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INTRODUCTION

Groundwater contamination is widely regarded as one of the major environmental policy problems for the 1980's and 1990's, and beyond (Pye, Patrick, and Quarles; OTA; Haimes and Snyder). While the percentage of the overall resource already contaminated appears to be small, the places where it has occurred are usually close to heavily populated areas where the economic losses are likely to be the greatest. More serious, possibly, than what has already happened are the contamination problems that have not yet been discovered. Because of the exceedingly slow propagation of contaminants in groundwater, the results of past agricultural and hazardous waste disposal practices will extend far into the future (NRC).

In response to increased public concern about groundwater contamination, Congress passed several laws during the past decade aimed in part at protecting groundwater (Walker and Bridgeman). In recent years, most of these laws have been directed at the U.S. Environmental Protection Agency (EPA). The legislation gives the EPA considerable latitude in developing guidelines for protecting groundwater, and it gives the states considerable freedom in selecting management strategies for some classes of groundwater. In this situation, economic analyses of alternative strategies provide useful information for guiding policy.

A major problem for economic analyses of management strategies, whether they be net-benefit analyses, cost-effectiveness analyses, or risk-cost tradeoff analyses, is the uncertainty, or variability, in estimates of the "outputs" used to rank alternatives (Dandy).[1] Of particular concern for management are the uncertainties in estimates of future levels of groundwater contamination at water supply wells, in estimates of health risks and economic losses associated with that contamination, in estimates of the costs of preventing or mitigating groundwater contamination, and in estimates of the benefits of management strategies intended to reduce or to prevent groundwater contamination or exposure to it (Raucher, 1986).[2]

Information on the magnitude of these uncertainties is important because different point estimates of benefits and costs can have different implications for efficient management strategies. For example, one set of outputs of the economic analysis may indicate that the most efficient strategy is full protection of the aquifer from contamination whereas another equally likely set may indicate that the most efficient strategy is little or no protection of the aquifer but treatment of the contaminated water prior to distribution and use. In such situations, more refined estimates of the outputs--health risks, economic losses, and costs--are needed in order to provide clear guidance for management decisions.

This is not to say that more refined estimates are necessarily worth the costs of additional data collection and analysis, at least for planning (Theil; Peskin and David). That would depend on the economic losses associated with wrong decisions (based on inaccurate information). Such losses can be defined <u>ex post</u> as the difference between the net benefits that would have accrued to the most efficient strategy and the net benefits that actually accrued to the strategy that was adopted. Of course, <u>ex post</u> net benefits are not available at the time of the planning decision. A more practical definition of the economic losses associated with a wrong decision is the <u>ex ante</u> expected value of losses (or some other weighting of potential losses that reflects the social preference for risk aversion). For each strategy, the <u>ex ante</u> expected loss is defined as the sum of the products of the economic losses associated with all possible future states of the world and the probabilities of those states (Chernoff and Moses). Thus, the maximum value of new information for planning (from an ex ante perspective) is limited to the ex ante maximum loss associated with the strategy to be implemented; the average value of new information is limited to the ex ante expected loss.

The uncertainties in economic analyses of alternative groundwater quality management strategies raise three questions for management:

- Is it possible to analyze the uncertainties in the outputs of economic analyses used to rank alternative management strategies?
- Is it possible to reduce these uncertainties enough to provide reliable guidance for management decisions?
- Are reductions in these uncertainties worth the costs of collecting and analyzing additional data in terms of the value of the new information?

This paper addresses the first two questions. Approaches to analyzing the uncertainties in outputs of economic analyses are discussed in the next section. Sources of uncertainty in economic analyses are identified in the following section. Prospects for reducing the uncertainties enough to provide reliable guidance for management decisions are assessed in the final section.

ANALYZING UNCERTAINTIES IN OUTPUTS OF ECONOMIC ANALYSES

The uncertainties in outputs of economic analyses are the result of the compounding of uncertainties from many sources spread throughout the analysis. Some of these sources can be reduced with more data and more analysis, and through a better understanding of the significant interrelationships in the analysis. Other sources, however, are inherent and either cannot be reduced or can be reduced only slightly. These include both uncertainties due to stochastic variations in nature that can be described ex ante by objective probability distributions and uncertainties due to projections of future levels of population, economic activities, and economic demand for a potable water supply that cannot be described ex ante by objective probability distributions.

Two methods have been used in water quality management studies to analyze prediction uncertainty--error analysis and Monte Carlo simulation (Beck). Error analysis is the more formal of the two methods. It is a convenient means for analyzing the effects on prediction accuracy of individual input errors when the basic structure of the model is adequate, that is, when the model has the inherent complexity and flexibility needed to reproduce observed behavior (McLaughlin). The problem with economic analyses of groundwater quality management strategies is the analyses are comprehensive and involve several segments, and the basic structures of the models used in some segments of the analysis are not adequate in that they either do not reproduce observed behavior or there are insufficient field observations under the conditions to be experienced (for planning) to determine if they do. In this situation, alternative model structures and Monte Carlo simulation provide an alternative (Fedra).

Two "forms" of uncertainty are distinguished in the economics and water resources literatures--risk and uncertainty (Von Neumann and Morgenstern; Luce and Raiffa; U.S. Water Resources Council). The term "risk" (not to be confused with health risk used by EPA and also elsewhere in this paper) is used to describe situations where the potential outcomes can be described by objective probability distributions. The term "uncertainty" is used to describe situations where the potential outcomes cannot be described by objective probability distributions. For purposes of this paper, the classical taxonomy has been extended to three forms.

The first form is "risk", as defined above. Both the events (potential outcomes) and the probabilities of those events are known a priori. The management strategies to be analyzed can be placed in a game theoretic context and alternative decision criteria can be compared and assessed based on the implications of all the events and on the probabilities of those events (Chernoff and Moses).

The second form of uncertainty is a variation of the first. Either the events (and thus the probabilities of those events) are not available a priori or the events are known a priori but the probabilities of those events are not. However, the events or the probabilities could be made available through additional data collection and analysis. Thus, this form of uncertainty can, in principle, be converted to "risk".

The third form of uncertainty is true "uncertainty". Either the events (and thus the probabilities of those events) are not available a priori or the events are known a priori but the probabilities of those events are not. However, unlike the second form, either the events or the probabilities of the events cannot be made available through additional data collection and analysis. No field or laboratory data currently exist or can be made available to identify all the possible events or to estimate the probabilities of those events, and real world experiments either cannot be conducted or they are impractical to conduct.

Examples of events that cannot be specified a priori are diseases caused by specific contaminants in groundwater that have yet to be identified and damages to the ecosystem that have yet to be experienced. Such unanticipated events are referred to as "surprise" in the environmental engineering and ecology literatures. Examples of probability distributions that cannot be estimated objectively a priori include projections of future levels of exposure to contaminants in groundwater and projections of future levels of economic demand for goods and services, such as groundwater, at particular locations.

This third form of uncertainty cannot be converted to "risk". However, the uncertainties in outputs can be estimated using Monte Carlo simulation techniques, objective probability distributions for the model parameters and model inputs that are available, and assumed probability distributions based on experience and on expert opinion for those that are not available (Gardner and O'Neil). Confidence in the probabilities of different outcomes can be gained through a Bayesian approach to the analysis, that is, through (sensitivity) analysis of the impacts of changes in the assumed a priori probability distributions on the identification of efficient management strategies and on the robustness of particular strategies. (A strategy is said to be robust if the strategy is relatively invariant to changes in the input data or to alternative models used in the analysis.)

Most outputs of economic analyses involve a complex mixture of "risk" and "uncertainty". Some of the "uncertainty" in these outputs can be converted to "risk", as described above. Some cannot. This is the nature of ex ante economic analyses used in planning.

SOURCES OF UNCERTAINTY IN ECONOMIC ANALYSES

Economic analyses of groundwater quality management strategies are necessarily comprehensive and involve a number of technical fields and academic disciplines. Because of this, it is convenient to divide the analysis into four segments:

- Sources of contamination, and alternatives for controlling releases.
- Transport of contaminants in the unsaturated zone.
- Transport of contaminants in the saturated zone, and aquifer rehabilitation.
- Economic losses due to groundwater contamination.

These four segments may be analyzed separately, beginning with the first. The outputs from the first segment become inputs to the second; the outputs from the second segment become inputs to the third; and so on.

Models are used in each segment of the analysis to predict outputs from a given set of inputs. These models differ in scope and complexity, from simple regression models based on empirical observations to full scale computer simulation models based on *a priori* theory. Some models may be more accurate than others, but all models introduce uncertainties into the analysis, to a greater or lesser extent.

There are three principal types of model uncertainty--model structure uncertainty, parameter value uncertainty, and input data uncertainty (Beck). Model structure uncertainty concerns the basic structure of the model, or its specification, and how well it (the model) approximates reality. Parameter value uncertainty pertains to the accuracy of the values of the parameters in the model. Input data uncertainty concerns the accuracy of the inputs used in calibrating the model. It also concerns the accuracy of the inputs used in predicting with the model. Some inputs derive directly from measured environmental data. Other inputs derive from the outputs of other models in the analysis.

The uncertainties in outputs derive mainly from individual sources of uncertainty in the four segments of the analysis. However, some sources do not fall conveniently into one of these segments. Examples include the social rate of discount used to compare costs and benefits that occur at different times (Lind, *et al*.), the length of the planning horizon, and the knowledge that a drinking water supply is contaminated (Raucher, 1983).

Sources of Contamination

The uncertainties in this segment of the analysis concern the specific chemical or chemicals that leach from the source or that migrate from the point of application; the reliability of protective systems, such as impervious liners placed under landfills; the timing of natural hazards, such as hurricanes, earthquakes, and periods of high rainfall; the timing of liner failures and thus of releases of contaminants; and the volumes, locations, and rates of through-put of contaminants to the unsaturate zone. Failure analysis based on the reliability of protective systems and on the probabilities of the timing and magnitudes of natural events is typically used to estimate the timing and rates of release of contaminants.

Transport in the Unsaturated Zone

Some of the contaminants that migrate from the areas where they are applied and from the locations where they are stored travel downward through the unsaturated zone. The uncertainties in this segment of the analysis concern the rate of flow in this zone, the chemical reactions that take place in this zone, and the locations and rates of through-put to the saturated zone. Different models are used in this segment of the analysis. An example is the wetting front model described by McWhorter and Nelson.

Transport in the Saturated Zone

The conventional approach to modelling contaminants in groundwater involves the assumption that convection and mechanical dispersion govern the transport of conservative solutes in porous media (Gorelick). Most geologic formations serving as aquifers are heterogeneous, characterized by a high degree of spatial variability of hydrogeologic properties. Recent field observations and theoretical studies have cast doubts on the applicability of the conventional approach to predict solute transport under these conditions (Anderson; Pickens and Grisak; Dagan).

A growing body of research indicates that hydrogeologic parameters vary in ways that can best be described as stochastic processes. From these varying geologic properties, it follows that groundwater velocity, which governs the transport of contaminants, can best be described as a random field. Thus, the conventional convection-dispersion equation may not be the "correct" governing equation of solute transport.

This source of uncertainty invites consideration of a probabilistic approach. In this approach, a basic model structure is assumed, based on *a priori* theory, and the prediction error is functionally related to the underlying sources of uncertainty. If the error sources are treated as random variables with specified probability distributions, the probability distributions of the prediction error can be derived (Kitanidis, 1986).

The uncertainties in this segment of the analysis also involve the chemical reactions that take place in the saturated zone.

Economic Losses

There are many different kinds of economic losses associated with groundwater contamination. They arise from both the use of contaminated groundwater and the avoidance of use, by households, businesses, and institutions; from the responses of government agencies and water supply utilities to groundwater contamination; and from the effects on the environment of contaminated groundwater that flows into surface waters.

Economic losses can occur even if the groundwater is not used and even if there is no flow of groundwater to surface waters. These losses are due to reduced intrinsic, or nonuser, values which include existence, bequest, and option values (Krutilla; Fisher and Raucher).

Of particular importance for groundwater contamination is option value. As long as an aquifer has potential for use, society would presumably be willing to pay something to maintain the option of using it sometime in the future. Because potential use depends on future demands for water, on the costs of extraction and distribution, and on the costs of alternative sources of supply, a currently unused groundwater supply, no matter how uneconomic it is to exploit at current prices, may have social value sometime in the future. For a more complete discussion of option value, see Desvousges, Smith, and McGivney; and Gallagher and Smith.

Significant uncertainties are associated with the different kinds of economic losses caused by groundwater contamination. Space does not permit a detailed discussion of each. An example of the uncertainties in estimates of economic losses associated with drinking water contamination is provided by Harrington, Krupnick, and Spofford.

CONCLUDING COMMENTS

This paper addressed two questions raised in the introduction:

- Is it possible to analyze the uncertainties in the outputs of economic analyses used to rank alternative management strategies?
- Is it possible to reduce these uncertainties enough to provide reliable guidance for management decisions?

The answer to the first question is a qualified "yes". The reason for the guarded answer is there are two parts to this analysis and the second part is considerably more difficult than the first.

The first part of the analysis involves determining the magnitude of the uncertainty in outputs. (One measure of the magnitude of uncertainty is a probability distribution of the outputs.) This analysis is relatively straightforward, but it requires considerable judgement and many computations. Monte Carlo simulation has been used for such analyses in other applications. It is a promising approach here.

The second part of the analysis involves attributing the uncertainties in the outputs to specific sources of uncertainty in the analysis. This is more complicated and involves considerably more computations than the first part of the analysis. Such analyses can be made, in principle, using Monte Carlo simulation, but it is not straightforward and it would require an enormous amount of computations.

The answer to the second question is also a qualified "yes". In most cases it will be possible to reduce the uncertainties in estimates of health risks, economic losses, and costs through more data collection and analysis and through more basic research. The key to this question, though, is whether or not the improved information will provide more reliable guidance for management decisions. That depends on each situation, but can be assessed, at least in principle, by analyzing the uncertainties in the outputs with the inherent uncertainty and with and without the reduceable uncertainty.

This paper explored the forms, types, and sources of uncertainties in economic analyses of alternative groundwater quality management strategies. It provides a framework for analyzing those uncertainties, and for comparing the costs of reducing those uncertainties with the value of new and improved information. A case study of groundwater contamination is needed in order to assess the practicality of analyzing the uncertainties in outputs of economic analyses in real situations.

FOOTNOTES

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1. The term "uncertainty" has different meanings in the literature. In this paper, it is used to convey the possibility of differences between predictions and outcomes (ex post). One indication of uncertainty is variability in predictions based on analysis. Such variability can be caused by stochastic variations in nature that can be described by known probability distributions and it can be caused by factors that cannot be described by known probability distributions. Differences between predictions and outcomes (ex post) can also be caused by factors that are unknown at the time of the ex ante analysis. Thus, uncertainty combines concepts of both accuracy (truth) and precision (reproducibility).

2. Uncertainties in estimates of the costs of preventing and mitigating groundwater contamination arise from two principal sources. One source is the market prices of goods and services used in the analysis that do not reflect full social costs or that overestimate true social costs. This source is not considered in this paper, although its contribution to the uncertainties in costs may be significant in some situations. The other source of uncertainty pertains to the reliability of preventive and mitigative measures and the effects of those measures on levels of groundwater contamination. This source is considered in this paper.

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