CHAPTER 7

Characterizing and Managing Groundwater Contamination Health Risks Under Uncertainty: An Economic Framework

7.1 Introduction

One of the most significant challenges to formulating efficient groundwater protection policies is the degree of uncertainty surrounding contamination and health risk assessment. Economics and related analytic tools can help shed light on the implications of uncertainties. For example, they can help indicate which specific uncertainties most significantly influence the potential benefits and costs of management options and, thereby, indicate research priorities. Economic and related analyses can also help define and resolve challenging public perception and social value issues that motivate concern over the potential health risks posed by groundwater contamination.

There are many steps to a groundwater risk assessment, and at each step there are significant uncertainties that may be introduced due to measurement error (e.g., inaccurate data) and system error (e.g., inaccurate models). And, as the steps are linked together in conducting an exposure and risk assessment, there are compounded uncertainties introduced by potential error propagation. Clearly, risk assessments for groundwater contamination incidents are highly uncertain.

Despite these uncertainties, groundwater management options must be designed, evaluated, selected, and implemented. Economic and other policy analytic techniques can be used to inform management evaluations at several levels. Inserting economic values for benefits and costs, where feasible, and applying Monte Carlo simulations or simple sensitivity analyses, one can identify which specific uncertainties have significant impact on a policy evaluation. In some instances, the
analyses indicate clear policy signals even with the uncertainties. In other cases, the results can be used in the decision theory context of the value of information to indicate research priorities—to identify which uncertainties have the greatest impact on a policy decision and, therefore, should be the focus of additional inquiry.

In the remainder of this chapter, several economic and policy analytic topics are addressed in terms of: 1) the additional uncertainty they may introduce into a management evaluation, and 2) their ability to inform policy evaluations of management options for groundwater, even where these uncertainties are extensive. In the section below, benefit-cost analysis is described as a conceptual framework for groundwater management under uncertainty. The chapter then proceeds to a discussion of valuing reductions in risk to human health, discounting to account for the intertemporal aspects of groundwater management and the link between risk attributes and public risk perception. The chapter closes with a discussion of how to use economic and related analytic tools to inform management decisions under uncertainty.


In evaluating groundwater management options designed to help reduce health risks, the economic technique of benefit-cost analysis (and the related tool of risk-based cost-effectiveness analysis) provides a framework for determining which alternatives generate the greatest degree of health protection relative to the expenditures required to implement them. Below we discuss the concepts of the benefits of groundwater protection, with health benefits described first and other types of benefits defined later; this text provides both conceptual structure for the subsequent discussions on uncertainties introduced by economic analysis and analytic methods of approaching the uncertainties.

The reader should note that although most of this discussion focuses on how to estimate, portray, and evaluate the benefits of groundwater management strategies, comparable issues may arise with respect to estimating the costs of groundwater protection policies. For example, it is often uncertain as to how effective a program might be (e.g., how much an action will reduce the probability of contamination occurring) or how long it may take for a remediation effort to reduce contaminant concentrations to appropriate clean-up target levels.

In addition, the use of benefit-cost analysis is portrayed in the context of decision-making by public officials and other individuals who are either responsible for, or hold some interest in, promoting the general welfare of the public. Thus, the economic framework described here is intended for use by agencies and individuals who either have some measure of authority over selecting management actions or, who as a matter of public or private interest, are motivated to ascertain the relative merits of alternative courses of action. Finally, the use of benefit-cost analysis as a means of promoting economic efficiency presumes a normative framework in which maximizing net social benefits is the objective. The next two chapters provide additional perspective as to the normative issues related to characterizing and managing groundwater-related risks and their associated uncertainties.
7.2.1 The Health Benefits of Groundwater Protection

In cases of groundwater quality management, the principal benefit is the reduction in risks to human health. Measuring these benefits is integrally linked to the risk assessment process, since the risk assessment provides the quantitative estimate of the level of health risk associated with a given management scenario.

In an economic analysis, risk assessments can be used in two ways. In the first approach, the analyst compares the risk assessment's quantified risk reduction directly to the incremental cost of a policy, generating a risk-based cost-effectiveness result in terms of the cost per unit of risk reduction (e.g., dollars spent per each expected case of cancer avoided). This cost-effectiveness approach avoids the issue of assigning monetary values to reductions in health risks. And, as illustrated in Raucher (1986), this approach can be used to rank the relative efficiency of management options according to the lowest cost per unit of health risk reduction. However, this approach does not indicate whether any of the options have benefits that outweigh their costs; there is no indication of whether the policies will improve social welfare.

Alternatively, the analyst can assign monetary values to the risk reductions quantified by the risk assessment and compare these monetized benefits to the option's cost. Under the benefit-cost approach, the options can be ranked according to the magnitude of their net benefits (the amount by which benefits exceed costs—and net benefits are negative where costs exceed benefits). Naturally, there are several conceptual, empirical, and ethical issues associated with assigning monetary values to human health risks, and these are discussed in greater detail below.

7.2.2 Other Benefits of Groundwater Protection

Groundwater management policies also may generate benefits other than, or in addition to, reductions in health risks. Policies that reduce the probability of a contaminant release generate benefits in terms of the avoided costs associated with implementing remedial actions at the source, treating contaminated groundwater, repairing ecological damage, and/or replacing or treating drinking water supplies that would otherwise be contaminated. Avoided costs also include the expense of monitoring to detect the location, extent and content of contaminant plumes, or to determine concentrations at a drinking water supply.

The relationship of these cost savings, or "damages avoided" to health risk reduction benefits is not necessarily additive. This is because of the substitutability of the elements. For example, costs of monitoring and drinking water treatment would be incurred in lieu of risking adverse human exposure to toxic compounds. A more complete discussion of these tradeoffs is presented within the conceptual framework provided in two earlier papers (Raucher, 1983 and 1986).

The benefits of groundwater protection also include values related to uses of the water for purposes other than direct human consumption. These other beneficial uses of the resource include irrigation, livestock watering, and commercial processing. The benefits of management options to protect the quality of groundwater used for these purposes result in potential cost savings (damages avoided). Benefits associated with these activities may include averted reductions in crop yield or
marketability, avoided livestock poisoning, and so forth. These types of benefits can
be valued at the expected cost savings, using monetary values observed in the market.

In addition to health risk reductions and damages avoided, there are other
types of benefits that accrue to society when groundwater resources are protected.
Of particular relevance to groundwater issues is the uncertainty regarding future
demands for, and supplies of, potable water. Contamination of a portion of an
aquifer may be of little consequence today or in the near future if the tainted
resource has no current or anticipated uses. However, because water is essential to
life and contamination exhibits aspects of irreversibility, and because society is averse
to risks and is uncertain of future water demand and supply, the economic concept
of option value applies.

There is an unresolved theoretical debate regarding the size and sign of option
value (e.g., Graham 1981; Freeman 1985; and Bishop 1982 and 1988), though
empirical evidence suggests it may be significant and positive for environment-related
commodities (e.g., Desvousges, Smith, and McGivney 1983; Fisher and Raucher
1984). The irreversibility aspects of groundwater contamination may also give rise
to quasi-option value as defined by Arrow and Fisher (1974). Quasi-option value,
the expected value of information when deferring an irreversible decision may allow
new data to reduce uncertainty regarding benefits or costs (Conrad 1980), is relevant
insofar as policies expected to postpone contamination postpone irreversible
decisions that would reduce options in future periods.

Apart from the use and option value described above, there are other
intrinsic, or non-use, benefits that society may place on groundwater protection
independent of an aquifer's current or anticipated future use or the potential near-
term costs of contamination. Principal components of intrinsic value relevant to this
issue are existence and bequest values. Existence value may arise out of satisfaction
gained from the knowledge that the resource is available for others (vicarious
consumption) and/or that ecological integrity is being preserved in its "natural state"
(stewardship). Bequest values, utility gains from the knowledge that a resource
endowment is being preserved for future generations, occasionally are labeled as a
form of vicarious existence benefits (Freeman 1981), or as an intergenerational
component of option value (Mitchell and Carson 1981). A rather large literature
now exists regarding these concepts (e.g., Krutilla 1967; and Fisher and Raucher
1984); thus, they are not discussed in detail here.

It also is important that a benefit-cost analysis contain a complete and
accurate account of the costs incurred by a policy or management decision. This may
be especially challenging in developing countries, in which the cost of groundwater
protection programs may include tradeoffs with health and medical benefits that
might be associated with expanded agricultural or industrial activity.

7.3. Valuing Reductions in Risk to Human Health:
Issues and Uncertainty

Benefit-cost analyses are based on risk assessments and, therefore, are subject to the
same uncertainties. In addition, the need to assign monetary values to policy
outcomes, such as reductions in health risks, and to account for the timing of impacts
introduces additional uncertainties into the analysis. These are discussed below.
7.3.1 Valuing Risk Reductions Rather than Lives

There are obvious ethical and conceptual concerns associated with placing monetary values on human health and lives. However, it is essential to distinguish at the outset of this discussion that the concepts described below do not attempt to value human life or health status, per se. Rather, the concepts involve valuing changes in levels of risk. It is the values assigned to quantified reductions in risk levels that have been discerned by economic research and that are applied in benefit-cost analyses. The distinction between valuing risk reductions rather than human lives becomes blurred due to the manner in which the concepts are applied. Risk reduction values may be observed when individuals opt to incur a cost to reduce a risk (such as purchasing smoke detectors for their homes) or, alternatively, when they accept monetary compensation to accept a risk (such as accepting a job with above average risks in return for higher wages). In these cases, a small change in risk is traded for monetary considerations.

By aggregating the risks and the monetary levels across the relevant population, one obtains the total change in risk and the total monetary value paid (or accepted). The risk concept is in terms of the statistically expected number of fatalities avoided (or adverse health effects avoided). Comparing the risk concept to the monetary value, one obtains a monetary value per "statistical life saved" (or statistical illness or injury avoided). The value per statistical life pertains to a mathematical expectation derived by applying low probabilities across a large population—the expectation is that some individual(s) will be stricken at some future time, but there is no sense as to who that specific individual may be. A statistical life is not the same as the life of a particular individual because it represents a low-level individual risk that is simply aggregated across many people.

The distinction between valuing risk reductions rather than human lives is particularly relevant to evaluations of groundwater protection options in an ex ante context (Smith and Desvousges, 1988) and where the policies apply broadly to a large population. This is because the risks posed to a specific individual, and the reduction in risk expected through the policy, are small and largely hypothetical. In contrast, in an ex post, localized context of a known contamination incident threatening a known population, the economic values per statistical life are likely to be inappropriate. This is because the individuals at risk are small in number and can be identified (e.g., the users of a particular well), and the potential risk levels may be relatively high in comparison to the low risks used in the valuation studies. In other words, as the risks become more focused, actual rather than "statistical" lives become relevant to the analysis. It also is important to note that although this method of valuing "risk reductions" rather than "lives" is widely accepted in economics and other disciplines, the concept remains controversial in applications to public policies related to human health.

7.3.2 Cost of Illness (COI) Versus Willingness to Pay (WTP) Estimates

It is important to note that there are different kinds of dollar estimates in the economics literature concerning mortality and morbidity. Two conceptually different categories of estimates are cost of illness (COI) and willingness to pay (WTP) estimates.
COI estimates include the medical expenditures and lost income associated with an illness or premature death. Non-financial costs such as pain and discomfort and the activity restrictions that do not affect income are not included. COI estimates are a useful way to describe the financial impacts of changes in mortality and morbidity, but from a social welfare point of view they do not capture the full impact of changes in illness.

WTP estimates are the maximum amount a person would be willing to pay to prevent or obtain changes in risks of mortality or morbidity. This amount, although subject to the income constraint of the individual, is expected to be a dollar equivalent to the change in income that would cause the same change in the individual's utility (well-being) as that caused by the change in the risk of illness. WTP estimates are more conceptually appropriate than COI values for evaluating public policy choices that are expected to affect human health. WTP estimates are more difficult to empirically obtain than COI estimates because there are fewer circumstances when such payments can be observed. Research methods used to estimate WTP values for changes in health continue to be developed and applied, but values obtained to date, although subject to some uncertainty, are reasonably consistent.

This paper emphasizes WTP estimates that have been obtained for changes in risks of mortality or morbidity because these are more appropriate for evaluating public policy alternatives than COI estimates. For society as a whole, WTP estimates can be expected to exceed COI estimates because the former will reflect financial as well as non-financial impacts and the latter will reflect only financial impacts. However, the individual may not incur all the financial impacts of his or her illness due to medical insurance and paid sick leave.

7.3.3 Values for Reducing Risks of Mortality

Research has been undertaken in the field of economics to determine the value to society and to the affected individual of changes in risk of mortality or morbidity. Much of the recent research on this topic has been reviewed by Violette and Chestnut (1983, 1986) and Chestnut and Violette (1984).

Available WTP (and willingness to accept) estimates for changes in risks of mortality are based on real life situations in which individuals make tradeoffs between a gain or loss and a change in the risk of death. In some cases actual market data are used and in other cases study subjects are asked to predict the tradeoff they would be willing to make in a hypothetical situation that is presented to them.

Four tradeoff situations that have been used in these studies are listed in Table 7.1. The last column in the table gives the range of values that have been obtained by most of the studies in each category. These are presented in terms of dollars per statistical life, but, as noted above, they should not be thought of as estimates of what an individual life is worth. They are rather a way to compare values for small changes in risks that affect a large number of people. For example, say a certain groundwater pollution control decision will reduce the annual risk of death from exposure to a given toxic substance from 3 out of 10,000 people to 1 out of 10,000 people for a total population of 10,000 people. Implementing the policy would, on average, be expected to save two lives per year. These are termed
Table 7.1
Risk/Dollar Trade-Offs Used in WTP Studies Concerning Risks of Premature Death

<table>
<thead>
<tr>
<th>Potential Cause of Death (number of studies)</th>
<th>Typical Level of Risk Experienced Annually*</th>
<th>Changes in Risk</th>
<th>Typical Range WTP Estimates per Statistical Life (millions of 1985 dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-the-job accidents (more than 10 studies)</td>
<td>.00001 to .0001</td>
<td>Higher wages for riskier jobs</td>
<td>$1.0 - $8.0</td>
</tr>
<tr>
<td>Motor Vehicle Accidents (three studies)</td>
<td>.00001 to .0003</td>
<td>Value of time it takes to drive slower or use seat belts to reduce risks of death; expenses for greater safety in public transportation</td>
<td>$0.6 - $3.0</td>
</tr>
<tr>
<td>Residential fires (one study)</td>
<td>.00009</td>
<td>Purchases of smoke detectors for private homes</td>
<td>$0.4 - $0.6</td>
</tr>
<tr>
<td>Smoking Cigarettes (one study)</td>
<td>Lifetime of smoking 1 pack/day reduces life expectancy 3½-4 years (for 40 year old this means an annual average increase in risk of death of about .004 to .005)</td>
<td>Changes in demand for cigarettes as information about risks of smoking became available</td>
<td>$0.4 - $0.7</td>
</tr>
</tbody>
</table>

*Risk levels reported in WTP studies. All the studies are reviewed in Violette and Chestnut (1983, 1986)
statistical lives because the change in the risks is faced by the population and there is no certainty that two people really will be saved in a given year and, also, no way to identify in advance which two individuals in the population would be saved. If each of the 10,000 individuals in the population would be willing to pay $100 per year for this reduction in the risk of his or her death, then the total willingness to pay would be $1,000,000 ($100 per person x 10,000 people), and given that two lives might be saved, the value per statistical life is $500,000.

The majority of the studies that have estimated WTP for changes in risks of death have used the risk/wage tradeoff that is observed in the job market. Most of these studies have used statistical analysis of wages, on-the-job risks of fatal accidents, and other job characteristics to estimate the compensation that is associated with higher on-the-job risks. The risks considered in these studies are associated with accidents in which the consequences are quickly known, rather than exposures to substances that may cause disease to occur several years later.

The estimates related to residential fires and cigarette smoking are based on only one study each. These estimates are, therefore, more uncertain than for the other categories of risks. Also, methodological difficulties in each of these studies add to the uncertainty in the results. Assumptions required in each of the studies are more likely to result in understating the values rather than overestimating the values, but this conclusion is not absolute due to possible error in both directions.

Overall, research results available to date suggest that for changes in risks of death that are fairly common, estimates of the value per statistical life are likely to be between $500,000 and $8,000,000. These values are for changes in risks when the risk levels are typically between one death per year for every 10,000 people and one death per year for every 100,000 people. Thus, they generally will be applicable to most groundwater contamination problems.

The U.S. Environmental Protection Agency has informally adopted the range of $1.7 to $9.1 million to value statistical lives, based on the literature review by Fisher, Chestnut and Violette (1989). Although not formally adopted as official Agency values, this range has been used by the US EPA to evaluate several of its regulatory programs (personal communication, Ann Fisher, US EPA). These values are relevant to the U.S., and probably also can be applied to other prosperous nations. However, in applications for developing nations, income constraints may imply that lower values are appropriate. Clearly, there are positive and normative issues that need to be considered when applying these values.

7.3.4 Values for Reducing Risks of Morbidity

Less research has been conducted in the field of economics concerning WTP estimates for changes in morbidity than for changes in risks of mortality, but some research findings are available. None of the morbidity risks associated with the groundwater contamination (primarily non-fatal cancers and gastrointestinal illnesses) have been specifically addressed in WTP morbidity studies that have been conducted to date, but findings for other kinds of risks are suggestive of what order-of-magnitude might be expected.

In two studies that have examined a variety of short-term symptoms, primarily respiratory symptoms, subjects were asked to give WTP estimates in response to hypothetical questions concerning these symptoms. The symptoms were described
to the subjects and the subjects were asked the most they would be willing to pay to
avoid a day with each symptom. Table 7.2 provides an overview of the symptoms
examined in each study and the WTP results obtained.

Loehman et. al (1979) defined "minor symptoms" as preventing some but not
all activity and "severe symptoms" as preventing most activity including work. The
mean WTP estimates (in 1985 dollars) for the minor symptoms in this study are
between $45 and $90, and for the severe symptoms are between $80 and $140. The
authors noted that the median WTP estimates (the amount below which 50% of the
responses fall) were significantly lower than the mean estimates, suggesting that the
mean values were being pulled up by a small number of very large values. Further
study is needed to determine the validity of these relatively large values given in
response to hypothetical WTP questions. The median values reported by Loehman
et al. are as small as one-tenth of the corresponding mean value. Loehman et al.
conclude that the median values are a better representation of the central tendency
of the responses than the mean values.

The mean WTP estimates obtained by Tolley et al. (1985) are between $35
and $115 for preventing one day of each symptom, a similar magnitude to the
Loehman et al. means. The value for preventing a day of nausea, the only
gastrointestinal symptom included, is about $78, in the middle of the range. Again,
there is some concern that these mean values are skewed due to a few very large
responses to the hypothetical questions.

Both Loehman et al. and Tolley et al. also asked for WTP estimates for
multiple days of symptoms. As expected, the responses indicate a lower value per
day. For example, when Loehman et al. asked for WTP estimates for preventing
seven days per year for each symptom, the mean WTP responses were between $15
and $35 per day. When Tolley et al. asked for WTP estimates for preventing 30 days
for each symptom, the mean WTP responses were between $15 and $30 per day.

In conclusion, there is limited empirical evidence with which to value
reductions in risks of non-fatal health effects. The appropriate value needs to
account for the type of morbidity, its severity, duration, the possibility of recurrence,
and so forth. As a pragmatic means of valuing non-fatal effects, one may opt to use
a cost of illness approach and specifically recognize that the COI values represent
lower bound values of the benefit of avoiding the health effect.

7.4 Discounting: Accounting for the Timing of Risk

7.4.1 Derive Present Values Based on the Social Rate of Time Preference

Groundwater management entails many intertemporal issues. Long time horizons
typically apply to potential contaminant release scenarios. For example, a landfill
may be expected to release contaminants after 20 years of operation if it is designed
and managed in one fashion (e.g., with double liners), or after 35 years if it is subject
to more stringent requirements (e.g., triple liners). In evaluating such management
alternatives, the question arises as to how one accounts for the time difference when
evaluating which option to pursue.

Even when management options reflect current releases, there often are long
times of travel that need to be factored into policy discussions. Therefore, when
ranking risks of alternative management strategies, or when comparing benefits and
### Table 7.2
Willingness to Pay (WTP) Estimates for Prevention of Short-Term Symptoms

<table>
<thead>
<tr>
<th>Study</th>
<th>Symptom</th>
<th>Mean WTP to Prevent 1 Day with Symptom (1985 $)</th>
<th>Median WTP to Prevent 1 Day with Symptom (1985 $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loehman, et al.</td>
<td>Minor Shortness of Breath</td>
<td>$86</td>
<td>$9</td>
</tr>
<tr>
<td>(1979)</td>
<td>Severe Shortness of Breath</td>
<td>$140</td>
<td>$19</td>
</tr>
<tr>
<td></td>
<td>Minor Coughing and Sneezing</td>
<td>$47</td>
<td>$4</td>
</tr>
<tr>
<td></td>
<td>Severe Coughing and Sneezing</td>
<td>$81</td>
<td>$12</td>
</tr>
<tr>
<td></td>
<td>Minor Head Congestion, Eye, Ear, Throat Irritation</td>
<td>$58</td>
<td>$7</td>
</tr>
<tr>
<td></td>
<td>Severe Head Congestion, Eye, Ear, Throat Irritation</td>
<td>$95</td>
<td>$15</td>
</tr>
<tr>
<td>Tolley et al.</td>
<td>Coughing</td>
<td>$44</td>
<td></td>
</tr>
<tr>
<td>(1985)</td>
<td>Sinus Problems</td>
<td>$51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Throat Congestion</td>
<td>$36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Itchy Eyes</td>
<td>$100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drowsiness</td>
<td>$36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Headache</td>
<td>$112</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nausea</td>
<td>$78</td>
<td></td>
</tr>
</tbody>
</table>
costs that occur in different time periods (often, different decades, and sometimes across generations), the intertemporal aspect of the issue needs to be accounted for so that the benefit-cost comparisons can be made on the basis of present values.

The economic technique for accounting for events in different time periods is called discounting. Discounting is based on the observation that individuals, and society as a whole, have a measurable degree of preference for well-being now relative to the future—that some compensation is required if an individual is asked to postpone consumption from today to some point in the future. This "social rate of time preference" is observed as the risk free, inflation adjusted rate of interest on savings, and currently is about 3% in the U.S. (Kolb and Scheraga, 1990). This type of measure is the conceptually appropriate rate with which to convert future benefits and costs into present values. All proper benefit-cost analyses should be based on present values generated by discounting in this fashion.

7.4.2 Reflect the Opportunity Cost of Capital in a Two-Step Discounting Approach

In the economics literature, there has been a long and contentious debate as to the appropriate rate of discount to apply in benefit-cost analysis. The basic issue stems from whether the discount rate should reflect the "opportunity cost of capital" (e.g., the rate of return that would have been realized if the resources devoted to groundwater management would have been invested elsewhere). This rate, for funds diverted from private investments, is on the order of 10% in the U.S.

Using a relatively high discount rate based on the cost of capital approach, rather than the lower rate implied by social time preference, can have a significant impact on a benefit-cost evaluation. The higher rate makes future benefits and costs less valuable in present value terms, and since most programs have near-term costs and longer-term benefits, this has the effect of making it more likely that present value costs will exceed benefits. That is, the higher the discount rate, the lower the net benefits (given the typical timing of benefits and costs).

A two-step procedure, as described by Steiner, Lind, and most recently, Kolb and Scheraga (1990), provides an analytically correct approach for accounting for both the social rate of time preference and the opportunity cost of capital. Basically, step one of the approach reflects the foregone return on capital by adjusting the costs only. This adjustment is made by annualizing the capital costs, over the lifetime of the investment, using a rate of return on capital (weighted to reflect the true source of the funds and, thus, the weighted opportunity cost of the capital).

Then, in step two of the procedure, both benefits and costs are discounted to present values based on the lower rate of social time preference. This approach properly accounts for both the opportunity cost of capital and the rate of time preference, and has now been adopted by the policy and planning office of the U.S. Environmental Protection Agency.

7.4.3 Normative Issues About Discounting

There are several normative issues that discounting raises, especially with respect to human health risks and concern for future generations. In the case of health risks, there is appreciable concern about the normative posture that a risk to health in the future is of less concern than a like-sized risk to health today. However, insofar as
intertemporal health risk comparisons are intragenerational, it is difficult to presume that individuals are indifferent between becoming ill today as opposed to incurring the same risk of an illness in a future year or decade.

For example, suppose society as a whole was forced to make a choice between two policies, where the first option saved ten statistical lives in the current year, and cost $1 million to implement. Further suppose that the second policy under consideration also required a $1 million current year investment, but that its benefits were expected to be ten statistical lives saved fifteen years in the future. Where both options have the same cost and yield the same health benefits, the one with current year risk reduction payoff would likely be selected over the second option (which has the same health risk reduction benefits as the first, except they are deferred for fifteen years). This choice would clearly indicate that there is a positive social time preference for health risk reductions; that a discount rate applies to human health risks. The hypothetical social choice becomes more interesting if the second option saved more than ten statistical lives, for then society must choose between ten today and some number greater than ten in the future—with the number of statistical lives at which the second option is selected in favor of the first implying the social rate of discount for health risks.

Moving beyond single generation issues adds additional complications. Incorporating concerns for future generations in empirical work is problematic, especially given uncertainties about future events and ethical issues regarding intergenerational equity. For example, future generations cannot participate in today's financial markets and so cannot influence today's interest rates. Still, we must somehow account for their preferences. For any positive rate of discount, present value calculations effectively reduce future benefits and costs to zero after a finite number of years. Using a zero discount rate as a means of reflecting concerns over the well-being of future generations avoids an artificial shortening of the time horizon, but results in a failure to acknowledge real opportunity costs and the positive rate of time preference that exist intragenerationally.

An alternative approach removes the intergenerational equity issue to a wholly normative plane in which each period's endowments are assigned before positive allocation decisions are allowed within any timeframe (Ferejohn and Page 1978; Page 1983). Under this theoretical concept, each "generation" would be endowed with a fixed allocation of resources. These resource endowments would be held in trust and, therefore, unavailable to preceding generations. Extending this logic to risk, each generation would be endowed with a maximum amount of risk that it could pass forward to future generations (i.e., each future generation is guaranteed a maximum amount of inherited environmental health risks).

These normative issues are not easily addressed in a positive analysis. One straight-forward approach for the practitioner is to use a social rate of time preference (e.g., 3%) and also a zero discount rate as a sensitivity analysis. This will clearly indicate to the decision-maker whether, and how much, the discounting issue affects the results in terms of selecting a course of action from among competing policy options.
7.5 Risk Attributes and Risk Perception

7.5.1 Introduction

Uncertainty regarding how to evaluate risk reductions is heightened because some groundwater risks may possess different attributes or affect different populations. The characteristics that vary across risks can be used as a means of evaluating such situations. Recent social science research has focused on the attributes of risky activities in order to discern how these characteristics may affect social preferences and, thus, how risk reducing management policies should be evaluated. In this section of the paper, research from the psychology field of behavioral decision theory is reviewed.

Psychological laboratory and field studies provide new evidence regarding how individuals make decisions in risky situations. Social scientists have found that risk is not simply defined, and that there are significant discrepancies between objective measures of risk, such as probabilistic incidence or fatality rates, and subjective risk judgments. The bundle of attributes associated with a given risk-generating activity may affect how individuals perceive the level of risk posed, and/or how they value actions that alter the level of risk incurred.

7.5.2 Perceived Versus Real Levels of Risk

The discrepancy between objective risk measures and subjective behavior related to a risk-generating activity may stem from how risk attributes affect the perceived level of imposed risk. That is, individual behavior may be based according to a perceived risk level that differs significantly from the objective level of risk. Such perceptions may be linked to the type of risk involved. For example, individuals may begin to overestimate the risk of traveling by plane shortly after a well-publicized aircraft disaster.

Psychology research, such as conducted by Lichtenstein et al. (1978), and Fischoff and MacGregor (1983), indicates the degree to which levels of risk may be grossly misjudged by the public. Table 7.3 provides evidence of the degree to which lethality judgments differ from actual mortality rates, regardless of how the effort to solicit individual responses is framed (e.g., asking "how many survive" rather than "how many die"). For example, the sample asked how many individuals out of 100,000 afflicted with influenza would die. The responses yield an average of 6 (column (b) in Table 7.3). However, the experimental group asked the same question, but phrased as the number of afflicted who survive (Column (d) in Table 7.3), yielded responses that implied a death rate of 511 (per 100,000).

Efforts to explain these misjudgments have found that certain characteristics contribute to the direction and magnitude of risk level misperception. Individuals consistently overestimate the probability of those events that are easily accessible to memory (Tversky and Kahneman, 1974). This "availability heuristic" may arise due to media coverage (as in the airplane disaster example cited above), recent personal experiences, or other similar factors.

Perceived levels of risk may also be distorted by other characteristics associated with the hazard. For example, individuals are likely to erroneously believe that they face a greater risk to health from air emissions from a nearby industrial
Table 7.3  
Differences in Perceived and Actual Risk Levels  
(Lethality Judgments with Different Response Modes)

<table>
<thead>
<tr>
<th>Malady</th>
<th>(a) Estimated Lethality Rate</th>
<th>(b) Estimated Number Who Die</th>
<th>(c) Estimated Survival Rate</th>
<th>(d) Estimated Number Who Survive</th>
<th>Actual Lethality Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influenza</td>
<td>393</td>
<td>6</td>
<td>26</td>
<td>511</td>
<td>1</td>
</tr>
<tr>
<td>Mumps</td>
<td>44</td>
<td>114</td>
<td>19</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Asthma</td>
<td>155</td>
<td>12</td>
<td>14</td>
<td>599</td>
<td>33</td>
</tr>
<tr>
<td>Venereal Disease</td>
<td>91</td>
<td>63</td>
<td>8</td>
<td>111</td>
<td>50</td>
</tr>
<tr>
<td>High Blood Pressure</td>
<td>535</td>
<td>89</td>
<td>17</td>
<td>538</td>
<td>76</td>
</tr>
<tr>
<td>Bronchitis</td>
<td>162</td>
<td>19</td>
<td>43</td>
<td>2,111</td>
<td>85</td>
</tr>
<tr>
<td>Pregnancy</td>
<td>67</td>
<td>24</td>
<td>13</td>
<td>787</td>
<td>250</td>
</tr>
<tr>
<td>Diabetes</td>
<td>487</td>
<td>191</td>
<td>52</td>
<td>5,666</td>
<td>800</td>
</tr>
<tr>
<td>Tuberculosis</td>
<td>852</td>
<td>1,783</td>
<td>188</td>
<td>8,520</td>
<td>1,535</td>
</tr>
<tr>
<td>Automobile Accidents</td>
<td>6,195</td>
<td>3,272</td>
<td>31</td>
<td>6,813</td>
<td>2,500</td>
</tr>
<tr>
<td>Strokes</td>
<td>11,011</td>
<td>4,648</td>
<td>181</td>
<td>24,158</td>
<td>11,165</td>
</tr>
<tr>
<td>Heart Attacks</td>
<td>13,011</td>
<td>3,666</td>
<td>131</td>
<td>27,477</td>
<td>16,250</td>
</tr>
<tr>
<td>Cancer</td>
<td>10,889</td>
<td>10,475</td>
<td>160</td>
<td>21,749</td>
<td>37,500</td>
</tr>
</tbody>
</table>

Source: Fischoff and MacGregor 1983.
The four experimental groups were given the following instructions:
(a) Estimate lethality rate: for each 100,000 people afflicted, how many die?
(b) Estimate number who die: X people were afflicted, how many die?
(c) Estimate survival rate: for each person who dies, how many were afflicted but did not die?
(d) Estimate number who survive: Y people died, how many were afflicted but did not die?

Note: Responses to questions (b), (c), and (d) were converted to deaths per 100,000 to facilitate comparison.
facility than from radon entering their residences through the ground. This misperception may stem from certain characteristics of the risks, such as the fact that radon derives from a natural source whereas industrial pollution is caused by human activity (for which other individuals may be held responsible). Such misperceptions may also stem from the fact that radon is invisible and odorless, whereas the industrial facility is visible and, perhaps, emits noxious fumes. These latter attributes might be construed as contributing to the availability heuristic, described above.

Low probability events present additional difficulties for individual perception. Research results indicate a bimodality in the types of perception errors found in low risk situations, even when the associated losses may be high. In some instances, individuals tend to overestimate the likelihood of low probability risks, as shown by the work of Kahneman and Tversky (1979). However, recent research by McClellan and Schulze (1986) shows that while many people overestimate small risks, they may also choose to ignore some low level risks completely. This refusal to acknowledge low probability/high consequence situations has been termed "editing." These all-or-nothing outcomes indicate that few individuals will react on the basis of accurate perceptions of a low risk hazard. Instead, they will act on the basis of one extreme view of the risk level or the other. Further research may indicate whether certain risk attributes contribute to which of the bimodal risk mis-estimation outcomes will tend to predominate for given hazards.

Risk level misperception raises several thorny policy issues. Should policymakers act on the basis of public pressures that is fueled by misperceptions of the level of risk posed? This type of pressure can lead to the over-regulation of some hazards and the under-control of others.

The strategy of risk communication is an important approach to trying to avoid this dilemma by correcting public misperceptions on the risk levels associated with various activities or sources. However, the success of a risk communication strategy will depend on whether the information is conveyed to the public in a manner that is effective at bringing the perceived level and severity of risk closer to objectively derived values. To accomplish this, officials must incorporate what is known about the psychology of risk-related behavior.

### 7.5.3 Risk Attributes and the Value Placed on Altering Risk Levels

Risk attributes will affect how individuals value efforts to alter the level of risk posed from a source. For example, individuals are likely to place a higher value on a policy that reduces the risk of a slow, painful death than they would if the risk pertained to a death that was quick and painless. While the levels of fatality are the same in both cases, the pain and suffering attribute associated with the hazard is likely to have a significant impact on how individuals respond to the risk.

Investigations by Slovic and several research associates have attempted to identify why some hazards inspire more fear or interest in individuals than do others, independent of the level of risk posed. This research has found that risks that tend to generate the greatest concern possess several shared attributes. Slovic et al. (1980) conducted factor analyses of results they obtained on individual perception and risk attributes and determined that risk characteristics can be condensed into two aggregate risk dimensions. These higher order risk dimensions are referred to as
"dread" and "unknown." Each encompasses several attributes that individuals perceive or react to in a highly correlated manner.

The "unknown" risk dimension includes attributes such as the detectability and latency of the risk. Also included is the degree to which the risk or adverse outcome is familiar and understood by science and the public at large. For example, exposure to a carcinogen may rate highly on the unknown dimension: exposure may not be observed, the adverse effects are likely to be delayed for many years, the process of carcinogenicity is still largely unknown to science, and there is no proven, consistent cure for many forms of cancer. Therefore, a cancer-related risk is likely to be ranked highly on the unknown dimension by individuals. Research results indicate that cancer and other relatively "unknown" risks are more feared than like-sized risks posed by more direct and better understood diseases or activities.

The "dread" dimension incorporates attributes such as the degree to which there is a lack of control over the activity, the extent to which exposure is involuntary, and the extent to which the risks are distributed inequitably and/or extend to future generations. Highly dreaded risks are those that instill a sense of helplessness or a lack of control, are targeted on a specific (group of) individual(s), and potentially inflict harm on our descendants.

The full list of dread attributes and unknown characteristics is provided in Table 7.4. Of the two dimensions, the dread factor is most important in terms of how individuals respond to risk or value efforts that reduce them.

7.5.4 Risk Attributes and Behavior in the Context of Groundwater Contamination

Table 7.4 presents the risks of groundwater contamination within the Slovic et al. factor analytic context of dread and unknown risks. By in large, the bacterial diseases are less unknown and less dreaded than the cancer risk posed by many toxic contaminants. This stems mostly from the fact that bacterial risks are well understood, manifest symptoms quickly, generally respond well to simple medical treatments (if diagnosed and treated promptly), are of limited duration, and are rarely fatal or catastrophic.

Cancers, on the other hand, are likely to be highly feared for their mysterious scientific qualities, the lack of effective remedies, the persistent (and, possibly, permanent) nature of the disease, and the rate of mortality associated with the affliction. Research evidence supports the notion that cancers are highly feared. Many of the risks found to rank highly on the two salient risk dimensions are carcinogenic (e.g., asbestos and pesticides). Also, Lichtenstein et al. (1978) found that all cancers (except stomach cancer) were overestimated in terms of fatality rates.

In contrast, bacterial risks are probably not considered as dreadful and unknown as the cancers. People are likely to have had much experience with mild bacterial attacks as well as different types of antibiotics, thus reinforcing the notion that bacterial infections do not pose serious risks. It should be noted that this perception would not be accurate in the case of typhus and cholera. Although no particular research has been done on the public's perception of these diseases (undoubtedly because these bacteria have become quite rare in many countries), it is conceivable that they would have higher "signal potential" than the others. Certainly both typhus and cholera were quite dreaded at one time.
Table 7.4
Factor Representation of the Risks Posed by Groundwater Contamination (Pathogens vs. Toxics)

<table>
<thead>
<tr>
<th>Risk Characteristic*</th>
<th>Pathogens (Bacterial Disease)</th>
<th>Toxics (Cancer)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UNKNOWN RISK</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not observable</td>
<td>generally</td>
<td>generally</td>
<td>Individual detection unlikely</td>
</tr>
<tr>
<td>Unknown to public</td>
<td>no</td>
<td>generally</td>
<td>GI distress is common</td>
</tr>
<tr>
<td>Effect delayed</td>
<td>no</td>
<td>yes</td>
<td>Cancer latency</td>
</tr>
<tr>
<td>New type of risk</td>
<td>no</td>
<td>somewhat</td>
<td>Cancer incidence rising</td>
</tr>
<tr>
<td>Unknown to science</td>
<td>no</td>
<td>somewhat</td>
<td>Cancer not fully explained</td>
</tr>
<tr>
<td><strong>DREADED RISK</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncontrollable</td>
<td>rarely</td>
<td>generally</td>
<td>GI distress responsive to treatment</td>
</tr>
<tr>
<td>Dreaded</td>
<td>somewhat</td>
<td>yes</td>
<td>Typhoid and Cholera dreaded</td>
</tr>
<tr>
<td>Globally catastrophic</td>
<td>unlikely</td>
<td>unlikely</td>
<td>Outbreak possible</td>
</tr>
<tr>
<td>Consequences fatal</td>
<td>rarely</td>
<td>often</td>
<td></td>
</tr>
<tr>
<td>Inequitable</td>
<td>somewhat</td>
<td>somewhat</td>
<td>Age distribution</td>
</tr>
<tr>
<td>Widespread</td>
<td>potentially</td>
<td>potentially</td>
<td>Many potentially exposed</td>
</tr>
<tr>
<td>High future risk</td>
<td>no</td>
<td>potentially</td>
<td>Mutagenicity</td>
</tr>
<tr>
<td>Not easily reduced</td>
<td>no</td>
<td>somewhat</td>
<td>Water treatment available</td>
</tr>
<tr>
<td>Risk increasing</td>
<td>somewhat</td>
<td>yes</td>
<td>No threshold cancer risk</td>
</tr>
<tr>
<td>Involuntary</td>
<td>somewhat</td>
<td>somewhat</td>
<td></td>
</tr>
<tr>
<td>Affects me</td>
<td>potentially</td>
<td>potentially</td>
<td></td>
</tr>
</tbody>
</table>

*Characteristics from Slovic, Fischoff, and Lichtenstein (1984)
The difference in the latency between bacterial disease and cancer is important not only in terms of the feeling of dread and helplessness associated with a long, unknown latency, but also in terms of dose-response thresholds. With bacteria, if symptoms do not occur within a few days, then the individual knows that he has not been exposed to an infective dose. With cancer, there is not a "risk-free" level of contamination; even trace amounts are believed to result in increased risks of developing cancer in later years. Because there is no known threshold for health risk for carcinogens, there is always a non-zero risk where any exposure is, or was, possible. Even if the omnipresent risk is slight, it will be perceived and valued differently than a no-risk situation. Indeed, individuals have been shown to disproportionately prefer situations in which there is no risk at all to situations of even de minimis risk.

7.5.5 Conclusions and Policy Implications

Psychologists have been exploring methods of developing a taxonomy that would help explain and predict how society responds to hazards. This research on risk perceptions has used psycho-physical scaling and multivariate analysis to produce meaningful quantitative representations of attitudes and perceptions of risk. The results of these studies indicate clearly that for laypeople, risk is perceived and valued according to several factors or attributes, not just the actual (or perceived) quantitative level of risk. Further, this line of research has indicated that these risk characteristics are interpreted in a consistent manner across hazards and individuals (Slovic et al., 1984).

While the research in behavioral decision theory has not specifically addressed the risks associated with groundwater contamination, some hypotheses may be offered that are consistent with the general research findings. In specific, it appears reasonable to expect that the cancers and other severe chronic risks associated with many toxic compounds rank higher on the dread and unknown dimensions than do the acute risks associated with pathogen contamination. This implies that, ceterus paribus, the public would value actions that reduce its groundwater-related exposure to toxic compounds more than it would value policies that minimize the risk associated with exposure to pathogens.

7.6 Using Economic and Related Analytic Methods to Inform Decision-Making Under Uncertainty

As noted above, economic analyses are subject to the same uncertainties embodied in groundwater risk assessment and introduce additional uncertainties into the analysis as well.

Nonetheless, economic and related techniques can also be used to determine the degree to which the uncertainties affect the evaluation outcome and thereby help enlighten decision-making under uncertainty. In this section of the chapter, three approaches to contending with uncertainty are discussed: implicit valuation, sensitivity analyses (including Monte Carlo techniques), and the value of information approach.
7.6.1 Implicit Valuation and Decision-Making

Implicit valuation refers to the process by which some benefits (or costs) of a management option are left unvalued and are presented to the decision-maker in the context of the net balance of other costs and benefits. In this manner, the analyst can isolate the most uncertain (or controversial) components of the evaluation, complete the balance of the analysis, and then portray the uncertain component against the net balance. This provides the decision-maker with a bounded problem rather than an open-ended one, and may indicate that the key uncertainties have no bearing on the desirability of the policy under consideration.

For example, in a case where there are considerable uncertainties regarding the monetary value of reducing the risk of an adverse health effect, the non-health components of the benefits can be monetized and compared to the program's cost (leaving the health benefits aside for the moment). If the non-health benefits outweigh the program's cost, then the fact that health benefits are not monetized (or quantified) is insignificant in terms of the policy decision—the option has positive net benefits absent health risk reductions, and the addition of the health benefits only makes the option more attractive. However, this is the simplest example, and often the analysis must progress to less clearly defined terms.

Consider an example where a groundwater management plan will cost $3 million and yield benefits of two varieties: (1) reduced treatment costs and improved irrigation yields, valued at $1 million; and (2) a reduction in human exposure to a suspected carcinogen, quantified at a reduction of two statistical cancer cases. Leaving the health benefits aside, the project has a net cost of $2 million (costs minus the monetized nonhealth benefits). The decision-maker now has to determine if the health benefits outweigh the net costs, which becomes a well-defined problem: Is avoiding a statistical cancer case worth at least $1 million ($2 million divided by the two expected cases)? Here, there is no need to assign an explicit dollar value to cancer cases per se; rather, the decision rests on whether a single excess case is likely to be worth at least $1 million. As there is evidence (as cited above) to indicate that the risk reduction value may well exceed $1 million, the policy-makers can make a decision without undue uncertainty. Alternatively, if the decision-makers decide not to proceed with the project, then they have implicitly assigned a value per case avoided of less than $1 million.

Implicit valuation can be used to help inform policy decisions regardless of the source of the uncertainty. In the previous example, the uncertainty could have centered around the number of statistical cancer cases to be avoided as well as the value to assign to each case. In such a circumstance, an informative form of implicit valuation is to create a matrix of scenarios with which individuals can identify "what they need to believe" in order to have a project show positive net benefits. Table 7.5 shows such a matrix, where health risk reductions may amount to between 0.5 and 3.0 cases avoided, and the value per statistical case avoided may range from $1 to $10 million. In order to believe that the project will generate the $2 million in health benefits that are needed to ensure that total benefits exceed costs, the values need to derive from the shaded portion of the matrix. This indicates that only if one believes that the risk level is less than 1.0 case and that the value per case is less than $2 million, then costs exceed benefits. This approach does not resolve the
uncertainty, but it clearly places the implications in perspective in a manner that
decision-makers can use.

<table>
<thead>
<tr>
<th>Number of Excess Cases Avoided</th>
<th>Estimated Expected Benefits Under Alternative Valuation and Risk Assessment Scenarios Value Per Statistical Case Avoided (millions of dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1.0</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

7.6.2 Sensitivity Analyses and Monte Carlo Simulations

The multi-dimensional implicit valuation matrix described above represents a simple version of a sensitivity analysis. Where there are uncertainties about specific parameter values, the analyst can portray benefit-cost results for any array or combination of input value assumptions that are relevant. Then, one can identify which values for which parameters are required to alter the policy decision.

As in the implicit valuation examples, this approach is useful in that it separates those uncertainties that affect the decision from those that are not policy-impacting. That is, it focuses attention on the specific uncertainties that will impact the decision, and it indicates the specific parameter values that determine the net benefit outcome. Thus, for example, a sensitivity analysis can indicate that despite a dozen sources of uncertainty, there are only two that significantly impact the decision, and it can indicate what values one would need to believe in order to push the project decision in one direction or the other.

Of course many analyses contain several sources of uncertainty and the uncertainties interact in complex ways. This can make sensitivity analyses cumbersome. A more sophisticated approach to utilize in these situations is the Monte Carlo simulation technique, as described in Chapter 3. In this approach, probability distributions are assigned to each of the uncertain parameters, with values selected from these distributions by a computer-based simulation program. The simulations are repeated many times, with probabilistically assigned combinations of parameter values inserted for each "realization" of the model. With sufficient numbers of realizations, one ends up with a probability distribution of the final
benefit-cost (or other end point) calculations. This approach creates statistical confidence limits around the outcomes, accounting for error propagation. Of course the outcomes are only as valid as the value ranges and probability distributions assigned to the relevant variables. However, the technique has much to recommend it in complex cases.

One example of an application of the Monte Carlo technique to a groundwater contamination case can be found in Spofford, Krupnick, and Wood (1989). The authors investigate the uncertainties in a benefit-cost assessment of the options available for remediating groundwater contamination impacting two community water supply wells at Woburn, Massachusetts. Four remediation strategies are evaluated with Monte Carlo simulations that addressed uncertainties in three critical components of the analysis: (1) the solute transport model used for predicting contaminant concentrations at the wells over a 40-year planning period; (2) the health risk assessment indicating the potency (slope of the dose-response function) of the contaminant of concern; and (3) the economic valuation component used to value statistical lives and to estimate the cost to individuals of avoiding contaminated water (absent remediation).

The three uncertain components interact with each other in important ways to affect benefit and cost calculations. For example, the solute transport uncertainties (in this case, focusing on parameter values for hydraulic conductivity, longitudinal dispersion, and transverse dispersion) alter the predicted contaminant concentrations at the well at each point in time, and this determines the number of years it would take for remediation strategies to reduce the concentrations to drinking water standards. This in turn determines the level of human exposure and the effectiveness (duration and cost) of remediation alternatives. The exposure levels then interact with the dose-response uncertainties to indicate the potential level of health risk (statistical cases of cancer cases). This then interacts with the valuation issues in terms of measuring the monetary value of the risk reduction benefits.

In the analysis, the Monte Carlo simulations were used to produce 5,000 realizations of the benefits, costs, and net benefits of the four remediation alternatives. This yields results that not only portray the net benefits of each option in terms of mean values, but also in terms of the likely variance of the values around the mean and the shape of the probability distribution for net benefits. Thus, one can determine, for example, whether an option with the greatest mean value of net benefits should be passed over in favor of an option with less variance about its mean (i.e., accepting greater certainty of net benefits as opposed to greatest expected value). The results also can be used to indicate which of the uncertainties have the greatest impact on the final outcome, and this can be used to set priorities for monitoring or other research activities.

7.6.3 The Value of Information

As noted in the previous chapter with respect to monitoring, where there is uncertainty that affects whether one policy is selected over another, then there also is a clear value for information that might resolve or narrow the uncertainties. In decision theory, the concept of the value of information derives from the fact that decisions made under uncertainty may be "wrong," meaning that costs will be incurred that, in reality, did not have to be--that a more efficient choice would have
been made if the uncertainty did not exist (or if it had been narrowed). Thus, information that may alter the policy choice has a value that is equivalent to the Bayesian concept of the ex ante probability that the decision will be altered times the expected value of the net benefits (cost savings) due to the altered policy.

This concept of the value of information has been applied earlier to the notion of monitoring regimes for groundwater contaminants. Monitoring information derives value to the degree that it alters a decision (such as whether to install contaminant removal technology at a well). If it is uncertain whether a contaminant is present at the well, then a decision to treat the water may needlessly waste money or, alternatively, a decision not to treat might needlessly expose individuals to a health-threatening contaminant. Absent the monitoring information, a decision will be made based on the expected value of the outcomes, derived from the a priori probability that the contaminant was present (with the decision based on minimizing expected costs). If one believes that monitoring will alter that probability to the extent that the decision to treat would be reversed, then the ex ante value of information equals the associated cost savings (e.g., of not needlessly treating the water) times the probability assigned a priori that the monitoring would yield this outcome. If the costs of monitoring are less than this expected value of the information, then monitoring should be pursued (alternatively, the expected value of the information indicates the upper limit of the budget that should be devoted to monitoring).

The use of benefit-cost analysis, coupled with sensitivity analyses and the associated techniques described above, can be extremely useful as a means of identifying the value of information. By identifying which uncertainties have a significant impact on which management option gets selected, and by indicating the net costs of alternative decisions, the analyst can construct a value of information approach for setting research priorities. In this manner, the uncertainties that have the greatest bearing on decisions are identified, and then the social welfare implications of the decisions can be coupled with this information to indicate which uncertainties impose the greatest expected social cost (in terms of contributing to the likelihood that costly wrong decisions may get made). These expected social costs reflect the value of information.

7.7 Conclusions

Economics and related social sciences offer analytic tools that can be used to enlighten groundwater management decisions, even though there are many scientific and economic uncertainties that remain unresolved. In this chapter, several sources of uncertainty have been described, and analytic methods have been presented so that benefit-cost techniques may be applied to evaluating groundwater management issues.

Benefit-cost analysis can be controversial, especially when applied to environmental and public health issues such as related to groundwater contamination. There are two extreme views of benefit-cost analysis, and the true value of the approach lies between the two.

At one extreme is the belief that due to the uncertainties and the normative problems raised by the approach, benefit-cost analysis is impossible to conduct or generates output that is meaningless. This view is short-sighted, for it fails to
recognize that the analyses can be used to identify which uncertainties are most instrumental to how one views a policy. And, it fails to recognize that in many instances the use of sensitivity analyses or Monte Carlo simulations will help develop a reasonably clear picture of the relative merit of alternative management options regardless of the uncertainties.

At the other extreme is the view that benefit-cost analysis holds "the answer" and that all management policies should be directed by the empirical results of the analyses. However, this extreme view is dangerous, for it may fail to recognize the uncertainties and normative issues that are relevant to the issue.

A more reasoned view of benefit-cost analysis is that it is a useful tool for guiding management policies, and that it needs to be conducted and its results interpreted within the context and uncertainties that apply to the case at hand. Benefit-cost analysis provides a valuable framework within which to organize information, structure management discussions, and establish research priorities.
REFERENCES


