Developments in Environmental Modelling, 15

Environmental Models: Emissions and Consequences

Risø International Conference
22-25 May 1989

Edited by

J. Fenhann, H. Larsen, G.A. Mackenzie and B. Rasmussen

*Risø National Laboratory, Systems Analysis Department, P.O. Box 49,
DK-4000 Roskilde, Denmark*

ELSEVIER
Amsterdam — Oxford — New York — Tokyo 1990

Keynote Paper

CHARACTERIZING UNCERTAINTY IN INTEGRATED ENVIRONMENTAL MODELS

Edward S. Rubin

Carnegie Mellon University
Pittsburgh, Pennsylvania 15213 USA

ABSTRACT

The use of integrated computer models for environmental research management, policy analysis, and regulatory decision-making is becoming widespread. The characterization of uncertainty in model predictions also has become an important dimension of model applications. This paper reviews methods commonly used to represent, propagate and report uncertainty in integrated models. Several models developed to analyze acid deposition impacts and control strategies in North America and Europe are used for illustrative examples.

1. INTRODUCTION

Computer models are widely used to predict the consequences of environmental emissions and their control. Important areas of application include the analysis of air pollution problems, surface and groundwater contamination, health risk assessments, and global climate change. The increased use of computer models has been stimulated by the growing demands of environmental regulatory requirements, and by the advances in scientific understanding of environmental systems resulting from decades of intense research and data collection. Perhaps the most powerful catalyst for model developments, however, has been the extraordinary leaps in computational power and speed that have occurred over the past decade. Personal computers today are ubiquitous as slide rules were several decades ago, and to an increasing extent the more advanced capabilities of computer workstations, mini-computers, mainframes and super-computers are becoming widely available for the modeling of environmental systems. These advances in computer technology have enabled construction of increasingly sophisticated and complex models reflecting the best science currently available to simulate the chemistry and physics of environmental systems.

Another breed of computer models are so-called "integrated" or "systems" models of environmental processes and their consequences. Integrated models are characterized by the broader perspective obtained from combining two or more component models to address a particular issue. For example, predicting the oxygen concentration in a river system may involve combining effluent emissions models for municipal, industrial and non-point sources with a stream flow model to predict dilution, transport and biochemical transformations. Modeling a regional problem such as acid deposition is far more complex. Here, the components of an integrated model could include not only source emissions and long range atmospheric transport, but additional models to describe the physical, chemical and biological changes in natural and man-made environments, and the direct and indirect effects or consequences of those changes.

The development of integrated environmental models typically arises from a need for policy guidance and/or regulatory decisions. In such applications, relationships are sought between the magnitude of a potential environmental hazard or risk and the levels of pollutant emissions subject to regulation or control. While it is the predictive power of such models that is of primary value for policy and regulatory purposes, the *confidence* in such predictions can be equally important. Where the science is uncertain, integrated models may also play a role in research management. In this paper, we focus on the use of integrated models to assess uncertainties that bear upon research priorities and public policy decisions.

2. CHARACTERIZING MODEL UNCERTAINTY

The subject of uncertainty has gained wide attention in recent years, and there is a significant literature dealing with its characterization, including applications to environmental models. Morgan and Henrion (1989) present an excellent review of this literature in their guide to dealing with uncertainty in quantitative risk and policy analysis. They also present a taxonomy of the types of quantities which may be uncertain (Table 1), and the principal sources of these uncertainties.

2.1 Uncertainty in Model Inputs. Uncertainties often exist in the "empirical" quantities of a given model. In addition, there is uncertainty about the actual model form or structure. Empirical quantities may be uncertain because of, (1) statistical variation (random error); (2) subjective judgment (systematic error); (3) linguistic imprecision; (4) sampling variability; (5) inherent randomness; (6) scientific disagreement; and (7) approximations (see Morgan and Henrion 1989). Additional uncertainty about model form usually reflects technical or scientific disagreements about underlying mechanisms and processes. In some cases this uncertainty can be converted into an uncertainty about a parameter value (e.g., a parameter whose value could be altered to represent a process either as linear or nonlinear, in lieu of separate models); but in many situations this is not feasible. Examples of uncertainty due to model structure are presented later in this paper.

There are also a number of ways to represent, propagate and analyze uncertainty (Rubin et al. 1984). One representation of uncertainty is a qualitative description. Thus, environmental modelers often acknowledge and discuss the existence of various uncertainties, but do not treat them quantitatively. Instead, only nominal or "best estimate" values are used for model parameters.

A common quantitative representation of uncertainty is to specify a range of two more more values for a particular quantity, (e.g., a low, nominal and high value). For empirical parameters, a probability distribution also may be specified. This could either be a discrete distribution over alternative values (e.g., an x percent chance of value v_1, a y percent chance of value v_2, etc.), or a continuous distribution specified either partially (e.g., by a mean and standard deviation, or by a confidence interval), or completely (e.g., as a uniform, normal, or other standard parametric distribution, or as points on a arbitrary density function). Non-probabilistic representation of uncertainty, such as a fuzzy set membership function over alternative values, also may be specified (Zadeh 1965), though this method is not commonly employed in environmental modeling.

2.2 Uncertainty in Model Outputs. Where quantitative measures are specified, the uncertainties induced in the model outputs may be obtained in a number of ways. Scenario analysis is perhaps the most common method. A scenario is a model run in which single values are chose for each uncertain quantity. Of course, this approach suffers a combinatorial explosion if there are many quantities with alternative values. In this case, a subset of "interesting" scenarios must be selected, with the choice of such scenarios dependent upon the application or problem at hand.

Another approach widely used in the physical sciences is first order (Gaussian) error

Table 1. Types and definition of uncertainty quantities in policy models (adapted from Morgan and Henrion 1989.)

Type of Quantity	Definition/Examples
Empirical parameters (or chance variables)	Quantities in the domains of natural sciences, engineering, or social sciences which are measurable, at least in principle, in the past, present or future (e.g., a chemical oxidation ratio, fuel price, demand elasticity, willingness-to-pay).
Decision variables (or control, or policy variables)	Quantities over which a decision-maker exercises direct control (e.g., the ambient standard for an air pollutant, the choice of fuel or pollution control equipment for a power plant).
Value parameters	Quantities reflecting the preference of decision-makers or the people they represent (e.g., a discount rate, "value of life," risk tolerance).
Model domain parameters	Quantities which specify the region or scope of the system being modeled, generally by specifying the range and increments for index variables such as time and space parameters (e.g., geographic domain, time horizon, time increments, spatial increments).
Outcome criteria	Quantities used to measure or rank the desirability of possible outcomes (e.g., a cost-benefit ratio, net present value, internal rate of return, utility.

propagation in which the derivative of an output with respect to each uncertain input is used, together with the uncertainty variance of each input, to evaluate the total output uncertainty and the contributions from each input. This approximation is reasonable only if the output is roughly linearly dependent on the inputs over the range of their uncertainty. Thus, it is less likely to be useful in complex integrated models where uncertainties are large and the linearity assumption is poor.

Two other approaches for propagating uncertainty employ probabilistic methods. One is a probability or decision tree. Here, a combinatorial scenario analysis is performed to compute the outcome value for all combinations of decisions and uncertain variables, which are specified by discrete probability distributions. The other method is probabilistic (or stochastic) simulation. In this method the uncertainty induced in each model output is estimated from either continuous or discrete probability distribution specified for model inputs. The most common version of this method is Monte Carlo simulation. A large number of scenarios is generated by sampling from the probability distributions for each uncertain input, producing a frequency distribution for each model output. To minimize computational efforts, more efficient sampling methods such as Latin Hypercube sampling can be employed (McKay et al. 1979).

Probabilistic methods can be especially powerful for structuring problems, evaluating risks, and informing the judgments needed for environmental policy and regulatory decisions. One important cautionary note, however, is that uncertainty in output results often can be overstated because of the assumed independence among uncertain model inputs or coefficients. While some procedures have been devised and used to account for the correlation structure of complex environmental models, more attention to this issue is needed as stochastic simulation methods become more widely utilized.

3. REPRESENTING UNCERTAINTY IN INTEGRATED MODELS

Given this general background what, then, is the best way to represent uncertainty in integrated models for a given problem or application? Clearly, there is no unique answer to this question. In each case, the choice must depend upon the nature of the problem, the goals of the analysis, and the resources available to the analyst (including time, money and expertise). Thus, the choice of an appropriate technique is largely a matter of judgment and experience, subject to the constraints that apply in each circumstance. To illustrate some of the different approaches to characterizing uncertainty, and to show how such methods may be applied to a complex environmental problem, the remainder of this paper focuses on the integrated modeling of acid deposition, which is an important current issue in North America and Europe.

3.1 A Conceptual Framework for Acid Deposition Modeling. Figure 1 shows the major elements potentially involved in an integrated model of acid deposition effects and control (Rubin et al. 1984). The components of this framework generally reflect disciplinary or study areas in which descriptive and predictive models have been developed for individual processes or phenomena. For example, large engineering and economic models have been developed in the U.S. and Europe to predict the magnitude of air pollutant emissions associated with electric power generation and industrial activity, and the effect on such emissions of alternative environmental regulations. Substantial efforts also have been devoted worldwide to developing long range atmospheric transport and chemistry models that characterize source-receptor relationships for air pollutants responsible for acid deposition. The effects of acid deposition on aquatic systems, forests, materials, agriculture and human health also have been characterized by mathematical models to varying degrees. To the extent that physical, chemical or biological

Fig. 1. A conceptual framework for acid deposition assessments

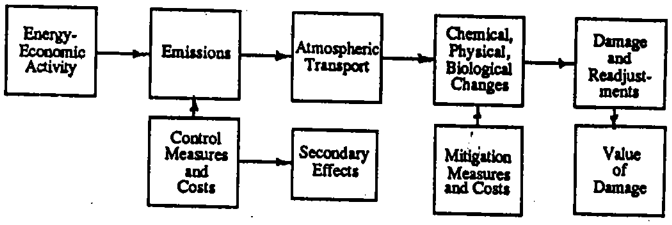


Table 2. Integrated models of acid deposition.

Model	Developer	Domain	Model Components	Uncertainty Method(s)
ACIDRAIN	Cambridge Decision Analysts (UK)	6 regions in UK + 3 in Western Europe for sources and receptors; 1980 to one future year (1995).	Emissions and UK control costs; atm. deposition; damage functions for lakes, fishlessness, forests, crops, buildings, monuments, human health; unit damage prices.	Scenario analysis; Probabilistic simulation; Alternate model forms
ADAM (Atmospheric Deposition Assessment Model)	Carnegie Mellon University (USA)	66 source regions (49 US states, 17 Canada sub-provinces); 30 sensitive receptors; 1980 to 2030 year by year	Emissions (5 sectors); control costs; atm. dep.; precip. pH; lake acidity; fish viability; + user-specified models for other effects or damage valuation.	Scenario analysis; Probabilistic simulation; Alternative models
ADEPT (Acid Deposition Decision Tree)	Decision Focus, Inc. (USA)	Arbitrary number of sources and receptors (but typically fewer than 10 each); arbitrary time horizon.	Emissions; control costs; atm. deposition; lake impacts; forest impacts; other impacts; lake liming; effects valuation; research costs.	Scenario analysis; Decision trees; Alternate model forms
BICRAM (Beij. Inst. Ctr. Res. Assess.& Mgmt.)	Beijer Institute/ University of York (Sweden/UK)	28 source regions (European countries); 150 km x 150 km receptor grid (Europe); arbitrary future year.	Energy use; emissions; control cost; atm. deposition; receptor sensitivity classes.	Scenario analysis
RAINS (Regional Acidification Information & Simulation)	Intl. Inst. for Applied Systems Analysis (Austria)	27 source regions (European countries); 150 km x 150 km receptor grid (Europe); 1960 to 2040 (annual or seasonal).	Emissions; control costs; atm. deposition; soil pH; lake acidity; groundwater sensitivity; direct forest impacts.	Scenario analysis

changes in the environment resulting from acid deposition can be quantified, economists and other social scientists have developed methods and models for valuing some of these changes in monetary or other terms. Other economic models have been developed to predict the direct and indirect costs of measures to abate acid deposition precursor emissions, and to mitigate the effects of acid deposition at the receptor (e.g., neutralizing lake acidity by the addition of lime).

Integrated computer models combining three or more of the elements in Figure 1 have been developed and used in Europe and the U.S. to analyze acid deposition control strategies and research priorities (Alcamo et al. 1987; Balson et al. 1987; Cooke et al. 1987; Rubin et al. 1987; Watson and Hope 1987). Table 2 summarizes certain attributes of these models and the methods they employ to characterize uncertainty. A major U.S. effort also is in progress to link some 20 to 30 different environmental models for a major assessment of acid deposition in 1990 (NAPAP 1989). While this assessment will not utilize a fully integrated computer structure to carry out this linkage, it is included here to illustrate another possible approach to integrated modeling and the representation of uncertainty.

3.2 Attributes of Integrated Models. In general, three levels of complexity are represented by the integrated acid deposition models developed for North America and Europe. One level, referred to here as "Level I," include relatively simple models that are conceptually complete and easy to use, with minimal data requirements and often highly aggregated or limited spatial coverage. The ADEPT and ACIDRAIN models are representative of this category. These models are designed to allow user judgment to drive the analysis. Both ADEPT and ACIDRAIN provide the user with alternative functional forms to represent key components of the integrated analysis (e.g., source-receptor relationships and dose-response functions for evaluating damages), and both provide some data to assist in quantitative analysis. Fundamentally, however, the choice of model components and parameters must be provided by the user. Credible applications of these models, therefore, may require substantial additional analysis and the participation of technical experts. Sophisticated quantitative methods, however, are provided for analyzing uncertainty and the implications of alternative judgments or decisions. Thus, Level I models are a valuable tool for "thinking through" the problem and examining the risks and consequences of different actions, model formulations, values, and research results.

At the opposite end of the spectrum, a "Level III" approach to integrated analysis employs the best state-of-the-science models for each component, minimizing reliance on expert judgment or "educated guesses." At the present time, only the NAPAP integrated assessment planned for 1990 fits in the Level III category. The merit of this approach is that it employs the most scientifically defensible models and a fine level of spatial and temporal resolution to address acid deposition issues as mechanistically as possible. But because many of these component models are extremely complex, data intensive, and cumbersome or costly to operate, this approach is not at all amenable to iteration, replication, or use by other parties at interest.

In the NAPAP plan, direct linking of emissions and effects models will not be attempted. Rather, component models will be run at different locations by different organizations with manual transfer of input and output data files used to accomplish the integration. The emissions and source-receptor models will be coupled to produce a range of deposition fields for different emission scenarios. Independently, the various effects and economic evaluation models will be exercised for a range of assumed deposition values. Full integration is then achieved by examining the consequences of a scenario-related deposition level.[1] To characterize uncertainty in results of the integrated analysis, NAPAP has adopted only a set of qualitative descriptions for key questions of interest.[2] Separate state-of-the-science reports, however, will include more rigorous quantitative analyses of uncertainty in individual model components.

A degree of complexity intermediate to Levels I and III is found in a "Level II" model. Rather than employing state-of-the-art component models directly, simplified representations of such models are employed (e.g., in the form of regression equations or tabular data obtained by exercising detailed models independently over a range of cases or input parameter values). For example, complex Lagrangian atmospheric transport models may be represented by a simple "transfer matrix" of coefficients derived by exercising the detailed model off-line for specified sources, receptors and meteorology. Other complex models representing emissions, control costs, and certain types of effects also may be amenable to representation in simpler algebraic or aggregated forms that nonetheless retain the scientific integrity of the parent model upon which they are based. ADAM, BICRAM, and RAINS are examples of Level II integrated models. While there are still significant differences among these models in terms of their scope, computational complexity, data requirements, and sub-model formulations, all seek to incorporate a high level of scientific or technical representation in model components. All are also amenable to transfer and operation either on a microcomputer or computer workstation, and all are capable of being expanded to include additional models or interactions beyond those that are presently provided. The representation of uncertainty is incorporated primarily through scenario analysis, except for ADAM which also permits stochastic simulation.

4. UNCERTAINTY METHODS AND APPLICATIONS

Several examples are presented here to illustrate methods of characterizing uncertainty in integrated environmental models of acid deposition. In each case, an analysis driven by a typical question of interest to policy makers and research analysts is assumed to provide context for the discussion.

4.1 Comparing Costs and Benefits. In principal, the consumate integrated model would allow the direct and indirect costs of abating acid deposition to be compared to the benefits that accrue from a reduction of environmental damages. The ability to assess current environmental damages, however, remains subject to large uncertainties, as do the benefits of source emission reductions. Inevitably, expert judgment must be relied upon heavily to evaluate many of these benefits. The two Level I models, ADEPT and ACIDRAIN, provide a framework for allowing decision makers and researchers to explore the consequences of alternative judgments in an

---

[1] Issues yet to be resolved include the precise methods for reconciling interface differences between component models, and for insuring internal consistency among models with similar or identical parameters. For example, calculation of deposition fields will involve coupling at least 13 different models (six economic driver models, six emission sector models and at least one, though probably multiple, detailed source-receptor models). For each type of acid deposition effect, several different models will be exercised, plus additional models for economic evaluation (NAPAP 1989).

[2] The system employs a series of "stars." No star (0) means "no scientific information." One star (*) means "limited information, but major uncertainties and knowledge gaps." Two stars (**) means "information base is broad but uncertainties generally large and ill-defined, or information is certain but very limited in scope." Three stars indicates "ample information with well-defined but sometimes large confidence intervals." Four stars means "substantial amount of consistent and highly accurate information." Rankings tentatively assigned to major component models are mostly one or two stars (NAPAP 1989).

explicit, probabilistic manner.

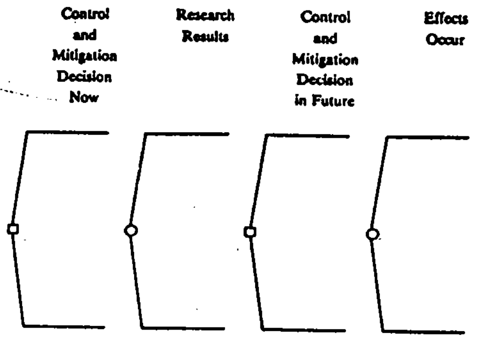
Uncertainties in ADEPT are expressed as probabilities in a decision tree, an example of which is shown in Figure 2(a). The "basic tree" is designed to evaluate alternative emission control policies and the expected value of perfect information. A "research emphasis" tree is designed to evaluate the implications of information that may result from new research. Results of an illustrative analysis to compare aggregate costs and benefits over a range of assumptions are shown in Figures 2(b) and (c). In one actual application of ADEPT in Wisconsin, a panel of seven scientists provided the expert judgments needed to evaluate the atmospheric transport relationships and ecological effects required as inputs to the model. In some cases, this involved the use of other models (Balson et al. 1987). The selection of these experts, and the methods used for soliciting, translating, and implementing their judgments into the integrated model relied heavily on the expertise of the analysts conducting the study.

The ACIDRAIN model developed for the U.K. makes similar demands on the model user, though guidance again is provided through model defaults (Watson and Hope 1987). In contrast to the discrete probabilities employed in a decision tree, ACIDRAIN provides for continuous probability distributions of uncertain parameters. Thus, the relationship between overall costs and benefits also can be expressed as a probability distribution based on Latin Hypercube sampling. As noted earlier, however, the credibility of such results may be controversial since they depend strongly on personal judgments. Nonetheless, the uncertainty analyses afforded by integrated Level I models may demonstrate that certain factors are not significant to a particular outcome or decision, despite the uncertainty, or that certain assumptions are critical to the outcome and need to be resolved through targeted research. Thus, as a method of gaining insights into the importance of alternative factors and judgments, this type of integrated model can be especially useful.

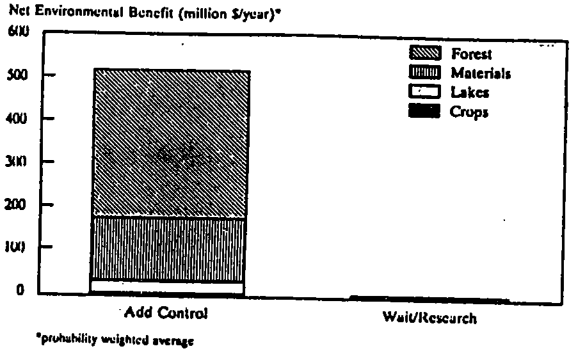
4.2 Relating Emissions to Environmental Effects. Current Level II models have physical, chemical or biological measures of effects as the end point of an integrated analysis. These measures serve as indicators of environmental risk or damage. Uncertainty is represented primarily by the analysis of alternative scenarios. Typically, these scenarios reflect different assumptions about future environmental emissions (or the factors responsible for them), or about environmental responses to changes in deposition (reflected in the structure and choice of environmental submodels and their parameters). The RAINS model has been extensively employed in Europe in this mode (Shaw and Alcamo 1988). In recent applications, several SO_2 emission scenarios have been formulated, and their implications for deposition levels, lake acidification, soil acidification, groundwater acidification, and direct forest impacts examined. Examples of model results are shown in Figure 3. Uncertainty is communicated via tables, graphs, and computer-generated maps onto which contour lines, bar graphs, shadings or colors are superimposed to compare different scenarios. The developers of RAINS also have extensively tested the sensitivity of submodel predictions to variations in input parameters which, in several instances, were represented probabilistically in stand-alone analyses outside the integrated framework (Alcamo et al. 1987).

The ADAM model developed for North America also employs scenario analysis to characterize uncertainty. In addition, ADAM employs a unique software environment (called Demos) specifically designed to facilitate the analysis of uncertainty (Henrion and Wishbow 1987). A non-procedural environment allows models to be easily constructed, altered, or replaced by models of a different form. Probabilistic treatment of model parameters also is available using Latin Hypercube sampling together with several standard or user-specified probability distributions. ADAM can thus propagate uncertainties through a chain of linked, science-based models coupling emissions to deposition and effects.

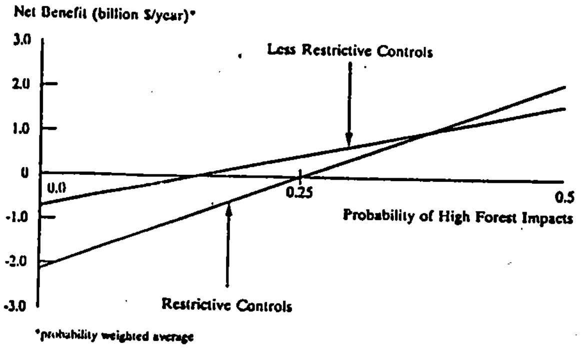
Fig. 2 Illustrative examples of the ADEPT model structure and cost-benefit results (Balson et al. 1987).



(a) Generic tree structure of ADEPT. Additional detail for each tree and for the linkage between emissions and effects is provided in the model.

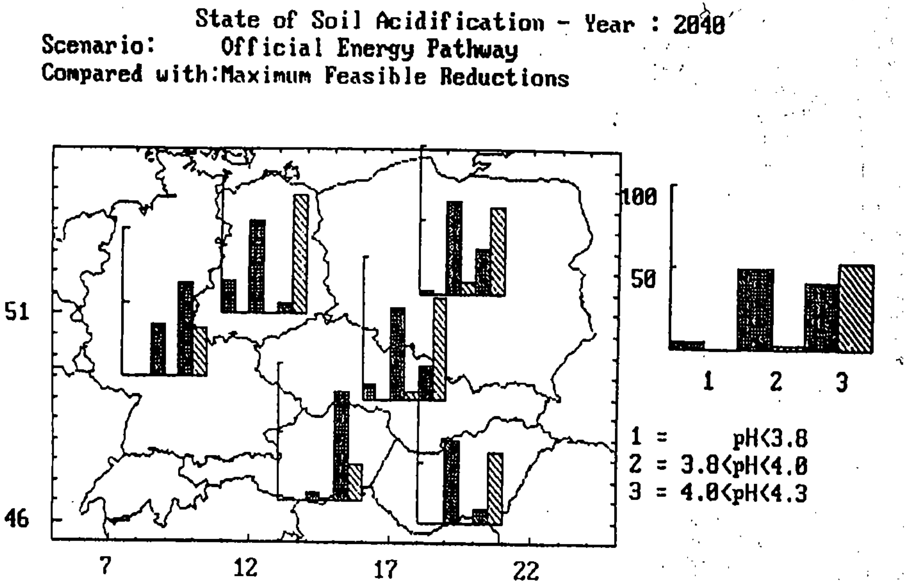


(b) Net environmental benefits compared to status quo. Figure shows net probability - weighted average benefits for two emission control scenarios.

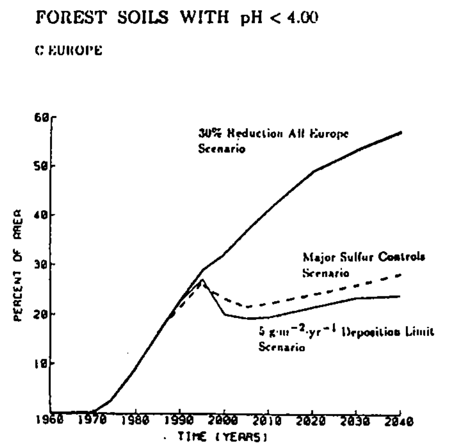


(c) Net benefit of two control strategies over wait / research. The sensitivity of net benefits to the uncertainty in forest impacts is illustrated.

Fig. 3 Illustrative example of the RAINS model analysis of forest acidification effects (Alcamo et al. 1987).



(a) Histogram of percentage area of forest soil pH within specified ranges in the year 2000; a comparison of the effects of two SO_2 emissions scenarios (maximum feasible vs. no reduction).



(b) Percentage of Central European forest soils with pH < 4.0 for three SO_2 emissions scenarios. Total geographic area considered is shown in Fig. (a) above.

Examples of the result obtained in this fashion are shown in Figure 4. In this analysis, two scenarios for future SO_2 emissions are compared, both of which are uncertain. One is a "base case" in the absence of new U.S. efforts to abate acid deposition. Uncertainty is introduced in assumptions about the future demand for electricity, the lifetime of coal-fired power plants, the future fuel mix for power generation, and other factors that affect SO_2 emissions.[3] The "acid rain control" scenario reflects recent Congressional proposals in the U.S. to reduce nationwide SO_2 emissions by 42 percent below 1980 levels. For simplicity, it is assumed that the emission reduction is fully implemented by 1995, leaving only an uncertainty associated with the magnitude of 1980 emissions. For each scenario, uncertainties in future SO_2 emissions from each of the 66 source regions are propagated through four subsequent models in which additional uncertainties arise: (1) long-range atmospheric transport; (2) precipitation acidity; (3) regional aquatic chemistry; and (4) potential fish viability. In all, uncertainties are ascribed to approximately 30 model parameters for each source-receptor pair (Rubin et al. 1987). Additional uncertainties arise if SO_2 control costs at the state level are also included in the analysis.

Uncertainty in model results can be expressed in a number of ways. One is by either a probability density function (PDF) or cumulative distribution function (CDF) for a quantity in a given year (e.g., the CDF of total sulfur deposition or regional lake alkalinity in 2010). Alternatively, the probability distributions for a particular scenario can be used to plot trend lines and specified confidence intervals, as illustrated for aggregate SO_2 emissions in Figure 4(a). Another useful way of displaying the consequences of a given scenario is to examine the *net change* in some environmental effect over the simulation period. Figure 4(b) illustrates such a result for the Adirondack Park region of the northeast United States. The figure also shows how uncertainties in individual model components contribute to the overall uncertainty in the number of lakes potentially able to support lake trout. A distribution function also can be developed for the *net difference between two scenarios in a given future year* when all model parameters except emissions are sampled probabilistically in an identical manner. For example, Figure 4(c) shows the net effect of the acid rain control scenario relative to the base case scenario on the percent of acidic lakes below a (user-specified) pH value of 5.5 in the year 2010. Not illustrated in Figure 4 is the additional uncertainty due to model form. For example, the source-receptor relationship used in ADAM can be an analytical model (as used here) or a transfer matrix of results from a Lagrangian model formulation. Were alternative models employed (including possible nonlinear formulations), results of the analysis would show a wider range of possible results.

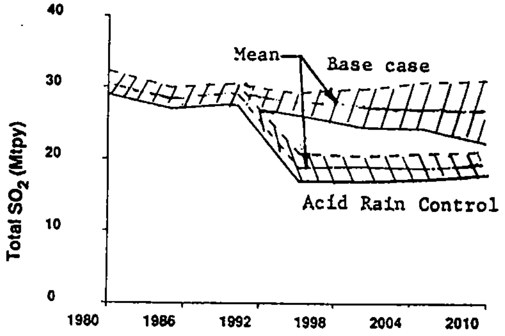
4.3 Achieving Target Deposition Levels. The concepts of "critical loads" and "target loads" have emerged as a basis for designing emission reduction strategies which achieve deposition levels judged to be protective of adverse environmental effects in a given region (Persson 1988). From the point of view of integrated modeling, this approach simplifies the problem considerably since effects and damage valuation models are not explicitly required. Now, the principal objective of integrated modeling is to identify efficient or cost-effective strategies for achieving deposition targets.

Among the models in Table 2, ADAM, BICRAM and RAINS are most well-suited for such analyses. Key uncertainties in the analysis of cost-effective strategies are the source-receptor relationships (including effects of meteorological variability), future emission levels, and emission reduction costs. Factors contributing to these uncertainties have been examined in

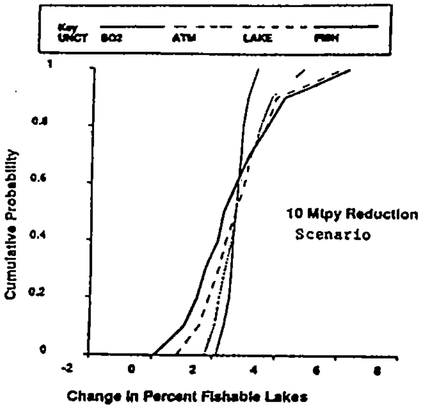
---

[3] An alternative formulation could analyze different base case scenarios individually. Here, a single probability distribution applied to the emissions from each source region is used to characterize uncertainty.

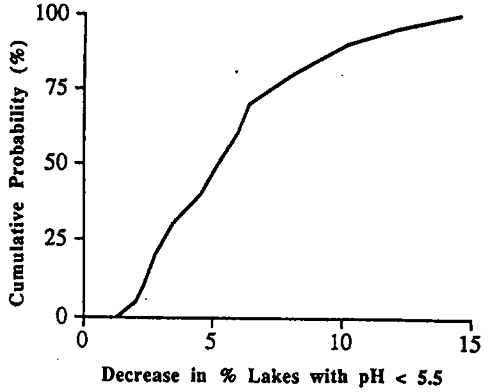
Fig. 4 Illustrative example of the ADAM model analysis of lake acidification effects (Rubin et al. 1987).



(a) North American SO_2 emissions for two scenarios, showing mean values and an 80 percent confidence band for each case.



(b) Net increase from 1980 to 2010 in fraction of lakes potentially able to support lake trout at Adirondacks Park. Figure shows cumulative probability and the contribution of each component model to the overall uncertainty for the acid rain control scenario.



(c) Net decrease in fraction of lakes below pH 5.5 in year 2010. Figure shows a cumulative probability distribution of the difference between the control and base case scenarios.

other studies (e.g., Streets, et al. 1985; Elliason 1986; Rubin, et al. 1986; Alcamo and Bartnicki 1987; Ellis 1989). Integrated models have the capability of quantifying these uncertainties using the methods discussed earlier.

An option in RAINS which permits optimization using deposition targets as constraints (Shaw and Alcamo 1988) can be especially helpful in finding efficient solutions in the presence of uncertainty (reflected by different scenarios). For Europe, BICRAM appears to offer the greatest detail in dealing with the dependence of future emission levels upon control technology, energy use and fuel choice uncertainties at the regional or national level (Laikin 1988). For the U.S., detailed estimates of SO_2 control costs as a function of emission reduction levels are available in ADAM for 18 scenarios representing alternative technologies, coals, and economic variables affecting costs for each state (Cushy and Rubin 1988). While the concept of target loads has not yet gained favor as a basis for national acid rain control policy in the U.S., some states (e.g., New York) have independently moved in this direction, and some modeling studies have been undertaken to characterize uncertainties for this type of strategy (e.g., Streets, et al. 1985; Ellis 1989). Canada also is exploring the use of integrated models to identify effective strategies for achieving target loads in the presence of uncertainty (Cohen 1989).

5. CONCLUSION

This paper has attempted to define and illustrate methods for characterizing uncertainty in integrated environmental models. The choice of methods was seen to depend significantly on the context of a particular investigation and on the computational complexity and design of the integrated model in question. The growing use of integrated models for environmental research planning, policy analysis, and regulation argues strongly for effective methods of characterizing uncertainty, and for conveying results in ways that promote insight and judgment about complex environmental issues and solutions. The use of probabilistic analysis can be especially effective in this regard, in conjunction with traditional methods of scenario analysis. The examples of integrated models for acid deposition also showed the benefits of a hierarchial approach to complexity, in which models of differing levels of detail can complement one another in the analysis of environmental effects, control strategies, policy decisions, and uncertainties.

ACKNOWLEDGEMENTS

I am indebted to Max Henrion, Granger Morgan and Mitchell Small for their helpful discussions and comments on this paper.

REFERENCES

Alcamo, J., et al. (1987). Acidification in Europe: a simulation model for evaluating control strategies. Ambio, 16, 232-45.

Alcamo, J. and Bartnicki, J. (1987). A framework for error analysis of a long range transport model with emphasis on parameter uncertainty. Atmos. Environ. 21, 2121-31.

Balson, W.E., Colville, G.R., Conner, K.K., North, W.D. and Spelman, J.R. (1987). Acid deposition: decision framework. Vols 1-5. RP 2156-1, Electric Power Research Institute, Palo Alto, CA.

Cohen, P. (1989). Environment Canada, Private communication.

Cooke, J.G., Chadwick, M.J., Kuylenstieerna, J.C., Laikin, R.E. and Weber-Cooke, G.B. (1987). Targetted abatement strategies for sulphur dioxide emissions in Europe. In: R. Perry et al. (eds). Acid rain: scientific and technical advances. Selper, London.

Cushey M. and Rubin, E.S. (1988). Simplified models of U.S. acid rain control costs. JAPCA, 38, 1523-27.

Eliassen, A. (1986). Source of uncertainty in Lagrangian long range transport model calculation. In: Quantifying Uncertainty in Long Range Transport Models, American Meteorological Society, Boston, MA.

Ellis, J.H. (1988). Acid rain control strategies. Environ. Sci. and Technology, 22, 1248-55.

Henrion, M. and Wishbow, N. (1987). Demos user's manual: version three. Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA.

Laikin, R. (1988). SO_2 and NO_x emission control: technologies and costs. Conference on Air Pollution in Europe: Environmental Effects, Control Strategies and Policy Options, Beijer Institute, Stockholm, Sweden.

McKay, M.D., Conover W.J. and R.J. Beckman (1979). A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics, 21, 239-245.

NAPAP (1989). Plan and schedule for NAPAP assessment reports. National Acid Precipitation Assessment Program, Washington, D.C.

Persson, G. (1988). The critical loads approach as a policy option to reduce transboundary air pollution. Conference on Air Pollution in Europe: Environmental Effects, Control Strategies and Policy Options, Beijer Institute, Stockholm, Sweden.

Rubin, E.S., et al. (1984). A conceptual framework for integrated assessments of the acid deposition problem. Final report to U.S. Environmental Protection Agency, Washington, DC, from Center for Energy and Environmental Studies, Carnegie Mellon University, Pittsburgh, PA.

Rubin, E.S., Cushey, M.A., Marnicio, R.J., Bloyd C.N. and Skea, J.F. (1986). Controlling acid deposition: the role of FGD. Environ. Sci. and Technology, 20, 960-969.

Rubin, E.S., Bloyd, C.N., Marnicio, R.J., Small, M.J., and Henrion, M. (1987). Atmospheric deposition assessment model: applications to regional aquatic acidification in eastern North America. In: Proceedings of IIASA Task Force Meeting on Environmental Impact Models to Assess Regional Acidification. International Institute of Applied Systems Analysis, Laxenburg, Austria.

Shaw, R. and Alcamo, J. (1988). Integrated assessment models for developing strategies for reducing regional acidification. Conference on Air Pollution in Europe: Environmental Effects, Control Strategies and Policy Options, Beijer Institute, Stockholm, Sweden.

Streets, D.M., Lesht, B.M., Shannon, J.D. and Weselka, T.D. (1985). Climatological variability: effects on strategies to reduce acid deposition. Environ. Sci. and Technology, 19, 887-893.

Watson, S.R. and Hope, C.W. (1987). ACIDRAIN: A model for analyzing the costs and benefits of pollution control. Final Report, Cambridge Decision Analysts, Cambridge, England.

Zadeh, L. (1965). Fuzzy sets. Simulation and Control, 8, 338-53.