Groundwater Quality Policy under Uncertainty

Erik Lichtenberg and Tony Penn

Department of Agricultural and Resource Economics
University of Maryland
College Park, Maryland 20742

February 4, 1996

Introduction

Non-point source (NPS) pollution of groundwater has received increasing public attention. Groundwater is a major water source: In the United States, for instance, half of the population relies on groundwater for drinking water supplies. In rural areas, virtually all drinking water comes from underground sources (U.S. Environmental Protection Agency 1987). The importance of groundwater has grown as rural land has been urbanized; in the United States, groundwater withdrawals have increased much faster since 1950 than surface water usage (Aldrich, 1980). As groundwater use has expanded, more and more cases of pollution have come to light (Office of Technology Assessment 1984; U.S. Environmental Protection Agency 1987). Many such cases involve pollutants that are documented or suspected human health hazards (Vogt and Cotruvo 1988).

Agriculture is the principal contributor of NPS pollutants such as pesticides and fertilizers (see for example Office of Technology Assessment 1984; Organization for Economic Cooperation and Development 1986; Hallberg 1989; Spalding and Exner 1993). A recent national survey conducted by the U.S. Environmental Protection Agency estimated that, in the United States as a whole, 52 percent of community water system wells and 57 percent of private rural domestic wells contained measurable amounts of nitrate, while 1 and 2 percent, respectively, had nitrate concentrations exceeding the current U.S. drinking water standard of 10 mg/l for nitrate-N. The same survey found that 10 percent of community water system wells and 4 percent of private rural domestic wells had measurable amounts of pesticide residues, of which virtually none and less than one percent, respectively, exceeded drinking water standards or health advisory levels (U.S. Environmental Protection Agency 1990). High nitrate concentrations in drinking water and diet more generally have been linked to methemoglobinemia ("blue baby syndrome") in bottle-fed infants, increased incidence of gastric cancer, and other adverse health effects (Hartman 1982). Some of the pesticides found in groundwater are acutely toxic, while others are believed to increase long-run health damage such as cancer.

Uncertainty is a central feature of groundwater contamination, indeed, all NPS, problems. NPS pollution problems are inherently stochastic, from a social planning point of view at least, because individual sources of pollutants cannot be identified. Even if NPS polluters know emissions with certainty, a public pollution-control agency must treat emissions as random. Agricultural runoff and leaching, for example, occur mainly during heavy rainfalls, which occur randomly. Lack of knowledge compounds this uncertainty: Typically, much remains unknown about the soils, geology, and microbial activity in the shallow and deep aquifers through which leachates travel, so that the influence of these factors, too, is known only stochastically.

There are two general approaches to handling NPS pollution of groundwater: reducing emissions and removing pollutants prior to use. The former is generally undertaken by polluters, the latter typically by water users, that is, water utilities or individual well owners. The efficient division of effort between emissions reduction and user remediation has been studied under certainty by Olson and Zeckhauser (1970), Shibata and Winrich (1983) and Oates (1983). Uncertainty may affect this division of effort. In addition, a third type of action is available for handling pollution problems that are inherently uncertain: research aimed at reducing that uncertainty. Land-grant universities throughout the United States and public agencies at the national (U.S. Department of Agriculture) and state levels are increasingly emphasizing research to improve knowledge about runoff and leaching in addition to developing agricultural practices for reducing NPS pollution.

This paper examines theoretically the interactions between such research and groundwater quality regulation. We conduct our investigation in a regulatory context like that of the United States. Following Lichtenberg and Zilberman (1988), we characterize water quality regulation like that required by the Safe Drinking Water Act in the United States as one where the concentration of pollutants in drinking water must meet not exceed a given standard with a given margin of safety, in other words, where regulation imposes a probabilistic standard. Our analysis differs from theirs in that we consider both emissions-reduction by polluters and remediation efforts of water users, be they public utilities or individual well owners. We examine how this efficient division of effort between emissions reduction and user remediation varies as vulnerability to leaching and crop values vary. We discuss the effects of increasing the stringency of both the nominal standard and the margin of safety, and implications for regulation and legislation, such as revision of the Safe Drinking Water Act in the United States. We examine research-induced changes in the distribution of pollution control costs between these two groups and the implications of these changes on support for research of this nature.

The Model

We begin with a characterization of pollution in the production process. For ease of exposition, we will refer to the polluting industry as agriculture. Assume that emissions are proportional to the use of a particular input used in the polluting industry, such as fertilizers or pesticides, denoted x. Let emissions be $\alpha x+\eta$, where α and η are random variables jointly distributed with respective means $\bar{\alpha}$ and $\bar{\eta}$, variances σ_α^2 and σ_η^2, and covariance $\rho\sigma_\alpha\sigma_\eta$. The random variable α represents factors associated with leaching of fertilizers or pesticides, such as crop nutrient uptake, soil characteristics, and rainfall. The random variable η represents all factors affecting NPS pollution of groundwater that are not directly involved in leaching, such as naturally-occurring nitrate from animal wastes or mineral deposits, soil microbial activity affecting denitrification or breakdown of pesticides, reduction of nitrate or breakdown of pesticides by minerals present in the aquifer, water flow rates through the aquifer, etc. The factors represented by η may be positively or negatively correlated with those represented by α, that is, ρ may be positive or negative.

In this characterization, the use of the polluting input increases both the mean and variance of emissions, so that uncertainty about emissions is greater in areas that use the polluting input more intensively. This seems a reasonable characterization of fertilizers and pesticides. The availability of agricultural chemicals for leaching and runoff is increasing in usage (see for example Hallberg 1989, Keeney 1982, or Spalding and Exner 1993). An increase in fertilizer or pesticide use will result in much larger emissions during heavy rainfalls, but little or no change in emissions otherwise, suggesting that the variance of emissions is increasing in fertilizer and pesticide use.

In the absence of regulation, composition of output and input use in agriculture is chosen to maximize profit

$$\sum p_k y_k - \sum w_j z_j - vx$$
$$s.t. f(y,z,x) \le 0,$$

where p_k is the price of crop y_k, w_j is the price of (non-polluting) input z_j, v is the price of the polluting input, and f(y,z,x) is a product transformation function, which we assume to be concave. Note that agricultural production is assumed to be independent of the random factors affecting leaching, α and η. We believe this assumption is reasonable, at least for rain-fed agriculture. Empirical evidence suggests that leaching in rain-fed agriculture (e.g., from corn fields in the United States) occurs mainly after the growing season; apparently, the crop holds nutrients largely in place in the water table (see for example Brinsfield and Staver 1989; Angle 1985; Angle, Gross and McIntosh 1989).

This problem can be concentrated into one of choosing the polluting input alone using a revenue function

$$R(p,w,x) = \max_{y,z}\left\{\sum p_k y_k - \sum w_j z_j - vx : f(y,z,x) \le 0\right\},$$

where $p = (p_1, ..., p_K)$ is a vector of output prices and $w = (w_1, ..., w_J)$ is a vector of input prices. The agricultural profit maximization problem then becomes one of choosing x to

$$\max R(p,w,x) - vx,$$

which has the necessary condition

$$R_x(p,w,\bar{x}) - v = 0$$

defining profit-maximizing polluting input use $\tilde{x}$. This condition is sufficient under the assumption that f(y,z,x) is concave (which implies that R(p,w,x) is concave as well).

We model pollution control in agriculture as a reduction in the use of the polluting input x. In literal terms, this assumption corresponds to treating pollution control measures as reductions in fertilizer or pesticide application rates. Reducing application rates is in fact one approach to reducing leaching of agricultural chemicals. For example, there is growing inter... in the United States on the use of in-season soil tests and measures of crop growth to calibrate fertilizer application rates so that they can be matched more exactly to crop uptake rates. Of course, other approaches are also used. For pesticides, for example, a common approach to protecting groundwater from leaching is to refrain from mixing, loading, and spraying pesticides within a given distance from a wellhead or groundwater recharge area. Use of a highly leachable pesticide may be banned, at least in areas considered vulnerable to leaching. Planting fall cover crops may be recommended for soaking up excess nitrogen left over from the growing season, preventing both runoff and leaching. Storage of manure and subsequent use as fertilizer may similarly be used to reduce runoff and leaching. Our model, while not literally correct in all cases, captures the essential feature of interest, namely, that these measures are generally costly: Reducing x below the profit-maximizing level $\tilde{x}$ imposes a cost on farmers in terms of foregone income.

An alternative to reducing emissions is to remove pollutants from water prior to use, that is, to remediate pollution. Let I be the water users' current expenditures on removing pollutants from drinking water. For example, I may represent annualized capital and operating expenditures on filtration systems or the cost of a new well tapping an uncontaminated aquifers. Let g(I) be the reduction in concentration of the pollutant in drinking water achieved by spending I, where $g'(I) > 0$, $g''(I) < 0$, so that the ultimate concentration of the pollutant in drinking water, N, is

$$N = \alpha x + \eta - g(I).$$

It is normally distributed with mean

$$E(N) = \bar{\alpha}x + \bar{\eta} - g(I)$$

and variance

$$V(N) = x^2\sigma_\alpha^2 + \sigma_\eta^2 + 2\rho\sigma_\alpha\sigma_\eta .$$

Note that, under the assumptions of this model, water-user remediation affects only the mean concentration of the pollutant in drinking water, leaving the variance unaffected. In physical terms, we assume that remediation lowers the concentration of the pollutant in treated water by a constant amount g(I), regardless of the concentration in incoming, untreated water.

While this model is written in additive form, it applies equally to multiplicative or exponential representations of the leaching process, which can be obtained using the traditional transformations used in econometrics. For example, it may be natural in many cases to express pollutant concentrations in well water in terms of percentage contributions from various sources (including negative absolute contributions or percentage contributions of less than one in the case of I). Such cases can be accommodated by setting N equal to the natural logarithm of the pollutant concentration.

Finally, let $S(N) = [V(N)]^{1/2}$ be the standard deviation of the concentration of the pollutant in drinking water. It follows from this definition that

$$S_x = \frac{\sigma_\alpha(x\sigma_\alpha + \rho\sigma_\eta)}{S} > 0$$

$$S_{\sigma_\alpha} = \frac{x(x\sigma_\alpha + \rho\sigma_\eta)}{S} > 0$$

$$S_{\sigma_\eta} = \frac{\sigma_\eta + x\rho\sigma_\alpha}{S} > 0,$$

S(N) is increasing in the use of the polluting input, in uncertainty about leaching (σ_α), and in uncertainty about groundwater contamination effects of factors not directly involved in leaching (σ_η). Additionally,

$$S_{xx} = \frac{\sigma_\alpha^2}{S}\left[1-\left(\frac{x\sigma_\alpha+\rho\sigma_\eta}{S}\right)^2\right] > 0$$

$$S_{x\sigma_\alpha} = \frac{x\sigma_\alpha}{S}\left[2-\left(\frac{x\sigma_\alpha+\rho\sigma_\eta}{S}\right)^2\right] > 0$$

$$S_{x\sigma_\eta} = \frac{\sigma_\alpha}{S}\left[\rho-\frac{(x\sigma_\alpha+\rho\sigma_\eta)(\sigma_\eta+x\rho\sigma_\alpha)}{S^2}\right] >< 0.$$

Polluting input use increases the standard deviation of the pollutant concentration at an increasing rate, and an increase in uncertainty about leaching increases the marginal effect of polluting input use on the standard deviation of the pollutant concentration. The impact of greater uncertainty about non-leaching groundwater contamination factors on S_x, however, is ambiguous. If η and α are negatively correlated, then greater uncertainty about η decreases S_x; if they are positively correlated, greater uncertainty about η decreases S_x if $\frac{(x\sigma_\alpha+\rho\sigma_\eta)(\sigma_\eta+x\rho\sigma_\alpha)}{S^2}$, which is less than one, is also less than ρ; otherwise, greater uncertainty about η increases S_x.

Optimal Emissions Reduction and Remediation Under Uncertainty

Legislation governing drinking water quality such as the Safe Drinking Water Act in the United States typically adopt 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. Lichtenberg and Zilberman (1988) have argued that this corresponds to imposing a safety-rule constraint on water providers of the form

$$\Pr\{N \geq \overline{N}\} \leq 1-P,$$

where $\overline{N}$ is the maximum allowable concentration or drinking water standard, and $0 \leq 1-P \leq 1$ is the probability that the standard is violated. Lichtenberg and Zilberman characterize P as the margin of safety mandated by such legislation.

This constraint can be rewritten in the form

$$N(P) \equiv E(N) + F(P)S(N) \leq \overline{N}$$

where E(N) and S(N) are the mean and standard deviation of N, respectively, for a large class of distributions of N, including the normal. Here, N(P) is the effective standard attained with margin of safety P, while $\overline{N}$ is the nominal standard. As Lichtenberg, Zilberman and Bogen (1989) note, this form of safety standard corresponds to a classical statistics approach to decision-making under uncertainty, since N(P) = E(N)+F(P)S(N) corresponds to the upper limit of a one-sided confidence interval with confidence level P (or significance level 1-P).

Under the assumptions of the leaching model presented above, this constraint on pollution can be written

$$\left[\overline{\alpha}x + \overline{\eta} - g(I)\right] + F(P)\left[x^2\sigma_\alpha^2 + \sigma_\eta^2 + 2x\rho\sigma_\alpha\sigma_\eta\right]^{1/2} \leq \overline{N}.$$

The socially optimal policy in such a regulatory context is found by choosing x and I to

$$\max R(p,w,x) - vx - I$$
$$s.t. \left[\overline{\alpha}x + \overline{\eta} - g(I)\right] + F(P)\left[x^2\sigma_\alpha^2 + \sigma_\eta^2 + 2x\rho\sigma_\alpha\sigma_\eta\right]^{1/2} \leq \overline{N}.$$

Assuming an interior solution, i.e., that both x and I are positive in an optimum, the necessary conditions characterizing such a policy are

$$R_x(p,w,x) - v - \lambda\left(\overline{\alpha} + F(P)S_x\right) = 0$$
$$-1 + \lambda g'(I) = 0$$
$$\overline{N} - \left[\overline{\alpha}x + \overline{\eta} - g(I)\right] - F(P)S = 0,$$

where $\lambda \geq 0$ is the marginal increase in the region's income due to an increase in the allowable concentration of the pollutant in drinking water, or, put another way, the marginal cost of meeting the standard with a margin of safety P (Lichtenberg and Zilberman 1988).

The first of these necessary conditions states that the polluting input should be applied up to the point where the value of its marginal product, $R_x(p,w,x)$, equals the sum of the price of the polluting input, v, plus the marginal cost of its contribution to pollution. This latter term equals the marginal cost of an increase in concentration of the pollutant, λ, times the increase in the upper bound of a confidence interval with confidence level 1-P, $\overline{\alpha}+F(P)S_x$. Put another way, increasing the use of the polluting input increases farm income by $R_x(p,w,x)-v$; this increase in farm income must be . balanced against the increased cost of meeting the drinking water standard with a margin of safety P, $\lambda(\overline{\alpha}+F(P)S_x)$. This condition implies that the optimal level of polluting input use will be less than the profit-maximizing level.

The second of these necessary conditions states that the value of the marginal product of spending on remediation measures by water users, $\lambda g'(I)$, must equal the marginal cost of spending, which is simply one. This implies further spending on remediation should be set such that the inverse of the marginal product of that spending, $1/g'(I)$, equals the marginal cost of meeting the standard, λ.

The third necessary condition states that the constraint is binding.

These necessary conditions are also sufficient as long as

$$R_{xx}-\lambda F(P)S_{xx}<0$$
$$\lambda g''<0$$
$$[R_{xx}-\lambda F(P)S_{xx}]\lambda g''>0$$
$$\Gamma\equiv[R_{xx}-\lambda F(P)S_{xx}][g']^2-[\overline{\alpha}+F(P)S_x]^2\lambda g''>0,$$

all of which hold under our assumptions about R(p,w,x), g(I), and S(N).

These necessary conditions indicate the efficient division of effort between emissions reduction and user remediation under this form of regulation. In what follows, we consider the impacts of vulnreability to leaching, crop prices, stricter water quality standards, research into leaching, and general research on groundwater on the division of effort between emissions reduction and remediation and thus on the incomes of farmers and water users under this form of regulation. The extent to which the regulatory burden is shared between farmers and water users, as derived above, varies. In the United States, for example, enforcement of non-point source pollution has been relatively neglected until recently, so that water users have shouldered most of the burden of meeting drinking water quality standards. However, farmers have shared this burden in a number of important cases. States like Iowa, for example, have imposed taxes on fertilizer in order to reduce nitrate leaching problems. Nebraska and other states have restricted fertilizer and pesticide use in areas found to be highly vulnerable to leaching. The U.S. Environmental Protection Agency requires pesticide users in vulnerable areas to take precautionary measures like setbacks from wellheads or recharge areas. The states in the Chesapeake Bay watershed have targeted soil and water conservation measures in agriculture as critical for meeting their commitments under the Chesapeake Bay Compact, which requires 40 percent reductions in nutrient loadings by the year 2000. Overall, it appears that there is the trend in the United States toward greater regulation of agricultural emissions. In what follows, we analyze likely effects of that trend.

Impact of Vulnerability to Leaching

Regions differ in their vulnerability to leaching in two general ways. First, average leaching rates may differ due to differences in soils, crops, or average rainfall. For example, areas with sandier soils or greater rainfall tend to experience greater leaching. Nitrate leaching from soybeans tends to be less than leaching from corn, which is fertilized heavily. We model these differences as changes in the average leaching rate $\bar{\alpha}$. Second, average concentrations of pollutant in well water may vary due to differences in geology, hydrology, microbial activity, or alternative sources of pollutant. Aquifers rich in glauconitic rock, for example, tned to be less vulnerable to nitrate leaching because they contain iron in a form available for reducing nitrate. Areas with heavy concentrations of septic systems tend to exhibit greater nitrate pollution of groundwater. We model these differences as changes in average background pollutant concentration $\bar{\eta}$.

Implicit differentiation of the necessary conditions for a maximum with respect to $\bar{\alpha}$ yields

$$\frac{\partial x}{\partial \bar{\alpha}} = \lambda \Gamma^{-1}\left(-\lambda[g']^2 + g''x[\bar{\alpha} + F(P)S_x]\right) >< 0$$

$$\frac{\partial I}{\partial \bar{\alpha}} = g'\Gamma^{-1}\left(-x[R_{xx} - \lambda F(P)S_{xx}] + \lambda[\bar{\alpha} + F(P)S_x]^2\right) > 0.$$

Areas with greater leaching rates will require greater user expenditure on remediation and lower polluting input use. Since $R_x(p,w,x)-v > 0$ at the efficient level of x, lower polluting input use implies lower farm income as well.

Implicit differentiation of the necessary conditions with respect to $\bar{\eta}$ yields

$$\frac{\partial x}{\partial \bar{\eta}} = -\Gamma^{-1}\lambda g''[\bar{\alpha} + F(P)S_x] < 0$$

$$\frac{\partial I}{\partial \bar{\eta}} = -\Gamma^{-1}g'[R_{xx} - \lambda F(P)S_{xx}] > 0.$$

Areas with greater background contamination will require greater reductions in polluting input use and greater user remediation expenditures. This latter result corresponds directly to Proposition 4 of Lichtenberg and Zilberman (1988).

This pair of results is exactly as one might expect: Regulation will be more costly for both farmers and water users in areas that are more prone to groundwater contamination.

Impact of Changes in Crop Prices

Consider next the effects of changes in crop prices. Implicit differentiation of the necessary conditions for a maximum with respect to the price of an arbitrary crop j yields

$$\frac{\partial x}{\partial p_j} = \Gamma^{-1}R_{xp_j}[g']^2 > 0$$

$$\frac{\partial I}{\partial p_j} = \Gamma^{-1}R_{xp_j}g'[\bar{\alpha} + F(P)S_x] > 0.$$

An increase in the price of an arbitrary crop j leads to an increase in polluting input use (and hence farmers' income), and a compensating increase in user remediation spending.

This result suggests that users should shoulder a greater share of effort in areas with higher-value crops. For example, optimal regulation of groundwater in Florida, which specializes in fruit and vegetable production, will feature greater reliance on user remediation than optimal groundwater regulation in hydrologically similar parts of Maryland, which produces mainly lower-value crops like corn and soybeans.

Impact of Stricter Drinking Water Standards

Consider next the effects of stricter drinking water standards, as might occur under reauthorization of the Safe Drinking Water Act, which was under consideration in the United States quite recently. Drinking water standards can be made stricter in two ways: (1) by reducing the nominal standard $\overline{N}$, and (2) by increasing the margin of safety P.

Consider first the effect of reducing the nominal standard $\overline{N}$. Implicit differentiation of the necessary conditions for a maximum yield

$$\frac{\partial x}{\partial \overline{N}} = \Gamma^{-1}\lambda g''[\overline{\alpha} + F(P)S_{xx}] > 0$$

$$\frac{\partial I}{\partial \overline{N}} = \Gamma^{-1}g'[R_{xx} - \lambda F(P)S_{xx}] < 0.$$

This result follows directly from Proposition 1 of Lichtenberg and Zilberman (1988). A stricter nominal drinking water quality standard reduces use of the polluting input (and, because R_x-v > 0, farm income as well) while increasing water users' remediation spending, that is, both farmers and water users share the burden of meeting stricter nominal standards.

Making drinking water standards stricter by increasing the margin of safety has the same qualitative effects. Implicit differentiation of the necessary conditions for a maximum gives

$$\frac{\partial x}{\partial P} = \lambda F'\Gamma^{-1}\left(-S_{x}[g']^{2} + g''S[\overline{\alpha} + F(P)S_{xx}]\right) < 0$$

$$\frac{\partial I}{\partial P} = F'\Gamma^{-1}\left(-g'S[R_{xx} - \lambda F(P)S_{xx}] + \lambda S_{x}[\overline{\alpha} + F(P)S_{xx}]^{2}\right) > 0.$$

An increase in the margin of safety P reduces polluting input use and thus farm income while increasing remediation spending by water users. In this case, as well, both farmers and water users share the burden of meeting the standard with a greater margin of safety.

This result differs slightly from that obtained by Lichtenberg and Zilberman (their Proposition 2), who found that an increase in the margin of safety would increase use of a policy instrument specializing in reducing uncertainty about pollution, but could decrease use of a policy instrument with relative specialization in reducing pollution on average. As Lichtenberg and Zilberman note, the optimal pollution control policy under this form of regulation will be a portfolio of instruments, some of which have a relative advantage in reducing pollution on average, others of which specialize in reducing uncertainty about pollution. In this model, remediation efforts by water users have a comparative advantage in reducing contamination on average, while emissions control by farmers have a comparative advantage in reducing uncertainty about contamination. As in Lichtenberg and Zilberman, an increase in the margin of safety in the present context leads to a reduction in polluting input use, which corresponds to increased spending on the policy specializing in reducing uncertainty about pollution. In contrast to their result, an increase in the margin of safety in the present context unambiguously leads to an increase in remediation spending (that is, an increase in spending on a policy that specializes in reducing pollution on average).

Stricter enforcement of drinking water quality standards in rural areas was a central them in recent policy discussions related to reauthorization of the Safe Drinking Water Act. These results suggest that efforts to enforce drinking water quality standards more strictly in rural areas are likely to engender far-reaching debates over standard-setting procedures. As noted above, drinking water standards are set to protect public health with an adequate margin of safety. The risk quantification procedures used by the U.S. Environmental Protection Agency typically result in margins of safety well above 99.99 percent: The parameters used in these calculations are typically upper limits of 95- or 99 percent confidence intervals, and combining them results in large increases in the effective margin of safety (see for example Lichtenberg (1992) for a discussion in the context of food safety). The use of these more "conservative", uncertainty-averse procedures increases the total cost of regulation and the costs incurred by all interested parties, that is, water users and farmers. One would thus expect risk quantification methodology to be as much a topic of debate as the appropriate nominal standard. And in fact, one reaction to efforts to stiffen enforcement of drinking water standards for rural areas in reauthorization of the Safe Drinking Water Act was the introduction of legislation aimed at changing the Environmental Protection Agency's risk-quantification methods.

Impact of Leaching-Related Research

One of the most important forms of policy response to NPS pollution problems has been funding of research into leaching of agricultural chemicals and other NPS pollutants. Research aimed at understanding leaching and runoff has been assuming increasing importance at land-grant universities (including agricultural experiment stations) and national research institutions, as reflected in a growing share of research expenditures. When successful, such research reduces uncertainty about leaching, which in our model corresponds to a decrease in σ_u.

Implicit differentiation of the necessary conditions for a maximum yields

$$\frac{\partial x}{\partial \sigma_u} = \lambda F(P)\Gamma^{-1}\left(-S_{x\sigma_u}[g']^2 + g''S_{\sigma_u}[\bar{\alpha} + F(P)S_x]\right) < 0$$

$$\frac{\partial I}{\partial \sigma_u} = g'F(P)\Gamma^{-1}\left(-S_{\sigma_u}[R_{xx} - \lambda F(P)S_{xx}] - \lambda S_{x\sigma_u}[\bar{\alpha} + F(P)S_x]\right) >< 0.$$

A reduction in uncertainty about leaching σ_u leads to an increase in polluting input use and thus farm income, but has ambiguous effects on remediation spending by water users. A reduction in uncertainty about leaching has unambiguous effects on emissions reduction efforts by farmers because these efforts have a comparative advantage in reducing uncertainty about pollution. Less uncertainty about pollution renders this comparative advantage less valuable in meeting the standard. The effect of a reduction in uncertainty about leaching has an ambiguous effect on remediation efforts by users because these efforts have a comparative advantage in meeting the standard on average: A reduction in uncertainty reduces the need for remediation overall by reducing the effective standard N(P), but may increase the need for remediation in order to compensate for lower emissions reduction effort (greater polluting input use). These contradictory effects can be seen in the expression for $\partial I/\partial\sigma_u$. The first term in parentheses represents the direct effect of a reduction in σ_u on the effective standard N(P); an decrease in σ_u decreases N(P by decreasing S(N), thereby decreasing demand forremediation spending. The second term in parentheses represents the indirect effect of a reduction in σ_u via a change in the productivity of (and hence demand for) emissions reduction, S_x. A decrease in σ_u reduces the productivity of farmers' emissions reduction efforts and therefore tends to increase demand for remediation spending.

In sum, farmers stand to gain unambiguously from research into leaching, and should thus be expected to support public spending on this topic. Water users may lose from such research, however, and may therefore oppose public spending on leaching research, preferring the regulatory regime holding under greater uncertainty. Universities and public research entities should thus not assume that greater allocation of research funds on leaching, runoff, and other NPS pollution problems will necessarily meet with broad public approval, even in rural communities.

The preceding conclusion depends critically on the regulatory regime, of course. In many areas, regulation of emissions is largely non-existent, so that remediation by water users remains the sole instrument for meeting drinking water quality standards. It is straightforward to show that under such conditions, water users will gain unambiguously from reductions in uncertainty about leaching and should thus support further research into leaching and runoff.

Applying the envelope theorem indicates that the social value of reducing σ_a in the regulatory context analyzed here is $\lambda F(P)S_{\sigma_a} > 0$, research into leaching of agricultural chemicals increases income by an amount equal to the marginal cost of meeting the drinking water standard times the reduction in uncertainty about meeting the standard times F(P), which, as Lichtenberg and Zilberman note, is a measure of society's aversion to uncertainty about pollution. However, one cannot show that the farmers' gains from reductions in uncertainty about leaching will always be sufficient to compensate water users for any consequent increases in remediation expenditures. Revenues raised from fertilizer taxes in Iowa, for example, are used to support research into NPS pollution and development of farming methods that reduce leaching and runoff. Funding such research from general tax revenues, however, may remain controversial with rural residents whose remediation costs stand to increase. In this context, regulation may be verwed as something imposed by fiat that does not meet a perceived public demand for water quality, so that water users may not take the gains from improved water quality into account.

Impact of General Research on Groundwater Quality

Research may be devoted specifically to improving understanding of leaching or more broadly to improving understanding of non-agricultural sources of NPS pollutants or hydrological and biological conditions that influence NPS contamination (e.g., microbial dentrification or reduction of nitrate by minerals such as glauconite). The previous section examined the effects of the former, modeled as reductions in σ_a. We now turn our attention to the impacts of this broader research, modeled as reductions in σ_η.

Implicit differentiation of the necessary conditions for a maximum yield

$$\frac{\partial x}{\partial \sigma_\eta} = \lambda F(P)\Gamma^{-1}\left(-S_{\alpha\sigma_\eta}[g']^2 + g''S_{\sigma_\eta}[\bar{\alpha} + F(P)S_x]\right)$$

$$\frac{\partial I}{\partial \sigma_\eta} = g'F(P)\Gamma^{-1}\left(-S_{\sigma_\eta}[R_{xx} - \lambda F(P)S_{xx}] - \lambda S_{\alpha\sigma_\eta}[\bar{\alpha} + F(P)S_x]\right).$$

Both $\partial x/\partial\sigma_\eta$ and $\partial I/\partial\sigma_\eta$ are ambiguous in sign. If η has a large positive correlation with α, so that $S_{\alpha\sigma_\alpha} > 0$, then a reduction in σ_η leads to an increase in polluting input use and thus farm income In this case, one might expect farmers to support general research on groundwater. Otherwise, both farmers and water users are just as apt to lose as gain from reductions in σ_η. As a consequence, one would expect to find little public support for research on groundwater generally, that is not targeted directly toward leaching.

Applying the envelope theorem indicates that the social value of reducing σ_η in the regulatory context analyzed here is $\lambda F(P)S_{\sigma_\eta} > 0$, general research on groundwater increases income by an amount equal to the marginal cost of meeting the drinking water standard times the reduction in uncertainty about meeting the standard times F(P). However, it remains possible that both farmers and water users could lose simultaneously from reductions in σ_η, so that entire rural communities might unite in opposition to public spending on such research.

Conclusion

Public agencies have responded to problems of non-point source contamination of groundwater by agricultural chemicals through both regulatory measures and research. Regulatory measures may be imposed on water users, by requiring them to install water treatment equipment capable of rendering contaminated water fit to drink, and on farmers, by inducing them to alter farming practices to reduce leaching. Research may be aimed specifically at leaching or more at a more general understanding of groundwater hydrology.

We examine both regulation and research in a regulatory context like that established by the Safe Drinking Water Act in the United States, which requires that water quality standards be met with an adequate margin of safety. Using the framework developed by Lichtenberg and Zilberman (1988), we derive the efficient division of effort between emissions reduction by farmers and remediation by water users. We show that both emissions reduction and user remediation should be greater in areas with greater vulnerability to leaching, and that areas specializing in higher-value crops should place greater emphasis on user remediation. We also show that stricter nominal standards and a greater margin of safety increase both farmers' and water users' costs, which suggests that either type of effort is likely to provoke united opposition from rural communities. Research that reduces uncertainty about leaching increases farmers' incomes but may lead to greater remediation expenditures by water users. Farmers may thus support such research being undertaken at land grant universities and other public entities, while other residents of rural communities oppose it. Because regulation may be perceived as imposed, rather than meeting public demand, farmers' gains may not be sufficient to compensate water users for any increased remediation expenditures. Research aimed at improving understanding of groundwater generally has ambiguous effects on both farmers and water users, suggesting that neither group is likely to support the expansion of such general research. In fact, it remains possible that both groups may simultaneously oppose public funding for such research.

References

Aldrich, S.R. 1980. Nitrogen in relation to food, environment, and energy. University of Illinois, Urbana, Special Publication 61.

Angle, J.S. 1985. Effect of cropping practices on sediment and nutrient runoff losses from tobacco. Tobacco Sci. 29:107-110.

Angle, J.S., C.M. Gross and M.S. McIntosh. 1989. Nitrate concentrations in percolate and groundwater under conventional and no-till *Zea mays* watersheds. Agric. Ecosyst. Environ. 25:279-286.

Brinsfield, R. and K. Staver. 1989. Cover crops: a paragon for nitrogen management. Presented at the Conference on Ground Water Issues and Solutions in the Potomac River/Chesapeake Bay Region, Washington, DC.

Hallberg, G.R. 1989. Nitrate in groundwater in the United States. In R.F. Follett (ed.), Nitrogen management and groundwater protection. Amsterdam: Elsevier.

Hartman, P. 1982. Nitrates and nitrites: Ingestion, pharmacodynamics, and toxicology. In F.J. de Serres and A. Hollaender (ed.), Chemical mutagens. New York: Plenum Press.

Lichtenberg, E. 1992. Alternative approaches to pesticide policy. Northeast J. Agric. Resource Econ. 21, 83-91.

Lichtenberg, E. and D. Zilberman. 1988. Efficient regulation of environmental health risks. Quart. J. Econ. 49, 167-178.

Lichtenberg, E., D. Zilberman and K.T. Bogen. 1989. Regulating environmental health risks under uncertainty: Groundwater contamination in California. J. Envir. Econ. Mgt. 17, 22-34.

Oates, W.E. 1983. The regulation of externalities: Efficient behavior by sources and victims. Pub. Finance 3, 362-374.

Office of Technology Assessment. 1984. Protecting the nation's ground water from contamination. OTA-0-233, Washington, DC.

Olson, Jr., M., and R. Zeckhauser. 1970. The efficient production of external economies. Am. Econ. Rev. 60, 512-517.

Organization for Economic Cooperation and Development. 1986. Water pollution by fertilizers and pesticides. Paris.

Shibata, H. and J.S. Winrich. 1983. "Control of pollution when the offended defend themselves. Economica 50, 425-437.

Spalding, R.F. and M.E. Exner. 1993. Occurrence of nitrate in groundwater—a review. J. Envir. Quality 22, 392-402.

U.S. Environmental Protection Agency. 1987. Improved protection of water resources from long-term and cumulative pollution: Prevention of ground-water contamination in the United States. Washington, DC.

U.S. Environmental Protection Agency. 1990. National survey of pesticides in drinking water wells phase I report. EPA 570/9-90-015, Washington, DC.

Vogt, C. And J. Cotruvo. 1988. Drinking water standards: Their derivation and meaning. In F.M. D'Itri and L.G. Wolfson, Rural groundwater contamination. Chelsea, MI: Lewis Publishers.