Staff Paper

A BENEFIT COST FRAMEWORK FOR GROUNDWATER CONTAMINATION RISKS

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Abstract

A benefit cost framework is developed for evaluating groundwater policy.
Contrary to recent empirical analyses, it is shown that risk preferences are
generally essential to decisions involving prevention and remediation costs.
The analysis identifies a subset of cases where preventive and remedial
expenditures may be allocated using cost minimization alone.

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Groundwater contamination is a subject of continuing policy debate at the local, state and federal levels. Fueling the concern are the importance of groundwater as a water supply, particularly in rural areas, and increasing evidence of groundwater contamination in regions across the U.S. (Pye, et al 1983).

Recent studies outline four key economic features of groundwater contamination. Uncertainty is a first and dominating feature of groundwater contamination. Uncertainty enters through doubts regarding the effectiveness of preventive measures, due to poorly understood contaminant transport processes, and from a lack of consensus regarding the dose-response relationships used to predict human health effects [Shechter, 1985a, 1985b].

Second, groundwater contamination is a sequence of events rather than a single event [Raucher, 1983, 1986]. For instance, in the case of a landfill, sufficient investment in containment may prevent any escape of hazardous substances. Containment--prevention--averts damages to intrinsic environmental services but is not essential in avoiding human exposure. If prevention fails and environmental contamination occurs, it is still possible to prevent human exposure and health effects through remedial action.

The sequenced structure of groundwater contamination implies that remedial action costs depend, in part, upon the success or failure of preventive action. If prevention succeeds, remedial action costs are zero. If prevention fails, remedial action requires some positive expenditure. The costs of a particular groundwater policy--a policy that combines preventive and remedial action--are uncertain or "state dependent" [Graham, 1981].

Third, there is little consensus on the concepts that should guide a

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benefit cost evaluation of groundwater policy. Shechter develops an expected
damages procedure that ignores risk preferences. Raucher's analysis implies
that the choice between preventive and remedial action may be made by
minimizing material costs--the cost of labor and materials. Risk preferences
enter the Raucher analysis only at the point of deciding whether to take any
policy action at all. The developing theory of benefit cost analysis under
uncertainty (Graham) suggests that both the Shechter and Raucher frameworks are
incomplete.

Finally, the existing work shows only a little concern for the aesthetic
or intrinsic environmental effects of groundwater contamination. In other
resource contexts, nonuse values have been shown to have a very significant
impact on net benefits (Walsh, Loomis, and Gillman, 1984).

The objective of this paper is to develop a benefit cost framework that
accounts for risk preferences, state dependent costs, and environmental
effects. In our framework, the measures of benefit and cost depend upon the
extent of risk markets and the ability to collect contingent payments. Risk
preferences are shown to be generally essential to decisions involving
tradeoffs between prevention and remediation costs. The analysis does
identify, however, a subset of cases where preventive and remedial action
expenditures may be decided using cost minimization criteria alone.

I. A Valuation Framework for Groundwater Contamination Policies

The concept of a potential Pareto improvement provides a common rationale
for applied benefit cost analysis. A potential Pareto improvement compares two
prospects: an initial situation that occurs with no policy action and an
alternative situation that would result from policy action. Policy action is a
potential Pareto improvement if those who gain by policy action could

potentially compensate the losers so that no one would be made worse off by the policy change. Empirically, the question is whether willingness to pay by the gainers dominates policy costs.

This section develops a benefit cost framework that accounts for risk preferences, state dependent costs, and environmental effects. The choice of a benefit or cost measure depends on the extent of risk markets available as well as an agency's ability to collect contingent payments.

A. Probabilistic Description of Contamination and Household Well-Being

Raucher's analysis suggests that groundwater contamination is characterized by a sequence of uncertain events. Consider the contamination that may occur at a landfill site. At the first stage of a contamination sequence, there is doubt regarding the success of containment of hazardous substances. If containment fails, leakage from the landfill results in groundwater contamination. Contamination results in damages to aesthetic or intrinsic environmental services but no immediate human exposure.

Exposure is conditioned upon a complex process of contaminant transport. Various types of remedial action policies may intervene in this transport process and prevent exposure. Remedial action policies seek to prevent human exposure but typically have little impact on intrinsic environmental damages.

The essential economic features of the contamination sequence are captured by considering a simple two-stage model. The first stage involves prevention of groundwater contamination. Contamination is a threshold event: groundwater is contaminated if the concentration of some contaminant exceeds a certain level; it is not contaminated if the concentration falls below a given level.

Preventive policies include controls on the use of certain industrial chemicals, controls on the use of agricultural chemicals such as pesticides and

fertilizers, increased reliance on the use of best management practices in agriculture, and more stringent containment requirements for hazardous waste disposal sites [Henderson et al, 1987, Pye, 1984]. A common feature of preventive strategies is that they are not certain to be successful. Rather, the probability of success depends on the amount of public and private investment in the strategy. This probability of preventive success is denoted $\pi_P = \pi_P(c_P)$ where c_P denotes the level of expenditure on prevention and $\pi_P' > 0$.

Remedial action decisions are made at the second stage of our two-stage contamination sequence. Remedial action policies are implemented once groundwater contamination occurs. Remedial policies may include actions such as the physical or chemical removal of contaminants from an aquifer and point of use or point of distribution treatment of the groundwater to remove contaminants from water intended for human use. The likely success of remedial action depends, <u>inter alia</u>, upon the level of investment. This probability of successful remedial action is denoted $\pi_R = \pi_R(c_R)$ where c_R denotes the level of expenditure on prevention and $\pi_R' > 0$.

Household well-being depends upon the success or failure of preventive and remedial actions. The household's utility function is $u(e,h,m)$ where e represents intrinsic environmental effects, h are the effects of exposure to contamination, and m is household income. If preventive action is successful, no environmental or health effects are experienced and household well-being is $u_P(m) = u(0,0,m)$. If preventive action fails, but remedial action is successful, the household experiences intrinsic environmental damages but no exposure. Household well-being is $u_c(m) = u(-1,0,m)$. Finally, if both preventive and remedial actions fail, the household experiences both environment damages and exposure resulting in utility $u_E(m) = u(-1,-1,m)$.

In an initial policy situation, an agency plans some fixed level of expenditure on preventive and remedial action. These levels of expenditure may be zero. The initially planned level of preventive expenditures, c_{P0}, yields a probability of successful prevention equal to $\pi_{P0} = \pi_P(c_{P0})$. Initial remedial action expenditures, c_{R0}, result in a probability of successful remedial action equal to $\pi_{R0} = \pi_R(c_{R0})$.

At the planned levels of expenditure, the probability of no environmental damages and no human exposure is π_{P0}, the probability of environmental damage but no human exposure is $\pi_{R0}(1-\pi_{P0})$, and the probability of exposure is $(1-\pi_{R0})(1-\pi_{P0})$. Initial expected utility is

$$(1) \qquad u^0 = \pi_{P0}u_P(m) + \pi_{R0}(1-\pi_{P0})u_C(m) + (1-\pi_{R0})(1-\pi_{P0})u_E(m).$$

B. The Benefit Cost Framework.

The potential Pareto improvement criterion provides the basis for the benefit cost framework. An agency seeks to determine whether there is some policy expenditure that would result in a potential Pareto improvement relative to the initial situation described in equation (1).

On the demand side of policy, we want to determine the maximum amount that individuals would be willing to pay for a policy change. Maximum willingness to pay is measured given the constraint that, if an individual were to pay this amount, he/she would be no worse off with the alternative policy than he/she would be with the initial policy.

On the supply side, we assume that an agency's analysis is prospective: it seeks to determine whether there is some--any--alternative policy that would pass a benefit cost test. Similar to the effort illustrated by Raucher, the agency plans to search for a preventive and remedial action expenditure pair

that passes the potential Pareto improvement test.

A framework that satisfies both the demand and supply side concerns is developed from a simple maximization problem. As the most general formulation of this framework, we assume that markets exist for diversifying both individual and agency risks. Individuals therefore base their valuations on a set of state dependent payments.

With complete markets, expected cost is the appropriate measure of agency expenditures. Expected cost is the sum of two terms. The first term is simply the level of planned preventive expenditures. The second term is the probability that prevention fails times the level of planned remedial action expenditures. Expected costs are therefore written $c_P + (1-\pi_P)c_R$.

If there is an alternative policy that would pass a benefit cost test, it is identified by the following optimization program,

$$(2) \quad \max_{\delta_i, c_j} \quad \pi_P \delta_P + \pi_R(1-\pi_P)\delta_C + (1-\pi_R)(1-\pi_P)\delta_E - c_P - (1-\pi_P)c_R$$

$$\text{s.t.} \quad u^0 \leq \pi_P u_P(m-\delta_P) + \pi_R(1-\pi_P)u_C(m-\delta_C) + (1-\pi_R)(1-\pi_P)u_E(m-\delta_E)$$

$$\pi_P = \pi_P(c_P), \quad \pi_R = \pi_R(c_R)$$

where $i \in \{P,C,E\}$, $j \in \{R,P\}$, δ_P is the state dependent payment if prevention is successful, δ_C is the state dependent payment if prevention fails and remedial action succeeds, and δ_E is the state dependent payment if both prevention and remedial action fail. Second order conditions are assumed to be consistent with a maximum. For simplicity and without loss of generality, we assume that initial policy expenditures are zero.

The solution to (2) defines a set of contingent payments, $(\delta_P^*, \delta_C^*, \delta_E^*)$; a set of planned expenditures on remedial and preventive action, (c_R^*, c_P^*); and the probabilities of successful remedial and preventive action, π_R^* and π_P^*. This

solution maximizes the ex ante benefits of policy action. If there is any policy that passes the benefit cost test, the policy expenditures that solve (2) also pass.

The first order conditions for allocation of planned remedial and preventive expenditures result in

$$(3) \qquad 1/\pi_R' = \lambda(u_C - u_E) + \delta_C^* - \delta_E^* \text{ and}$$

$$(4) \qquad (1/\pi_P')(1 - \pi_P'c_R^*) = \lambda[u_P - \pi_R^*u_C - (1-\pi_R^*)u_E] + \delta_P^* - \delta_C^* - \delta_E^*.$$

where λ is the Lagrangian multiplier for the Lagrangian equation implied by (2) and u_P, u_C, and u_E are the state dependent utilities corresponding, respectively, to successful prevention, the contaminated state, and the state that results in exposure.

Equation (3) states that the net benefit maximizing level of remedial expenditure sets marginal remedial action costs equal to marginal benefits. The left-hand side (LHS) of equation (3) gives the marginal cost of increasing the probability of successful remedial action. Since λ is the inverse of the marginal utility of income, the first term on the right-hand side (RHS) of equation (3) is the marginal impact on expected utility due to an increase in the probability of prevention. The second and third terms on the RHS describe the net effect on expected willingness to pay of a change in the probability of prevention.

Equation (4) is analogous to equation (3). It states a marginal cost, marginal benefit criterion for the allocation of preventive expenditures. A unique feature of equation (4) is that the marginal cost of prevention, $1/\pi_P'$, is discounted by the term $(1 - \pi_P'c_R^*)$. Note that $(1 - \pi_P'c_R^*)$ is not greater than one since $\pi_P' > 0$ and $c_R^* \geq 0$. The discount term enters equation (4) since an

increase in the probability of prevention reduces the likelihood of incurring the costs of remedial action. The allocation rule for preventive expenditures--equation (4)--accounts for both the direct benefits of prevention as well as the impact of prevention on expected remedial action costs.

Equations (3) and (4) together imply that, in general, the choice between preventive and remedial action expenditures cannot be made on the basis of cost analysis alone. An analysis of marginal costs and marginal risk preferences--marginal benefits--is essential to identifying an allocation of preventive and remedial expenditures that results in a potential Pareto improvement. In general, an analysis such as Raucher's, based as it is on a comparison of costs alone, is misleading with respect to the desirability of preventive versus remedial action.

The general model in (2) can be adapted to a range of constraints on the opportunities for risk diversification or the ability of an agency to collect contingent payments. One could consider cases where there are no individual risk markets, no agency risk markets, no contingent payment, or no environmental effect. These constraints are simply entered as algebraic constraints on the optimization problem.

An empirically important case is where there are no individual risk markets, no possibility of collecting contingent payments, and no significant environmental effects. These restrictions may represent the policy context of contmination in many aquifers, particularly those in urban areas or underlying agricultural regions. The overwhelming concern may be to prevent human exposure. This possibility of negligible environmental effects in some aquifers is implicit in recent proposals for groundwater protection (USEPA, 1984).

An absence of environmental effects is represented by redefining the household's utility function so that $u(0,0,m) = u(-1,0,m)$. Subject to this redefinition, state dependent utilities, u_P and u_R are equal. With no environmental effects, the optimization program is

(5) $\max\limits_{OP,c_j}$ $OP - c_P - (1-\pi_P)c_R$

   s.t. $u^0 \leq [\pi_P + \pi_R(1-\pi_P)]u_P(m-OP) + (1-\pi_R)(1-\pi_P)u_E(m-OP)$

   $\pi_P = \pi_P(c_P), \ \pi_R = \pi_R(c_R)$

where $j \in \{R,P\}$. The solution to (5) gives an option price and a remedial and preventive cost allocation plan that maximize net benefits. Unlike the absence of risk markets, the absence of environmental effects is accounted for by modifying an existing constraint rather than by adding a constraint.

The first order conditions for cost allocation imply a relatively simple criterion for allocating expenditures across prevention and remedial action. The remedial and preventive action first order conditions are, respectively,

(6) $1/\pi_R' = \lambda(u_P - u_E)$ and

(7) $(1/\pi_P')(1 - \pi_P'c_R) = [\lambda(u_P - u_E)](1 - \pi_R^*)$

where λ is the arithmetic inverse of the expected utility of income.

The allocation rule for remedial action expenditures is a simple equation of marginal costs and benefits. The LHS of equation (6) gives the marginal costs of remedial action and the RHS states marginal willingness to pay for a change in the probability of non-exposure.

The allocation rule for preventive action is somewhat more interesting. The LHS gives the marginal costs of prevention discounted as in equation (4) by

the effect of prevention on the likely reduction in remediation costs. The
term in brackets on the RHS gives marginal willingness to pay for a change in
the probability of non-exposure and $(1 - \pi_R^*)$ is the probability of unsuccessful
remediation. In this case when environmental effects are absent, the only role
of prevention is to make up for the possible failure of remedial action. Since
prevention plays this limited role, marginal willingness to pay for prevention
is discounted by the probability that remedial action fails.

More strikingly, equations (6) and (7) can be combined to eliminate
preferences--willingness to pay--from the question of allocating expenditures
across prevention and remediation. Substituting the LHS of equation (6) into
the RHS of (7), results in

(8) $(1/\pi_P')(1 - \pi_P' c_R) = (1/\pi_R')(1 - \pi_R^*)$.

Equation (8) states that expenditures should be allocated to preventive and
remedial action such that their appropriately discounted marginal costs are
equal. An equation identical to (8) could be derived from the problem of
minimizing the expected cost subject to a fixed probability of exposure

(9) $\min_{c_j}$ $c_P + (1-\pi_R)$

        s.t. $\pi_E = (1-\pi_R)(1-\pi_P)$

where $j \in \{R,P\}$ and π_E represents a given probability of exposure.

III. Implications

A benefit cost framework has been developed that is appropriate to the
uncertainties inherent in groundwater policy. The framework identifies
measures of benefit and cost that are relevant to the constraints of different
valuation contexts. To reflect the extent of risk markets, these benefit and

cost measures are defined by the addition of simple algebraic constraints to a general optimization framework.

The analysis indicates that the extent of markets for diversifying individual and agency risks, and an agency's ability to collect contingent payments play an important role in determining the relevant measures of benefit and cost. On the demand side, neither option price nor the expected value of the fair bet point is necessarily the appropriate measure of benefits. The appropriate measure depends upon the constraints of the evaluation context.

On the supply side, expected cost is the appropriate cost concept where an agency has access to risk markets or is risk neutral. If contingent costs are used in place of expected costs, measured net benefits may be negative for policies that are, in fact, potential Pareto improvements.

The allocation of preventive and remedial action expenditures was shown to be relatively straightforward when intrinsic environmental services are not a concern. In this case, it is possible to partially separate preference analysis from cost considerations. Preventive and remedial action expenditures may be allocated on cost minimization criteria alone. The separation of preference and cost considerations is only possible for prevention versus remedial action decisions and only where intrinsic environmental effects are absent. The decision regarding the level of protection to provide or the level of expenditure to incur involve a comparison of both costs and benefits.

The cost allocation rules for the case of no environmental effects go beyond a simple comparison of raw marginal cost data. In a valid analysis, the marginal cost of prevention is discounted by a term that accounts for the impact of prevention on expected remedial action costs. Marginal remedial action cost is discounted by the probability of failure.

Finally, the question of identifying relevant constraints requires judgement. In many cases, selection of the appropriate constraints is not unambiguous. A reasonable degree of caution would suggest sensitivity analysis; a comparison of benefit cost results under alternative constraint decisions. Some solace may be gained from the idea that constrained concepts such as option price and contingent costs are satisfactory, though not optimal, benefit cost measures: that is, a benefit cost test constructed using option price and contingent costs correctly identifies non-potential Pareto improvement policies as having negative net benefits and at least a subset of true potential Pareto improvement policies as having positive net benefits.

A number of issues require additional research. First, there is the question of the strength of environmental effects. Empirical research is needed to measure the strength of environmental effects under alternative conditions. The relative strength of environmental effects will determine the degree to which cost analysis can be separated from demand analysis.

Second, there is the clear need to adapt existing valuation methods to the problem of estimating the willingness to pay locus. Smith (1985) suggests that hedonic methods may be restricted to measuring option price. If additional research supports this restriction, then contingent valuation or experimental markets may be the only approaches to estimating contingent payments.

Contingent valuation research has only recently given explicit recognition to the issues involved in estimating option price. This recent research has raised difficult issues involving risk perception, risk communication, and the consistency of individual decisions when confronted with risky options (Smith and Desvousges, 1988). State dependent payments remains unexplored but will surely confront issues at least as complex as those surrounding option price.

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