Prevention Versus Treatment Under Precautionary Regulation: A Case Study of Groundwater Contamination Under Uncertainty

by

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PREVENTION VERSUS TREATMENT UNDER PRECAUTIONARY REGULATION: A CASE STUDY OF GROUNDWATER CONTAMINATION UNDER UNCERTAINTY

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Abstract: Policy discussions of agricultural pollution problems characterize prevention as more cost effective and precautionary than *ex post* treatment. We derive conditions under which treatment alone is more cost effective in situations involving multiple sources of emissions, multiple sites affected, and a commonly used precautionary approach to uncertainty. We also show that a greater degree of precaution can result in less reliance on prevention. An empirical case study indicates that treatment alone is the most cost effective means of dealing with nitrate in most Maryland community water system wells. The use of leaching prevention measures is restricted to the most intensive poultry producing areas. The incremental cost of precaution is substantial.

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Introduction

Policy discussions of agricultural nonpoint source pollution problems have focused almost exclusively on prevention. There appear to be several distinct motivations for this emphasis. First, materials balance considerations suggest that such an approach makes sense: In principle, pollutants exist because raw materials are not converted completely into finished products, so that there exists a potential for improvements in productive efficiency that would simultaneously reduce pollutant emissions. In other words, preventive measures may provide "win-win" opportunities for simultaneously increasing farm profitability and environmental quality. Second, a focus on prevention is often justified on the grounds of cost effectiveness. In the case of groundwater contamination, for example, the per-acre costs of many leaching reduction measures appear to be low compared to water treatment costs. Third, in the case of groundwater, at least, preventive measures may appear preferable for precautionary reasons, that is, reducing the risk of environmental degradation that could prove irreversible or excessively costly to remedy. Cost effectiveness and precaution are the main reasons the U.S. Environmental Protection Agency cites for expanding ground water protection programs under the Federal Insecticide, Fungicide, and Rodenticide Act and under the 1996 Amendments to the Safe Drinking Water Act during the 1990s: "Given the importance of ground water as a source of drinking water for so many communities and individuals and the cost and difficulty of cleaning it up, common sense tells us that the best way to guarantee continued supplies of clean ground water is to prevent contamination" (U.S. Environmental Protection Agency).[1]

Empirical economic analyses have followed broader policy discussions in focusing almost exclusively on prevention. Virtually all of the studies cited in Lee's review of the agricultural economics groundwater contamination literature examined only pollution prevention via changes in crop choice and/or agricultural practices. (Rare exceptions include Ready and Henken's analysis of well testing and remediation decisions, which focuses exclusively on treatment of contaminated well water; Innes and Cory's analysis of well testing, customer notification, and treatment in cases where consumers may switch to drinking bottled water; and Lichtenberg, Zilberman, and Bogen's analysis of a situation in which prevention was infeasible.)

But preventive strategies may not always be either cost-effective or precautionary in situations involving agricultural nonpoint source pollution. This paper develops a theoretical analysis of the conditions under which treating pollution *ex post* may have a lower expected cost than preventing pollution in the first place. The analysis also indicates that a greater emphasis on precaution may, paradoxically, lead to increased reliance on treatment rather than prevention. We illustrate the theoretical analysis using a case study of nitrate contamination of drinking water wells in Maryland.

The principles of determining the efficient division of pollution control effort between prevention and treatment were explored under certainty by Olson and Zeckhauser, Oates, Shibata and Winrich, and Butler and Maher. Polinsky and Shavell and Barrett and Segerson study the roles of prevention and treatment in dealing with randomly occurring discrete contamination events, such as accidental spills. Innes and Cory study the roles of prevention and treatment under alternative forms of polluter liability in cases where consumers can switch to bottled drinking water.

This paper extends the literature in several ways. First, we model pollution in a continuous stochastic framework rather than in terms of a single discrete event (an accidental spill) that occurs with a given probability. Second, we model situations with multiple sources of pollution that differ in amounts emitted and costs of reducing emissions. Third, we model situations characterized by multiple sites subject to contamination that differ in their vulnerability to pollution. Fourth, we analyze what is arguably the most widely used form of precautionary regulation, the engineering approach that involves setting an upper bound on the frequency with which a nominal standard is violated. This approach corresponds to a safety fixed approach to dealing with uncertainty (see for example Beavis and Walker; Lichtenberg and Zilberman; Lichtenberg, Zilberman, and Bogen; and Harper and Zilberman).

Prevention, Treatment, and Pollution

We consider the case of an industry composed of heterogeneous firms that emit a pollutant causing an uncertain level of damage at multiple, heterogeneous sites.

Let $\gamma \in [\gamma^l, \gamma^u]$ index the types of firm in the industry and $g(\gamma)$ denote the number of firms of type γ. Let $c(x,\gamma)$ denote expenditures associated with a given level of pollution prevention effort x by firms of type γ. We assume that $c(x,\gamma)$ is convex in prevention effort x for all firm types. Pollution from the industry affects different sites differentially. For simplicity, assume that the reduction in emissions from each type of site is $w(\gamma)x(\gamma)$, i.e., proportional to pollution prevention effort. The total reduction emissions from preventive effort in the industry is thus $X = \int_{g^l}^{g^u} w(g)x(g)g(g)dg$. Without loss of generality, assume that the effective marginal cost of pollution prevention $e(x,\gamma) \equiv c_x(x,\gamma)/w(\gamma)$is decreasing in γ, i.e., a higher value of γ indicates greater efficiency in pollution prevention.

Let $\theta \in [\theta^l, \theta^u]$ denote the vulnerability of each type of site to pollution, with higher values of θ indicating greater vulnerability. Let $h(\theta)$ denote the number of sites of vulnerability θ in the region affected by the pollutant. Let $I(\theta)$ denote effort expended on treating pollution at a site of type θ and $K(I)$ denote treatment expenditures. We assume that $K(I)$ is convex in treatment effort for all θ. We assume that pollution prevention affects pollutant levels at all sites but that treatment affects only the site treated.

Most agricultural pollution is subject to substantial uncertainty due to the influence of stochastic factors such as weather conditions or due to lack of information about difficult-to-observe physical factors such as subsoil and hydrologic conditions. For example, leaching of nutrients and pesticides depends on stochastic factors such a rainfall, surface and soil temperatures, and other factors that vary randomly as well as seasonally (Jury and Nielsen). Transport, volatilization, degradation, and chemical transformation of nitrate and pesticides are influenced by subsurface soil conditions, microbial activity, and underground geochemical factors that are difficult to observe and that also vary stochastically over time (see for example Jury and Nielsen; Office of Technology Assessment). The effects of pollution prevention measures are similarly subject to uncertainty. For example, runoff and leaching under conservation tillage depends on rainstorm size and timing and the route of infiltrating water in addition to organic matter in the field and other soil conditions (Baker).

We formalize this uncertainty as follows. Let $F(N; X, I, \theta)$ be the probability that the level of the pollutant at a site of type θ is no greater than N, conditional on aggregate pollution prevention X and treatment at that site I(θ). Both pollution prevention and treatment reduce pollution and thus increase the probability that pollution at a given site does not exceed N, that is, (letting subscripts denote derivatives) $F_X > 0$, $F_I > 0$. Greater vulnerability to pollution corresponds to a lower probability that pollution at a given site does not exceed N, that is, $F_\theta < 0$.

Cost Effective Precautionary Regulation

Legislation governing environmental quality typically adopts the public health profession's point of view regarding uncertainty by requiring that water providers make provision to meet standards for contaminant concentrations with an adequate margin of safety. This approach is precautionary in that it concentrates on unacceptably bad outcomes, specifically, limiting the frequency with which such outcomes occur. Lichtenberg and Zilberman have argued that this corresponds to imposing a safety-rule constraint of the form

$$F(N; X, I, \theta) \geq P \ \forall\ \theta \tag{1}$$

where N is the maximum allowable concentration of the pollutant, and $0 \leq P \leq 1$ is the probability that the pollutant concentration does not exceed the maximum allowable level. Lichtenberg and Zilberman characterize P as the margin of safety mandated by such legislation.

The cost effective combination of prevention and treatment under such an approach can be found by choosing vectors x(γ) and I(θ) to minimize the sum of prevention and treatment expenditures,

$$\int_{g^l}^{g^u} c(x(g),g)g(g)dg + \int_{q^l}^{q^u} K(I(q))h(q)dq \tag{2}$$

subject to the constraint (1). The necessary conditions for a minimum are

(3) $$c_x(x,g) - w(g)\int_{q^l}^{q^u} l(q)F_X(N;X,I,q)h(q)dq \geq 0$$

(4) $$K'(I) - l(q)F_I \geq 0$$

(5) $$P - F(N;X,I,q) \leq 0\ .$$

Under our assumptions there should exist minimum types of firms engaging in pollution prevention and sites engaging in treatment. Let γ* denote the least efficient (highest effective marginal cost) type of firm engaging in pollution prevention and θ* denote the least vulnerable type of site receiving treatment. If regulators are indifferent between having firms of type γ* engaging in pollution prevention and not doing so and between having sites of type θ* treating and not treating, then γ* and θ* are defined by the equations

(6) $$e(0,g^*) - \int_{q^*}^{q^u} l(q)F_X(N;\int_{g^*}^{g^u} w(g)x(g)g(g)dg\ ,I,q)h(q)dq = 0$$

(7) $$P - F(N;\int_{g^*}^{g^u} w(g)x(g)g(g)dg, 0, q^*) = 0\ .$$

Substitution of condition (4) into condition (3) for any site with vulnerability θ ≥ θ* gives the standard condition that the optimal combination of prevention and treatment involves equating the marginal cost of prevention with the total marginal cost of treatment at all sites,

(8) $$e(x,g) = \int_{q^*}^{q^u} K'(I)\frac{\partial I}{\partial X}h(q)dq\ \ .$$

where $\frac{\partial I}{\partial X} = \frac{F_X(N;X,I,q)}{F_I(N;X,I,q)}$ is the marginal rate of substitution between prevention and treatment at a given site of type θ under a nominal standard N.

The costate variable $\lambda(\theta)$ gives the change in total cost due to a change in the margin of safety P at a site of a given type θ and can be thus interpreted as the marginal cost of precaution at sites of that type. The overall marginal cost of precaution is thus $\int_{q^*}^{q^u} l(q)h(q)dq$.

Conditions (3)-(5) will also be sufficient if marginal reductions in F are decreasing in both prevention and treatment (F_{XX}, $F_{II} < 0$) and if there are no economies of scale in treatment (as we have assumed). If the objective function is not globally convex, however, the most cost efficient form of regulation may involve either prevention or treatment alone. Treatment alone will be cost efficient whenever condition (3) holds as a strict inequality for all firms,

$$e(0,g) - \int_{q^*}^{q^u} l(q)F_X(N;0,I,q)h(q)dq > 0 \quad \forall g \ . \tag{9}$$

One can envisage a number of situations in which this might occur. First, prevention may be quite costly either because it requires large expenditures ($c_x(0,\gamma)$ large for all γ) or because it is not very effective ($w(\gamma)$ small for all γ or $F_X(N;\, 0,I,\theta)$ small for all θ). Second, the number of sites affected by pollution may be small ($H(\theta^u)$-$H(\theta^*)$ is small) so that the avoided cost of treatment is small. Third, the marginal cost of treatment ($\lambda(\theta) = K'(I)/F_I(N;\, 0,I,\theta)$) may be low for all sites affected by pollution.

The degree of precaution (as indicated by the margin of safety P) will influence the degree to which prevention is desirable. Intuitively, one might expect a greater degree of precaution (a higher margin of safety) to lead to greater emphasis on prevention. But the opposite may occur. Conditions (3)-(7) suggest that changes in the margin of safety P will have both intensive and extensive margin effects on total preventive effort X. The former consist of changes in prevention by inframarginal firms (types $\gamma > \gamma^*$). The latter consist of changes in the least efficient firm engaging in pollution prevention (type γ^*). One would expect the extensive margin effect on total preventive effort to be positive: Increases in the margin of safety should increase the number of firms engaging in pollution prevention by lowering γ^*. One would also expect the direct effects of increasing the margin of safety on preventive effort by inframarginal firms to be positive: Greater precaution implies a higher marginal cost of precaution λ, which creates an incentive for greater preventive effort by inframarginal firms. Moreover, greater precaution means that more sites will be out of compliance with the regulatory constraint (θ^* decreases), which increases the returns to preventive effort (i.e., avoided treatment costs). But increases in the margin of safety can also have negative effects on preventive effort by inframarginal firms. Greater precaution means that more firms will engage in preventive effort (γ^* decreases), reducing the marginal productivity of preventive effort by inframarginal firms (and thereby creating an incentive to reduce that effort). Greater precaution also means more treatment at inframarginal sites (I increases at sites with vulnerability $\theta > \theta^*$). If the marginal productivity of prevention is decreasing in treatment ($F_{IX} < 0$), then the increase in treatment creates an incentive for decreased preventive effort by inframarginal firms. If these negative effects of greater precaution on preventive effort by inframarginal firms are large relative to the positive effects of greater precaution, increasing the margin of safety could result in less, rather than more pollution prevention. Thus, it is not necessarily the case that greater precaution implies more prevention.

A Case Study of Nitrate in Maryland Drinking Water Wells

We applied this framework to the case of nitrate contamination of drinking water wells in Maryland by combining a statistical model linking nitrate concentrations in drinking well water to agriculture with estimates of the cost and effectiveness of prevention and water treatment technologies. We begin by analyzing the cost efficient combinations of preventive agricultural best management practices and water treatment to meet the current nominal nitrate standard in community water system wells at a 95 percent margin of safety. We then investigate changing the margin of safety on the cost efficient combination of prevention and treatment and in the total cost of complying with the current nominal standard. Next, we investigate the sensitivity of the cost efficient combination of prevention and treatment to assumptions about nitrate leaching from agricultural activity, focusing on the case where nitrate leaching from agriculture is substantially higher than the best estimate of the statistical model. Finally, we test the sensitivity of the cost efficient combination of prevention and treatment to the number of wells affected by leaching from agriculture by extrapolating the community water system model to incorporate individual household wells.

Agriculture and Nitrate in Maryland Drinking Water Wells

Lichtenberg and Shapiro estimated a statistical model relating nitrate concentrations in finished water from community water system wells during the period 1976-1992 to hydrological characteristics of the wells used by each system (e.g., depth and aquifer characteristics), acreage of major crops in the county in which the system was located, livestock inventories in the county in which the system was located, and rural residential land use, as measured by the number of septic systems in the county in which the system was located. The water quality data contained 810 observations on nitrate taken from 213 community water systems. Lichtenberg and Shapiro used tobit to correct for bias introduced by the fact that nitrate cannot be detected at concentrations below 0.1 mg/l. They compared linear and exponential specifications; nonnested hypothesis tests unambiguously favored the exponential specification. Crop acreage and livestock numbers were measured as averages for the 10 years preceding each well test, so their results are most appropriately interpreted as indicative of long-run effects. Corn was the only crop, and broilers were the only kind of livestock, associated with elevated nitrate concentrations in both models. The exponential model indicated that each 1,000 acres of corn was associated with a 3.05 percent increase in long-run nitrate concentrations, while each 1,000 broilers was associated with a 0.02 percent increase in nitrate concentrations. Our analysis of pollution prevention thus concentrates on leaching reduction practices suitable for corn and broiler production.

We focus on wells not in compliance with the drinking water standard for nitrate, 10 mg/l. Let Z_{ij} denote the (column) vector of regressors excluding corn and broilers associated with system j in county i with detectable nitrate. Let β be the (row) vector of coefficients associated with these regressors. Let β_A be the coefficient of county corn acreage A_i and β_B be the coefficient of the number of broilers in the county B_i. The predicted mean log nitrate concentration in system j in county i with detectable nitrate is $\beta Z_i+\beta_A A_i+\beta_B B_i$. Let

$$\Omega = \begin{bmatrix} V_1 & V_2 & V_3 \\ V_2' & s_{AA} & s_{AB} \\ V_3' & s_{AB} & s_{BB} \end{bmatrix}$$

denote the partitioned covariance matrix of the vector of estimated coefficients $[\beta\ \beta_A\ \beta_B]$, where V_1 is the covariance matrix of β, V_2 is the column vector of covariances between the elements of β and β_A, V_3 is the column vector of covariances between the elements of β and β_B, σ_{AA} is the variance of β_A, σ_{BB} is the variance of β_B, and σ_{AB} is the covariance between β_A

and β_B. The variance of the predicted log nitrate concentration in system j in county i with detectable nitrate is

$$V(\hat{N}_{ij}) = Z_{ij}'V_1Z_{ij} + 2Z_{ij}'V_2A_i + 2Z_{ij}'V_3B_i + A_i^2\sigma_{AA} + B_i^2\sigma_{BB} + 2A_iB_i\sigma_{AB} + \sigma_u^2,$$

where σ_u^2 is the variance of the residual error. The nitrate concentration in the drinking water provided by a system exceeded with probability P in the absence of either prevention or treatment is thus

$$N_{ij}(P) = bZ_{ij} + b_A A_i + b_B B_i + \Phi^{-1}(P)[V(\hat{N}_{ij})]^{1/2} \quad , \tag{10}$$

where $\Phi^{-1}(P)$ is the inverse (z-score) of a standard normal cumulative distribution at probability P. Table 1 gives descriptive statistics for community water systems predicted to be out of compliance with the current nominal standard of 10 mg/l at a 95 percent safety margin in the absence of either prevention or treatment. These systems are located in five counties on the Eastern Shore and ten counties in Central and Southern Maryland.

Pollution Prevention in Corn and Broiler Production

The agronomic literature suggested three alternatives for reducing leaching from corn: Planting a cereal cover crop, reducing fertilizer use, and removing land from production. Cereal cover crops appear to be the least costly of these three.[2] Most leaching occurs in the late fall after the corn harvest: During the growing season, the corn crop holds nitrate in the soil solution. Cereal cover crops take up residual nitrogen before it can leach. A review of agronomic studies using shallow wells to measure nitrate concentrations leaching out of the root zone indicates that cereals like rye reduce nitrate leaching on the order of 50 percent (Meisinger et al.). The cost of a cereal cover crop is $28 per acre for seed, no-till drilling, and application of a knockdown herbicide.

Reducing leaching from broiler production requires storage of poultry litter and subsequent use of litter as crop fertilizer. Experience with such nutrient management systems for poultry has been limited. Poultry litter has a higher nutrient content than cow manure, making calibration of application rates more difficult. It is also high in phosphorus, and land application of poultry litter (including use as fertilizer under a nitrogen based management strategy) has resulted in excess phosphorus levels in soils. This excess phosphorus runs off into surface water but has not leached into groundwater.

For the purposes of this study, we assumed a nutrient management system consisting of storage of poultry litter followed by application to a corn crop as a substitute for chemical fertilizers. This system was assumed to eliminate completely leaching associated with broilers. The rate of nitrate leaching from poultry litter was assumed to equal the rate from chemical fertilizer (Sallade and Sims); thus, nutrient management not combined with cover crops was assumed to leave nitrate leaching from corn unchanged. The net nutrient management cost was $0.02825 per bird.[3] It was assumed that poultry litter was applied at a nitrogen-based application rate of 0.2530 tons (506 pounds) per acre recommended by Maryland Cooperative Extension during the mid-1990s, an amount sufficient to supply 150 pounds of nitrogen per acre. We ignore limits on the use of poultry litter on land that currently has excess phosphorus that are currently being phased in. This assumption results in an underestimate of the costs of nutrient management, at least in the short run while excess phosphorus levels persist.

Nutrient management can be used alone or in conjunction with cover crops to take up residual soil nitrogen at the end of the corn growing season. The cost and effectiveness of cover crops was assumed to be the same with poultry litter as with chemical fertilizer.

Treatment of Nitrate in Drinking Water

Filtration was assumed to be the most cost-effective means of treatment. For community water systems, EPA estimates indicate that ion exchange is the least costly method of removing nitrate from drinking water. Ion exchange removes between 75 and 99 percent of nitrate. Capital and operating and maintenance costs depend on the size of the system due to economies of scale. In its analysis of the costs of complying with the Safe Drinking Water Act, EPA has published estimated costs per household of ion exchange with a 95 percent removal capacity for a dozen sizes of water systems ranging from populations of 25 to over 1 million (Federal Register). To ensure that total treatment costs increased monotonically with system size (population served), we fit a cubic function giving total treatment cost as a function of system size. The midpoints of the population ranges for each system size reported by EPA were used as the independent variable. The product of this midpoint and per-household costs was the dependent variable. The following curve fit the data exactly:

$$K(L_j) = 37.870L_j - 0.0000245L_j^2 + 1.86\text{x}10^{-11}L_j^3, \tag{11}$$

where $K(L_j)$ is the annualized total cost of ion exchange for system j and L_j is the population served. This estimated curve was used to calculate treatment costs for each community water system.

Computation of the Efficient Combination of Prevention and Treatment

The coefficients of corn and broilers in the Lichtenberg-Shapiro model can be interpreted as the impacts of these agricultural activities on the long-run concentrations of nitrate in community water system wells. Reductions in these impacts due to agricultural pollution prevention can be modeled as reductions in these coefficients. The effects of treatment can be modeled as a reduction in the mean of the predicted nitrate concentration for systems with detectable nitrate. We assumed that cover crops and poultry nutrient management exhibited constant returns to scale. The EPA estimates indicate that filtration by community water systems exhibited increasing returns to scale.

The efficient *ex ante* combination of prevention and treatment was derived by minimizing the county-level cost of meeting the constraint on the predicted concentration of nitrate in each water system through the choices of (1) the share of corn acreage in each county on which to plant cover crops, (2) the share of the total number of broilers in each county receiving nutrient management, and (3) the share of drinking water in each system in each county receiving filtration. The broiler industry is concentrated on the Eastern Shore of the Chesapeake Bay and is negligible in Central and Southern Maryland. We therefore ignored nutrient management as an option in the latter.

The relevant non-linear programming problem in each county i in Central and Southern Maryland was:

$$\min \ \mathrm{c}t_i\mathrm{A}_\mathrm{i} + \sum_j \mathrm{K}(d_\mathrm{j}\mathrm{L}_\mathrm{i})$$

$$\begin{gathered} s.t. \ln(1-d_jM)+bZ_i+(1-a\,t_i)b_AA_i+ \\ \Phi^{-1}(P)[Z_{ij}'V_1Z_{ij}+2(1-a\,t_i)Z_{ij}'V_2A_{ij}+(1-a\,t_i)^2A_i^2s_{AA}+s_u^2]^{.5} \le \ln(N) \ \ \forall \mathrm{j} \\ 0 \le \tau_\mathrm{i} \le 1 \ \ \forall \mathrm{i} \end{gathered}$$

$$0 \leq \delta_j \leq 1 \ \ \forall j,$$

where τ_i is the share of corn acres planted to cover crops in county i, δ_j is the proportion of the water from system j treated by filtration (which is assumed to equal the share of the population served receiving treated water), c is the per-acre cost of a cover crop, A_i is the county's corn acreage, and $K(\delta_j L_j)$ is the cost of filtration in system j as specified in equation (11). In the constraint, $\ln(1-\delta_j M)$ represents the reduction in the natural log of nitrate from treatment where M is the nitrate removal proportion from water treatment, 96.5 percent and Z_{ij} is the vector of characteristics associated with system j in county i having detectable nitrate. The maximum allowable nitrate concentration N was set equal to the current EPA standard for nitrate in drinking water, 10 mg/l.

The relevant non-linear programming problem for each county i on the Eastern Shore was:

$$\min \ \ c(t_{1i} + t_{2i})A_i + qy_i B_i + \sum_j K(d_j L_j)$$

$$s.t. \ \ln(1-d_j M) + bZ_{ij} + (t_{1i} + t_{2i})(1-a)b_A A_i + (t_{3i} + t_{4i})b_A A_i + (1-y_i)b_B B_i +$$

$$\Phi^{-1}(P)[Z'_{ij}V_1 Z_{ij} + 2((t_{1i} + t_{2i})(1-a) + (t_{3i} + t_{4i}))Z'_{ij}V_2 A_i + 2(1-y_i)Z'_{ij}V_3 B_i +$$
$$2((t_{1i} + t_{2i})(1-a) + (t_{3i} + t_{4i}))(1-y_i)s_{AB} + ((t_{1i} + t_{2i})(1-a) + (t_{3i} + t_{4i}))^2 s_{AA} +$$
$$(1-y_i)^2 s_{BB} + s_u^2]^{1/2} \leq \ln(N) \ \ \forall i.$$

$$0 \leq \tau_i \leq 1 \ \forall i$$
$$0 \leq \delta_j \leq 1 \ \ \forall j$$
$$\sum_{k=1}^{4} t_{ki} = 1$$
$$\phi\psi_i B_i = (\tau_{1i} + \tau_{3i})A_i$$

The choice variables are the proportion of corn acres in county i in a cover crop with and without nutrient management, τ_{1i} and τ_{2i} respectively, the proportion of corn acres not in a cover crop both with and without nutrient management,τ_{3i} and τ_{4i}, respectively, ψ_i, the proportion of the total number of broilers in the county receiving nutrient management, and δ_j, the proportion of water from each system receiving treatment. The cost of nutrient management equals w, the cost of nutrient management per unit of inventory, times the proportion of broilers receiving nutrient management, ψ_i, times the number of broilers in the county, B_i. The final constraint states that the corn acreage needed to absorb the litter generated by the birds in nutrient management, $\phi\psi_i B_i$, must equal the corn acreage used for nutrient management, $(\tau_{1i} + \tau_{3i})A_i$. Here, $\phi = 0.00435$ (calculated by dividing 2.2 pounds of litter generated per bird by 506 pounds of litter applied per acre) is the corn acreage needed to absorb the litter from a single bird at the recommended application rate.

Empirical Results

We began by comparing the optimal division of effort to meet the current nitrate standard at a safety margin of 95 percent with current policy, which relies on filtration alone. We then investigated the effects of adjusting for uncertainty by comparing the optimal division of effort under margins of safety ranging from 50 percent to 95 percent. Finally, we examined the sensitivity of the results to changes in the estimated effectiveness of prevention and in the number of wells affected by nitrate contamination.

Optimal versus Current Policy

As Table 2 indicates, agricultural pollution control accounts for a remarkably small share of the optimal division of effort. In Central and Southern Maryland, the 10 mg/l standard with a 95 percent margin of safety is achieved at least cost by filtration alone. Filtration alone is also the least-cost method of achieving compliance in three (Caroline, Dorchester, and Kent) of the five Eastern Shore counties having community water systems with predicted nitrate concentrations in excess of the current standard with a 95 percent safety margin. Nutrient management does play an important role in meeting the standard in the remaining two Eastern Shore counties, which, incidentally, constitute the center of the poultry industry in the state. In Worcester County, the cost efficient level of prevention involves applying litter from 36 percent of the broiler flock to 65 percent of the county's corn acreage. In Wicomico County, the cost efficient level of prevention involves applying litter from 73 percent of the broiler flock. Cover crops are not used at all in meeting the current standard on the Eastern Shore.

The cost-efficient allocation of prevention and treatment in Wicomico County requires applying poultry litter to over three times the amount of land available in that county alone.[4] Such a plan seems reasonable. About 32,000 acres outside of Wicomico County would be needed to absorb the poultry litter generated under the unconstrained cost efficient level of nutrient management in Wicomico County. There are almost 52,000 acres of corn on which nutrient management would not be used in the three Maryland counties adjacent to Wicomico (Dorchester, Somerset, and Worcester). Additional corn acreage would likely also be available in adjacent Sussex County in Delaware.

Current policy places the burden of complying with drinking water standards solely on water providers. In Central and Southern Maryland, current policy appears to coincide largely with the efficient of combination of prevention and treatment. On the Eastern Shore, however, ignoring prevention increases the cost of meeting the nitrate standard in Maryland drinking water wells substantially, despite the apparently limited role these prevention measures play. Meeting the current nitrate standard with a 95 percent safety margin through filtration alone on the

Eastern Shore costs $1.47 million for community water systems (Table 2). Meeting this standard on the Eastern Shore using poultry nutrient management in addition to filtration costs only $0.64 million for community water systems. Thus, the cost of meeting the current nominal standard through treatment alone on the Eastern Shore is 131 percent higher than the cost of meeting the standard through a combination of prevention and treatment measures.

Impact of Increases in Precaution

Figure 1 shows the total cost of meeting the current drinking water standard for nitrate of 10 mg/l with margins of safety ranging from 0.5 (which corresponds to meeting the standard on average) to 0.95. All community water systems in Central and Southern Maryland have predicted nitrate concentrations below the nominal standard of 10 mg/l at a margin of safety as high as 0.55, while all community water systems on the Eastern Shore have predicted nitrate concentrations below the nominal standard at margins of safety below 0.8. Thus, measures to reduce nitrate in drinking water are needed only because of aversion to uncertainty, that is, only due to precautionary desires. As the margin of safety rises, the cost of compliance rises rapidly. Regressions of the natural log of compliance cost on the margin of safety (with no intercept) indicate that each one percentage point increase in the margin of safety increases compliance cost by 13 percent in Central and Southern Maryland and 17 percent on the Eastern Shore. As in the case of pesticide contamination of well water in California studied by Lichtenberg, Zilberman, and Bogen, aversion to uncertainty imposes a substantial cost.

As the margin of safety increases, more systems fall out of compliance with the nominal standard. Both treatment and the use of nutrient management rise monotonically with the margin of safety as a result (see Figure 2). Changing the margin of safety does not have a monotonic effect on the use of cover crops, however. Cover crops are not used at all on the Eastern Shore. They are used only in a single county (Harford County in Central Maryland) and then only at a margin of safety of 85 percent. This result is due to the presence of economies of scale in treatment. One community water system in that county serves a large population (63,000). The remaining community water systems in that county are quite small, serving 2,300 or fewer. At a margin of safety of 85 percent, a low level of treatment would be needed to maintain compliance. The avoided cost of treatment $K'(I)[\partial I/\partial X]$ is quite high due to the size of the population served, making leaching prevention via the use of cover crops cost efficient. As the margin of safety rises above 85 percent, the use of cover crops is no longer sufficient to prevent the need for treatment to maintain compliance with the nominal standard in this system. As the level of treatment in this system rises, the avoided cost of treatment falls and prevention becomes excessively costly relative to treatment (i.e., inequality (9) holds).

Sensitivity to Assumptions about Leaching from Agriculture

The greater the amount of nitrate leached from agriculture, the more cost effective one would expect prevention to be. If the Lichtenberg-Shapiro model underestimates leaching from corn and broilers, using the estimated parameters of that model could result in underestimates of the cost efficient use of leaching reducing agricultural best management practices. We explored the sensitivity of the cost efficient division of effort between prevention and treatment to the possibility of underestimates in leaching from agriculture by increasing the parameters relating to leaching potential from corn and broilers and simultaneously reducing the constant term in each county sufficiently to keep the initial nitrate contamination level constant. In other words, we increased β_A and β_B by the respective amounts $\Delta\beta_A$ and $\Delta\beta_B$ and then subtracted

$\Delta\beta_A A_i + \Delta\beta_B B_i$ from βZ_{ij} for each system with detectable nitrate in each county, a procedure that increases the share of nitrate attributable to corn and broilers without increasing the initial nitrate contamination level. We used the upper limits of individual one-tailed 99 percent confidence intervals for the estimates of leaching from corn and broilers as plausible upper end estimates. We thus set $\Delta\beta_A = 0.026749$ and $\Delta\beta_B = .00014$, resulting in estimates that were respectively 88 and 70 percent higher than the best estimates. This assumption implies that cover crops and nutrient management effect greater absolute reductions in nitrate leaching, making prevention relatively more cost effective.

As in the base case, treatment alone remained the most cost efficient means of meeting the nominal standard at a 95 percent margin of safety in all counties in Central and Southern Maryland and three counties on the Eastern Shore (Table 3). In Wicomico and Worcester Counties nutrient management was used on a smaller share of the broiler flock, so that assuming that nutrient management was more effective led to less, rather than more extensive use of it. In Wicomico County, the share of water treated fell as well—more effective prevention resulted in a reduction in treatment. In Worcester County, however, the share of water treated remained the same as in the base case. Overall, the results suggest that the marginal cost of treatment is so much lower than that of prevention in most of Maryland that reliance on treatment is likely to remain the most cost efficient strategy for managing nitrate in groundwater even if agricultural best management practices could be made substantially more effective in reducing nitrate leaching.

Sensitivity to the Number of Affected Wells

The theoretical analysis indicates that prevention tends to be more cost efficient when the number of affected sites (i.e., sites with vulnerability no less than θ^*) is larger. The preceding empirical analysis has considered only community water systems, ignoring the far more numerous individual household wells. We investigated the sensitivity of the results to changes in the number of affected wells using data on the numbers and depths of individual household wells. Since tests of private well water quality were not available, we extrapolated the Lichtenberg-Shapiro parameter estimates on the basis of well depth. We assumed treatment of drinking water by reverse osmosis, which reduces concentrations by an average of 95 percent at an estimated annualized cost of $151 per household.[5]

Incorporating individual household wells in this manner increased the number of wells out of compliance with the nominal standard but caused little change qualitatively in the cost-efficient division of effort between prevention and treatment. In Central and Southern Maryland, the nominal standard was met with a 95 percent margin of safety at least cost through filtration alone in all counties but one; in the latter, meeting the standard proved infeasible through filtration alone. On the Eastern Shore, the nominal standard was met at a 95 percent margin of safety entirely through treatment in four counties of the eight having wells with predicted nitrate concentrations in excess of the current standard at a 95 percent margin of safety. As in the base case, nutrient management played an important role in meeting the standard in the remaining four counties, all of which are located in the principal poultry producing area.

Conclusion

Discussions of agricultural pollution problems in policy circles and in the economics literature have tended to focus on preventive measures such as changes in farming practices. In some cases, exclusive interest in prevention may be warranted; for example, technologies for treating large bodies of water like the Great Lakes or the Chesapeake Bay are not generally available at present. But in other cases (e.g., contamination of drinking water wells by agricultural chemicals), treatment is both technically feasible and, sometimes at least, relatively inexpensive. This paper considers the cost minimizing mix of prevention and treatment for the latter class of environmental problems. We develop a theoretical model that incorporates key features of agricultural pollution problems, notably (1) heterogeneous firms (and thus pollution control costs), (2) heterogeneous sites subject to pollution, and (3) uncertainty about the extent of pollution at each site. We analyze precautionary regulation that seeks to keep violations of a maximum allowable pollution level below an acceptable frequency of occurrence. The analysis indicates that under some plausible conditions greater precaution or more stringent regulation may make it desirable to reduce overall preventive effort and rely more on treatment. We illustrate the theory using an empirical example involving contamination of drinking water wells in Maryland due to leaching of nitrate from corn and broiler production. The empirical analysis indicates that treatment of well water is more cost effective than the use of agricultural best management practices to prevent nitrate leaching everywhere in Maryland except for the center of the poultry industry, where nutrient management plays an important role in managing nitrate in drinking water wells.

While we attempted to be conservative in estimating the costs of prevention, several aspects of our approach may have underestimated the attractiveness of prevention. First, we assumed that nutrient management and cover crops affected nitrate leaching only in the counties in which they were used. This assumption accurately characterizes Central Maryland, where groundwater occurs in unconfined rock fractures, and Southern Maryland, where aquifer recharge zones are located mainly in the same counties as wells drawing on those aquifers. It is less accurate for the Eastern Shore, where the recharge zones of confined aquifers are located in neighboring counties. Ignoring cross-county reductions in leaching results in underestimates of the cost-effectiveness of prevention. However, the results of the private household well analysis that tested the sensitivity of the results to the number of wells affected suggest that including such cross-county effects would likely not change the cost-efficient division of effort much, if at all. Second, the safety-fixed decision criterion used here assumes there is no benefit from inframarginal reductions in nitrate leaching; in other words, reductions in nitrate concentrations at levels above or below the nominal standard have a shadow value of zero. Such an assumption is plausible in the case at hand. EPA has set the nominal standard for nitrate at a fraction of the lowest concentration at which adverse effects have been observed. It is thus likely that reductions in nitrate concentrations have little, if any, marginal effect on drinking water safety. Third, preventive measures in agriculture may provide more than one kind of environmental benefit. In Maryland, for example, agricultural best management practices that prevent leaching into groundwater also reduce runoff of nutrients (notably nitrogen and phosphorus) into surface waters, including the Chesapeake Bay. It is possible that more extensive use of these practices is justifiable on the basis of reductions in surface water pollution even if it is not on the basis of groundwater contamination. In the case of the Chesapeake Bay, however, reducing surface water pollution requires shifting from nitrogen-based to phosphorus-based nutrient management strategies. The latter feature lower litter application rates per acre of cropland than the former. As a result, litter must be transported a longer distance on average, so that nutrient management is more costly than assumed here.

At the same time, several factors make it likely that the marginal costs of preventive measures are likely to be higher than assumed in our analysis. First, preventive activities probably exhibit increasing rather than constant marginal costs. Even if the relevant agricultural technologies are characterized by constant expenditures per acre, the effectiveness of leaching reduction and/or the effect of leaching reduction on nitrate concentrations in well water vary from site to site, giving rise to increasing marginal costs of reductions in well water nitrate concentrations. Second, informational constraints may make prevention significantly more costly than assumed here. The models presented here assume that least cost prevention is feasible, that is, that regulators can identify the cost and effectiveness of on-farm pollution reduction measures at each type of farm enterprise (differentiated by type of crop, type of livestock, topographic and geological features, etc.). In reality, regulators rarely have such abilities. Much of the time, regulators do not know the true cost and effectiveness of on-farm pollution reduction measures are not known. Even when they have such information, they may be legally unable to utilize it. As a result, they may be forced to employ second-best policies that involve payment of information rent. (For example, second-best mechanisms are likely to be unenforceable for agricultural chemicals due to the ease with which secondary "black markets" can arise and the difficulty of suppressing them.) In such situations prevention will be even more costly than modeled here and treatment, where feasible, will be correspondingly more desirable.

Finally, it should be noted that our empirical results arise from a case involving groundwater contamination by nitrate. The cost-effectiveness of prevention relative to treatment is likely to differ in cases of contamination by other agricultural chemicals. Treatment is likely to be more costly for more complex chemicals, for example, organic compounds like pesticides. Of course, prevention may be more costly, too. The main lesson to be drawn is that there is no sound justification for basing policy on a *presumption* that prevention is more cost-effective than treatment; rather, the least-cost mix of prevention and treatment is an empirical question.

Footnotes

[1] In broader policy discussions the notion that those responsible for creating a problem should also be responsible for fixing it is often cited as a motivation for emphasizing prevention over treatment. As is well known among economists, however, the "polluter pays" and similar principles can be implemented via financing (i.e., having polluters defray the costs incurred by those using a polluted resource) regardless of the division of effort between prevention and treatment.

[2] The implicit cost of eliminating leaching using cover crops is $56 per acre. The available data suggested that both land retirement and reducing fertilizer use were more expensive than using cover crops. The average rental rate for crop land in Maryland is about $50 per acre. With adjustments for quality and returns to labor and management, it seems likely that the per-acre cost of land retirement exceeds $56 per acre. The cost of reducing leaching by reducing fertilizer application equals the lost revenue from reduced corn yields divided by the reduction in leaching. Information on the former can be obtained from estimated nutrient response curves; unfortunately, there is little information on the latter. The only published study we could find indicated an implicit cost of eliminating leaching of $154 per acre; details of the calculations can be found in Penn.

[3] The cost of nutrient management was calculated as follows. Fixed costs were assumed to equal $16,608 for a storage shed adequate for litter from 50,000 birds plus $12,500 for a spinner spreader capable of spreading litter from 175,000 birds. Both were annualized at an interest rate of 4.96 percent over lifetimes of 20 and 5 years, respectively. Insurance for both items was estimated to be 1 percent of the total fixed cost. Maintenance for the storage shed

and spreader were estimated to be 1 and 5 percent, respectively, of the total fixed cost. Average costs per broiler were obtained by dividing by the number of birds served. Savings from reduced chemical fertilizer purchases were deducted from these costs. Each 1,000 birds were assumed to produce 1.1 tons of litter (2.2 pounds per bird). Litter was assumed to have a composition of 2.88 percent nitrogen, 3.17 percent phosphorus, and 2.05 percent potassium (Carr et al.). Thirty percent of the nitrogen and all of the phosphorus and potassium was assumed to be available immediately (Sims and Wolf). Nitrogen, phosphorus, and potassium were assumed to cost $.30, $.19, and $.15 per pound respectively.

[4] The constraint on corn acreage proved binding in Wicomico County. We therefore recalculated the optimal levels of treatment and prevention using the alternative constraint

$$\tau_{1i} + \tau_{3i} = \psi_i,$$

which corresponds to an assumption that sufficient land is available in neighboring counties to absorb all of the poultry litter needed for the optimal use of nutrient management in Wicomico County.

[5] Additional details of the empirical methodology used in the individual household well sensitivity analysis are available on request.

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Table 1. Estimated Number of Community Water Systems Not in Compliance with Nitrate Standard at a 95% Margin of Safety

County	Number of Systems Tested	Percent of Systems Noncompliant	Upper Tail of One-Tailed 95% Confidence Interval for Nitrate (mg/l)		
			Minimum	Maximum	Mean
Central and Southern Maryland					
Allegany	7	43	10.25	12.25	11.25
Anne Arundel	34	9	10.85	48.24	33.21
Baltimore	4	100	78.60	219.12	169.80
Carroll	18	100	82.24	166.97	121.88
Cecil	40	80	10.47	39.90	24.80
Frederick	18	100	42.91	264.45	107.42
Garrett	4	25	10.68	10.68	10.68
Harford	15	100	25.75	106.34	70.92
Montgomery	3	100	37.60	52.57	44.17
Washington	10	100	46.48	166.29	91.42
Eastern Shore					
Caroline	20	20	13.64	109.28	46.26
Dorchester	8	25	12.89	14.02	13.46
Kent	7	29	22.86	32.06	27.46
Wicomico	17	76	13.66	110.78	68.94
Worcester	15	47	24.45	42.98	29.00

Source: Calculated from data and estimated coefficients reported in Lichtenberg and Shapiro. See text for methodology.

Table 2. Roles of Prevention and Treatment in Meeting Drinking Water Nitrate Standard with a 95% Margin of Safety in Community Water Systems

Central and Southern Maryland				
County	Prevention	Treatment		Cost
	Share of Corn Acres with Cover Crops	Number of Systems Treated	Mean Share of Water Filtered	
Allegany	0.00	2	0.108	$366
Anne Arundel	0.00	3	0.567	$4,881
Baltimore	0.00	4	0.964	$38,401
Carroll	0.00	17	0.947	$652,120
Cecil	0.00	28	0.533	$182,460
Frederick	0.00	17	0.909	$695,040
Garrett	0.00	1	0.066	$751
Harford	0.00	13	0.867	$2,321,100
Montgomery	0.00	3	0.797	$120,300
Washington	0.00	10	0.889	$158,940
Regional Total		98		$4,174,359

Eastern Shore			
	Prevention	Treatment	Cost

	Share of Corn Acreage with:				Share of Broilers with Nutrient Management	Number of Systems Treated	Mean Share of Water Filtered	
County	Cover Crop, Nutrient Management	Cover Crop, No Nutrient Management	No Cover Crop, Nutrient Management	No Cover Crop, No Nutrient Management				
Caroline	0.00	0.00	0.00	1.00	0.00	3	0.534	$3,088
Dorchester	0.00	0.00	0.00	1.00	0.00	2	0.265	$18,097
Kent	0.00	0.00	0.00	1.00	0.00	2	0.648	$96,273
Wicomico*	0.00	0.00	3.05	0.00	0.732	12	0.080	$331,220
Worcester	0.00	0.00	0.645	0.355	0.363	5	0.141	$187,460
Regional Total						24		$636,138
Eastern Shore—Treatment Only								
Caroline	0.00	0.00	0.00	1.00	0.00	3	0.534	$3,088
Dorchester	0.00	0.00	0.00	1.00	0.00	2	0.265	$18,097
Kent	0.00	0.00	0.00	1.00	0.00	2	0.648	$96,273
Wicomico	0.00	0.00	0.00	1.00	0.00	12	0.831	$1,036,800
Worcester	0.00	0.00	0.00	1.00	0.00	5	0.662	$314,900
Regional Total						24		$1,469,158

* Nutrient management is assumed to be unconstrained by corn acreage available in Wicomico County alone. The share of county corn acreage with nutrient management and no cover crop has been rescaled to represent the ratio of the corn acreage on which nutrient management is used to the total corn acreage available in Wicomico County alone. If nutrient management could be used only on corn acreage in Wicomico County alone, the share of the broiler flock under nutrient management would equal 0.240, the share of Wicomico County corn acreage under nutrient management would equal 1.00, the mean share of water treated would equal 0.672, and the total cost would be $953,860.

Table 3. Roles of Prevention and Treatment in Meeting Drinking Water Nitrate Standard with a 95% Margin of Safety in Community Water Systems with Plausible Upper End Estimates of Nitrate Contributions from Corn and Broilers.

Central and Southern Maryland				
County	Prevention	Treatment		Cost
	Share of Corn Acres with Cover Crops	Number of Systems Treated	Mean Share of Water Filtered	
Allegany	0.00	2	0.108	$366
Anne Arundel	0.00	3	0.567	$4,881
Baltimore	0.00	4	0.964	$38,401
Carroll	0.00	17	0.947	$652,120
Cecil	0.00	28	0.533	$182,460
Frederick	0.00	17	0.909	$695,040
Garrett	0.00	1	0.066	$751
Harford	0.00	13	0.867	$2,321,100
Montgomery	0.00	3	0.797	$120,300
Washington	0.00	10	0.889	$158,940
Regional Total		98		$4,174,359

Eastern Shore

	Prevention					Treatment		Cost
	Share of Corn Acreage with:				Share of Broilers with Nutrient Management	Number of Systems Treated	Mean Share of Water Filtered	
County	Cover Crop, Nutrient Management	Cover Crop, No Nutrient Management	No Cover Crop, Nutrient Management	No Cover Crop, No Nutrient Management				
Caroline	0.00	0.00	0.00	1.00	0.00	3	0.534	$3,088
Dorchester	0.00	0.00	0.00	1.00	0.00	2	0.265	$18,097
Kent	0.00	0.00	0.00	1.00	0.00	2	0.648	$96,273
Wicomico*	0.00	0.00	1.85	0.00	0.444	12	0.042	$190,190
Worcester	0.00	0.00	0.374	0.626	0.211	5	0.141	$132,980
Regional Total						24		$440,628

* Nutrient management is assumed to be unconstrained by corn acreage available in Wicomico County alone. The share of county corn acreage with nutrient management and no cover crop has been rescaled to represent the ratio of the corn acreage on which nutrient management is used to the total corn acreage available in Wicomico County alone. If nutrient management could be used only on corn acreage in Wicomico County alone, the share of the broiler flock under nutrient management would equal would equal 0.240, the share of Wicomico County corn acreage under nutrient management would equal 1.00, the mean share of water treated would equal 0.507, and the total cost would be $753,700.

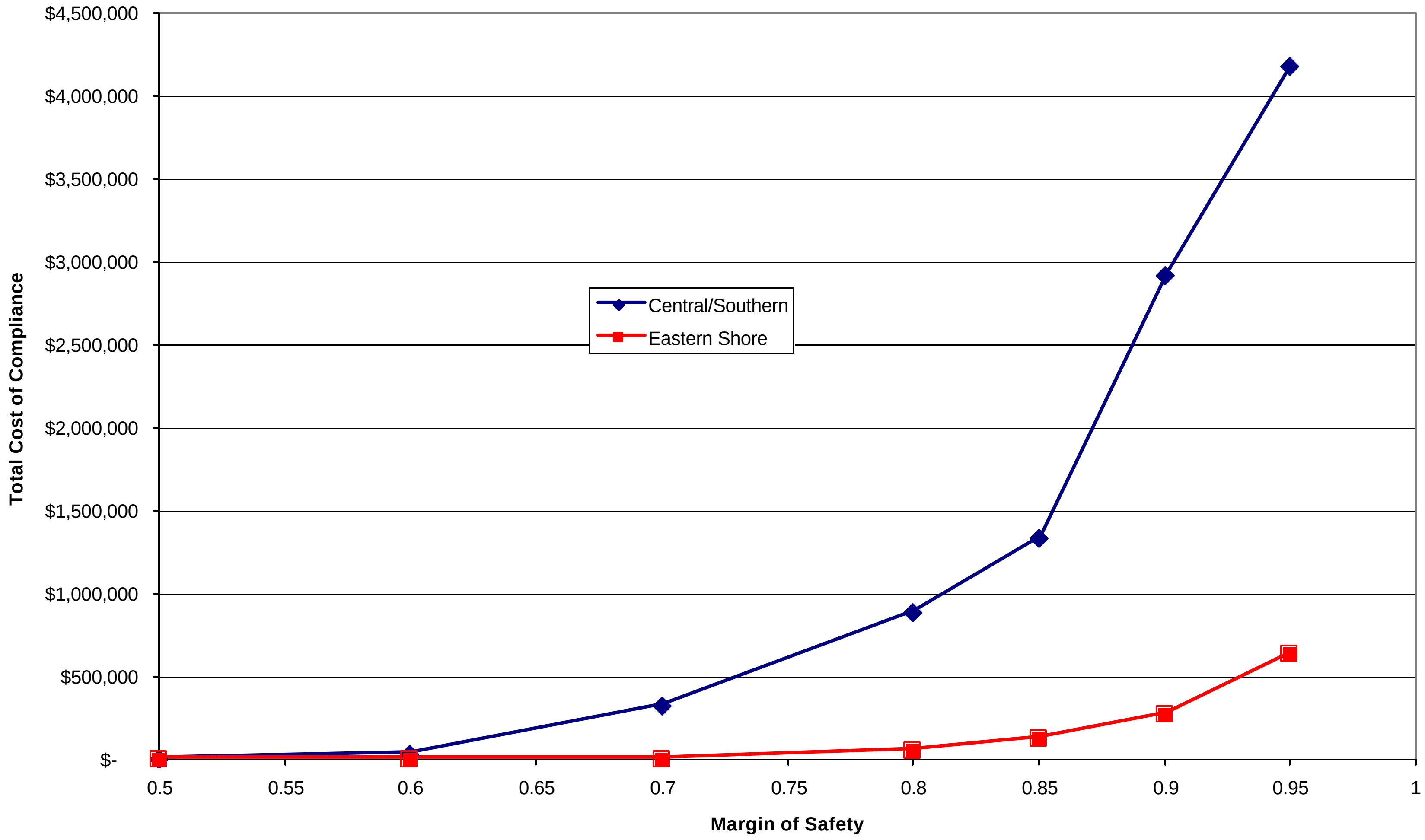

Figure 1. Impact of Precaution on the Cost of Compliance with the Nitrate Standard in Community Water System Wells

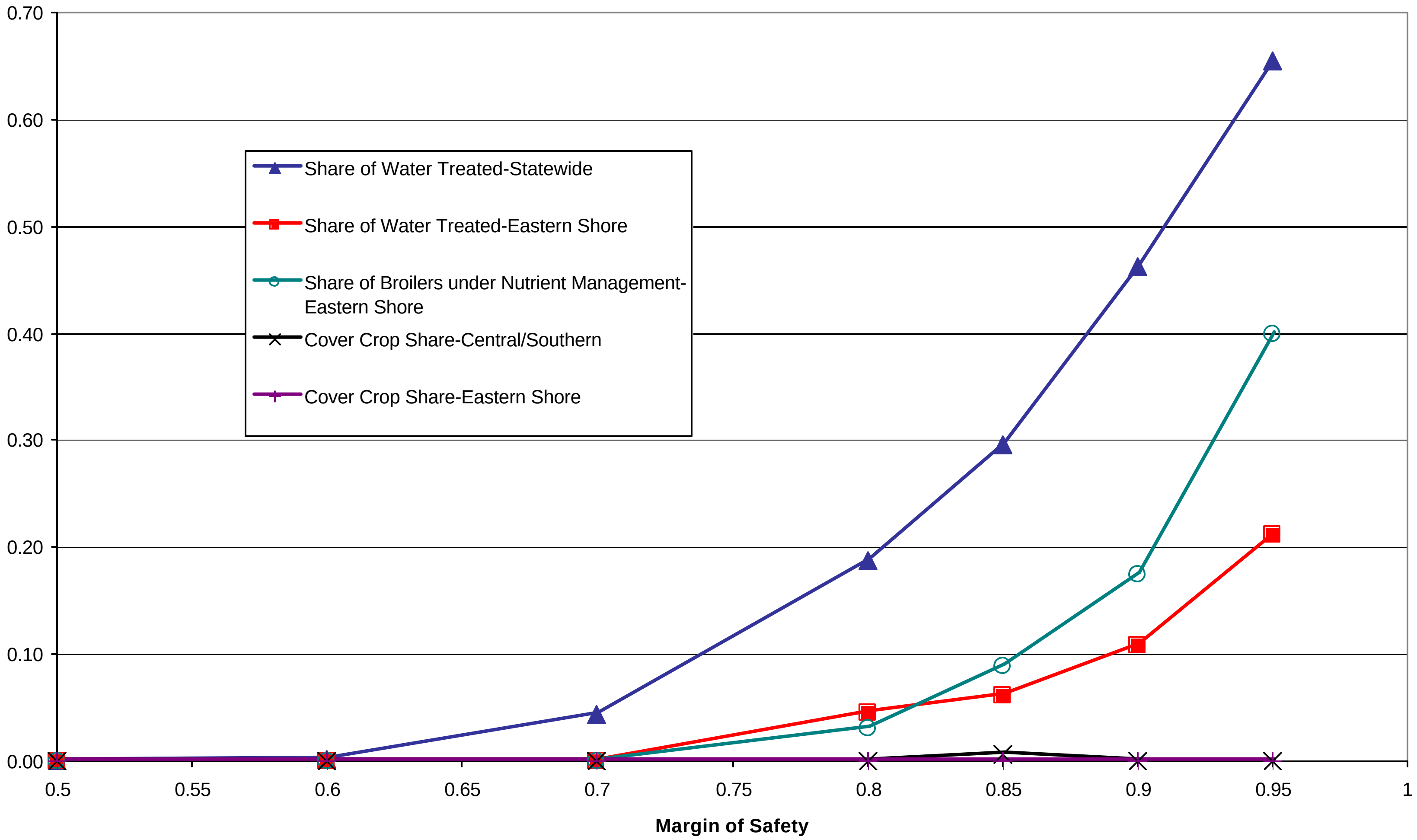

Figure 2. Impact of Precaution on Cost Efficient Prevention and Treatment in Community Water Systems