambient water quality at least cost) because a particular policy could produce a variety of results due to the natural variability associated with the nonpoint process (Braden and Segerson, 1993; Shortle and Abler, 1997; Shortle, 1990).

There may be instances where achieving certain types of policy goals cost-effectively may increase expected damages. For example, suppose a policy goal is to meet a mean ambient pollution target and that Method A meets this goal at least cost (Method A is the cost-effective approach). Even if mean ambient levels are decreased, Method A may unintentionally increase the variability of pollution levels, increasing expected damages and making society worse off (Shortle, 1990). However, without the ability to measure damages, it may not be possible to recognize when such situations arise.

There are situations where a policy goal is expected to reduce damages, even though damages remain unknown. For example, Method A will reduce mean damages if ambient pollution levels are reduced for each potential state of nature (for each possible realization of random events). Similar results do not apply to runoff-based goals, however, and appropriately specified goals based on ambient pollution levels will generally be preferred (Horan, 1998).

Another problem with physically based policy goals is comparing different methods of achieving the same goal. The economically preferred method of pollution control achieves a goal with greatest expected social net benefits (defined as the sum of private pollution control costs plus the expected benefits of pollution reduction). The economically preferred method is economically superior to all other methods that achieve the same goal because it takes damages into consideration. The other methods, including cost-effective ones, do not. Since damages often remain unquantified, it would be convenient if *economically preferred* and cost-effective methods always coincided. However, the economically preferred method of achieving a physically based goal will generally differ from the cost-effective method that achieves the same goal (Horan, 1998). The differences are due to risk effects that arise because the cost-effective method does not account for the impact of each production choice on expected damages. For example, suppose Policy A corresponds to $50 in control costs and yields a $100 expected reduction in damages, for a net expected social gain of $50. Suppose Policy B achieves the same physical goal at a cost of $60, but the policy yields a $120 expected reduction in damages (a greater reduction in damages may result under Policy B if Policy B reduces the variability of pollution relative to Policy A), for an expected net social gain of $60. Policy A is the cost-effective policy because it achieved the policy goal at a lower cost. Policy B is the economically preferred policy because it generates a greater net social gain, and is the one that policymakers would choose if they had information about damages. However, Policy A will generally be chosen because economic measures of damages are seldom known.[5]

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[4] Expected runoff levels could be measured with a simulation model.

[5] With a deterministic pollution process (as is often assumed for point sources of pollution), ambient water quality goals or runoff goals can always be used to ensure a reduction in damages even when damages remain unknown, and to ensure that the least-cost method of achieving particular goals is economically preferred over all other methods. This is because ambient pollution or runoff levels can be controlled with certainty, and a deterministic reduction in these measures would correspond to a reduction in damages. Similar results do not apply to nonpoint pollution control, however,

The final class of goals is based on input use and technology choices. For example, instead of designing policies to reduce mean nitrogen loadings, the goal may be a specified reduction in nitrogen fertilizer application rates (e.g., a 20-percent reduction in nitrogen use in a watershed). Such goals provide policymakers with more direct control (than water quality goals) over the specific production factors that influence the distribution of outcomes. Consequently, these goals can be chosen to ensure both a reduction in expected damages and an expected improvement in water quality, and to ensure that the outcome is economically superior to all other possible outcomes. Obviously, complete control over the distribution of outcomes is possible only when goals are specified for each input and technology choice that influences runoff. However, adequate control (in terms of the criteria described above) is possible if goals are chosen for those producer choices that are most correlated with runoff, and if any pollution-increasing substitution effects (i.e., when producers switch to alternative technologies or inputs that may generate more pollution) are limited or of little consequence. Moreover, these goals are advantageous because they can be set deterministically, making it easier to verify whether or not the goals are met. In contrast, it may take years to obtain a large enough sample to determine if a mean ambient water quality goal is achieved (Horan, 1998).

For simplicity, we focus on three types of goals in this report: mean ambient-based goals, mean runoff-based goals, and input- and technology-based goals.[6] The cost-effective outcomes based on mean ambient goals are denoted CE(a), cost-effective outcomes based on expected runoff goals are denoted CE(r), and cost-effective outcomes based on input use and technology are denoted CE(x). All cost-effective plans are characterized by conditions similar to the efficiency conditions discussed earlier, with the expected social benefits of pollution reduction measured in terms of the policy goals.[7] Thus, nonpoint policies must encourage three types of responses for least-cost control: (1) reduction (increase) in the use of variable inputs that increase (mitigate) runoff, (2) adoption of appropriate technologies, and (3) appropriate land-use decisions at the extensive margin (decisions about whether or not to bring land into or out of production, and what to do with land that is taken out of production—for example, plant trees, grass, etc.). The mathematical conditions describing the cost-effective solutions are provided in Appendix 2B.

Second-Best Policies and Outcomes

Cost-effective and efficient outcomes provide benchmarks from which to gauge the economic performance of alternative policies. That is, these outcomes define actions that would optimally be taken to satisfy NPS pollution policy goals in an ideal world where the set of policy instruments is not restricted and when there are no transactions costs (e.g., costs associated with implementing, administering, and enforcing policies, as well as the costs of obtaining information to design policies) associated with implementing optimally designed policies. Obviously, transactions costs and policy limitations are important and should not be ignored when designing policies. In practice with these limitations and costs, the best possible outcome would achieve policy goals at the lowest cost, given the types of instruments that are used and the costs associated with using them. Such an outcome is generally referred to as **second-best**.[8] While second-best policies are optimal in practice, their economic performance in the sense of being able to achieve a goal at least cost is still measured relative to the ideal of a cost-effective or efficient baseline. This provides a useful method of comparison between alternative types of policies, especially when data on transactions costs are unavailable (as they often are).

Characteristics of Nonpoint-Source Pollution Influence Policy Design

The characteristics of nonpoint-source pollution (unobservable runoff, natural (weather-related) variability, site-specific nature, etc.) influence how various policy options for controlling NPS pollution might

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because designing policies to control aspects of the probability distributions of ambient water quality or runoff is not the same as designing policies to control expected damages. The probability distributions associated with damages, ambient pollution, and runoff are not the same, and control of one distribution does not necessarily imply control of the other.

[6] Many other types of physical goals exist. Even though expected runoff goals are not preferred relative to other goals, we include these goals in our discussion because runoff reduction is often an important goal in practice (e.g., EPA-USDA, 1998).

[7] In addition, analogous definitions for marginal, inframarginal, and extramarginal acreage exist for cost-effective solutions, where social costs of pollution are defined in terms of policy goals.

[8] We use the term "second-best" somewhat loosely. Technically, efficient policies are first-best. Cost-effective policies are also second-best because they are not efficient. For simplicity and consistency, we make a distinction between cost-effective and alternative second-best policies.

Table 2-1—Example policy objectives

Objective	Definition
Efficiency	Maximize aggregate farm profits less expected damages
Cost-effectiveness:	
Mean ambient target	At least cost, reduce expected ambient pollution levels to a specified level. Such an outcome is denoted CE(a).
Mean runoff targets	At least cost, reduce expected runoff to specified levels. Such an outcome is denoted CE(r).
Input and technology targets	At least cost, achieve input use and technology adoption goals. Such an outcome is denoted CE(x).
Second-best	When restricted to policy instruments that are not capable of achieving policy goals at least cost, instruments can be set at levels that achieve the goals at the lowest cost possible for those instruments. The set of policy instruments may be restricted to reduce administrative and enforcement costs, and to be informationally less intensive and applied more uniformly across producers.

perform. The impacts of these characteristics on policy performance will be dealt with more fully in the following chapters, but it is useful to provide an introductory discussion here.

Observability of runoff and loadings

Agricultural nonpoint-source pollution is difficult to measure or to observe. Most problematic from a policy standpoint is the inability of policymakers (as well as farmers) to observe runoff from a field and loadings into water systems. In addition, monitoring the movement of nonpoint-source pollutants is impractical or prohibitively expensive. Impacts on ambient water quality can be observed. However, because NPS pollution is generated over the land surface and enters water systems over a broad front, and because of the natural variability of the pollution process, these measures of ambient quality do not indicate where pollutants enter the water resource or from which cropland they originate.

The inability to observe loadings would be mitigated if there were a strong correlation between ambient quality and some observable aspect of production. For example, the quality of a shallow aquifer that is entirely overlain by cropland is directly related to how the fields are managed. A policy could then be directed at the production process with a reasonable expectation of the water quality impacts. However, such correlations are extremely unlikely, and where relationships can be established, they are unlikely to hold up across a range of conditions. Because a regulator cannot infer producers' actions by observing the state of water quality, the policymaker is uncertain as to whether poor water quality is due to the failure to take appropriate actions or to undesirable states of nature, like excessive rainfall (Malik, Larson, and Ribaudo, 1994).

Finally, production inputs critical for forecasting NPS pollution may also be unobservable or prohibitively expensive to monitor. For example, there is a close correlation between chemical contamination of groundwater and the amount of a chemical applied and soil type. Chemical characteristics of the pesticide, soil characteristics, and depth to groundwater can all be easily determined. However, application rates and timing are generally not observable to a regulating agency without costly and intrusive monitoring. Producers have a special knowledge about their operations that they may not be willing to share with potential regulators.

Natural variability and pollution flows

Nonpoint-source pollution is influenced by natural variability due to weather-related events (e.g., wind, rainfall, and temperature). As a result, a particular policy will produce a distribution of water quality outcomes (Braden and Segerson, 1993). This by itself does not preclude *ex ante* efficiency through the use of standard policies. However, it greatly complicates policy design. For example, nearly all soil erosion occurs during extremely heavy rain events. Practices that control erosion from "average" rainfalls but fail under heavy rain events will likely be ineffective in protecting water resources from sediment. In addition, natural variability may limit the effectiveness of models in predicting water quality from production decisions since runoff and loadings are not observable.

The natural variability of the NPS pollution process limits policies from being able to achieve ambient or runoff targets at least cost. By nature, policies produce a distribution of results. Therefore, policy must specify both the runoff or ambient targets and the frequency at which those goals are achieved (Shortle 1987, 1990). For example, a nitrogen control policy may require that an ambient goal of 10 mg/liter be met for 75 percent of the samples taken over the course of a year.

Heterogeneous geographic impacts

The characteristics of nonpoint-source pollution vary by location due to the great variety of farming practices, land forms, climate, and hydrologic characteristics found across even relatively small areas. This site-specific nature of NPS pollution has important policy implications. For example, even if models could be developed to measure runoff and loadings, they would have to be calibrated for the site-specific qualities of each individual field. The information required for such calibration would be significant, and possibly unavailable. Therefore, spatial characteristics of cropland and transport/dispersion of pollutants introduce additional uncertainties into the estimation of loadings into water resources (Miltz, Braden, and Johnson, 1988). Policy tools flexible enough to provide cost-effective pollution control under a variety of conditions would outperform tools that are not self-adjusting (Braden and Segerson, 1993).

Transboundary effects

The effects of agricultural nonpoint-source pollution can often be felt far from their source. Chemicals with long half-lives and sediment (pollutants that tend to maintain their properties in a water environment) can affect water users far from where they originate. For example, much of the atrazine and nitrates that enter the Gulf of Mexico each year via the Mississippi River are applied to cropland in the Upper Corn Belt States of Minnesota, Iowa, and Illinois (Goolsby and other, 1993).

Uncertain water quality damages

As with most types of pollution, the economic damages associated with water quality impairment are often difficult to observe or to ascertain. Knowledge of the relationship between economic damages and water pollution is essential for establishing water quality goals or incentive levels that maximize societal welfare. The impacts of pollution on water quality are often nonmarket in nature. For example, nitrates in the Chesapeake Bay are believed to reduce submerged aquatic vegetation (SAV) levels. There is no market for SAV; however, SAV has economic value because it provides habitat for economically valuable fish populations, among other things. Without organized markets, information on the value of water quality may be difficult to obtain. Even if these impacts are observed and can be attributed to specific sources, valuation requires the use of a nonmarket valuation technique such as travel cost or contingent valuation (Ribaudo and Hellerstein, 1992). Such exercises are both time consuming and costly, and the reliability of such techniques is in question. Therefore, a cost-effective policy that achieves a more easily measured physical goal might be more practical than one based on estimated damages.

Time lags

The movement of a pollutant off a field to the point in a water system where it imposes costs on water users may take a considerable amount of time. Time lags of this sort have two policy implications. First, observed ambient water quality conditions may be the result of past management practices, or of polluters no longer in operation. Second, the results of a policy may not be immediately apparent, making it difficult to assess its effectiveness.

Selecting Policy Tools for Reducing Nonpoint-Source Pollution

Policy instruments at the Federal, State, or local level for controlling water pollution fall into five general classes: (1) economic incentives, (2) regulation, (3) education, (4) liability, and (5) research and development.[9] Policymakers must consider a number of important economic, distributional, environmental, and political characteristics when selecting an instrument.

Economic performance

The instruments differ in their ability to maximize net social benefits by correcting an externality. Some may be able to achieve only a second-best solution because external pollution costs are not fully accounted for when production decisions are made. The policy instruments also distribute costs of pollution control differently between polluters and the rest of society. For example, subsidies place the burden of pollution control on taxpayers, while taxes place the burden on polluters.

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[9] These instruments will be covered in detail in the following chapters.

The **basis** of a policy instrument is the point in the pollution stream to which the instrument is applied, and has a bearing on the performance of the instrument. Instruments can be applied either to farmers' actions or to the results of their actions. For point sources, the preferred basis is discharge because it is directly related to water quality and because it is easy to observe (Baumol and Oates, 1988). However, the choice is not so clear for nonpoint sources. Proposed bases include ambient pollution levels, expected runoff levels, input use, technology, and output. Bases most closely correlated to water quality (runoff and ambient pollution) are preferred to those that are more indirectly related, such as agricultural output (Braden and Segerson, 1993). Directing policy instruments at bases that are only indirectly correlated with water quality may lead to unrelated effects and inefficient management.

Administration and enforcement costs

The costs of administering a water quality protection policy and enforcing it are related to a variety of factors, including the nature of the pollution problem, the legal system, and the information required to implement an instrument efficiently. These costs have particular importance for policies aimed at controlling nonpoint-source pollution. Nonpoint runoff is difficult to monitor due to its stochastic and diffuse nature. Likewise, measurements of ambient concentration and chemical loss may be subject to error. In addition, while it is straightforward to monitor the use of purchased inputs, not so the use of all polluting inputs such as manure applications. If the cost of detecting noncompliance is too high, polluters will be able to skirt the policy (Braden and Segerson, 1993). Administration and enforcement costs need to be weighed against the potential environmental benefits of the policy.

Flexibility

Policy instruments may be flexible both for producers and for the managing agency. A policy instrument is flexible for producers if they are able to reduce pollution control costs by adjusting their production and pollution control decisions in the face of changing economic conditions (such as changes in input and output prices or the availability or new technologies), changing environmental conditions (such as rainfall), and site-specific physical conditions (such as slope and soil quality) and, in at least some situations, still meet policy goals.

A policy instrument is flexible for a resource management agency if it continues to provide the proper signal or incentive to producers in the face of changing economic and environmental relationships that underlie its construction. An inflexible instrument would require an adjustment to continue meeting a policy goal if conditions changed. Adjusting a policy instrument may be costly. The resource management agency is left with a choice of either efficiency loss if the instrument is not adjusted, or potentially high transactions costs if the rate is adjusted. Flexibility is an empirical issue that has not been addressed in the nonpoint literature and that will likely depend on specific circumstances. However, in the face of changing economic and environmental relationships, flexibility may be increased if the agency has fewer instruments to adjust. For example, if a single runoff tax can be used to provide the same results as two input taxes, then the runoff tax would be more flexible for the agency because fewer adjustments would be required if relationships changed. In this report, we focus primarily on flexibility with respect to producers, and also on flexibility for an agency in terms of how many instruments are required.

Innovation

A policy instrument should encourage and reward farmers for using their unique knowledge of the resource base to meet policy goals (Shortle and Abler, 1994; Bohm and Russell, 1985; Braden and Segerson, 1993). Instruments that provide these incentives are more likely to achieve cost-effective control than those that do not.

Political and legal feasibility

Even though several policy instruments are equally capable of an economically efficient outcome, they may not be perceived as equal for legal or political reasons. The difficulty in observing nonpoint runoff may be a source of legal problems for instruments using runoff or ambient quality as a base. For example, it may be difficult to hold individual farmers legally responsible for observed water quality damages when the sources of NPS pollution cannot be observed. The stochastic nature of nonpoint pollution also makes it difficult to accurately infer damages or runoff based on farm practices (Shortle, 1984; Tomasi, Segerson, and Braden, 1994). In addition, ambient pollution levels may be the result of past management decisions due to time lags in pollution transport. Thus, absent contributors to the ambient pollution level may cause current farming operations to be unfairly punished.

An instrument's political feasibility may be related to ethical and philosophical arguments. For example, in the absence of any water quality laws, the right to clean rivers and streams is not assigned to any group. As a result, an activity such as farming, which produces runoff that can pollute rivers and streams, is not obliged to consider the impacts of its activities. This can be considered an implicit "right" to pollute. Taxes and permits may then be politically unpopular among farmers because these instruments implicitly shift pollution "rights" from farmers to the users of water resources. Alternatively, a subsidy to reduce pollution implicitly affirms the producer's "right" to pollute. Those who seek cleaner water must pay for it. This position may be protested by the victims of pollution, who believe they have a right to clean water, and by other industries that are legally required to reduce pollution. In an era of widespread anti-tax sentiment, a tax-based environmental policy may be impossible to implement, despite efficiency considerations.

Choosing an Appropriate Institutional Structure

Are water quality programs best implemented at the local, State, regional, or national levels, and with what type of coordination across levels? Major government activities for any environmental policy include setting standards, selecting appropriate policy tools, implementation, and enforcement. Policy can be centralized, where all activities are handled by the Federal Government (possibly with local input), or localized with State or local governments having all or most of the responsibilities. Braden and Matsueda (1997) present a set of environmental problem characteristics that can be used to determine the level of governance best able to provide efficient control. Some of these characteristics involve the nature of the pollution problem, while others concern the abilities of different levels of government to operate programs efficiently.

Regional differences

Nonpoint-source pollution varies by place due to the great variety of farming practices, land forms, climate, and hydrologic characteristics found across even small areas. Since benefits and costs of policies are likely to vary along with these factors, a policy should take them into account (Shortle, 1995; Sunding, 1996)

Both centralized and local governments can tailor policy to local conditions. A centralized policy would require that decisionmakers obtain much local information, resulting in potentially high transaction costs (Fort, 1991). These costs could be reduced by using more uniform standards and policies, but at the expense of greater inefficiency. Local governments are better able to set standards that reflect local demands for water quality and to take into account local economic and physical characteristics in setting policy (assuming they have the resources to acquire information). Many Federal environmental laws recognize local variation and pass some of the responsibilities for standard setting and policy implementation to the States.

Influence of interest groups

Through bargaining and other influences, special interest groups can often influence both the quantity and price of public goods such as environmental quality, resulting in an inefficient allocation of resources (Braden and Matsueda, 1997). Decentralized policies give local special interests more influence because they are proportionately larger and face less competition in the local economy than in, say, the national economy (Fort, 1991; Esty, 1996; Braden and Matsueda, 1997; Lester, 1994). For instance, threats to move an important local industry could influence local leaders to underprovide environmental protection. Agricultural interests often have an important voice in agricultural areas where nonpoint-source pollution would be generated. Centralized policies would have an advantage over local policies in counteracting local special interests.

Uncertainty

Uncertainty can take two forms: uncertainty about the causes and consequences of an environmental problem, and uncertainty about the consequences of public policies (Braden and Matsueda, 1997). Nonpoint-source pollution is characterized by uncertainty in production, movement, and impacts on water quality. Uncertainty about the causes and consequences of an environmental problem can be reduced through research. Environmental research generates information that is a pure public good, and so its cost is appropriately spread across the entire population (Braden and Matsueda, 1997). Centralized government is seen as better suited to provide this research because the research results would be available to all (Braden and Matsueda, 1997; Esty, 1996).

An advantage posited for decentralized policies is that States will try different policy approaches, and through these "experiments" the most effective policies will emerge (Esty, 1996; Braden and Matsueda, 1997); however, no single researcher controls experiments, tabulates results, or draws conclusions. A centralized system, with State cooperation, could be in a better position to conduct policy experiments. Centralized leadership could set the limits or scope of policy experiments; spread the costs of research, data gathering, and interpretation; and subsidize sharing of information with States (Braden and Matsueda, 1997).

Transboundary issues

Local jurisdictions have an advantage over more centralized authorities in developing policies tailored to local conditions. However, some agricultural pollutants travel long distances (Goolsby and others, 1993). Under these circumstances, the smaller the jurisdictions providing environmental protection, the greater the chance for the costs of pollution and benefits of policies to fall outside (Esty, 1996). Locally based policies tend to account only for local benefits and costs (Braden and Matsueda, 1997; U.S. Congress, 1997). The result is an inefficient allocation of resources. A basic principle of federalism is that economic efficiency in the provision of public goods is best served by delegating responsibility for the provision of the good to the lowest level of government that encompasses most of the associated benefits and costs (Shortle, 1995). With pollutants that travel long distances, this prinicple could enlist very large regions.

Widespread, routine transboundary problems require policies that apply widely; a centralized authority might achieve economies of scale in setting standards and implementing policy (Braden and Matsueda, 1997). Efficient policy requires that all beneficiaries be considered, even if they reside outside a government's area of control (Esty, 1996; Fort, 1991). This includes those who suffer from pollutants transported outside the area of jurisdiction (transboundary supply) as well as consumers who reside outside the jurisdiction area but value water quality within (transboundary demand). Following the rule of fiscal federalism, defining jurisdiction on the basis of all beneficiaries leads to more centralized policies.

Of course, local jurisdictions could handle transboundary problems through interstate agreements and compacts. However, very seldom have States come together without Federal prodding to address regional water quality issues, despite common goals and the fact that an individual State may be unable to meet water quality goals without better control of interstate pollution. For example, the Northeastern States for years tried to get Midwestern States to better control sulfur emissions that were causing acidification of Northeastern lakes, without success (Price, 1982). Only four compacts or inter-regional commissions are devoted to water quality and the management of major rivers that cross State boundaries: Delaware River Commission (New York, New Jersey, Delaware, and Pennsylvania), Interstate Sanitation Commission (New Jersey, New York, and Connecticut), Ohio River Valley Water Sanitation Commission (Pennsylvania, Ohio, Illinois, Indiana, Kentucky, New York, Virginia, and West Virginia), and the Susquehanna River Basin Commission (New York, Pennsylvania, and Maryland) (EPA, 1995).

Watersheds cross political jurisdictions, and by all accounts, are the most appropriate geographic units for implementing specific water quality protection plans (EPA-USDA, 1998). A watershed is the geographic area in which water, sediments, and dissolved materials drain to a common outlet—a point on a larger stream, a lake, an underlying aquifer, an estuary, or an ocean. A watershed is also known as a drainage basin. If watersheds are defined as the USGS 8-digit hydrologic unit, of which there are 2,111 in the contiguous 48 States, 35 percent of the land area in these States is within watersheds that span more than 1 State (table 2-2). Thus, States must cooperate to manage land (for nonpoint-source pollution) and point sources in order to provide efficient water quality protection in many watersheds. Without cooperation, a single State may be unable to address a water quality problem in such watersheds, or may have to implement unnecessarily stringent measures to achieve water quality goals.

If larger rivers are of most concern and the targets for water quality improvement, then individual State actions will require widespread cooperation. For example, defining watersheds at the 6-digit hydrologic unit code (600 watersheds), 71 percent of the land area is within watersheds that cross State boundaries. At

Table 2-2—Land area in watersheds that cross State borders, 48 contiguous States

State	8-digit[1]	6-digit	4-digit
		Percent	
Alabama	42	85	100
Arizona	21	53	60
Arkansas	44	71	100
California	17	40	53
Colorado`	43	92	92
Connecticut	90	100	100
Delaware	68	100	100
Florida	20	36	36
Georgia	32	66	100
Idaho	40	100	100
Illinois	43	58	68
Indiana	51	66	100
Iowa	39	100	100
Kansas	41	100	100
Kentucky	48	91	100
Louisiana	34	44	56
Maine	13	16	16
Maryland	87	100	100
Massachusetts	74	100	100
Michigan	17	42	66
Minnesota	22	60	63
Mississippi	37	100	100
Missouri	52	92	100
Montana	22	60	60
Nebraska	47	65	71
Nevada	31	85	100
New Hampshire	81	100	100
New Jersey	60	75	100
New Mexico	48	78	100
New York	41	67	70
North Carolina	51	58	58
North Dakota	27	61	87
Ohio	39	65	65
Oklahoma	50	91	100
Oregon	29	84	88
Pennsylvania	35	85	100
Rhode Island	100	100	100
South Carolina	48	74	100
South Dakota	35	87	100
Tennessee	59	100	100
Texas	21	39	41
Utah	42	95	100
Vermont	82	94	94
Virginia	57	100	100
Washington	19	29	38
West Virginia	62	100	100
Wisconsin	41	89	100
Wyoming	36	96	100
U.S.	35	71	79

[1] Hydrologic Unit Codes used to identify watersheds in the United States. There are 2,111 8-digit watersheds, 600 6-digit watersheds, and 99 4-digit watersheds.

the 4-digit hydrologic unit level (99 watersheds), 79 percent of land area is in watersheds that cross State boundaries. However, there are few examples of such cooperation. The transaction costs of all the agreements necessary to handle all transboundary problems would be enormous. Centralization, depending on the skill of the policymakers and implementers, may reduce transaction costs and maintain efficiency.

Water quality spillovers can occur not only over space, but also over time. Some dimensions of environmental quality are not easily restored once degraded. Ground water is an example. Concern for future generations is more difficult to incorporate in local policy decisions than at the national level (Oates and Schwab, 1988). An individual's children and their offspring will probably live elsewhere, creating a myopic view of environmental quality that could lead to a suboptimal provision of environmental goods (Oates and Schwab, 1988). Centralized decision-making, in principle, is better suited to internalize the "demand" for current environmental standards from future generations.

Economies of scale

A single product standard set at the national level imparts efficiency benefits on manufacturers who then do not have to meet 50 different State standards. For nonpoint-source pollution, economies exist in the technical expertise to set, monitor, and enforce standards (Braden and Matsueda, 1997; Fort, 1991; Esty, 1996; Smith and other, 1993). For example, there is no need to conduct research on the health and environmental effects of a pesticide in all 50 States. These effects would be the same everywhere. Data collection, testing quality assurance/quality control, fate and transport studies, epidemiological and ecological analyses, and risk assessments all represent highly technical activities in which expertise is important and scale economies are significant (Esty, 1996). In fact, the Federal Government provides much information in the areas of water quality monitoring, land use surveys, health studies, and fate and transport studies that States can use to implement their own programs. States may implement their own research programs to get finer detail, but many States lack the technical capacity to do this (Lester, 1994; Esty, 1996).

Interjurisdictional competition

One of the classic arguments for centralized control is the so-called "race to the bottom" (Esty, 1996; Oates and Schwab, 1988), which holds that State and local governments engage in active competitions with each other for new business (jobs and tax base). Under these conditions, local officials do not propose tax rates or environmental regulations that go much beyond those in "competing" States. The costs of environmental regulation on business are more easily translated into monetary terms than benefits, and are concentrated on a relatively few entities (polluters) (Esty, 1996). The end result is that all States under-provide environmental quality, leading to an inefficient allocation of resources.

This scenario is hotly debated (Revesz, 1992; Esty, 1996). While the argument is plausible, there has been little systematic analysis of whether States actually engage in distortionary competition (Oates and Schwab, 1988; Braden and Matsueda, 1997). Oates and Schwab used a neoclassical model to demonstrate that a race to the bottom is not inevitable and that States can provide the optimal level of public goods. However, this result requires some stringent assumptions, including no distortionary taxes (such as taxes on capital) and a "benevolent" bureaucracy that seeks and knows public values for nonmarket goods. When these assumptions do not hold, a race to the bottom cannot be discounted (Oates and Schwab, 1988).

Lester (1994) identified a number of States that are capable of providing a higher level of environmental quality but have chosen not to do so. The differences between States in the level of environmental protection is not, however, evidence of destructive competition. In fact, different environmental protection across States could be consistent with an efficient market solution. Destructive competition would be evident if environmental protection, given citizen demand for quality and the costs of control, is less than optimal in at least some States. There is currently no empirical data that destructive competition occurs (U.S. Congress, 1997).

Summary and Conclusions

Nonpoint-source pollution is produced at inefficiently high levels because farmers do not generally account for pollution's costs to others when making their production decisions. An ideal goal of policy to control such pollution is to get farmers to consider these external costs (an efficient solution). However, such a goal may be unattainable if the governing agency has limited information about damages or the pollution process. As an alternative, policy may be designed to attain specific water quality or input and technology goals (e.g., a limit on mean ambient pollution levels, or a limit on mean runoff levels) at least cost (a cost-effective solution).

The characteristics of nonpoint-source pollution pose particular challenges for designing and implementing efficient or cost-effective pollution control policies. These characteristics include:

- runoff and loadings cannot be observed;
- NPS pollution is characterized by natural (weather-related) variability;
- characteristics of NPS pollution vary over geographic space;
- pollution can travel long distances;
- water quality damages are difficult to observe or to measure;
- considerable time lags complicate assessment.

Policymakers have a number of policy tools available for addressing agricultural nonpoint-source pollution, including economic incentives (taxes, subsidies, permit trading), standards, liability, education, and research. Which ones are most appropriate depends on a number of economic, distributional, and political considerations, including how well the tool achieves the policy goals, the costs of administering and enforcing the policy, the ability of the policy to adjust to different economic and physical conditions, how well the policy encourages innovation, and political and legal feasibility.

Another issue is whether a policy is best implemented by local, State, or national levels of government, and the degree of coordination necessary for effective pollution control. The success of a particular institutional structure is influenced by geographic variability in nonpoint-source pollution characteristics, the ability of special interest groups to move a policy away from the optimal economic solution, the ability of the institutional structure to address uncertainty, the geographic scale of the pollution problem, and the likelihood of interjurisdictional competition's resulting in less-than-optimal policies.

Appendix 2A—Nonpoint-Source Pollution Policy Conditions for Efficiency[10]

Consider a situation in which a particular resource (e.g., a lake) is damaged by a single residual (e.g., nitrogen) from nonpoint sources of pollution. The ambient concentration of the pollutant is given by

$$a = a(r_1, r_2, ..., r_n, W)$$

where a is the ambient concentration ($\partial a/\partial r_1 > 0$), r_i ($i = 1, 2, ..., n$) is runoff from the ith agricultural production site, and W reflects the influences of weather and other stochastic events on the transport process.

Runoff from a particular site is a function of the production activities on that site. Production activities will involve either choices made along a continuum (e.g., chemical application rates, irrigation rates, etc.) or discontinuous choices (e.g., tillage, chemical application methods, crop choice, rotation, etc.). Continuous choices are assumed to correspond to variable input use. Denote the (m x 1) vector of inputs chosen for use on the ith acre by x_i. For simplicity, discontinuous choices are represented by a scalar, A_i, which is referred to as the technology in use. For example, $A_i = 1$ might correspond to the production of continuous corn with no-till tillage, $A_i = 2$ might correspond to production using a rotation of corn and soybeans, using mulch-till tillage, etc. Runoff from the ith site is given by the runoff function, $r_i = r_i(x_i, A_i, v_i)$, where v_i is a site-specific random variable describing natural occurrences affecting runoff. No assumptions are made about the relation between the technology's productivity and runoff (i.e., a more productive technology does not necessarily correspond to greater or lesser runoff levels). Instead, a variety of possibilities could arise, depending on the technology.

Farmers are assumed to be risk-neutral. The expected profit from site i for any choice of inputs and technology is given by the strictly concave function $\pi_i(x_i, A_i)$. Larger values of i are assumed to correspond to sites with less productive land and that are more conducive to NPS pollution generation (e.g., soil type, slope of land, distance from water etc.).[11] For simplicity, farmers in this particular region are assumed not to have any collective influence on the prices of inputs or outputs, and that input and output markets are free from distortions. Finally, the economic cost of damages caused by pollution is given by $D(a)$ (D', $D'' \geq 0$)

An *ex ante* efficient allocation maximizes the expected net surplus (quasi-rents, less environmental damage costs) to society (Just, Hueth, and Schmitz 1982, Freeman 1993). The appropriate objective function, restricted on technology, is the following[12]

$$J(A) = \underset{x_{ij},n}{Max} \sum_{i=1}^{n} p_1(x_i, A_i) - E\{D(a)\}$$

The necessary conditions for a maximum are

$$\frac{\partial J}{\partial x_{ij}} = \frac{\partial p_i}{\partial x_{ij}} - E\{D'(a)\frac{\partial a}{\partial r_i}\frac{\partial r_i}{\partial x_{ij}}\} = 0 \quad \forall i, j \qquad (2A\text{-}1)$$

$$\frac{\Delta J}{\Delta n} \approx p_n(x_n, A_n) - E\{\Delta D(a)\} \approx 0 \qquad (2A\text{-}2)$$

where $\Delta D(a) = D(a(r_1, \ldots, r_n, W)) - D(a(r_1, \ldots, r_{n-1}, W))$ (i.e., the difference in damages with and without site n).

Condition (2A-1) equates marginal net private benefits from the use of x_{ij} with expected marginal external damages from the use of the input. If the externality is ignored, then condition (2A-1) is violated and the level of input use for inputs that increase runoff (i.e., inputs for which $\partial r_i / \partial x_{ij} > 0$) will be too high while the level of input use for inputs that decrease runoff (i.e., inputs for which $\partial r_i / \partial x_{ij} < 0$) will be too low. The resulting runoff levels will be too high and a Pareto maximum will not be achieved.

Condition (2A-2) describes the incremental impact of the nth site on expected net benefits. If the nth site is defined optimally, then the addition of any other site

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[10] This appendix develops the mathematical foundations for Pareto efficiency. The basic framework closely follows that of Horan et al. (1998a) and Shortle et al. (1998a).

[11] In reality, the relationship between site productivity and conduciveness to runoff is not one-to-one. A more realistic specification would include separate, jointly distributed indices for these two attributes. See Shortle and others (1997) for a model with dual indices and Horan and others (1998a) for a formal derivation that makes use of information on both productivity and conduciveness to runoff.

[12] Following most NPS pollution literature, it is assumed that society is risk-neutral. A more general model would choose input levels in an expected utility framework.

will have a negative incremental impact. Positive profits are earned on the marginal site, n, and all inframarginal sites because $E\{\Delta D(a)\} > 0$. If external damages are ignored, the amount of land able to produce profitably is greater than otherwise. The result is increased runoff due to increased production in the industry, and hence ambient pollution levels will be higher than is economically efficient. Together, conditions (2A-1) and (2A-2) define the efficient scale of production for the marginal site.

Finally, the optimal technology vector, A^*, is determined by solving for an efficient allocation for each possible value of A and comparing expected net benefits. Technology A^* is more efficient than technology A' when $J(A^*) - J(A') > J(A')$. Thus, the optimal technology vector satisfies the condition

$$J(A^*) - J(A') \geq 0 \;\forall A' \qquad \text{(2A-3)}$$

which reduces to

$$\begin{aligned} p(x_i(A_i), A_i^*) - p_i(x_i(A_i'), A_i') &\geq E\{D(a(r_1^*, \ldots, r_i^*, \ldots, r_n^*, W))\} \\ &-E\{D(a(r_i^*, \ldots, r_{i-1}^*, r_i(x_i(A_i'), A_i', v_i), r_{i+1}^*, \ldots r_n^*, W))\} \quad \forall A_i' \end{aligned} \qquad \text{(2A-4)}$$

where $r_i^* = r_i(x_i(A_i^*), A_i^*, \nu_i)$. The choice of technology will be inefficient if the externality is ignored, due to the technology's impacts on runoff.

Appendix 2B—
Cost-Effective Policy Design

Pollution control policies can be designed to minimize costs (or, equivalently, to maximize net benefits in the absence of damages) subject to a constraint based on the ambient pollution level, a set of constraints based on runoff when the damage and pollutant transport relationships are unknown, or input and technology constraints. Policy designed in this situation will generally not be efficient; however, it can lead to a cost-effective solution as input use is allocated among farms at least cost to meet an exogenously specified constraint. Specifically, the resource management agency's problem can be written as

$$\underset{x_{ij}, A_i, n}{Max} \quad J = \sum_{i=1}^{n} p_i(x_i, A_i) \qquad \text{(2B-1)}$$

subject to a constraint or set of constraints based on an ambient or runoff target(s).

The degree of reliability with which water quality or runoff targets are to be achieved must be specified because a particular policy will produce a distribution of outcomes (Braden and Segerson 1993). Many constraints have been proposed in the literature, however, two are of particular interest (Beavis and Walker 1983; Beavis and Dobbs 1987; Shortle 1990; Horan 1998):[13]

$$E\{a\} \leq a_o \qquad \text{(2B-2)}$$

$$E\{r_i\} \leq r_{io} \;\; \forall i \qquad \text{(2B-3)}$$

where a_0 is an exogenously chosen ambient target, and r_{i0} is an exogenously chosen runoff target for the ith site in production.

A Cost-Effective Solution Based on a Mean Ambient Target

The Lagrangian corresponding to the maximization of (2B-1) subject to (2B-2) is

$$L = \sum_{i=1}^{n} p_i(x_i, A_i) + \lambda\,[a_0 - E\{a\}]$$

where λ is the Lagrangian multiplier. Assuming an interior solution, the first-order conditions with respect to input use and the number of sites are

$$\frac{\partial L}{\partial x_{ij}} = \frac{\partial p_i}{\partial x_{ij}} - \lambda E\{\frac{\partial a}{\partial r_i}\frac{\partial r_i}{\partial x_{ij}}\} = 0 \quad \forall i, j \qquad \text{(2B-4)}$$

$$\frac{\Delta L}{\Delta n} \approx p_n - \lambda E\{\Delta a\} \approx 0 \qquad \text{(2B-5)}$$

where $\Delta a = a(r_1, \ldots, r_n, W) - a(r_1, \ldots, r_{n-1}, W)$. These conditions have the same interpretation as conditions (2A-1) and (2A-2), except that marginal costs are defined in terms of the constraint as opposed to damages. The shadow value λ is the value of the optimal tax/subsidy rate when farmers and the resource management agency share the same expectations about the nonpoint process.

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[13] Constraints may also be of the form $P(a \leq a_0) = 1 - \alpha$ where α is the probability that a will exceed the target (Beavis and Walker 1983). We do not focus on this type of constraint because it would be difficult to use in practice (Shortle 1990).

Finally, the optimal technology vector, A^*, is determined by solving for an optimal allocation for each possible value of A and comparing aggregate profits. The optimal technology vector satisfies the condition

$$L(A^*) - L(A') \geq 0 \forall A' \qquad \text{(2B-6)}$$

In particular, the following condition must hold

$$\begin{gathered} p_i(x_i(A_i^*), A_i^*) - p_i(x_i(A_i'), A_i') \geq \\ \lambda E\{a(r_1^*, ..., r_i^*, ..., r_n^*, W)\} \\ -\lambda E\{a(r_1^*, ..., r_{i-1}^*, r_i', r_{i+1}^*, ..., r_n^*, W)\} \quad \forall i, \forall A_i' \end{gathered} \qquad \text{(2B-7)}$$

Conditions (2B-6) and (2B-7) have the same interpretation as (2A-3) and (2A-4).

The cost-effective solution will generally not be efficient (Horan, 1999).[14] Moreover, use of a smaller ambient target, $a_1 < a_0$, may not result in a more efficient outcome if the variability of a is increased as a result of using the smaller target (Shortle, 1990).

A Cost-Effective Solution Based on Mean Runoff Targets

The Lagrangian corresponding to the maximization of (2B-1) subject to (2B-3) is

$$L = \sum_{i=1}^{n} p_i(x_i, A_i) + \sum_{i=1}^{n} \lambda[r_{i0} - E\{r_i\}]$$

where λ_i is the Lagrangian multiplier for the ith runoff constraint. Assuming an interior solution, the first-order conditions with respect to input use and the number of sites are

$$\frac{\partial L}{\partial x_{ij}} = \frac{\partial p_i}{\partial x_{ij}} - \lambda_i E\{\frac{\partial r_i}{\partial x_{ij}}\} = 0 \quad \forall i, j \qquad \text{(2B-8)}$$

$$\frac{\Delta L}{\Delta n} \approx p_n - \lambda_n[r_{n0} - E\{r_n\}] \approx 0 \qquad \text{(2B-9)}$$

Condition (2B-8) has the same interpretation as condition (2A-1), except that marginal costs are defined in terms of the constraint as opposed to damages. The shadow values λ_i equal the optimal tax/subsidy rates when farmers and the resource management agency share the same expectations about the nonpoint process.

Assuming the constraint (2B-3) is satisfied as an equality, condition (2B-9) reduces to a zero profit condition for the marginal site. However, since input use in the cost-effective solution will generally differ from input use in the competitive solution, the marginal site in the cost-effective solution will generally differ from the marginal site in the competitive solution.

Finally, the optimal technology vector, A^*, is determined by solving for an optimal allocation for each possible value of A and comparing aggregate profits. The optimal technology vector satisfies the condition

$$L(A^*) - L(A') \geq 0 \ \forall A' \qquad \text{(2B-10)}$$

In particular, the following condition must hold

$$\begin{gathered} p_i(x_i(A_i^*), A_i^*) - p_i(x_i(A_i'), A_i') \geq \\ \lambda_i E\{r_i^*\} - \lambda i E\{r_i' \quad \forall i, \forall A_i' \end{gathered} \qquad \text{(2B-11)}$$

Conditions (2B-10) and (2B-11) have the same interpretation as (2A-3) and (2A-4).

The cost-effective solution will generally not be efficient.[15] Moreover, use of smaller runoff targets, $r_{i1} < r_{i0} \ \forall i$, may not result in a more efficient outcome if the variability of r_i for some i is increased as a result of using the smaller targets (Shortle 1990).

A Cost-Effective Solution Based on Input Use

Input goals may be defined in terms of either site-specific input use or aggregate input use within a region such as a watershed. For simplicity, only the former case is considered here. Goals may also be defined either for all inputs that contribute to runoff, or for only a subset of these inputs. For example, nitrogen runoff from agriculture depends not only on the amount of nitrogen applied, but also on plant uptake which is a function of crop yield. Each input

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[14] It is not possible to attain an efficient solution unless (1) there is only one site with one production choice, or (2) the covariance between marginal damages and marginal ambient pollution is zero for all sites and inputs.

[15] It is not possible to attain an efficient solution unless: (i) there is only one production choice, or (ii) the covariance between marginal damages from runoff and marginal runoff is zero for all sites and inputs.

that influences crop yield will therefore generally influence runoff; however, policy goals may be specified only as reductions in nitrogen fertilizer use.

Let z_i denote the $(m' \times 1)$ vector of inputs for which goals are defined, and let y_i denote the $([m - m'] \times 1)$ vector of inputs for which there is no goal ($x_i' = [y_i, z_i]$). Input-based goals are then defined by

$$z_{ij} \le \bar{z}_{ij} \quad \forall i, j \tag{2B-12}$$

where $\bar{z}_{ij}$ is the target for use of the *j*th input on the *i*th site. The goals defined by (2B-12) are flexible in that they may be site-specific, or they may be uniform across firms within a region (in which case $\bar{z}_{ij} = \bar{z}_{1j}\ \forall i, l$). Moreover, (2B-12) is equivalent to an input reduction goal (for those inputs that increase runoff) or an input expansion goal (for those inputs that reduce runoff), specified in either absolute terms ($z_{ij}^C - z_{ij} \le \bar{A} = z_{ij}^C - \bar{z}_{ij}\ \forall i,j$, where z_{ij}^C is firm *i*'s competitive level of use of input *j*) or percentage terms ($[z_{ij}^C - z_{ij}]/z_{ij}^C \le P = [z_{ij}^C - z_{ij}]/z_{ij}^C\ \ \forall i,j$). An example of the latter goal would be a 25-percent reduction in nitrogen application rates within a region. In this case, the goal is uniform while the input use target $\bar{z}_{ij}$ is, in general, site-specific.

The Lagrangian corresponding to the maximization of (2B-1) subject to (2B-12) is

$$L = \sum_{i=1}^{n} \pi_i(z_i, y_i, A_i) + \sum_{i=1}^{n}\sum_{j=1}^{m'} \lambda_{ij}[z_{i0} - z_i]$$

where λ_{ij} is the Lagrangian multiplier for the *j*th input constraint for the *i*th site. Assuming an interior solution, the first-order conditions with respect to input use and the number of sites are

$$\frac{\partial L}{\partial z_{ij}} = \frac{\partial \pi_i}{\partial z_{ij}} - \lambda_{ij} = 0 \quad \forall i, j \tag{2B-13}$$

$$\frac{\partial L}{\partial y_{ij}} = \frac{\partial \pi_i}{\partial y_{ij}} = 0 \quad \forall i, j \tag{2B-14}$$

$$\frac{\Delta L}{\Delta n} \approx \pi_n - \lambda_n[r_{n0} - E\{r_n\}] \approx 0 \tag{2B-15}$$

Condition (2B-13) has the same interpretation as condition (2A-1), except that marginal costs are defined in terms of the constraint as opposed to damages. The shadow values λ_{ij} equal the optimal incentive rates for input use.

Assuming the constraint (2B-12) is satisfied as an equality, condition (2B-15) reduces to a zero profit condition for the marginal acre. However, since input use in the cost-effective solution will generally differ from input use in the competitive solution, the marginal site in the cost-effective solution will generally differ from the marginal site in the competitive solution.

Finally, the optimal technology vector, A^*, unless it is specified by policy goals, is determined by solving for an optimal allocation for each possible value of *A* and comparing aggregate profits. The optimal technology vector satisfies the condition (2B-10). In particular, the following condition must hold

$$\pi_i(x_i(A_i^*), A_i^*) - \pi_i(x_i(A_i'), A_i') \ge \sum_{j=1}^{m'} [\lambda_{ij}(A_i^*)x_{ij}(A_i^*) - \lambda_{ij}(A_i')x_{ij}(A_i')] \quad \forall i, \forall A_i' \tag{2B-16}$$

Condition (2B-16) has the same interpretation as (2A-4).