International Congress on Environmental Modelling and Software

3rd International Congress on Environmental Modelling and Software - Burlington, Vermont, USA - July 2006

Jul 1st, 12:00 AM

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Noha Gaber

Pasky Pascual

Gary Foley

Neil Stiber

Elsie Sunderland

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Noha Gaber*, Pasky Pascual, Gary Foley, Neil Stiber, Elsie Sunderland,
US Environmental Protection Agency, Office of Research and Development
*Corresponding Author: gaber.noha@epa.gov

Abstract: Models have emerged as essential tools in environmental management, whether used to further the understanding of complex environmental processes or to inform decisions for environmental planning, remediation, protection or regulation. However, their utility aside, there is also an acknowledgment of their limitations. The question is not whether or not to use models, but rather how best to develop and use models to arrive at credible, defensible and robust decisions and what attributes make a model useful for a given situation. To understand the role of models and decision support tools in environmental management, we must first consider the different types of decisions made, particularly within a regulatory or policy-making context and the different decision-making contexts and processes. This paper will explore the requirements for effective model-based decision support as well as the role that characterizing and communicating uncertainty plays in influencing the utility of the use of models in environmental decision making. The paper will also build upon the recent work of the Council of Regulatory Environmental Modeling of the US Environmental Protection Agency to identify the major guiding principles for effective model development, evaluation and use to inform environmental management decisions and policy.

Keywords: *decision making; regulatory; model evaluation; uncertainty*.

1. INTRODUCTION

The nexus between science and policy, research and action generates continuous debate and discussion. In the complex world of environmental management and health protection, this discussion focuses on how the outputs of scientific research can be applied effectively to policy formulation and decision making. This paper elucidates potential measures to avoid the science/policy disconnect to achieve "better" decision support. By analyzing and integrating both the sides of the equation: the environmental decision making processes and the process of providing scientific knowledge to decision makers, we can improve decisions notwithstanding the inherent uncertainties in scientific knowledge.

As environmental models have become essential tools in the science arsenal, the analysis provided by this paper will focus on the US Environmental Protection Agency's (EPA) efforts to establish a protocol for the development, evaluation and application of environmental models to allow the development of robust and defensible environmental decisions and policies.

2. ENVIRONMENTAL DECISION-MAKING

Environmental systems are characterized by uncertainty, dynamic interactions and multiplicity of scales (Poch et al 2002). Often environmental management decisions must be made with uncertain facts, disputed values, high stakes and within pressing time-frames (Faucheux and Froger 1995). While developing these policies and decisions often relies on many forms of knowledge, including scientific knowledge, the culture of science that generates and analyzes the knowledge used by environmental decision makers is very different from the culture of politics that uses the resulting information for decision making (Engel-Cox and Hoff 2005). From the science perspective, a problem is identified, various hypotheses are tested, remedial policies suggested and implemented, then the situation improves (Pielke 2002). On the other hand, from the policy formulation and decision making perspective, the process involves integrating many sources of information, balancing the trade-offs between social, political and economic considerations, while maintaining accountability to different stakeholders (Tonn et al. 2000, Linkov and Ramadan 2002). Furthermore, scientific input into the decision making process does not necessarily follow a linear uni-directional course, but is an iterative process, with many inputs and feed-back loops. Recognizing the fact that science itself is not a monolithic entity (indeed it may be said that the different scientific disciplines speak different languages), it must be acknowledged that a successful exchange between scientists and decision makers requires greater communication and understanding of the requirements, limitations and processes of each side.

Engel-Cox and Hoff (2005) suggest that for scientific data to be successfully exchanged and used in policy formulation and decision making, it must meet a number of key criteria, namely: relevance, timeliness, clarity, integrity and visualization. Relevance relates to the policy-makers need for information that is focused on their area of interest. As policy decisions are often driven by time constraints related to statutory deadlines, timely information is that which is available to the decision-maker within the right decision-making timeframe. Clarity depends on clear and concise communication of factual scientific data, including limitations and uncertainties. The integrity of scientific information that is provided for use in decision-making, i.e., that it follows the principles of sound science and is applied in a transparent manner, is crucial to defensibility of the decisions. Visualization is another important attribute to allow decision makers to understand both the conclusions and uncertainties of the scientific information which may be used decision-making. Thus, based on these criteria, distilling scientific data and communicating key caveats and uncertainties are crucial aspects of meeting the needs of the decision making process in terms of providing timely, high quality and relevant information.

2.1 Modeling for Decision-Support

A model is a representation of the behavior of an object or process, often in mathematical or statistical terms (EPA 2003). With the promise they offer of describing or providing understanding of complex systems under current conditions or under envisioned future circumstances or scenarios, models have emerged as essential tools in environmental management. Oxley et al (2004) differentiate between two main categories of environmental models based on their origins. According to this classification, research models are those which originate in the problem-driven empirical or theoretical domains and are designed to advance understanding. Policy models are designed to provide reliable products useful in decision making (Oxley et al 2004, Pielke 2000). This predictive and decision support capability make models especially attractive to decision makers who are charged with the task of "formulating alternative courses of action extending into the future and selecting among alternatives by expectations of how things will turn out" (Fortin 2002). In decision support activities, the focus of a modeling exercise is typically on the response of a system to outside forces (external changes or policy changes) and the systems' performance (i.e. the resulting values of the outcomes of interest) in these future contexts (Walker et al.2003). Success of the modeling activity as measured by effective decision support relies not only on producing "good information" but by considering the context of the modeling exercise concurrently with the decision making process. Modeling for decision support is thus a three-part holistic process involving research, communication and decision making (Pielke 2000). These sub-processes are inter-related and take place in parallel with significant feedback among them. In essence, the success of model-based decision support relies on providing the right information, in the right manner at the right time. Pielke (2000) identifies three characteristics of model applications which are important for successful decision support: a model's accuracy and sophistication and the decision maker's experience in interpreting model predictions.

A model's accuracy is determined by its ability to correctly conceptualize natural processes. However, simply comparing prediction with actual events does not provide enough information with which to evaluate its performance. Because models contain simplifications of reality, model predictions will not correspond exactly with reality and can never be completely accurate. Additionally, "validated models" (e.g., those that have been shown to correspond to field data), do not necessarily generate accurate predictions of reality for multiple applications. Thus, some researchers assert that no model is ever truly "validated," though it can only be invalidated for a specific application (Oreskes et al., 1994). Furthermore, a model's appropriate use is directly related to the purpose or situation to which it is applied. This requires an understanding of the assumptions employed in developing the model and an appreciation of its limitations. This emphasizes the need for accurate documentation of the model development process. Documentation is also necessary during the model application stage. In the course of modeling, many choices must be made and options selected which may lead to biases in the model results (Kloprogge and van der Sluijs 2002). Documentation of this process and its limitations and uncertainties is essential to increasing the utility and acceptability of model outcomes. Additional criteria for successful model-based decision making are the degree to which model complexity is suited to the decision at hand and to which the model outputs may be translated into direct operational action. Furthermore, the time-scales involved in applying models must be suited to the decision time-scale.

2.2 Importance of Characterizing and Communicating Uncertainty

Uncertainty is a central characteristic of the complex and open environmental and human systems and consequently of the decisions that affect these systems. Failure to consider uncertainty can lead to less-than optimal decisions (Lowell 2004). Unfortunately, although it is widely held that decision makers are uncomfortable with uncertainty and expect scientists to provide certainty, decision-making under uncertainty is a fact of life and even with advances in knowledge, uncertainty may increase rather than decrease (van Asselt and Rotmans 2000). Due to the complex factors and driving forces inherent in environmental decision making, there is a risk that uncertainty is misused as a reason to preclude or delay action, where opposing scientific and/or political positions exist (IIASA 2002). Enhancing decision making will not come as a result of eliminating uncertainty, but by gaining a deeper understanding of the nature of the different types of uncertainties involved in the management of the environment. Walker et al. (2003) note that the scientists' or modelers' perspective of uncertainty varies considerably from that of decision makers. On the one hand, the modelers' view focuses on the accumulated uncertainties associated with the outcomes and robustness of the decision support exercise; on the other hand, the policy-makers' view includes how these uncertainties impact the outcomes of their decisions and on conflicting objectives, priorities and interests, i.e. goal uncertainty (Walker et al 2003, van Asselt and Rotmans 2000).

Varying degrees of uncertainty may be distinguished: epistemic uncertainty (incomplete knowledge or understanding) and inherent system variability. Furthermore, the level of uncertainty itself can never be known with absolute certainty, i.e. we do not know what we do not know (Pielke 2000). Walker et al. 2003 propose a matrix to conceptualize the different dimensions of uncertainty, based on:

- The location of uncertainty: where the uncertainty manifests itself within the model complex;
- The level of uncertainty: where the uncertainty manifests itself along the spectrum between deterministic knowledge and total ignorance;
- The nature of uncertainty: whether the uncertainty is due to the imperfection of our knowledge or is due to the inherent variability of the phenomena being described.

Within a modeling for decision support context, uncertainties arise within the modeling exercise itself and from the decision making process. Model-based uncertainties include (1) uncertainty in input data (whether from uncertainty in parameterizations or in the initial conditions); (2) uncertainty in model structure, completeness and choice of algorithms; and (3) uncertainty in model operation (Fortin 2002, van Asselt and Rotmans 2000). The decision making process is subject to another set of uncertainties related to goals the decision maker aims to satisfy (goal uncertainty), the alternative options which may be considered (action uncertainty) and the costs and benefits of those alternatives (yield uncertainty) (van Asselt and Rotmans 2000). Consideration of all these uncertainties is central to effective decision support. The aim is not to simply simulate all possible strategies and to estimate the costs and benefits of each. Rather, the aim is to assist decision makers in choosing and implementing the most robust strategies by providing information as to the potential consequences of an event and giving the likelihood/ probability of different events occurring (Lowell 2004).

3. BEST PRACTICES FOR ENVIRONMENTAL MODELING

3.1 Introduction

To achieve its mission and fulfill its regulatory duties, the EPA often uses models and their results to inform regulatory decisions. In 2000, the EPA established its Council for Regulatory Environmental Modeling (www.epa.gov/crem) in an effort to improve the quality, consistency, and transparency of EPA models. In January 2004, the EPA released two tandem products from the CREM. The *Draft Guidance on the Development, Evaluation and Application of Regulatory Environmental Models* (EPA, 2003), which provides recommendations for best practices for model development, evaluation, and use. The companion product, the Models Knowledge Base (EPA, 2004) is a web-accessible repository where this metadata about model development, evaluation, and use can be documented.

The *Draft Guidance* provides an overview of best practices for evaluating the quality of environmental models that is suitable for all users and contains appendices with technical information and examples that are intended for specific user groups. These principles and practices are intended to be generally applicable to all models that are used to inform EPA decisions, regardless of domain, mode, conceptual basis, or form (EPA, 2001). It provides recommendations and suggestions but does not create legal rights or impose legally binding requirements on EPA or the public.

3.2 Model Development

The *Draft Guidance* describes a four-step process for model development: (1) identify the issue(s) to be addressed; (2) develop the conceptual model; (3) construct the model framework (mathematical model), and (4) parameterize the model to build the application tool. Each step in this process provides opportunities for feedback and iteration. The principles of model development have been developed to complement the systematic quality assurance (QA) project planning for models that is outlined in existing EPA guidance (EPA, 2002a). The following points summarize the recommendations for model development:

- Present a clear statement and description (in words, functional expressions, diagrams, and graphs, as necessary) of each element of the conceptual model and the science behind it.
- When possible, test competing conceptual models/hypotheses.
- Use sensitivity analysis early and often.
- Determine the optimal level of model complexity by making appropriate tradeoffs among competing objectives.
- Where possible, model parameters should be characterized using direct measurements of sample populations.
- All input data should meet data quality acceptance criteria in the QA project plan for modeling.

3.3 Model Evaluation

Given the inherent uncertainty in the approximation of reality produced by models, model developers and users are faced with the challenge of determining when a model, despite its uncertainties, can be appropriately used to inform a decision. Model evaluation provides a vehicle for dealing with this problem. The *Draft Guidance* defines model evaluation as the process used to generate information to determine whether a model and its analytical results are of a quality sufficient to serve as the basis for a decision. In simple terms, model evaluation provides information to assess the following factors (after Beck, 2002a):

1. How have the principles of sound science been addressed during model development?
2. How is the choice of model supported by the quantity and quality of available data?
3. How closely does the model approximate the real system of interest?
4. How does the model perform the specified task while meeting the objectives set by QA project planning?

These four factors address two components of model quality: the intrinsic mechanisms and generic properties of a model and model evaluation in the context of the use of a model within a specific set of conditions. Hence, it follows that model quality is an attribute that is meaningful only within the context of a specific model application. Information gathered during model evaluation thus supports the decision maker when formulating decisions and policies that rely on the results of models.

As stated above, model evaluation seeks to ensure model quality. At EPA, the concept of quality is guided by the Information Quality Guidelines (IQGs) (EPA, 2002b). The IQGs apply to all information that is disseminated by EPA, including models themselves, input data, and model results. According to the IQGs, quality has three major components: integrity, utility, and objectivity. Objectivity comprises two distinct elements: presentation and substance. Presentation includes whether dissemination of the information is presented in an accurate, clear, complete, and unbiased manner and in a proper context. The substance element focuses on ensuring accurate, reliable, and unbiased information. These elements are emphasized in the *Draft Guidance* as part of the model evaluation process that addresses the questions listed above.

The proposed best practices emphasized in the *Draft Guidance* are: peer review (EPA, 2000) of models, QA project planning including data quality assessment, model corroboration and sensitivity and uncertainty analysis. In this guidance, corroboration is defined as a qualitative and/or quantitative evaluation of the accuracy and predictive capabilities of a model. Given the iterative nature of the model evaluation process, it follows that these qualitative and quantitative assessment techniques may be effectively applied throughout model development, testing and application.

3.4 Model Application

Model Application, (i.e., model-based decision making), is strengthened when the underlying science is transparent via: (1) comprehensive documentation of all aspects of a modeling project and (2) effective communication between modelers, analysts, and decision makers. This transparency encourages a clear rationale for using a model in a specific regulatory purpose. The *Draft Guidance* presents best practices and recommendations for integrating the results of environmental models into EPA decisions. Environmental models should provide decision makers with meaningful outputs and enable them to understand the modeling processes that generated these outputs. Decision makers need to understand the relevant environmental processes at a level that is appropriate for the decision of interest. In other words, decision makers should be empowered by being shown the inside of the "black box," as well as its outputs. Documentation enables decision makers and other users of models to understand the process by which a model was developed, its intended application niche, and the limitations of its applicable domain. One of the major objectives of documentation should be the reduction of application niche uncertainty.

3.5 Models Knowledge Base

The Models Knowledge Base is an inventory of environmental models. The contents of each model record are intended to include the types of information that are recommended by the *Draft Guidance* and that would be beneficial to prospective model users. In addition to an abstract and contact information for each model, it contains information about model use and model science. The Models Knowledge Base was developed in coordination with EPA's program offices and regions. The records in the Models Knowledge base include a spectrum, not a complete set, of models from EPA's various offices. The Models Knowledge Base can serve as a central repository, facilitate model selection, and provide pointers to the home pages for individual models. The modeling community is encouraged to provide feedback about the Models Knowledge Base and its models.

Inclusion of a specific model in the Models Knowledge Base is not an endorsement for its use. Models that do not appear in this Models Knowledge Base may also be appropriate for use. EPA recommends that models should only be used for the particular application for which they were designed and only after they have been appropriately evaluated. Decisions about the suitability of a specific model that is included in the Models Knowledge Base for a particular application should be made in consultation with experienced model users (viz. EPA staff, EPA contractors, or staff of other agencies), as necessary.

4. CONCLUSIONS

Models have demonstrated their utility in advancing understanding of environmental systems and processes and in providing information to support development of environmental management decisions. To further enhance their decision-support utility, model development and use must be viewed within the context of the model's proposed application. By developing a shared understanding of the decision making process, the role and limitations of model development and use in environmental management, and the inherent uncertainties associated with both processes, effective model-based decision support may be realized. A number of key recommendations may be distilled for both the modeling and decision making perspectives:

- Science and Modeling Context:
  - Understanding the decision making process and the role of models and other scientific data within it.
  - Understanding the objective of the decision making process and how model outputs are translated to operational action.
  - Developing scientifically sound models, which provide the appropriate level of accuracy and sophistication in a timely manner.
  - Greater transparency and documentation of model development, evaluation and application and communication of assumptions and limitations.
  - Characterizing and communicating model-related uncertainties.
  - Understanding impact of uncertainties on decision making process.
- Policy and Decision –Making Context:
  - Involvement in the modeling process and communicating requirements.
  - Understanding fitness of use of model and model evaluation.
  - Transparency in use of model outputs in decision making.
  - Experience of interpreting model results and understanding their limitations.

5. ACKNOWLEDGEMENTS

This paper is partially based on the EPA's *Draft Guidance on the Development, Evaluation, and Application of Regulatory Environmental Models*, a work-in-progress, which is currently undergoing external peer review by the EPA's Science Advisory Board. Although this paper was

reviewed by EPA and approved for publication, it may not necessarily reflect EPA policy.

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