Allocative Implications of Comparisons Between the Marginal Costs of Point and Nonpoint Source Pollution Abatement

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This paper examines the possible use of information on the relative marginal costs of point and nonpoint source water pollution abatement to assess the efficiency implications of shifting a greater portion of the burden for water quality protection to nonpoint sources. The inherent uncertainty about the effects of changes in resource allocation for nonpoint pollution abatement on nonpoint pollution loads is recognized in the analysis. This uncertainty is shown to result in significant limitations on the use of marginal cost comparisons even when point and nonpoint pollutants are perfect substitutes.

Policies for improving surface water quality in the U.S. have focused primarily on reducing point source pollution. Nonpoint source pollution, although a major problem in many areas, has remained largely unregulated [EPA (1984); GAO]. The resulting lack of progress towards national water quality goals has become a leading environmental policy concern and has motivated an interest in new initiatives for reducing nonpoint pollution [Harrington et al.; Thomas; Savage]. In addition, it has been argued that the relative costs of point and nonpoint abatement are such that existing levels of water quality protection, as well as further water quality improvements, could in many cases be achieved more efficiently by a greater reliance on nonpoint abatement [e.g., Elmore, Jaksch, and Downing; National Commission on Water Quality].

This paper examines the possible use of information on the relative marginal costs of point and nonpoint source pollution abatement to assess the efficiency implications of shifting more of the burden for water pollution control to nonpoint sources. This matter is of practical as well as theoretical interest given the substantial imbalance in the current allocation, strong criticisms of the efficiency and effectiveness of U.S. water quality programs, and the apparent consensus that substantially more is known about the costs than the benefits of pollution abatement.

The analysis is based on a highly abstract examination of the characteristics of an allocation of resources for point and nonpoint source pollution control which attains a given pollution control target at least-cost. The pollution control target is defined in such a manner that failure to attain it at least-cost implies that an efficiency gain can be obtained by a reallocation of resources for point and nonpoint source control.

The conceptual framework developed for the analysis incorporates two key aspects of nonpoint source pollution which have significant implications for the use of information on the relative costs of point and nonpoint source abatement. One characteristic is that nonpoint pollution, which is largely a consequence of runoff from cropland and urban areas, is inherently stochastic. For example, weather plays a key causal role. Second, the diffuse nature of nonpoint pollution makes accurate monitoring on a continuous and widespread basis impractical.

Cost-Effective Control

Assume that a given water quality problem is caused by point source (PS) discharges and nonpoint source (NPS) runoff. The PS discharges are taken to be nonstochastic and readily observable. Conversely, the NPS runoff is stochastic and cannot be accurately mon-

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itored at reasonable cost.[1] The allocation problem is to minimize the cost of achieving a target related to the levels of the pollutants from the two sources.

Among other things, a solution to this cost-minimization problem requires a framework for relating changes in resource allocation for NPS control to the level of NPS pollution. Such a framework may be provided by a probabilistic model of nonpoint pollution which relates expectations of nonpoint loadings to observations of land use, weather, soil characteristics, and other relevant data. Such models have been developed and research to improve the state-of-the-art continues [e.g., Decoursey; EPA (1976, 1979)]. While a probabilistic model cannot provide a perfect substitute for accurate direct monitoring, it can serve as an important tool for managing the uncertainty about nonpoint loadings and, therefore, as an important tool for making decisions about the allocation of abatement among sources. Questions related to the existence and identification of a socially preferred model, although of interest, are not addressed here.

The following treatment is adapted from a recent paper by Shortle and Dunn. Let z_1 be the true but unobservable flow of the NPS pollutant. According to the preferred model,

$$(1) \quad \text{Prob}\,[z_1 \leq z^*_1] = \text{Prob}\,[g(x, w, \lambda) \leq z^*_1]$$

where $g(\cdot)$ is an NPS loading function, x is an observable measure of NPS "pollution abatement effort," w represents weather conditions which play a causal role in NPS pollution, and λ represents unknown parameters of the loading function.[2] The loading function is taken to be twice continuously differentiable, decreasing in x (i.e., $\partial g/\partial x \equiv g_x < 0$), and does not exhibit increasing marginal returns to NPS pollution abatement (i.e., $\partial^2 g/\partial x^2 \equiv g_{xx} \geq 0$).[3] The latter assumption, along with other convexity assumptions, are adopted to imply a situation in which the marginal costs of PS abatement and expected NPS abatement are increasing while the expected marginal benefits of PS and NPS abatement are decreasing. It is recognized that this situation may not characterize each instance.

Ex ante uncertainty about the level of NPS pollution for a given level of abatement effort due to uncertainty about forthcoming weather is incorporated by treating w as a random variable. Uncertainty about the level of NPS pollution for a given level of abatement effort due to imperfect knowledge of the physical and chemical processes influencing what transpires after the weather has occurred is incorporated by treating λ as a random variable. This latter uncertainty, along with the impracticality of accurate monitoring, preclude knowing the level of NPS pollution for given weather conditions and NPS abatement effort.

Let $f(w, \lambda)$ be the joint density function for w and λ. Using this density function and $g(\cdot)$, the expected level of z_1 for a given level of NPS abatement effort prior to observing the weather is

$$(2) \quad \mu_1(x) = \int\int g(x, w, \lambda)\, f(w, \lambda) dw d\lambda.$$

Similarly, the expected level of z_1 for a given level of NPS abatement effort after observing the weather is

$$(3) \quad \mu_2(x, w_0) = \int g(x, w_0, \lambda)\, f(w_0, \lambda) d\lambda$$

where w_0 denotes the realized value of w. Of these two conditional expectations, the first is of particular interest from a planning perspective since decisions about resource allocation for NPS control (e.g., land use) must be made prior to observing the weather.

Given this probabilistic framework for relating changes in resource allocation for NPS control to the level of NPS pollution, the next step in the development of the least-cost pollution control problem is the specification of the target that is to be achieved at least-cost. In more conventional treatments of cost-effective pollution abatement, the target is often taken to be a specified level of the pollutant flow [e.g., Baumol and Oates]. However, the monitoring problem and the stochastic nature of NPS pollution make such a target impractical. A variety of alternative types of probabilistic targets can be imagined. For example, the target may involve an upper bound on the expected level of the NPS flow or an upper

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[1] Point source discharges are also stochastic and difficult to monitor accurately in some cases. Treating them as such would not alter the principle results of this analysis. However, as a matter of degree and for the purposes of contrast, it is reasonable to view point source discharges as nonstochastic and readily monitorable.

[2] The use of an index of NPS pollution abatement effort simplifies the analysis considerably and facilitates focusing on the issues at hand. The existence of such an index is not, however, essential to the analysis since the principle results could be derived with a more complicated model of NPS abatement.

[3] Although nonincreasing marginal returns are characterized by a negative second-order derivative in familiar instances, it requires $g_{xx} \geq 0$ in this context.

bound on the probability of the flow exceeding a specified level [e.g., Beavis and Walker].

Since the objective of this analysis is to learn what can be said about the efficiency implications of a reallocation of abatement between point and nonpoint sources based solely on comparisons of their relative marginal costs, the target must be such that failure to achieve it at least-cost implies that an efficiency gain, or more appropriately, an *ex ante* efficiency gain, can be obtained by such a reallocation. The only target which can meet this criterion is an expected water quality damage cost target, where the expectation is taken prior to observing the weather since that is the time when decisions about NPS abatement effort must be made. Accordingly, such a target is adopted for the moment. Consideration is subsequently given to whether the relationship that is established to exist between the abatement marginal costs in the least-cost solution, or progress towards this relationship, can be obtained without knowledge of the damage cost function.

Let $D(z = z_1 + z_2)$ be the water quality damage cost function where z_2 is the level of PS discharges. This specification assumes that the PS and NPS pollutants are perfect substitutes. The implications of relaxing this assumption will be noted below. The damage cost function is taken to be twice continuously differentiable, increasing, and convex in z.

Using (1), the expected damage cost for a given level of PS abatement and NPS abatement effort prior to observing the weather is

$$\text{(4)} \qquad E[D[g(x, w, \lambda) + (\hat{z}_2 - y)]]$$

where $\hat{z}_2$ is the level of PS discharges that would prevail in the absence of public intervention for pollution control and y is the level of PS abatement relative to $\hat{z}_2$, i.e., $y = \hat{z}_2 - z_2$. The assumptions made about the NPS loading function and the damage cost function imply that the expected damage cost is decreasing and convex in NPS abatement effort and PS abatement.

Using (4), the rate of substitution between PS abatement and NPS abatement effort required to maintain a target expected damage cost level, say $\overline{ED}$, may be expressed as

$$\text{(5)} \qquad \left.\frac{dy}{dx}\right|_{\overline{ED}} = \frac{E[D'g_x]}{E[D']}.$$

The numerator of (5) is the expected reduction in the damage cost at the margin due to additional NPS abatement effort while the denominator is the expected marginal damage cost due to a reduction in PS abatement. Since the expected product of two random variables is equal to the product of their means plus their covariance, the numerator of (5), prior to observing the weather, may also be written as

$$\text{(6)} \qquad E[D']\mu_1' = COV(D', g_x).$$

It follows that (5) can also be written

$$\text{(7)} \qquad \left.\frac{dy}{dx}\right|_{\overline{ED}} = k\mu_1'$$

where

$$\text{(8)} \qquad k = 1 + \frac{COV(D', g_x)}{E[D']\mu_1'} > 0.$$[4]

The term μ_1' in (7) is the expected reduction in NPS pollution at the margin due to an increase in NPS pollution abatement effort. As such, μ_1' gives the rate at which NPS abatement effort may be substituted for PS abatement to maintain a given expected value of the total pollution load. Accordingly, (7) implies that the rate at which NPS abatement effort may be substituted for PS abatement to maintain an expected damage cost target is proportional to the rate at which NPS abatement effort may be substituted for PS abatement to maintain a given expected pollution load.

It is evident from (8) that the factor of proportionality (k) between these two rates of substitution depends upon the sign of the covariance between the marginal damage cost and the marginal effect of NPS abatement effort on NPS pollution (i.e., $COV(D', g_x)$ in (8)). The assumption that $D'' > 0$ obviously implies that $COV(D', z_1) > 0$ and from this it follows that the sign of $COV(D', g_x)$ is the same as that of $COV(z_1, g_x)$. It can be demonstrated that $2COV(z_1, g_x) = dVAR(z_1)/dX$ (e.g., see Just and Pope). Hence, if the variance of NPS pollution increases (decreases) with the level of NPS abatement effort, then $COV(D', g_x)$ is positive (negative) and the factor k is smaller (greater) than unity. This means that the rate of substitution of NPS abatement effort for PS abatement that will m^intain an expected damage cost target is smaller (greater) in absolute value than the rate of substitution that will maintain a given

[4] Where $D' > 0$ and $g_x < 0$, the signs of (5), and therefore, (7) and (1) are negative. Given that $\mu'_1 < 0$ in (7), it follows that $k > 0$.

expected pollution load if the pollution variance increases (decreases) with the level of NPS abatement effort. Which of these possibilities is the case is an empirical issue which is not addressed here. Instead, both are considered.

The cost of NPS abatement effort is expressed as $C_1(x)$ and the cost PS abatement is expressed as $C_2(y)$. Both cost functions are assumed to be twice continuously differentiable, increasing, and convex. Using the sum of these cost functions, the rate of substitution between PS abatement and NPS abatement effort required to maintain a given total control cost, say $\overline{TC}$, is expressed as

$$\left.\frac{dy}{dx}\right|_{\overline{TC}} = \frac{-C_1'}{C_2'}. \tag{9}$$

The numerator of (9) is the marginal cost of additional NPS abatement effort while the denominator is the marginal cost of PS abatement.

An *ex ante* cost-effective allocation of PS abatement and NPS abatement effort for a target of the type assumed here is now formally defined as a solution to a problem having the following structure:

$$\min_{x,\,y} C_1(x) + C_2(y)$$

subject to

$$E[D[g(x, w, \lambda) + (\hat{z}_2 - y)]] \leq \overline{ED}$$
$$x, y \geq 0$$
$$\overline{ED} \text{ given.}$$

An interior solution to this problem is characterized by an equality of the two rates of substitution defined by (7) and (9), i.e.,

$$\frac{-C_1'}{C_2'} = k\mu_1'.^5 \tag{10}$$

Such a solution is illustrated graphically in Figure 1 where the curves which are concave to the origin are combinations of x and y which maintain given total abatement cost levels and the curves which are convex to the origin are combinations of x and y which maintain given expected damage cost levels. Abatement costs are greater but expected

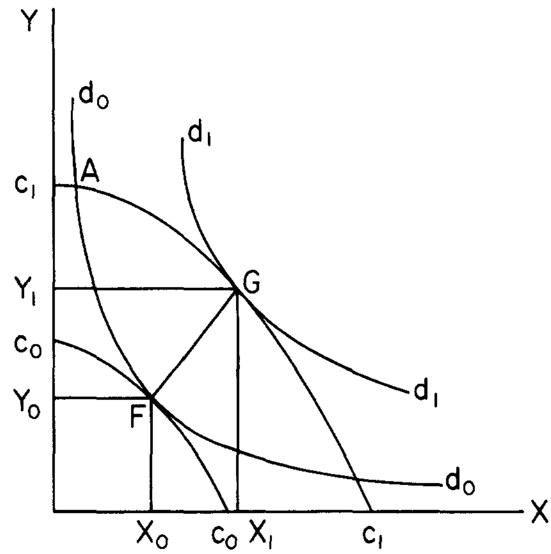

Figure 1. Least-Cost Allocation of Point and Nonpoint Source Abatement Effort

damage costs are lower for allocations to the northeast of the origin. If the curve D_0D_0 represents the combinations of x and y which provide the given expected damage cost target, $\overline{ED}$, then the least-cost allocation of PS abatement and NPS abatement effort is (x_0, y_0) at point F, where the curve d_0d_0 is tangent to the iso-abatement cost curve c_0c_0. Alternatively, if the curve d_1d_1 represents the combinations of x and y which provide the target expected damage cost target, then the least-cost allocation is (x_1, y_1) at point G, where the curve d_1d_1 is tangent to the iso-abatement cost curve c_1c_1.

Implications of Abatement Cost Comparisons

With the exception of the boundary cases, an economic imbalance between PS abatement and NPS abatement effort may be defined to exist whenever (10) does not hold since it would be possible to reallocate resources to obtain an expected efficiency gain. The gain may be the result of reducing the total costs of pollution abatement while maintaining the existing expected damage cost level (e.g., a reallocation from A to F in Figure One); reducing the expected damage cost level while maintaining the existing abatement cost level (e.g., a reallocation from A to G); or reducing the costs of abatement while also decreasing the expected damage cost (e.g., a move from A to a point on the curve FG, where FG is a

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[5] The result can be derived from the Kuhn-Tucker conditions for the cost-minimization problem. Given that the constant qualification is satisfied, the Kuhn-Tucker conditions are necessary and sufficient under the assumptions made about the forms of the objective and constraint functions.

locus of combinations of NPS abatement effort and PS abatement which satisfy (10)). Note, however, that a balanced allocation (i.e., one which solves the above cost-minimization problem) does not imply either *ex ante* or *ex post* efficiency. For example, neither F nor G necessarily minimizes either the expected or realized sum of abatement and damage costs. On the other hand, it can be shown that an *ex ante* efficient allocation (i.e., an allocation which minimizes the expected damage cost plus the cost of abatement) implies a balanced allocation as defined here. Hence, with the exception of the boundary cases, an *ex ante* efficient allocation will satisfy (10).

The purpose of the discussion that follows is to examine two questions: (1) Can comparisons of the marginal abatement costs be used to identify a balanced allocation without prior knowledge of the damage cost function? (2) If not, can such comparisons be used to improve the allocation in some situations?

To address these questions, it is useful to rearrange (10) to obtain

$$(11) \qquad \frac{-C_1'}{\mu_1'} = kC_2'.$$

The term $-C_1'/\mu_1'$ on the left-hand side of (11) may be interpreted as the marginal cost of expected NPS abatement. As noted above, the factor k is smaller (greater) than unity if the variance of NPS pollution increases (decreases) with NPS abatement effort. Hence, (11) implies that the marginal cost of PS abatement will be more (less) than the marginal cost of expected NPS abatement in a balanced allocation if the variance increases (decreases) with the level of abatement effort.

Now consider the first question posed above. Specifically, can comparisons of the marginal abatement costs be used to identify a balanced allocation without prior knowledge of the damage cost function? Since the factor k depends upon the numerical values of E[D′] and COV[D′, g_x], the answer to this question is negative. The logic behind this conclusion is straight-forward. Because NPS pollution is stochastic, the effect of NPS pollution abatement effort is to alter the distribution of a random variable, i.e., NPS loadings, rather than to provide a precise level of abatement. Accordingly, achieving a balanced allocation requires changes in resource allocation which provide an equally preferred distribution at a lower abatement cost, a preferred distribution at the same abatement cost, or a combination of an improvement in the distribution along with an abatement cost reduction. The factor determining whether a given distribution is preferred to another is the damage cost function. Hence, without knowledge of the damage cost function, it is not possible to identify a balanced allocation.

Now consider the second question. Specifically, can comparisons of the marginal abatement costs be used to improve the allocation in some situations? To address this question, suppose that the variance of NPS pollution increases with the level of abatement effort. In this case, (11) along with the conclusion that $0 < k < 1$ imply a set of allocations which are unambiguously imbalanced (i.e., those for which $-C_1'/\mu_1' \geq C_2'$) and another set which are candidates for being balanced (i.e., those for which $-C_1'/\mu_1' < C_2'$). The impossibility of identifying a balanced allocation on the basis of marginal cost comparisons noted above implies that the relative efficiency of allocations in the candidate set (i.e., the set for which $-C_1'/\mu_2' < C_2'$) cannot be evaluated without knowledge of the damage cost function. However, where $-C_1'/\mu_1'$ and C_2' are, respectively, increasing functions of NPS abatement effort and PS abatement, then $-C_1'/\mu_1' > C_2'$ means that an expected efficiency gain can be obtained by substituting PS abatement for NPS abatement effort. A similar analysis could be conducted for the case in which the variance decreases with the level of abatement effort, the difference being that the two sets of allocations and the direction of efficiency improving substitutions within the unambiguously imbalanced set would be reversed. Hence, marginal cost comparisons can be used to improve the efficiency of the allocation when they indicate an allocation which is unambiguously imbalanced.

It must be noted that if the pollutants are not perfect substitutes, then the relationship between the marginal abatement costs in a balanced allocation will not be as established here. Whether $-C_1'/\mu_1'$ is greater or lesser than C_2' in a balanced allocation when the pollutants are not perfect substitutes is ambiguous without knowledge of the damage cost function. This could be demonstrated by substituting a damage cost function of the form $H(z_1, z_2) \neq D(z = z_1 + z_2)$ for the latter of these functions in the previous analysis of the characteristics of a least-cost allocation. It follows that neither balanced nor imbalanced allocations can be indicated by marginal cost comparisons and, therefore, that the allocative implications of marginal abatement cost comparisons are nil when the pollutants are not perfect or near perfect substitutes.

A final point worth noting is that the foregoing analysis does not imply that knowledge of the costs of PS and NPS abatement cannot be used to achieve any exogenously determined pollution control objective at least-cost. As noted above, targets for pollution control which recognize the uncertainties about nonpoint source pollution loads can take a variety of forms. As long as the target is related to the levels of PS abatement and NPS abatement effort, knowledge of the control costs can be used to identify a least-cost solution. However, reallocations which achieve any feasible target need not represent expected efficiency gains and could result in an expected efficiency loss.

Concluding Comments

An examination of the possible use of information on the relative marginal costs of point source and nonpoint source water pollution abatement to assess the efficiency implications of shifting more of the burden for water pollution control to nonpoint sources is presented in this paper. The inherent uncertainty about the effects of changes in resource allocation for nonpoint abatement on nonpoint pollution loads is recognized explicitly in the analysis. The analysis is focused specifically on the possibility of using marginal cost comparisons to achieve a balanced allocation of abatement between point and nonpoint sources. Such an allocation is defined as one in which the total costs of abatement are minimized subject to an upper bound on the expected environmental damage costs of point and nonpoint source pollution. Although a balanced allocation does not imply an *ex ante* efficient allocation, an imbalanced allocation implies that an expected efficiency gain can be obtained by a reallocation of abatement between the sources.

Although some of the specific results of this analysis are contingent upon the underlying assumptions, there are two which are quite general. First, the conclusion that the marginal costs of point source and expected nonpoint source abatement will differ in a balanced allocation when the pollutants are perfect substitutes is due to the uncertain effect of resource allocation on nonpoint pollution loads. Since this uncertainty is a general characteristic of nonpoint pollution, this conclusion is also general. Second, whether the pollutants are perfect substitutes or not, the exact numerical relationship between the marginal costs of point source and expected nonpoint source abatement in a balanced allocation cannot be determined without a well-defined damage cost function.

These two results imply that balanced allocations cannot be inferred from marginal cost comparisons alone in any case. Moreover, if the pollutants are not perfect substitutes, then the entire relationship between the marginal costs as well as their exact numerical relationships in balanced allocations will be ambiguous without a well-defined damage cost function. It follows that the allocative implications of marginal cost comparisons are nil when the pollutants are not perfect substitutes.

If the pollutants are perfect substitutes, then limited progress towards a balanced allocation may be inferred from marginal cost comparisons when such comparisons indicate an unambiguously imbalanced allocation. This is illustrated by the formal analysis presented above, which is limited to the case in which the pollutants are perfect substitutes, the marginal costs of point and expected nonpoint source abatement are increasing, the variance of NPS pollution increases with the level of NPS abatement effort, and the expected marginal benefits of point and nonpoint source abatement are decreasing. In this case, the marginal cost of point source abatement exceeds the marginal cost of expected nonpoint source abatement in a balanced allocation. Accordingly, given that the marginal costs are increasing, an expected efficiency gain can be obtained by substituting point source abatement for nonpoint source abatement whenever the marginal cost of expected nonpoint source abatement exceeds the marginal cost of point source abatement. However, if the marginal cost of point source abatement exceeds that of expected nonpoint source abatement, then the direction of the substitutions required to achieve a balanced allocation cannot be inferred on the basis of marginal cost comparisons alone. Alternatively, the condition in which allocations can be identified as unambiguously imbalanced and the direction of the efficiency-improving substitutions will be reversed if the variance decreases with the level of abatement effort.

The specific implications of alternative relative magnitudes of the marginal costs of point and expected nonpoint source abatement noted above are contingent upon several assumptions adopted for the analysis. These assumptions may not characterize each case.

References

Baumol, William J., and Wallace E. Oates. 1975. *The Theory of Environmental Policy.* Englewood Cliffs NJ: Prentice Hall, 1975.

Beavis, Brian, and Martin Walker. 1983. "Achieving Environmental Standards with Stochastic Discharges." *Journal of Environmental Economics and Management.* 10(1983):103–111.

Decoursey, D. G. "ARS Small Watershed Model." Collaborative Paper CP-82-89, International Institute of Applied Systems Analysis, Luxembourg, Austria, 1983.

Elmore, Tom, John Jaksch, and Donna Downing. "Point/Nonpoint Source Trading Programs for Dillon Reservoir and Planned Extensions For Other Areas." In *Perspectives on Nonpoint Source Pollution.* U.S. Environmental Protection Agency, 1985.

Harrington, Whinston, Alan J. Krupnick, and Henry M. Peskin. "Policies for Nonpoint-Source Water Pollution Control." *Journal of Soil and Water Conservation.* 40(1985):27–32.

Just, Richard E. and Rulon D. Pope. "Stochastic Specification of Production Functions and Economic Implications." *Journal of Econometrics.* 7(1978):67–86.

National Commission on Water Quality. *Report To Congress by The National Commission on Water Quality.* Washington, D.C.: U.S. Government Printing Office, 1976.

Savage, Roberts. "State Initiatives in Nonpoint Source Pollution Control." *Journal of Soil and Water Conservation.* 40(1985):53–54.

Shortle, James S. and James W. Dunn. "The Relative Efficiency of Agricultural Source Water Pollution Control Policies." *American Journal of Agricultural Economics.* 68(1986):668–677.

Thomas, Lee M. "Viewpoint: Management of Nonpoint Source Pollution: What Priority?" *Journal of Soil and Water Conservation.* 40(1985):33–36.

U.S. Environmental Protection Agency, Office of Research and Development. *Loading Functions for Assessment of Water Pollution From Nonpoint Sources.* May, 1976.

———. Environmental Research Laboratory. *Effectiveness of Soil and Water Conservation Practices for Pollution Control.* October, 1979.

———. Office of Water Program Operations. *Report to Congress: Nonpoint Pollution in the U.S.* January, 1984.

U.S. General Accounting Office. *Cleaning Up the Environment: Progress Achieved but Major Unresolved Issues Remain.* July, 1982.