THOUGHTS ON THE APPLICATION OF SCIENCE TO DECISIONMAKING

Richard L. Bernknopf
Economist
U.S. Geological Survey

and

Herman A. Karl
Geologist
U.S. Geological Survey

INTRODUCTION

Scientists and science organizations are being encouraged to investigate societally relevant issues and to incorporate science into public policy. Many policy issues that involve science also involve diverse economic, political, social, and aesthetic values as well, and rarely, if ever, is scientific information alone the basis of public policy. How, then, do we go about incorporating science with other values in the public policy process to arrive at the desired, or even an acceptable, outcome from society's perspective? Can policy decisions be improved by reducing scientific uncertainty? Herein, we address the first of the above questions by describing a strategy, or model, for the application of science to policy, and explore the second question by summarizing a hypothetical study that assesses ground water vulnerability on the island of Oahu, Hawaii. A goal of the methodology, exemplified by the case study, is to transform scientific information into a form compatible with the decisionmaking process. In this way the science becomes an analytical tool for policy, and the illustrative value of the information as a descriptor of change (which may be a signal of harm to environmental resources) in natural systems is increased.

STRATEGY FOR APPLICATION OF SCIENCE TO POLICY

Interdisciplinary research and information derived from earth, life, and social science data and associated process models can contribute to both policy analysis and decisionmaking. However, there are often no clear and unequivocal answers to land-use and environmental issues, owing both to the uncertainties inherent in the scientific information and the need to consider economic, political, social, and aesthetic values. Most scientific information is not in a form readily usable by non-scientists. Applications require adapting scientific information to a decision-oriented framework. This adaptation is called an integrated assessment, and consists of four necessary components: (1) identification of physical processes that affect a societal issue and development of a conceptual physically-based stochastic model, (2) development of a map-based linkage of the human-physical environmental interface, i.e., an estimation of environmental risk; implementation of the approach by integrating and analyzing spatial information in a Geographic Information System (GIS) environment, (3) development of a conceptual model for decisionmaking under uncertainty, and (4) development of a management model that incorporates a cost-benefit analysis (CBA), i.e., an estimation of the net benefits to society.

The integrated assessment results in probabilistic environmental risk maps. In our proposed model of incorporating scientific information into the decisionmaking process, these GIS-based regional environmental risk maps are the foundation for dialogue among stakeholders, who use the maps to understand levels of hazard and prioritize the need for loss-reduction measures, and to evaluate the benefits of restoration/preservation and development alternatives. Stakeholders, working with technical experts and facilitators, build and interactively refine and use, risk maps to develop alternative loss-reduction scenarios. Scenarios reflect the value-preferences (social, economic, aesthetic, and political) of the stakeholder participants who are representatives of the community. CBA is applied to the scenarios which allows stakeholders to examine and evaluate resource allocation alternatives and to compare these alternatives to current policies. Economic costs and benefits associated with various individual and collective preferences in this way also become more explicit. This integrated process can be repeated periodically, using decision-theoretic concepts, to test the effectiveness of implemented policies. Thus, environmental risk maps can provide a powerful new tool for adaptive management approaches to mitigating natural and environmental hazards.

SCIENCE AND POLICY ANALYSIS

There is considerable scientific uncertainty about natural processes in time and space. Scientists strive to reduce uncertainty through experiments to understand the physical processes at the local scale. The uncertainty in the natural process model increases from the local to the regional scale because of the variability, complexity, and non-linearity of natural systems. For these reasons, many scientists are reluctant to extrapolate the results of their experiments from local to regional scale. In addition to the variability inherent in open systems, incomplete information and disagreement among scientists contribute to uncertainty. Scientists endeavor to reduce the uncertainty in their models by collecting more data, which is a deterministic approach. However, additional information will not necessarily result in consensus, or even reduce uncertainty. It could actually increase uncertainty because scientists may disagree on the interpretation of the data, and more data may raise more questions. Scientific uncertainty impacts both economic and social decisionmaking. Natural and social scientists may respond differently to the uncertainty in natural systems (for an expanded discussion see NRC, 1995). For physical scientists viewing the environment from the perspective of the ecosystem, this uncertainty often dictates a conservative (precautionary) approach to use of the environmental resource, whereas social scientists viewing the environment from the perspective of the human system, may prefer a more aggressive use of the resource (NRC, 1995). Although uncertainty can never be eliminated, a stochastic model, which identifies and explains the sources of the uncertainty in the deterministic scientific information, can be useful in extrapolating data from the local to the regional scale.

Policy decisions are made at scales that exacerbate the uncertainties in natural systems. Although uncertainty increases from the local to the global scale, probabilistic risk maps constructed using stochastic models can be used to analyze alternative policy decisions. Scientific information presented in this way helps policymakers to understand the consequences of alternative regulations regardless of the uncertainties. Many in society are questioning the relevance and value of scientific information for decisionmaking. To be useful for public policy, Federal science programs should focus on the solution of an issue of societal relevance, and outcomes from these programs should benefit society. It is our view that if our understanding of natural systems and physical processes can be improved (i.e., uncertainty reduced) by refining the science, decisions based on that scientific information will be improved, and benefits will accrue to society. (We recognize that in fact, however, a policy choice may be implemented for a political, economic, or social reason even if the best science supports the alternative.) For example, improved decisions based on scientific information that reduce losses to vulnerable resources (prevention of contamination of potable ground water) and from natural hazards (earthquakes, coastal erosion, etc.) benefit society. Loss-avoidance strategies involve a reduction of these risks. Risk involves an exposure to a chance injury or loss. The fact that risk inherently involves chance or probability leads directly to a need to describe and deal with uncertainty (Morgan and Henrion, 1990).

SCIENCE FOR RISK ASSESSMENT AND LOSS REDUCTION

Risk analysis is the assessment of the adverse impacts associated with specific environmental hazards to the built, natural, and social environments. Risk analysis consists of two main parts: risk assessment and risk management. Risk assessment is concerned with the qualitative or quantitative examination of the vulnerability (exposure) of an individual or a community to a potential hazard. It includes data gathering, scientific testing, and evaluation of a hazard that provides a fundamental input for policy analysis. Risk assessment is a tool for extrapolating a risk number from scientific data that can be used in policy analysis (Carnegie Commission, 1993). While the tool may rely on scientific and policy assumptions that can be troublesome, we can use it to help identify important factors and sources of disagreement in a problem, and to help anticipate the unexpected.

Risk management is the process by which the results of a risk assessment are integrated with political, economic, and engineering information to arrive at decisions about the need and methods for risk reduction. Alternative options and actions for reducing the risks can be measured with CBA. The CBA approach to an analysis involves an evaluation of the trade-offs associated with achieving goals concerned with protection of the environment. CBA is not an absolute measure. It is a guide among a range of factors that decisionmakers must implicitly take into account (Railton, 1990).

Tool for Analysis

Risk has a spatial and temporal hazard component (*H*). In other words, the risk of a hazardous outcome, like a landslide, actually occurring is not the same everywhere or each time there is a rainstorm. When they do occur, direct and indirect loss of an environmental resource (*L*) results, and the damages could be costly. A failure of this type (*h*) varies spatially and occurs when physical thresholds (*tr*) are exceeded. In the landslide example, this occurs when the assimilative capacity of a hillside is surpassed and the factor of safety falls below equilibrium. The thresholds are based on natural processes that are composed of earth science variables including geology, hydrology, and topography. Events (*e*) recur over long periods of time with some regularity. In the short run though, there is considerable uncertainty regarding the size and timing of events. The probability of a hazard p(*H*) is:

$$p(H) = p(h|tr) \cdot p(tr|e) \cdot p(e).$$

Thus the risk to people and their property E(*L*) is a function of the hazard probability p(*H*) and the value of the resource at risk *V*:

$$E(L) = p(H) \cdot (V).$$

Individuals make loss-reduction decisions in an uncertain economic and social environment based on their perceptions of the outcome of a hazardous event (state of nature) and act in a manner that allows them to achieve highly valued goals. These might include living in a particularly beautiful natural setting, or continuing to run the family farm, or simply buying an affordable home. Given goals such as these, people build homes in a flood plain because they believe that the chances of a catastrophic flood to be low, at least during their lifetime. In theoretical terms "expected utility," or the expectation of enjoying the benefits associated with the building of this home, is influenced by personal beliefs about the uncertainty of both the occurrence and severity of a hazardous incident. These perceptions are modulated by underlying attitudes toward risk (Lewis and Nickerson, 1989). A second factor that influences an individual's attitude toward risk is the nature of the technology by which they protect themselves. The following case study illustrates the application of the integrated assessment method and the general concepts outlined above.

HYPOTHETICAL APPLICATION ON THE ISLAND OF OAHU, HAWAII

The availability of potable ground water supplies is a major environmental-quality concern throughout the U.S. Remediation measures exist as one possible means of "cleaning up" ground water contamination problems. An alternative preventive approach to mitigate future contamination incidents is regional-scale nonpoint source (NPS) vulnerability assessments designed to limit ground water resource exposure. An ounce of prevention is worth a pound of cure. The method of assessing ground water vulnerability in this study is founded on a scientific theory that describes the ease with which contaminants move through the soil and into ground water, known as the Retardation Factor (RF). The RF is a screening index which could be the core of a risk-based regulation to permit (restrict) the application of specific pesticides in specific soils.

In a cost-effectiveness analysis, the RF-based preventive measure is compared to a wellhead treatment program (a remediation technique) for the Hawaiian island of Oahu (Bernknopf *et al.*, in press). The model is a demonstration of where on the island to avoid unnecessary environmental risks. Concerns have existed about the effectiveness and reliability of regulatory standards that have been based on water resource vulnerability assessments. The most obvious concern is related to the uncertainty in regional-scale nonpoint-source (NPS) vulnerability assessments. Certain soil types preferentially sorb specific pesticides. Thus, these pesticides are inhibited from contaminating the ground water. The scientific information permits us to choose among those pesticide-soil combinations that can increase agricultural production and maintain a potable water supply. In other words, should a pesticide be restricted from use in a specific location if, in fact, it could be used efficiently and safely?

One way to use a regional-scale assessment is to incorporate the uncertainty in the underlying Earth Science information into a risk-based regulation. In this circumstance, regulators are assumed to behave as if they are risk averse and would implement a regulation that includes the assessment uncertainty (Bernknopf *et al.*, 1997). Furthermore, the regulator would be cautious and prudent in applying the regulation. While this approach is possible, refining the data by lowering the uncertainty contained in the leaching index is better still. However, less uncertainty comes at a cost for increasing the density and range of Earth Science data. Gathering more data to reduce the uncertainty in the regional-scale vulnerability assessment is beneficial. It improves our ability to identify those areas with the appropriate soil-pesticide combinations that can lead to an increase in the area acceptable for pesticide application, consequently enhancing agricultural production. Any increase in the area acceptable for pesticide application is a benefit to the utilization of the regulation and a measure of value to the supporting Earth Science information.

Public programs for mitigating losses associated with ground water contamination have taken the form of safety rules that restrict or tax the use of hazardous chemicals (Wise and Johnson, 1991) or require some form of well-water treatment (Leon-Guerrero *et al.*, 1994). These policy instruments and on-site remediation measures are designed to reduce the health and environmental impacts of ground water contamination at specific locations. These approaches do not incorporate a regional vulernability assessment that includes a leaching index like the RF. A likely outcome of the programs is the imposition of inefficient mitigation that is either too restrictive or too permissive. The hypothetical case study is based on past studies of ground water contamination in the Pearl Harbor Basin (Leon-Guerrero *et al.*, 1994; Loague, 1994). The simplifying assumptions and major limitations of the RF, relative to known processes of near-surface chemical transport and fate, are described in greater detail by Rao *et al.,* (1985); Loague *et al.,* (1989, 1990); Loague (1991); and Kleveno *et al.,* (1992).

In the demonstration there are two alternative ways of reducing the environmental hazards associated with pesticide application: (1) increase the amount of scientific information collected and decrease the uncertainty of the components of the RF, and (2) conduct a region-wide wellhead treatment program to remove any pesticides from the ground water before consumption over the productive lifetime of the resource. Comparison of the alternatives is based on a cost-benefit analysis (CBA) of each approach to loss reduction.

Alternative A

In this case, CBA is used as a *prospective* tool to provide an estimate of the relative net gains or losses from future payoffs of reducing the uncertainty in the RF. Earth Science information is an input to a decision to permit or restrict the application of a pesticide in a specific area to prevent an adverse environmental impact in the future. The expected payoffs for refining the RF are: (1) reduction in the uncertainty associated with future decisions concerning the application of pesticides, and (2) cost-effective provision of loss-reduction information to regulators. In this context CBA provides an essential guide to the decision maker for evaluating the future societal impacts of a regulatory standard. Reducing the standard deviation of RF reduces the risk of permitting the application of a chemical to a soil which will likely contaminate the underlying ground water resource. If uncertainty about the actual behavior of pesticides in the soil and in the aquifer is minimized, there is an improvement in the allocation of resources because more accurate management decisions can be made.

Alternative B

As part of an ongoing effort, Leon-Guerrero *et al.,* (1994) considered the wellhead treatment costs, for ground water contaminated with pesticides, by factoring capital investment and annual treatment and operating costs into annual financial returns from pineapple production. In this case, CBA can be used as a *retrospective* analytical tool to evaluate whether a previous decision to implement a project resulted in a net gain or loss to society. This option treats the policy as a controlled laboratory experiment. A wellhead treatment alternative is an investment in the remediation of contaminated ground water that results from the identification of trace amounts of pesticides used in agricultural production. The expected payoffs of ground water treatment are: (1) unlimited application of pesticides to produce the maximum agricultural product, and (2) no restrictions on where specific crops can be planted. In this context CBA also is a guide to the decision maker, but in a different way. This application of the tool provides a systematic approach to examine whether allowing pesticide application and consequently treating the ground water for later consumption has been beneficial to the public.

The choice to spend public money again in this manner can be examined and a decision based on past experience can help resolve issues concerned with this type of public debate.

Cost-Benefit Analysis

CBA, as applied here, is used to help decide whether we, as a society, should invest in reducing the uncertainty of Earth Science information to optimize agricultural production while minimizing the risk of ground water contamination or to maximize agricultural production by implementing a wellhead treatment program. The choice can involve significant public expenditure, so it is necessary to weigh the advantages and disadvantages of the alternatives. Using the integrated-assessment approach, potential gains and losses are identified, converted to dollars, and compared using established decision criteria (Nas, 1996). The analysis must include (1) an identification of costs and benefits, (2) a comprehensive valuation of the costs and benefits of the potential environmental impacts, and (3) a comparison of the costs and benefits in present-value terms (the future stream of benefits and costs is discounted to a single time dimension, i.e., the present).

In the hypothetical model, it is assumed that increasing the number of samples results in a reduction of uncertainty. Given this assumption, the net present value of the benefits of denser information based on a regulatory standard is listed in Table 1. Also contained in Table 1 is the net present value of the benefits for Alternative B used in the Pearl Harbor Basin example of pineapple production. This alternative assumes that all ten pesticides can be applied at any time during a 25-year production period.

The stylized demonstration contrasted conducting a contamination prevention program based on scientific data collection (program A) with wellhead treatment to remediate a contaminated ground water supply (program B). The comparison is the difference in present value of the net benefits per hectare of the alternative programs. The Earth Science information collection program for all models that included the 10% reduction in uncertainty is more cost effective than a wellhead treatment program (e.g., for model 1, the 25% option; \$48,446/hectare - \$46,071/hectare = \$2,375/hectare). The only exception was the 31% model option. However, this is not true when the choice is the Earth Science information collection program for all models that included the 90% uncertainty reduction (e.g., for model 1, the 25% option; \$43,333/hectare - \$4,6071/hectare = \$2,738/hectare). In this case, the wellhead treatment alternative is more cost effective. Here the only exception was the 15% model option. The "most appropriate" answer is to conduct the Earth Science information collection alternative (A) that includes the 10% reduction in uncertainty. Of course, these results are hypothetical, meant only to demonstrate the approach, and do not reflect economies of scale.

Issues for Policy Analysis

Despite all of the potential pitfalls, policy analysis does proceed. The approach of Bernknopf, *et al.,* (in press), has been to integrate scientific information in the form of a regional-scale vulnerability assessment measure and link it to a policy decision process. In the example they applied an integrated Earth Science-Economic model in a GIS to tradeoff pesticide-use restriction, crop yield and acreage, and ground water treatment both locally and regionally in an economic framework of optimizing agricultural production. The method is used to evaluate two alternatives intended to minimize the adverse health impacts of pesticide leaching to a ground water resource. The comparison demonstrates that the use of a regional leaching index, the RF, as the basis for regulation, has positive net benefits, and under certain circumstances can be more efficient than a wellhead treatment program.

Policy analysis must rely on dependable assessments of NPS ground water vulnerability. Economic benefits of Earth Science information result from the cost effectiveness of reducing the uncertainty of hazard levels in relation to a specified environmental standard. If reliable Earth Science information is unavailable, there certainly will be a suboptimal allocation of resources.

CONCLUSIONS

The hypothetical case study assumed that scientific information was the basis for deciding upon policy alternatives, and described a way to use scientific information as an analytical tool. However, policy decisions will be made with or without scientific input, and indeed, frequently, some other factor is the basis for implementing a policy choice. The Department of the Interior and U.S. Geological Survey strategic plans, and various "blue ribbon panel" reports (see especially NRC, 1995) recommend several strategies to ensure that sound science is incorporated into government policy and community-based decisionmaking. Many of these recommendations and findings are reflected in our proposed model for applying science to policy. Physical scientists should improve their knowledge of the social sciences, adaptive management techniques, and the political process so that they can better communicate the value of scientific information as an integral component of the decisionmaking process that leads to public policy.

ACKNOWLEDGMENTS

This is a Center for Earth Science Information (CESIR) contribution. We would like to thank Elisabeth Graffy and Daniel Sarewitz for their insightful comments that improve the clarity of the manuscript.

REFERENCES

Bernknopf, Richard L., Allison K. Lenkeit, Laura B. Dinitz, and Keith Loague, in press. "Estimating a Societal Value of Earth Science Information in the Assessment of Nonpoint Source Pollutants," in Corwin, D.L., K. Loague, and T.R. Ellsworth ed., *AGU Special Publication: Application of GIS, Remote Sensing, Geostatistics, and Solute Transport Modeling to the Assessment of Nonpoint Source Pollution in the Vadose Zone.*

Bernknopf, R.L., D.S. Brookshire, M. McKee, and D.R. Soller. 1997. "Estimating the Social Value of Geologic Map Information: a Regulatory Application," *Journal of Environmental Economics and Management*. 32, p. 204-218.

Carnegie Commission on Science, Technology, and Government. 1993. *Risk and the Environment Improving Regulatory Decision Making*, New York, 150 p.

Kleveno, J.J., K. Loague, and R.E. Green. 1992. "An Evaluation of a Pesticide Mobility Index: Impact of Recharge Variation and Soil Profile Heterogeneity," *Journal of Contaminant Hydrology*. 11, p 83-99.

Leon-Guerrero, E.D., K. Loague, and R.E. Green. 1994. "Wellhead Treatment Costs for Groundwater Contaminated with Pesticides: a Preliminary Analysis for Pineapple in Hawaii," *Environmental Management*. 18, p. 93-104.

Lewis, Tracy, and David Nickerson. 1989. "Self-insurance Against Natural Disasters," *Journal of Environmental Economics and Management*. 16, p. 209-223.

Loague, K.. 1991. "The Impact of Land Use on Estimates of Pesticide Leaching Potential: Assessments and Uncertainties," *Journal of Contaminant Hydrology*. 8, p.157-175.

Loague, K. 1994. "Regional Scale Ground Water Vulnerability Estimates: Impact of Reducing Data Uncertainties for Assessments in Hawaii," *Ground Water*. 32, p. 605-616.

Loague, K.M., R.S. Yost, R.E. Green, and T.C. Liang. 1989. "Uncertainty in a Pesticide Leaching Assessment for Hawaii," *Journal of Contaminant Hydrology*. 4, p. 139-161.

Loague, K., R.E. Green, T.W. Giambelluca, T.C. Liang, and R.S. Yost. 1990. "Impact of Uncertainty in Soil, Climatic, and Chemical Information in a Pesticide Leaching Assessment," *Journal of Contaminant Hydrology*. 5, p. 171-194.

Morgan, G.M., and M. Henrion. 1990. *Uncertainty,* Cambridge University Press, Cambridge, 332 p.

Nas, T.F. 1996. *Cost-benefit Analysis: Theory and Application*, SAGE publications, Thousand Oaks, CA.

National Research Council. 1995. *Science, Policy, and the Coast -- Improving Decisionmaking: National Academy Press*, Washington, D.C., 85 p.

Railton, P. 1990. "Benefit-cost Analysis as a Source of Information about Welfare," Chapter 4, in Hammond, P.B., and Coppock, E., ed., *Valuing Health Risks, Costs, and Benefits for Environmental Decision Making*, National Academy Press, Washington, p. 55-82.

Policy Council and Strategic Planning Team. 1996. *Strategic Plan for the U.S. Geological Survey 1997 to 2005* (electronic version), 75 p.

Rao, P.S.C., A.G. Hornsby, and R.E. Jessup. 1985. "Indices for Ranking the Potential for Pesticide Contamination of Groundwater," *Soil Crop Sci. Soc. Florida Proc.* 44, p. 1-8.

U.S. Department of the Interior. 1997. *Strategic Plan Overview*, (electronic version) 30 p.

Wise, S., and S.R. Johnson. 1991. "A Comparative Analysis of State Regulations for Use of Agricultural Chemicals," in R.E. Just and N. Bockstael (eds.)

Commodity and Resource Policies in Agricultural Systems, Springer-Verlag, Berlin, p. 46-71.

Richard Bernknopf is an economist who has been with the USGS for over 25 years and has served as a consulting professor at Stanford University for 4 years. Starting in 1973, Dr. Bernknopf has worked in the Office of the Director and in the Geologic Division in Reston, VA, and in Menlo Park, CA. He also is the co-director of the Center for Earth Science Information Research (CESIR) at Stanford University. Dr. Bernknopf's research focuses on the demonstration of the relevance (value to society) of natural science information and the translation of that information into a form compatible with decision-making processes.

Herman Karl is a marine geologist who has been with the USGS for over 21 years in Menlo Park, CA. As a research associate at the Stanford Center for Earth Science Information Research, his current research interests focus on the application of science to public policy and the integration of the natural and social sciences.

Table 1* Total net benefits in $/hectare for areas acceptable for pesticide use at three levels of uncertainty (actual, hypothetical reductions of 10% and 90%) for ten selected pesticides for the five major soil orders assuming 15%, 25%, and 31% increases in net revenue from pesticide application. The total number of hectares in the study area is 86,942.

	Actual uncertainty	10% uncertainty reduction	90% uncertainty reduction
Alternative A			
15%	$54,333	$54,368	$47,944
25%	47,750	48,446	43,333
31%	21,907	25,200	25,239
Alternative B	46,071		

* Adapted from Table 9 in Bernknopf, *et al.*, in press.