Mathematical Models in Environmental Assessment

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FOREWORD

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Gwen Eisler assisted with the production of this final report.

EXECUTIVE SUMMARY

The lack of scientific rigour in environmental impact assessment (EIA) has been identified as a major problem (Beanlands and Duinker 1983; Canadian Environmental Law Research Foundation 1986). The solution clearly lies in the development and application of better methods for assessing impacts. The solution also lies in better utilization of existing tools, such as mathematical models. Where models have been applied, they have increased the scientific rigour of the assessment.

Benefits of Models and Modelling

Many benefits arise from the use of mathematical models simply because the quantitative information they provide is, in general, more useful than qualitative information. Another beneficial aspect of mathematical models is that they depend on an explicit conceptual model. If the underlying assumptions are not clearly laid out, a quantitative model cannot be constructed. Because assumptions must be made explicit during the process of modelling, they can be examined and critiqued. In disagreements over potential environmental impacts, it is highly desirable to have such an explicit framework for focusing discussions. A third aspect of mathematical models is their capacity to answer "what if?" questions. This makes quantitative models ideal tools for comparing alternatives and examining the importance of various assumptions.

Prediction and Other Applications

Most applications of mathematical models in EIA highlight the credibility of the quantitative predictions and the process of constructing and working with the model. Model predictions are important when the EIA is focused on

the accurate evaluation of specific impacts or in comparisons of different alternatives. In cases where different views need to be synthesized into an overall framework, the process of modelling is often more important than the predictive capabilities of the model; the participation of interested parties in model development can greatly improve the usefulness of a model.

Because of their predictive abilities, models are often used to provide a quantitative basis for impact predictions. In the case of air quality analysis, for example, models are used to make predictions about concentrations or loadings of pollutants for comparison against environmental quality standards. In another example, fisheries losses due to hydro-electric development, models are applied make direct predictions of effects. Because model predictions, like all predictions, are uncertain, they have often been downplayed or discounted in making the final analysis. Ironically, it is the predictive capabilities of models that make them so useful in other aspects of environmental assessment.

Conceptual models and conceptual modelling are very useful in the scoping phase of environmental assessment. Model building requires that the boundaries of the analysis be drawn and also forces decisions to be made about which components of the system will be the focus of the analysis. A well-designed conceptual model that links project activities with measures of impact provides a strong analytical framework for an assessment.

Mathematical models have proven their usefulness in evaluating alternative development scenarios. Once a model of the biophysical system and/or socio-economic system has been developed, different development scenarios can be simulated and their results compared. Different mitigation and remedial measures can be tested in the same manner. An exciting new application of models is in the statistical design of monitoring programs. By integrating a model that simulates the sampling and data collection process with the model of environmental system, the uncertainties and errors associated with monitoring can be examined. This allows the designer of the monitoring program to make informed decisions about the appropriateness of different sampling programs in relation to desired levels of confidence estimates of environmental changes.

Another interesting application is the role models can play in follow-up studies in environmental assessment. Follow-up studies are necessary if we are to assess the ultimate impacts and to evaluate the quality of impact assessments. Often the quantitative predictions of models are the only reliable data sets upon which to assess the accuracy of impact predictions. Thus, models will likely become increasingly important in follow-up studies.

Case Studies

An earlier report (de Brossia 1984) produced for the Canadian Environmental Assessment Research Council (CEARC) discussed many current and potential applications of modelling in EIA with particular emphasis on the application of physical models to problems of pollution control and abatement. The terms of reference for this study were designed to extend CEARC's review of the use of mathematical models to five subject areas not adequately addressed in the earlier report: socio-economic impact assessment, biophysical impact assessment (subdivided into air, water, and ecological), toxic chemical assessment, technical risk assessment, and health risk assessment. The case studies, which provided empirical evidence on the application of models in environmental assessment, span these five subject areas and are briefly described in the following paragraphs. Each case study provided insights into how models were and might be used.

In applying the North Dakota Economic-Demographic

Assessment Model to the Fort Union Coal Project, the modelling was integrated into the Bureau of Land Management's public information program. In this process, the model was designed to be responsive to economic issues identified during consultations with the public, interest groups, and government agencies. Bureau of Land Management staff concluded that using the model in the initial stages of assessment allowed for explicit statements of definitions, data needs, and assumptions. This allowed the assessment to focus on the major issues.

The Buoyant Line and Point Source Model was used to predict the pollutant dispersion pattern of fluoride emissions from aluminum reduction plant proposed for Vanderhoof, B.C. The main purpose of the model was to determine the aerial extent and location of potential effects to vegetation. The results of the model were to be used (the project was cancelled) in negotiations to determine the size of the buffer zone needed around the proposed facility.

In the Wreck Cove Hydroelectric Project in Nova Scotia, a simple temperature-oxygen model was applied to help define final project design and operation options. A subsequent follow-up study on the predictions made in the environmental assessment documents pointed out the need for post-operational monitoring studies to confirm, calibrate, and validate models.

The long history of applying models and modelling to the issues surrounding the Hudson River controversy provides many insights into the use and abuse of models. One important observation is that the issue of fish mortality was not resolved until theoretical models were abandoned in favour of simpler, empirically-based models.

The EXAMS exposure assessment model was applied to a field test of the dispersion of a detergent chemical in a municipal waste-water system. This example pointed to a significant level of uncertainty associated with the model's predictions. As a consequence, it is doubtful that a realistic assessment of the ecological effects could have been made.

The risk of an oil spill associated with each component of the proposed production and transportation system for the Beaufort Sea Proposal was evaluated through the use of several models. In applying formal technical risk assessment methods to provide a numerical estimate of risk, there was considerable disagreement about the appropriateness of the models and the basic assumptions used. In the end the conflict was resolved during the Environmental Assessment and Review Process hearings through a highly simplified joint statement of the contending parties.

An environmental pathways analysis was used to assess the regional radiological impact of uranium mining and milling activities in Northern Saskatchewan. A number of different types of models were integrated to conduct a cumulative impact assessment of the radiological dose to human and biota. The resulting predictions were characterized by a great deal of uncertainty due mainly to the complexity of models, lack of site specific data, and nature of the cumulative impact assessment methodology.

Recommendations for Research

The recommendations are organized into three major groups: those concerned with consolidating existing best practice; those of a scientific and technical nature; and those of an institutional nature. The first set of recommendations are directed towards developing a knowledge base that will allow EIA practitioners to make informed decisions about models, such as which models (if any) should be used, and when and how they should be applied. The scientific and technical recommendations are directed towards difficult problems with regard to the inputs, outputs, structure, and integration of models. The institutional recommendations deal with the use of models as tools for communication, negotiation, and coordination. The institutional recommendations also address problems of model misuse and barriers to successful application.

Information needs to be consolidated on existing best practice regarding the use of models in environmental assessment. This consolidation should take place through:

- the development of a comprehensive framework for classifying past and potential applications of models and modelling as to model type, the application area, and phase of EIA process to which the model applies;

- studying modelling strategies previously used to coordinate large environmental assessments or research programs, and using the results of such studies to design a procedure for developing future modelling strategies; and

- the development of an expert system for prescribing the details of a modelling strategy for an environmental impact assessment.

A number of scientific and technical problems need to be resolved. These should be addressed through:

- a study to demonstrate how the data input needs of a model could be used to direct the data needs for the environmental assessment;

- a study to establish a set of validation standards for commonly used models in EIA;

- encouragement by CEARC of research programs that directly relate to improving the scientific understanding underlying each of the scientific disciplines which support EIA (special encouragement should be given to researchers who are using models and modelling as part of their research);

- a study to investigate the technical feasibility of constructing integrated interdisciplinary models for EIA; and

- an analysis of a case where an integrated set of models have been used in environmental assessment.

Improvements leading to more effective use of existing models, and scientific and technical solutions, will not be worthwhile without improving the institutional arrangements regarding model acceptance and use. A institutional analysis should be carried out to ascertain: how current formal environmental assessment institutions (e.g., FEARO, NEPA) affect the quality and potential application of models, and how institutions are affected by the use of models.

More specific institutional questions need to be addressed through:

- a study employing institutional analyses to better understand how to merge models into the institutional environment;

- a study conducted to determine the extent and seriousness of misuse and misinterpretation of model results in the context of environmental assessment;

- a study conducted to investigate how models and modelling can productively bring substantive information to bear in resolving environmental conflict;

- a study to evaluate the utility of existing procedures, which are based on modelling, to integrate and coordinate environmental assessments; and

- a study to both assess Canadian capabilities to undertake modelling in EIA, and investigate the costs and benefits of increasing the use of models in EIA.

1.0 INTRODUCTION

This report, prepared for the Canadian Environmental Assessment Research Council (CEARC), is the second of two reports addressing the use of mathematical models in environmental impact assessment (EIA). The first report (de Brossia 1984) reviewed the current and potential application of modelling in EIA with particular emphasis on the application of physical models to problems of pollution control and abatement. Although de Brossia provided an excellent review of this topic, his report neglects other types of model applications in EIA. Therefore, this study focuses on five categories of problem areas given incomplete treatment in de Brossia's study: socio-economic impact assessment; biophysical impact assessment; toxic chemical assessment; technical risk assessment; and health risk assessment. This final report provides some background to the topic, in the way of a general overview and analysis of case studies, as well as a set of recommendations regarding the use of mathematical models in EIA.

Each of the five categories represents a specific problem area, with unique modelling tools, within EIA. The structure and use of these models reflect different levels of scientific understanding of issues in the various categories. There are, however, some general aspects of modelling and model classification that apply to all problem areas. These principles are presented in Chapter 2 of this report (Background) and discussed with respect to the various phases of EIA.

Although modelling proponents often emphasize the predictive capability of models in EIA, models have also been used for other purposes. In Chapter 3, the use of models in evaluating alternatives, design of monitoring programs, mitigation planning, and follow-up and validation studies is discussed.

The methods used in developing the background material and, ultimately, in writing this final report are detailed in Chapter 4. An integral part of this study was a critical evaluation of the working report at a workshop. The workshop participants are listed in Appendix 1. Their suggestions and enthusiasm contributed substantially to the improvements made to that report.

It was not the intent of this study to comprehensively review the state-of-the-art of mathematical models in the defined categories. Nevertheless, to better understand the usefulness of quantitative models, Chapter 5 presents a brief overview of some environmental issues which have been the focus of modelling activities and the general structure of the models that have been applied. Each of the above five categories is discussed.

The primary interest of this study is an analysis of the <u>use</u> of models in EIA, not a description of the models themselves. To provide an empirical basis for this analysis, a number of cases studies (spanning all five categories) are presented in Chapter 6. Each case study provides insights on the role and application of models in EIA. While the lessons drawn from the case studies may be somewhat subjective, they raise important questions about the usefulness of mathematical models in environmental assessment.

Recommendations for research (Chapter 7) fall into three groups: those concerned with consolidating existing best practice; those of a scientific and technical nature; and those of an institutional nature. The recommendations with respect to consolidating existing best practice are directed towards developing a knowledge base that will allow EIA practitioners to make informed decisions on model use. EIA practitioners will have the necessary information to decide which models (if any) to use, and when and how they should be applied. The scientific and technical recommendations are directed towards difficult problems with regard to model inputs, model outputs, model structure, and integration of models. The institutional recommendations deal with the use of models as tools for communication, negotiation, and coordination. The institutional recommendations also address problems of model misuse and barriers to successful application.

2.0 BACKGROUND

The practice of environmental assessment relies heavily on expert, judgement aided by an assortment of analytical tools. Whileothers might choose a different classification, Shopley and Fuggle (1984) identified eight analytical approaches: ad hoc; checklists; matrices; networks; overlays; modelling procedures; evaluation; and adaptive. All approaches, with the exception of the first, attempt to systematically structure problems so they are more amenable to scientific analyses. In contrast, "pure" expert judgement, a type of ad hoc analysis, is characterized by a process of assessment that can never be duplicated because the conclusions of each expert are based on a unique combination of experience, training, and intuition. In some assessments, unfortunately, this is the only required or possible approach. In other instances, when more rigorous scientific methods are available, it is often unwise to rely only on expert judgement.

In more systematic approaches, the experts first articulate an analytical structure or conceptual model of the problem. The conceptual model may take the form of a cross-impact matrix, a fault tree, a box and arrow diagram describing energy flow, or it may simply be a set of statements describing the system under study. In all cases, the relationships or linkages between various parts of the system are identified. Conceptual models are widely accepted and provide excellent means for explaining the interrelationships in complex systems.

While conceptual models are a necessary first step in any analysis, they are basically limited to indicating that "X" will affect "y", or to asserting that activity "a" will cause a minor, moderate, or major impact on species "y". More sophisticated conceptual models use box and arrow diagrams for illustrating relationships between system variables. Such diagrams (if not overly complex) are very useful for thinking about the system of concern, and deciding what should be included in more detailed analyses (perhaps with mathematical models). For this reason, box and arrow models can be very useful in the early phases of an EIA, when the terms of reference are being formulated and the problem is identified. To move beyond this level of analysis QUANTIFICATION is necessary. To quantify, the conceptual model must be formulated as a mathematical model.

Mathematical models are similar to conceptual models in that they are both abstractions or simplifications of the system of concern. The simplest mathematical models used in EIA are single relationships between two variables, where the independent variable (the "x") is a measure of some human activity (e.g., phosphorus input to a lake), and the dependent variable (the "y") is a measure of impact (e.g., concentrations of algae in the lake). Though only a single equation, the quantitative relationship between phosphorus and algae provides much more information concerning the magnitude of potential impacts than does the conceptual model "increased phosphorus inputs lead to increased algal biomass". Also, such an equation has potentially greater credibility than its conceptual analog, because the equation's parameters and variables can be based on a statistical analysis of empirical data. For mathematical models that consist of a single equation, the key "structural features" are the shape of the curve that represents the linkage between "x" and "y", and the strength of the empirical data at different points along the curve.

Simple mathematical relationships can be used directly in many areas of impact assessment (e.g., dose-response curves linking exposure to carcinogens with the probability of contracting cancer) or can form the building blocks of more complex models, consisting of sets of equations (e.g., economic-demographic models used in socio-economic impact assessment). As the number of mathematical relationships, particularly non-linear relationships, increases in a model, the tools required to compute predicted outcomes must become more sophisticated. The analyst either resorts to relatively sophisticated mathematical approaches (e.g., solving several differential equations), or constructs a computer simulation model which uses computational power to work through the consequences of a large number of relatively simple equations connected together.

Mathematical models vary in many respects. Reckhow and Chapra (1983) provided a convenient set of criteria for classifying models:

- Empirical or mechanistic. Empirical models, like the phosphorus-algae example above, are based ". ..more on fitting a set of data and less on theoretical principles" (Reckhow and Chapra 1983). Mechanistic, or theoretical, models are the converse. They describe, in a mathematical form, the theoretical principles which govern a particular system. Examples of theoretical-mechanistic models are ecological population dynamics models and chemical fate models that take account of biochemical processes. Though good models have both empirical and mechanistic features, most can be classified as being either fundamentally empirical or theoretical.

- Simulation or optimization. Simulation models describe the function of a system in such a way that the model can predict the system's response to many different scenarios or assumptions. The set of responses are then examined to assess potential impacts. Optimization models are used to find a solution that is best (either the minimum or the maximum) of some predefined function. The best solution is usually constrained by such considerations as cost or environmental quality.

- Static or dynamic. Static (or steady-state) models describe time-independent behavior. Usually the predicted state of the system is that which the system would ultimately reach assuming no other perturbations. Dynamic models describe how the behaviour of the system changes through time.

- Lumped parameter or distributed parameter. This criterion is the spatial analog to the static-dynamic classification of time dependency. Lumped parameter models are "zero dimensional" in that they assume uniform conditions throughout the modelled system (i.e., space-independent). Distributed parameter models are structured to allow variable conditions in one or more spatial dimensions (i.e., space-dependent).

- Deterministic or stochastic. This criterion differentiates between models on the basis of the variability incorporated into the inputs and outputs of the model. Deterministic models assume zero variability - they use a single expected value for each input parameter and variable and produce a single expected prediction. Stochastic models represent parameters and variables as probability density functions, thereby potentially incorporating measured variability and/or uncertainty due to measurement error. The predictions of stochastic models are also probability density functions.

These criteria are not entirely independent. For example, dynamic descriptions of complex systems almost invariably require computer simulation models, particularly when some processes in the system are discontinuous.

The types of models discussed in the case studies of this report fall along a gradient or continuum from empirical to mechanical or theoretical models. In undertaking this review, it was not practical or desirable to catalogue or review all existing models that fall along the continuum. The approach taken was to discover applications of models that represent different points along the full range of the continuum. For example, the case studies range from environmental pathways models in health risk assessment to an ecological process model of the effects of power plants on striped bass in the Hudson River. It is interesting to note that the issue at stake in the Hudson River case was only resolved after the detailed process models were abandoned for simpler empirical models.

Keeping in mind the above discussion of conceptual, mathematical, and computer simulation models, we now briefly examine their role in EIA. Through questioning the benefits and problems of using models, we try to uncover, in a general sense, how models function in this context.

2.1 Should Models be Used in Environmental Assessment?

The answer is yes. There was unanimous agreement among the workshop contributors to an evaluation of the EIA process in Canada (Beanlands and Duinker 1983) that modelling was a useful and appropriate scientific tool.

2.2 What are the Potential Benefits?

Duinker (1985) summarized many benefits which may be derived from using models in environmental assessment:

- stating assumptions explicitly;
- developing and testing impact hypotheses;
- identifying information gaps to structure further information gathering;
- rigorous detailing of system components and their relationships;

- compiling and organizing data;
- organizing concepts and ideas;
- predicting impacts;
- estimating confidence coefficients of predictions;
- identifying and testing mitigation measures:
- providing a means for communication and education; and
- providing a forum for interdisciplinary cooperation.

Actually, many of these benefits are a result of the modelling process and not, strictly speaking, of models themselves. Successful development and testing of mathematical models, however, increases the likelihood of deriving the above benefits.

Increased communication is probably the most commonly observed benefit when all actors participate in the modelling process. The process of developing a quantitative model forces communication between various disciplinary experts and potential users of the model. Projects involving a high degree of effort in communication between the modeller and the decision maker are often the most successful. For example, in an application of an air quality model in the United States, the modellers participated in meetings, were constantly available for questioning, and the model was well-documented so others could understand the process of model development (Dennis 1982).

Quantitative modelling can also improve the clarity of an analysis in an EIA. One wide ranging effect of modelling is making the assumptions of the analysis explicit. Without an emphasis on quantification, an opportunity to clarify assumptions might never occur (Dennis 1982).

Finally, quantitative models are often the only scientifically defensible predictive tool available.

2.3 What are the Problems?

> "Despite academic preoccupations with numerical indices and their sophisticated manipulation [in mathematical models], managers and decision makers have difficulty in relating to them and incorporating their information content into rational action in the decision making process." (Hirst 1984).

All models have some degree of uncertainty; consequently, judgement is required in interpreting the results of modelling. This implies that the model's assumptions and data validity should be checked (Dennis 1982). Some models produce a single numerical value, with no sensitivity analysis. Although the decision maker's task is easier, there is less opportunity for the assumptions to be evaluated for accuracy or relevance. With new projects in new geographic areas there may be insufficient data for input into predictive models (Miller 1983).

Quantitative models are valuable for predicting effects of pollutants, but are less reliable for predicting general ecological impacts. Therefore, it is worthwhile considering the expectations concerning the purpose of modelling in impact assessment (Beanlands and Duinker 1983). Beanlands and Duinker (1983) also found models were used sporadically in EIAs they reviewed. This could be a result of uncertainty at both the technical level and, with respect to the utility of models, at the decision making level.

An emerging problem is an over-reliance on models that have become generally acceptable to both the decision makers and technical experts. As they grow more familiar with a model, there is a tendency to be less critical of the model's limitations. In addition, widespread use of these models usually creates a resistance to change which may inhibit improvements in our analytical capabilities and **may** lead to neglect of aspects of the problem not addressed by the model. One might suspect that this acceptance may contribute to the fact that few models are evaluated, documented, or subjected to hindsight review.

Arthur C. Clarke, the noted science fiction writer, once said that **any** sufficiently advanced technology is indistinguishable from magic. This principle often appears to apply to the responses of people unfamiliar with computers or with the predictions of computer models. The responses of such people to computer models parallels individual responses to magicians; that is, varying from wonder to healthy **skepticism** to deep suspicion and fear. For some, the mystique of the computer may lead to unwarranted confidence in the predictions of mathematical models. For others, any model hidden inside a computer is assumed to be driven **by** sleight of hand and is fundamentally not worthy of their trust.

2.4 <u>What Types of Models Should be Used in EIA, and When?</u>

The most appropriate choice of model (or modelling strategy) for an EIA is a difficult one. At least two factors come into play in deciding what type or types of model are preferred:

- the amount of scientific understanding and data available to analyze the issue; and

- the level of confidence in predictions required to successfully resolve the issue (often related to the contentiousness of the issue).

Both factors vary with the stage of the EIA and with the type of project under consideration. As the EIA progresses, understanding generally increases, and issues become more focused, requiring increasingly more accurate predictions for'a narrower set of questions. Therefore, the model (or models) used in the EIA should change with each stage of the assessment process. Models and modelling have differing roles to play in each of the scoping, assessment, and implementation phases of EIA.

2.4.1 Scoping

In general, scoping involves: identification and analysis of issues; preparation of a project description; setting boundaries on the geographical scale of impacts; determination of the period of time over which impacts are to be projected; and preliminary identification of the major components of the social, economic, and ecological systems that might be impacted.

Conceptual box and arrow models are particularly useful during the scoping phase of an EIA for organizing and synthesizing information for further analysis.

2.4.2 Assessment

In most cases, a formal assessment involves: description of the existing environment (baseline information); detailed description of the project; prediction of effects; assessment of the significance of the effects; design of mitigation measures designed to ameliorate the effects; determination of the net effects of the project after mitigation; design of monitoring programs to determine the actual effects and success of mitigation measures; and assessment of remaining uncertainties with respect to the effects.

Models are most frequently applied in the assessment stage of EIA for the prediction of effects. Models are also potentially very useful for evaluating alternatives, evaluating alternative mitigation measures, and designing environmental monitoring programs.

2.4.3 Implementation

Once a project is approved, a number of environmental management programs are usually implemented. These programs include: routine surveillance to ensure compliance with set terms and conditions; monitoring of the actual effects to allow operational changes to be made to mitigation and compensation measures; provisions for research, experimental management, or demonstration projects; and audits and evaluation to maximize the use of new information, which is usually gained at considerable expense.

In addition to their role in the design of monitoring and mitigation, models can be used in follow-up and post-audit studies to interpret the results from these programs.

3.0 ANALYTICAL TOOLS IN ENVIRONMENTAL ASSESSMENT

Models, as analytical tools for environmental assessment, give the assessment a more systematic and scientific basis. As noted in the previous chapter, they are used for various purposes in different aspects of the assessment process: to make quantitative predictions, as analytical frameworks, and for synthesizing and manipulating data. In this chapter we illustrate how models can specifically be applied to scoping, evaluating alternatives, evaluating mitigation measures, design of monitoring programs, follow-up and post-audit studies as well as the prediction of impacts.

3.1 Scoping

Conceptual models and the process of modelling can be used effectively during the scoping phase of an EIA when the terms of reference are formulated and the problems are defined. The informal input of regulators, the proponent, experts, and the public are easily incorporated into such models. Both quantifiable and non-quantifiable impacts can be represented, and the overall synthesis of issues in such models helps to bound and focus the problem. Examination of a detailed conceptual model by experienced experts helps to determine which issues can be addressed by quantitative models, and which must be addressed by other methods. The conceptual model thus forms the foundation for the modelling strategy adopted during the EIA. A well-defined conceptual model has the potential to become the basic analytical framework for the overall EIA.

3.2 Prediction

Mathematical models are often used as tools for the prediction of environmental impacts. Perhaps the most common application is in evaluating whether effluents and emissions meet air and water quality standards. In these cases there is no direct assessment of biophysical impact; rather models make predictions of pollutant concentrations or loadings for comparison with established standards. In other applications (e.g., assessing ecological impacts), models make predictions of actual effects. Ecological models of fish and wildlife populations are good examples.

Ideally, predictive models should be both calibrated and validated. Calibration involves selecting the best values for the parameters used by the model. It is usually performed by varying the parameters until some measure of the difference between predicted and observed conditions is minimized. Validating the model involves testing predictions on a set of data different from that used for calibration. Models applied at this stage, particularly within relatively well-understood subject areas such as hydrology, may be sufficiently well-calibrated and validated to provide quantitative predictions with confidence.

However well validated and calibrated a model may be, its predictions will always have a degree of uncertainty associated with them. Because of this, the predictive results of models have often been discounted or ignored in making final assessments of environmental impacts. It is the predictive capabilities of models, however, that make them especially useful in other aspects of environmental assessment.

3.3 Evaluation of Alternatives

In some EIAs there is an explicit need to evaluate alternatives and models have been shown to be invaluable tools for this purpose. In this application, a model should be capable of generating predictions that allow for a confident separation of reasonable and unreasonable alternatives, based on a wide range of criteria. Generally, the accuracy and precision of model predictions need not be very great, though predictions must obviously be credible to be useful. Gaming with a model at this stage is very important for developing communication between the proponent, regulators, and modeller. The proponent learns new constraints on the project design; regulators learn new system interactions (which often imply a different planning or management strategy); and the modeller learns what forms of model output are of greatest interest, and', therefore, critical to future modelling efforts. If the problem is very poorly understood and lacks data on most components, it may be better not to model at all, but rather to expend efforts on gathering basic information to describe the system and select feasible alternatives.

Gaming with models is also useful to assess trade-offs when evaluating alternative project configurations. Because models only include estimates of the expected changes in quantifiable variables, however, impacts for qualitative variables (e.g., most social and cultural values) must be inferred by careful contemplation of predicted scenarios with the people potentially affected. At the evaluation stage it is therefore important to return to the box and arrow conceptual model, identified at the beginning of the EIA, which usually includes non-quantifiable components of the system.

The analysis and evaluation of alternatives should always include an assessment of the uncertainty in model predictions, to allow full recognition of uncertainty by the decision makers who select the preferred option. For simple models, the uncertainty in model predictions can be quantified using pencil and paper methods, such as first-order analysis. In first-order analysis (Reckow and Chapra 1983), error estimates are based on first order Taylor series expansions of the mathematical functional representation of the model. The Taylor series approximation is taken about at the mean values for the independent variables. This allows an assessment of the error contribution of the independent variables to the total prediction error.

Estimating the uncertainty of more detailed models requires computer-intensive methods such as Monte Carlo analysis. In this analysis, the model is run hundreds of times, with the values of uncertain parameters randomly varied according to their known or suspected probability distributions. The probability distribution of predictions reflects the aggregate uncertainty in the model. As models become increasingly complex, uncertainty analysis becomes difficult and expensive, and for very large models, impossible. Parsimony in model construction is, therefore, very important.

3.4 Design of Monitoring Programs

The experimental design of monitoring programs, an often neglected area of environmental assessment, can benefit from modelling. By incorporating the observed or estimated level of natural variation into the model, the designer of the monitoring program can quantitatively determine the appropriate level of intensity of sampling to detect effects of a given magnitude. For many ecological issues, the paucity of pre-development data means that no amount of post-development monitoring will be sufficient to detect project impacts. The design of the monitoring program should also include consideration of the potential for adaptive management of the project, should negative impacts occur. Dynamic system models can help to assess how quickly the system will be able to respond to corrective actions, and, therefore, orient managers towards effective post-development management.

In applying models to examine the statistical design of a monitoring program, the following analytical steps are normally undertaken:

- a simple theoretical mathematical model (usually a simulation model) of the system under study is developed;

- the level of natural variation associated with different environmental components is added to the model; and

- then an error structure to account for observation error is included in the model.

This model can then be used to generate time series data for statistical analysis. Two time series data are generated: a baseline that represents what would have occurred if the source of the potential impact had not been present; and a case where the system has undergone the simulated impact. A given model scenario requires assumptions about the level of natural variation in important environmental components, the amount of observation error associated with the time series to be generated, and the magnitude of the direct impact on the system. For a given scenario, a Monte Carlo simulation is usually performed to generate a distribution of outcomes.

The resulting synthesized data sets are assumed to include both natural variation and observation error. Statistical analysis of these data requires the specification of an appropriate statistical model or test. In determining the appropriate monitoring program, the level of statistical certainty (confidence level), the magnitude of the change to be detected, and the proposed sampling program need to be considered. The following questions can be addressed:

- Given a confidence level **'x'** is required, and the sampling program is **'y'**, how large must a change **'z'** be before it can be detected; or

- Given a confidence level of **'x'** is required, and a change of **'z'** is to be detected, what is an appropriate sampling program?

- Given a sampling program **'y'**, and a change of **'z'** is to be detected, what is the confidence level?

3.5 Mitigation Planning

Models are potentially very useful for evaluating mitigation measures. If the estimated costs of mitigation are very high, however, a great deal of empirical support (compelling evidence) is required to back up model predictions. In the case of the Hudson River controversy (discussed in Section 6.5), it took over a decade to develop an acceptable level of empirical support for model predictions.

The use of models in mitigation planning is relatively straightforward. It is simply a process of comparison of a number of different alternatives. First a model of the system under study is constructed. This model has to represent the causal basis for impact in enough detail to allow for discrimination between alternative mitigation measures. Then the results of the model are determined with some baseline development scenario. At this stage the model can be used to ask "what if" questions about the effectiveness of mitigation measures. By comparing the model predictions with and without various mitigation measures the potential effectiveness of mitigation measures can be assessed.

Examples where models might be used in assessing mitigation measures include: assessing different flow regulation regimes associated with hydroelectric development, evaluating habitat enhancement, and comparing different control strategies for emissions and effluents.

3.6 Follow-up and Validation Studies

Follow-up studies on environmental assessments are necessary to determine actual impacts and assess the accuracy of environmental impact predictions. Follow-up studies concerned with the latter have often encountered problems with auditing predictions because of the manner in which the predictions were made. Predictions from quantitative models are readily audited, however, because these models require explicit statements of assumptions. In many cases, models provide the only quantitative estimates of impacts and, as such, their results represent the only auditable data-sets on predictions. Comparison of results from follow-up studies with model results, while a form of model validation, can also provide information on the success or failure of the overall environmental assessment.

The degree to which mathematical models are used in an environmental assessment is a function of the credibility attached to the model. Credibility is in part related to the validation studies that have been performed on the model to confirm the models' predictions. In many applications in environmental assessment, models are poorly calibrated and validated. The results of monitoring programs could be used to test and amend the model. Opportunities to validate models are often lost, however, due to lack of planning or interest in the collection of follow-up data. After the environmental assessment is complete, there seems to be little incentive to collect information on the actual impacts. This information would be invaluable in assessing the predictions of various models. The supplemental investment in testing and updating the model would pay dividends both in environmental management of the existing project and in the design and assessment of other future developments of a similar nature.

Model predictions provide good data-sets for follow-up studies concerned with evaluating the accuracy of predictions in environmental impact statements. Data collected in follow-up studies or monitoring programs, if directed by the structure of the model, could be used in model validation studies.

4.0 METHODS

This project proceeded through five interrelated stages: a literature search and survey of experts, a case study analysis, a working report, a review workshop, and the final reporting.

4.1 Literature Search and Survey of Experts

In the initial stages of investigation, the CAN/OLE (National Research Council of Canada) computerized information system was used to find relevant documentation on the use of models. We searched three databases, BIOSIS, ELIAS (Environment Canada library), and NTIS (U.S. government documents), with little success. The limited number of documents uncovered were either technical manuals for running the models, theoretical discussions of model structure, or the actual environmental impact statement (EIS), in which the results of modelling were a small part. We also reviewed a small part of the literature, available at local university libraries and in our own library, on modelling in each of the application areas.

Because the literature search provided little information on model use, we relied on personal communication to identify suitable examples of the application of models in environmental assessment. A list of people surveyed for information is provided in Appendix 2.

4.2 Case Study Analysis

The main thrust of our early efforts was to identify a set of case studies where models had actually been applied. Two criteria guided early efforts: the model had to be used in the context of a formal assessment process; and it had to be a computer model. These criteria excluded many interesting and informative applications and had to be modified. In the end, we used the following two criteria: the model had to have been applied; and it had to fall within the application areas defined by the terms of reference.

The overall study had a small sample size. It was limited in the breadth of application areas considered and in the number of case studies within each application area. It was further limited in the amount of detail that could be presented about each model application. Thus, while the case studies provided a good set of lessons, we are cautious about overgeneralizing our results.

4.3 The Working Report

Based on the analysis of the case studies, a number of observations were made and a number of questions were raised. These, along with the documentation of the case studies, were assembled in a working report. Specific research recommendations were not made in the working report.

4.4 The Workshop

Eleven experts familiar with modelling in the context of EIA met in Toronto on March 12 - 13, 1986, to review the working report and the issues it raised. The overall purpose of the workshop was to provide a well-structured forum for focused, interdisciplinary discussions of the use of mathematical models in EIA. Each expert was asked for an opinion on the research needed to improve the state-of-the-art in modelling for EIA. The workshop participants drafted recommendations for research which formed the basis for the content of Chapter 7.

4.5 The Final Report

Subsequent to the workshop, the comments of the participants were integrated into this final report and a set of research recommendations were prepared.

5.0 THE USE OF MATHEMATICAL MODELS IN ENVIRONMENTAL ASSESSMENT

The scope of this study is restricted to the use of mathematical models in socio-economic impact assessment, biophysical impact assessment, toxic chemical assessment, technical risk analysis, and health risk assessment. The section provides a brief background on each of these application areas.

5.1 Socio-economic Impact Assessment

CEARC (1985) views social impact assessment (SIA) as an inquiry which seeks to investigate and understand the social consequences of planned change and the processes involved in the change. The product of an SIA can be used in decision making and as a source of public information. In the final analysis, SIA is about people and every attempt should be made to have people's concerns clearly understood so that the decisions affecting them are both responsive and responsible. CEARC believes four types of social changes are usually investigated as part of SIA: demographically-, economically-, resource-, and culturally-related changes.

Leistritz and Murdock (1981) take a narrower view. They believe the purpose of SIA is to:

- project social and economic profiles of study areas under baseline and impact conditions;

- sensitize the decision maker to critical problem areas and key relationships; and

- provide direction to further research.

One view of SIA classifies impacts into economic, demographic, public service, fiscal, and social (Leistritz and Murdock 1981). Computer projection models for assessing local and regional economic impacts have been considerably refined and received extensive use in the United States for the assessment of regional impacts. Most models feature an integration of the economic and demographic aspects. Models for assessing public service and fiscal impacts are fewer and less refined. There are few, if any, models for assessing social impacts. Social impacts are often broken down into socio-cultural and psychological impacts. While there is work being done to determine these impacts, mathematical and simulation models of social impacts are still in an experimental stage.

5.2 Biophysical Impact Assessment: Air

Models are used in air quality analysis for a number of purposes: predict pollutant dispersion; predict pollutant deposition patterns; test theories of atmospheric physics and chemistry; explore emission control strategies; and assist in construction of atmospheric materials budgets. Models of varying complexity may be required depending upon whether the user is interested in pollutant emissions, atmospheric transport and mixing (atmospheric physics), transformation (atmospheric chemistry), deposition (both wet and dry), or combinations of these, Existing models will reflect past as well as current interests and needs of different user groups. Major air quality policy issues currently addressed by using models include: ground level pollutant concentrations relative to existing standards; regional deposition patterns; and source/receptor (emissions/deposition) relationships. Although results from air quality models are most often used in EIA for regulatory purposes, they are also valuable in industrial and urban planning.

Initially, air quality models were developed to predict pollutant dispersion in the immediate vicinity of a specified source (up to several kilometres), but in recent years increasing importance has been placed on issues of a more regional (up to hundreds of kilometres) or global nature. As well, air quality issues were historically addressed on relatively short time scales, but now simulation models are used to address long-term issues (e.g., global climate warming).

Basically, there is a gradient of model types available for analysis of atmospheric pollutant issues. At one end of the spectrum are statistical (empirical) models, while at the other end are theoretical (process) models. Statistical/empirical models are used not only to assist in synthesis and analysis of field data, but also in development of large scale atmospheric budgets focused on pollutant exports (transboundary pollution). Theoretical models that use information and data on physical and chemical processes are especially well-suited for hypothesis testing and use in analyzing complicated issues involving pollutant transformation and long distance transport. Consequently, depending on the particular requirements of the end user, different types of models may be selected. Because there is a growing awareness that there is some level of uncertainty associated with model outputs, research is now underway to refine statistical forecasting approaches using techniques like Box-Jenkins modelling (Box and Jenkins 1970), in which auto regressive integrated moving average models (ARIMA) are used to fit time series data. As more complicated issues emerge, however, there is an increasing need for theoretically-based simulation models.

Simulation models are becoming accepted as powerful analytical tools in dealing with air quality issues. The two main types of mathematical models currently in use are distinguished by the underlying theory, either Gaussian or Lagrangian. Models developed with Gaussian equations are used to describe effluent dispersion and depend on the atmospheric diffusion theory elaborated by Sutton in 1932. Although models of this type were used on a voluntary basis prior to 1977 (when the U.S. Clean Air Act was amended), their use has increased sharply since that time because of legal requirements. Now, both the U.S. Environmental Protection Agency (EPA) and Canadian Atmospheric Environment Service (AES) use single and multiple source Gaussian plume models in their regulatory programs. Gaussian models, by their design, are limited to relatively small spatial scales; consequently, they are inappropriate for dealing with long range transport of atmospheric pollutants (LRTAP). As concern over LRTAP issues (e.g., acid precipitation) increases, more attention has been focused on Lagrangian-based models. In these models, discrete pollutant parcels are advected and diffused by a time- and space-dependent wind field to produce a fixed space-time average pollution concentration. To date, most LRTAP models focus on oxides of sulfur.

5.3 Biophysical Impact Assessment: Water

Mathematical and simulation models have been applied to a large number of issues related to water quantity and quality. The review of modelling by de Brossia (1984) provided a detailed inventory of applications. The following list groups applications according to the major issues, proceeding from water quantity to water quality concerns.

- Water Withdrawals: water management, downstream effects (instream flow, physical carrying capacity for aquatic biota), aquifer supply.
- Water Discharges: hydro power yield, tail races, diffusers, surface channel jets.
- Flooding: frequency, extent (stage), damage.
- Ice: formation, cover, movement.
- Stormwater: routing, sewer overflows, water quality.
- Temperature/Oxygen Regimes: temperature/oxygen regimes in reservoirs, rivers and lakes (effects

of altered mixing or flow, thermal plumes, etc.).

- Soil/Sediment Transport and Erosion: soil loss, effects of shoreline modifications, reservoir flooding, river diversion or augmentation, dredging.

- Trophic State: phosphorus and nitrogen loadings, algal biomass, biological oxygen demand, sewage and coliforms, water-based recreation impacts.

- Pollutant Loading and Dispersion: non-point sources; dispersion of inorganic pollutants, oil, radioisotopes, pulp and paper effluents, etc.

- Water-Sediment Interactions: heavy metal and radioisotope accumulation in sediments, contaminant resuspension by dredging or scouring, mine tailing and drilling mud disposal.
(The above two issues are discussed further in Section 5.5, Toxic Chemical Models.)

- Groundwater Quality: movement of radioisotopes, persistent organic chemicals or mine wastes through soil and rock to the water table.

This list, long as it is, is by no means comprehensive. Obviously, the research and modelling techniques vary widely across these diverse areas. Some general statements can be made, however. Accurate estimates of water flow and movement are a prerequisite to all types of water quality models. These flow estimates may be either measured directly or predicted using hydrological models.

Both empirical and theoretical models have been used in most of the above areas. Both dynamic and steady-state models are applied to water issues, though steady-state models are preferred due to their relatively small data requirements. A common technique is to examine water quantity or quality under extreme conditions (e.g., floods, droughts, low flow, or minimum dilution).

The mathematical form of models dealing with water varies from single empirical equations (e.g., predicting runoff, flood frequency, or algal biomass) to complex three-dimensional convection-diffusion models. The spatial form of the model adopted is a function of the nature of the substance being modelled, the environmental setting, and the zone of greatest potential impact.

The most commonly predicted variables in water models are flows and chemical concentrations. Generally, these outputs are compared to standards to determine whether potential impacts are significant, though occasionally, biological responses are integrated into the models themselves. Economic submodels, sometimes with optimization routines, are often linked with water quantity models to determine the potential costs and benefits of different water management schemes.

5.4 Biophysical Impact Assessment: Ecological

Compared to physics and chemistry, ecology is a relatively young science. As a result, the approaches available for predicting ecological impacts are more primitive than for impacts on water quantity and quality, which are driven by physics and chemistry. Notwithstanding the "youth" of ecology, it is probably also true that the ecological components of systems are inherently less predictable than their physical and chemical components, due to the large number of complex interactions which determine the distribution and abundance of plants and animals. The wide range of ecological evaluation techniques extends from field observations to laboratory tests to computer simulation models.

In general, ecological models have been used more for research than for impact prediction. Since the 1940s, the science of ecology has developed a considerable number of theoretical models concerned with the dynamics of populations and communities. These models are seldom applied, however, because either their parameters do not correspond to measurable features of real plants and animals, or because they are too difficult to measure accurately. Predictions from ecological models are most useful for gaining an understanding of the system, and the implications of different management strategies, rather than making precise predictions. Applications of ecological models to EIA include:

- aquatic ecosystem models incorporating nutrients, bacteria, algae, zooplankton, and fish (see Hall and Day 1977; Spaulding *et al.* 1983);

- dynamic models for fisheries management (Holling 1978; Webb *et al.* 1986), pest management in forests (McNamee *et al.* 1983), wildlife management (McNamee *et al.* 1984), impact evaluation of water withdrawals (Barnthouse *et al.* 1984), or assessment of the extent of acidification damage to fisheries (Jones *et al.* 1983);

- static habitat bookkeeping models, such as the Habitat Evaluation Procedure (HEP) (U.S. Fish and Wildlife Service 1980); and

- empirical models to predict fish presence/absence (Reckhow *et al.* 1987) or fish yield (the morphoedaphic index (MEI) developed by Ryder *et al.* 1974).

Sensitivity analysis, resulting in a probability distribution of events, is often used in ecological applications. Sensitivity analysis is simply the varying of the model's assumptions and parameters to test the degree to which model behavior is affected by the changes. This use of modelling leads to increased understanding because the responses of a system to extreme conditions are simulated or determined without spending years in the field or performing elaborate laboratory tests. This is not to say that these methodologies are not required; field studies and laboratory tests can 'be designed more effectively after first using modelling to provide preliminary estimates of results.

Whereas quantitative models are valuable for predicting the fate of pollutants, models for predicting general ecological impacts are not yet generally accepted. Such models, however, are being used increasingly more often for problem scoping, planning, and the design of monitoring programs.

5.5 Toxic Chemical Assessment

The number of synthetic organic chemicals produced and released into the aquatic environment has rapidly increased in the last two decades. The focus of many studies has been to discover whether or not these chemicals are toxic. Efforts to understand the impact of these chemicals on aquatic systems have been largely directed toward two areas:

- bioassays to assess the toxicity of synthetic chemicals and complex effluent mixtures of these chemicals (Marking and Dawson 1975; Parkhurst et al. 1979a, 1979b); and

- models to assess the fate of these chemicals, and thus estimate environmental exposures (Dickson et al. 1982).

Although this section of the report focuses on the second area, it is worth noting that integration of models and bioassays (dose and response) is not apparent in most literature on toxic chemicals. This absence may be due to the preferences of engineers and biologists to define problems in a way that minimizes the amount of detailed interaction with each other's disciplines. Consequently, through lack of interaction, bioassays often do not reflect the forms of exposure observed in the field (Auble et al.

1982). Another consequence is that intensive efforts to refine fairly complex exposure models have been developed without considering the types of uncertainties inherent in estimating biological response. Both problems can lead to exposure predictions which cannot be easily translated into biological responses.

Toxic chemical models are frameworks for integrating two multi-dimensional groups of factors:

- the distribution and transformation properties of the chemical; and

- those properties of the environment which control the fate of the chemical (i.e., both its final distribution and final form).

These factors are integrated by means of differential equations which incorporate many different physical, chemical, and biological processes. Detailed reviews of toxic chemical modelling structures and methods are found in Burns (1982, 1985) and in O'Connor and St. John (1982). Briefly, the physical processes typically represented include advective and dispersive fluid transport, entrainment, adsorption/desorption, volatilization, sediment transport, and exchanges across the sediment-water interface. The major chemical processes generally included in these models are ionization, hydrolysis, direct and indirect photolysis, and oxidation-reduction reactions. There is considerable variation among models in the biological processes simulated. Microbial transformations are almost invariably included as they affect virtually all chemicals. Other biological processes found in some models are biosorption, bioaccumulation, and algal metabolism/transformation of synthetic organics. The relative importance of these processes obviously varies among synthetic chemicals with different properties. Variation in the importance of different processes can also occur with the distance from the pollution source, as the chemical undergoes transformations, or is carried into zones with different physical or chemical properties.

5.6 Technical Risk Analysis

The concept of risk assessment is often loosely applied to describe several different activities. These activities (Grima et al. 1985) fall into two stages:

- risk analysis - measure the probability and severity of harm. This stage is comprised of:

  risk identification: identify the risks of the event and associated consequences; and

  risk estimation: estimate probabilities of events and consequences.

- risk evaluation - where values and judgements are explicitly stated. Decision makers determine trade-offs between impacts. They also develop management strategies at this point based on the information provided in the analysis stage.

Because risk assessment can be broadly defined, the scope of this analysis has been restricted to examining the more probabilistic and system modelling-based techniques for technical risk analysis. Health risk assessment is discussed in the next section. Risk analysis techniques based on probability theory (i.e., probability of an event occurring) are relatively straightforward mathematically but can be information-intensive. This need for a great deal of data (usually historical) means there must be an adequate data base for risk analysis models to be of use in EIA.

Bercha (1985) grouped risk analysis techniques under three categories: general risk evaluation: network analysis; and Monte Carlo simulation. Each level involves increasingly sophisticated modelling methodologies and complexity.

Bercha subdivided the first category into Delphi methods, bootstrapping methods, Bayesian methods, general statistical methods, general probabilistic methods, and mathematical modelling techniques. The structure of these mathematical models is such that there is an initiating event and identification of the hazard potential. An example application of such a model is predicting the atmospheric dispersion of a sour gas cloud. Network analyses include risk flow diagrams, fault trees, and event trees. This type of analysis is especially useful for examining systems that have no history; that is, systems using new technology or new processes. Monte Carlo simulation techniques are used to simulate mathematically intractable probabilistic relationships. Results of Monte Carlo analyses include probability distributions of events based on risk parameters. These techniques may be usefully combined in any given application.

Technical risk analysis models are among the most sophisticated and potentially the most objective of all techniques for use in EIA. While the techniques are sound, they rely heavily on probabilistic information. In many cases, assumptions have to be made about the likelihood of a given event. This introduces a large degree of subjectivity and uncertainty into what appears to be a wholly objective analysis. These uncertainties in estimation of probabilities are matched with uncertainties in interpretation. The best example is that of our difficulty in interpreting the risk associated with a low probability-high consequence event (Grima et al. 1985).

5.7 Health Risk Assessment

Models, while having great potential for application in health risk assessment, often do not play much of a role. Their greatest contribution to date appears to be in unearthing many of the assumptions underlying current practices in health risk assessment. The potential role for models is best revealed by examining the four major steps involved in health risk assessment (National Research Council 1983):

- hazard identification - the process of determining whether exposure to an agent can cause an increase in the incidence of a health condition;

- dose-response assessment - the process of characterizing the relationship between the dose of an agent administered or received and the incidence of an adverse health effect in exposed populations and estimating the incidence of the effect as a function of human exposure to the agent;

- exposure assessment - the process of measuring or estimating duration of human exposure to and intensity and frequency of the agent currently present in the environment, then estimating the hypothetical exposures that might arise from the release of new agents into the environment; and

- risk characterization - the process of estimating the incidence of the health effect under various conditions of exposure described in the exposure assessment.

While this is a somewhat narrow view of health risk assessment, it encompasses those aspects that are amenable to some form of quantitative analysis.

Traditional toxicological procedures define a safe level of exposure for humans as some arbitrary fraction of that dose level at which no effects are observed in a group of test animals (Munro and Krewski 1981). The use of safety factors appears to rest, at least tacitly, on the assumption of a threshold dose below which no adverse effects will occur. There is evidence for many carcinogens, however, that the assumption of a threshold may not apply. Because of this evidence, more robust models have been developed. The mathematical models for dose-response assume an increasing probability of response associated with increasing dose. Common functional forms adopted for dose-response relationships include linear and logistic shapes. The acceptance of a particular functional form for a dose-response model forces examination of the assumptions underlying the model chosen. Most dose-response models are tested for statistical fit to epidemiological and animal-bioassay data. While there is considerable controversy about the appropriateness of extrapolation from each of these types of data, it is possible to develop confidence intervals for low dose extrapolation (Crump and Howe 1985).

Models have a vital role to play in determining the degree of exposure that the human population has to radiation or a toxic chemical. Exposure implies that the hazard is transported in some medium (air, water, soil). As there is a large number of models for transport of pollutants in the air and water, and many more models of the biochemical processes that occur within the media, one might expect to find examples of exposure assessment. While these may be available, this analysis could not find examples where rigorous exposure assessments were done in the context of health risk assessment.

Perhaps the greatest potential role for models in health risk assessment is integrating dose-response relations with models that simulate various exposure conditions. If such a model was developed early in the assessment, it would guide research and data collection for the dose-response mathematical model and determine the output of the exposure model.

Health risk assessment is usually applied to evaluate the effects of a specific chemical in the environment. It is not often applied to an investigation of synergistic effects or an overview of the effects of a new system. The primary purpose of risk assessment is to estimate the risk of using a particular element, and in most cases, establish regulations for maximum exposure levels.

In the past, health risk assessment has not been part of environmental assessment for several reasons:

- health risks usually lag behind development and are difficult to quantify in view of all the interactions that take place (World Health Organization 1979);
- health departments and regulations are often separate from planning/environmental departments and procedures (World Health Organization 1979);
- the models used in health risk assessments describe steady-state, static relationships which appear to have little relevance to environmental assessments (Selikoff 1983); and
- data for these analyses cannot be directly collected, and confidence limits on the results are extremely variable. As a result, it is difficult to establish absolute operational safety limits for a project (Miller 1983).

5.8 Integration of Fate Models with Effects Models

The preceding overview shows that while there are many models in use that predict the physical and chemical fate of contaminants, there are few models in use that predict ecological and health effects of those contaminants. In general, a realistic assessment of effects requires predictions of contaminant levels in the environment. A major difficulty is to link fate models with models of effects. However straightforward it seems in principle to link these models, in practice, models for determining fate and effects are difficult to find. In fact, well established procedures for linking fate models and effects models are equally difficult to find. While there are many areas of application that need improvement, applications concerned with health and ecological risk assessment best illustrate the problems and difficulties in this type of model use. Classic examples are cases where models that calculate exposure to contaminants or radiation and are not coupled to the appropriate dose-response curves.

Difficulties in adequately predicting effects has led to the development of air and water quality standards with supposed wide margins of safety. Mathematical models are usually developed to determine the exposure or dose. If the predicted dose meets the set standard, then there is no need to assess the effects. This practice serves to inhibit the development of models that consider the effects (as opposed to the fate) of contaminants.

There are also a number of scientific and technical problems. The field of ecological risk assessment provides a good illustration of the problems. The four major steps in risk assessment (i.e., risk identification, dose-response assessment, exposure assessment, and risk characterization) provide a strong conceptual framework for assessment. In most cases, the critical step of risk characterization is poorly done because of problems in linking the exposure assessment with the dose-response assessment. For non-human biota there is often toxicity data (e.g., LC 50, LD 50) for only certain species. In some cases mathematical models have been developed for the dose-response relationships. However, in practice it is difficult to find toxicity data that is relevant to the system being modelled in the exposure assessment. As a result, in ecological risk assessment data are seldom available for all species in an ecosystem and risk assessments are often based on toxicity data for surrogate species. To extrapolate from one species to another is difficult. To extrapolate from laboratory data to field situations is even more difficult, yet, given the paucity of data, it is often necessary to perform assessments in the absence of more detailed data. In spite of the problems, models can help by providing default values based on generalized ecosystems allowing for preliminary assessments to be made. Mathematical models appear to the only way of providing accountable extrapolations from laboratory toxicity data.

6.0 CASE STUDIES

In any environmental assessment, analysis is only a part of the overall assessment. The use of mathematical models in various analyses is highly variable and usually not well documented. The best way to gather information about the application of models is to review case studies. Case studies reveal not what should have happened but what actually happened. A number of model applications were screened for detailed case analysis. Those not selected for detailed review are presented in Appendix 3. The case studies detailed in this chapter were developed through interviews and reviews of supporting documentation. In an attempt to achieve some consistency, the analysis of each case study was guided by the following groups of questions:

Integration into the Environmental Assessment Process

- What impacts or issues did the model address?
- For what analytical purpose was the model used?
- How was the model used in the EIA process?

Model Structure and Validation

- What was the model structure and its major hypotheses?
- Was the model calibrated to the specific site tested?
- Were the model's predictive capabilities tested previously?
- Has data been collected since development to test the model's predictions?

Model Limitations and Uncertainties

- What are the chief limitations of the model?

- Could these limitations have been overcome with more data?

- How much data collection is required to apply the model to a similar problem?

- Did the practitioners recognize uncertainties?

Implementation

- Was the model successful in achieving each of its intended objectives?

- How much difference did the model make to either the eventual form of the project or to decisions taken regarding approval?

In the following discussion of case studies, the information obtained in attempting to answer these questions is presented under four major headings corresponding to the four sets of questions. For each case study, an attempt was made to draw lessons from the application. Although these assessments are subjective, they are useful for the questions they raise or answer about the use of mathematical models in EIA.

6.1 Socio-economic Impact Assessment

North Dakota Economic-Demographic Assessment Model (NEDAM)

In 1980, planning intensified for a lease sale on lands in the Fort Union Coal Region in the eastern quarter of Montana and the western part of North Dakota. As part of the EIA for the coal lease lands, the Bureau of Land Management (BLM) used NEDAM, a socio-economic model developed at North Dakota State University (Leistritz et al. 1982a; Coon et al. 1984). Over a period of three years 1980 - 1983, the model was used in conjunction with a public information program and scoping process to identify concerns and predict impacts. In the latter stages of the analysis, a team of social scientists reviewed and fine-tuned the results of the model to more accurately reflect local conditions.

The model was used primarily to provide predictions of impacts in the following four areas: regional economy, regional demographics, local government revenues, and public services.

6.1.1 Integration into the Environmental Assessment Process

The BLM uses a two phase planning program for evaluating potential resource development areas. Phase I involves land use planning over a wide area to determine whether or not to actively exploit resources. If there are sufficient reasons to anticipate resource extraction, then Phase II planning begins. Phase II is the activity planning for a specific resource (e.g., coal) and includes the EIA. For the Fort Union Coal Region, a research team was organized to perform the EIA of the proposed project. The economist on this team decided to use NEDAM as a tool to aid the socio-economic part of the assessment.

6.1.2 Model Structure and Validation

This model has six subcomponents: economic (input-output), demographic (cohort-survival), economic-demographic interface, residential allocation, public service requirements, and fiscal impact. The inputs are data from census records and local government statistics of service usage and revenues. The base level of analysis is a planning region (comprised of as many as fifteen counties). The output is either at the regional, county, or municipal level, reported on an annual basis over a 25 year period. Baseline and single and multiple project impact projections are provided by the model. The baseline is a projection of the demographic and economic trends from the 1960s and 1970s. For the Fort Union Coal Region environmental assessment, the spatial extent of the model was expanded from including only the state of North Dakota to include the state of Montana.

The model has undergone extensive validation by critically examining the components, evaluating the model response to perturbations, and comparing the model results with historical data. By using local demographic and economic values as input data, the model was calibrated to the project area. When the spatial extent of the model was expanded to include Montana, the new input data had to account for the distinct differences in the regional economies between the two states. For example, Montana has a substantial lumber/wood product component to their economy not present in the agricultural economy of North Dakota.

6.1.3 Model Limitations and Uncertainties

Because of uncertainties inherent in the model, the practitioners chose only to use the model to generate preliminary results. Later, the results of the model were analyzed and fine-tuned by work groups consisting of social scientists familiar with the local conditions. The chief limitation of the model is that the input-output sub-model used in the economic module assumes there will be no structural changes (e.g., a sharp increase in the price of energy) in the economy over time and that past trends will continue. This limitation could be overcome by evaluating scenarios with significantly different economic conditions. This has not been done, however, because the model is expensive to prepare and run, which in itself is a major limitation.

Another limitation inherent in this type of model is that the predictions are tied directly to the development scenario. In the Fort Union case, it would be difficult to test predictions as the actual level of development has not coincided with the scenarios assessed in the model. Testing of predictions implies monitoring. Because BLM has not allocated the resources to carry out monitoring studies on the Fort Union Coal project, there has been no evaluation of the predictive capability of NEDAM.

6.1.4 Implementation

The most significant aspect of this application is the model's role in the EIA process. With the Fort Union Coal project, BLM combined their public information program with the modelling and impact analysis to generate discussion and bring out new information. In this process, the model was designed to provide information on economic issues identified during initial discussions with the public, various interest groups, and government agencies. Then, the social assessment group (composed of local social scientists) analyzed the output from the model and made social predictions. Both the economic predictions from the model and social predictions from the analysts were the subject of peer group and public review. In this sense, the model was used more as a means of bringing diverse interests together for discussions rather than solely as a predictive tool.

Overall, BLM staff have found that when people contribute to the problem formulation step, there is less resistance to the final results (Loren Cabe, BLM, pers. comm). In addition, by using a model in the initial stages of assessment, the definitions, data, and assumptions are explicitly stated. Consequently, discussions can focus on major issues rather than semantics or hearsay.

6.2 Biophysical Impact Assessment: Air - Dispersion

BLP Model (Buoyant Line and Point-source)

The BLP model was developed by the Aluminum Institute of America, based upon the Environmental Protection Agency's (EPA) CRSTER model, and is of the UNIMAP type. It was designed for air dispersion analysis of fluoride and other atmospheric emissions from new and existing aluminum smelters. The primary purpose of this model is to determine the extent and orientation of the zone around the proposed smelter where ground level fluoride concentrations would exceed some specified level. Model results are then used to delimit the buffer zone around the smelter where damage to terrestrial and other ecosystems may occur.

Subsequent to its development in the United States, a modified version of the BLP model has been used for projects with Alcan, ALCOA, ALIMAX, and INTALCO in Quebec, North Carolina, Washington, and Australia respectively. Follow-up studies have been conducted to compare predicted results with field data at several of the sites (Coupal et al. 1986; Friar and Coupal 1985).

The following case study deals with the use of the BLP model in British Columbia to evaluate the Alcan aluminum reduction project proposed for Vanderhoof.

6.2.1 Integration With the Environmental Assessment Process

The BLP model was used to predict the environmental effects of fluoride emissions on vegetation surrounding the proposed Vanderhoof site. The primary use of the model was to identify the impact scale; viz., the extent and location of the area likely to be subjected to fumigation. According to Richard Bennett (B.C. Ministry of Environment, pers. comm.) up to 80% of the environmental assessment was based upon results from the modelling output. Another important feature was that modelling allowed for exploration of different emission scenarios, thereby facilitating the interaction between the proponent and regulator. In this application, the model was used in informal negotiations to arrive at an acceptable scenario.

6.2.2 Model Structure and Validation

The model used in this application was calibrated to the site by incorporating site-specific information on meteorological data, terrain, and the configuration of the proposed aluminum plant into the model. Because the model was developed and used elsewhere, information was also available on its past performance. The version of the model used in this project had a circular spatial grid of roughly 10 - 12 km in diameter. The temporal resolution used ranged from one hour to one year, for which average values of expected ground concentration were predicted.

6.2.3 Model Limitations and Uncertainties

Recognizing the uncertainties of the model output, a procedure was developed whereby the proponent did the initial modelling which was then checked by the B.C. Ministry of Environment through follow-up runs. The chief limitations to this model are those common to Gaussian models, namely inability to satisfy all necessary assumptions: continuous release, steady meteorological conditions, uniform atmospheric stability, non-reactive gas, etc.

In the opinion of Richard Bennett, the limitations outlined above could not be overcome by more data because they are due to design features of the model. In order to apply the BLP model to another site, at least 12 months of continuous, hourly meteorological data would be required. It would also be necessary to refer to a longer meteorological record at some well-studied, nearby site to determine how representative the one-year data are.

6.2.4 Implementation

Although the model was judged to be successful in accomplishing the intended objectives, it is not possible to verify this because falling world aluminum prices caused the project to be cancelled. If the project had gone ahead, however, results from the modelling would have affected not only the amount of land Alcan would have been required to buy for the buffer zone, but also the facility design.

The major lesson here is that a model can serve as a tool to aid in negotiation of the environmental design of the project. This may be a particular attribute, however, of air quality models. Negotiations were possible because the results of the models were believed by both parties (viz., taken to be reasonable); the air quality regulatory agencies have adopted design standards which, if met, will normally guarantee regulatory approval; and there was no need to consider the actual health and environmental effects because the projected emissions were below the standards.

6.3 Biophysical Impact Assessment: Air - Deposition

MIX Model (Mixed Layer Statistics Dispersion)

The MIX model was developed by the Canadian Atmospheric Environment Service (AES) to simulate atmospheric emissions dispersion from point sources. It has been used to evaluate, for example, the Atikokan project (a coal fired thermal generating station in northwestern Ontario) where it was subjected to review by the International Joint Commission (IJC) and EPA, both of whom found the model to be acceptable (Ron Portelli, Concord Scientific Corporation, pers. comm.). The following case study deals with the recent use of this model for evaluating emissions from Syncrude's Mildred Lake Plant (an oil sands upgrading plant located near Fort McMurray, Alberta).

6.3.1 Integration with the Environmental Assessment Process

The MIX model was used to determine environmental loading of 26 metallic elements, including lead and mercury, released from Syncrude's main stacks at Mildred Lake. The model output was then used to help address social concerns regarding effects of metallic deposition on native health, especially for children in Ft. Mackay. The final report (Concord Scientific Corporation 1984) contained loadings maps which were used in public hearings. These maps, combined with sulphur deposition information from another study, were the basis for a public education program during the hearings. On the basis of the hearings, a recommendation was made to permit emissions at current levels.

6.3.2 Model Structure and Validation

The MIX model is statistically based. For use in this project, predictions were made for elemental deposition over a 20 year period, with emissions calculated on an annual basis. Deposition patterns were predicted for an area circumscribed by a circle 1900 km in diameter. Although the model was not specifically calibrated to the Mildred Lake location, site-specific parameters relating to the emissions point (i.e., the stack) were used, as were meteorological data from Ft. Simpson and Edmonton AES stations. As described above, the model had previously been rigorously evaluated in the Atikokan project.

6.3.3 Model Characteristics

Although practitioners using this model clearly recognized uncertainties inherent in the model output, very little emphasis was given to this, either in the final report or in the hearings. The practitioners assumed that using a longer time-frame (e.g., 20 years) would decrease the likelihood of violated assumptions in influencing the accuracy of such long term predictions. The chief limitations of the model are those related to Gaussian assumptions; previously described in the section Biophysical Impact Assessment: Air - Dispersion.

According to Ron Portelli (pers. comm.), limitations of the MIX model could be overcome with appropriate input information, such as standard meteorological data of extended duration. This would include mixed air heights and upper air speeds which could be provided in part by relating site-specific data to nearby AES stations. The amount of data required to apply the model to another location would depend on both the type of terrain in which the project was located, as well as the proximity to a meteorological station for which necessary data were available.

6.3.4 Implementation

Even though information on downstream deposition rates was essential for emissions approval, the model predictions of loading for 26 metallic elements had no effect on either the design or operation of the Mildred Lake facility. Because atmospheric emissions are continually monitored during operation of the plant, data are available to verify the predicted emissions rates. To date, though, these data have not been analyzed from the perspective of prediction testing. A survey- currently being conducted on element levels in vegetation may be useful in determining the accuracy of predicted deposition rates.

The major lesson in this application is that the model output was able to allay concerns over health risks in the public hearings and with health assessment professionals. This shows an implicit acceptance of the model and indicates that its output can contribute to issue resolution. Exposure levels estimated by the model, however, were not explicitly linked to a health risk assessment. The assessment, therefore, had to rely on established standards. Because deposition levels predicted by the model were within acceptable standards, it was concluded that there was little health risk.

6.4 Biophysical Impact Assessment: Water Quality

Wreck Cove Hydroelectric Project

One of the best documented Canadian applications of a water quality model to an EIA is the Wreck Cove hydroelectric project. The Wreck Cove project was constructed between 1975 and 1978 on the northeast side of Nova Scotia's Cape Breton Island. The project involved the creation of four major interconnected reservoirs, as well as seven river diversions. Prior to project construction, one of the major issues was future water quality within and downstream from the major reservoirs. The consultants who prepared the project's EIA used a mathematical model to help assess this issue (Beak Consultants Ltd. 1977b; Snodgrass and Holloran 1977); this modelling application is analyzed herein.

6.4.1 Integration with the EIA

Unlike many other EIAs, the Wreck Cove study was not directed towards providing input to project approval decisions. The project was already approved prior to commencement of the EIA, and the study was specifically focused on two "post-approval" objectives (Beak Consultants Ltd. 1977a: 1):

1) make an initial assessment of environmentally sensitive areas and recommend interim measures for mitigation; and

2) define the final project design and operation options most consistent with environmentally sound management of the area.

Modelling was applied to address the second objective. The intent was to consider the relative impact of various operating strategies on the temperature and oxygen conditions for fish. The consultants recognized at the outset of the study that precise quantitative predictions were not feasible due to lack of data, but that a ranking of different designs and suggestions for mitigation, might emerge (W.J. Snodgrass, Beak Consultants Ltd., pers. comm.).

The modelling was integrated with the EIA process primarily through two mechanisms: direction from an oversight body and coordination with the engineering consultants. After reviewing previous work, an advisory body and interagency task force made specific recommendations on the issues that needed to be addressed. Consequently, questions to be answered by modelling flowed easily from these recommendations, according to a modeller involved in the project;

a single meeting of the modellers and the the task force was sufficient to confirm that the modellers were proceeding in the right direction. The modellers met several times with the engineering consultants to develop a set of feasible operating options to test with the model. As it turned out, the base case option originally proposed by the engineering consultants was preferable to other options. The exploration of other options, though it did not lead to any major changes in project design, revealed indirect and subtle interactions between reservoirs. This knowledge helped to confirm the wisdom of the operating policies proposed for the base case (Snodgrass and Holloran 1977).

6.4.2 Model Structure and Method of Application

The model used in this case study was a one dimensional (i.e., vertical) temperature-oxygen model, first developed by Markofsky and Harleman (1971, 1973). This model assumes that the reservoir is horizontally well-mixed, and describes vertical transport by means of both advective currents and molecular diffusion. When applied in the Wreck Cove case, the model predicted daily temperatures and dissolved oxygen concentrations at various water depths within each of four reservoirs.

Perhaps of more general interest to this study was the process by which the model was selected, modified, and applied. The modelling followed nine steps, which are listed below because they illustrate how successful model application requires numerous adaptations of existing models. The steps were:

- review of the structure and past record of available models;
- selection of the best candidate model (the model of Markofsky and Harleman cited above);

- testing of the model on an existing reservoir with a good dataset to evaluate its predictive accuracy (Fontana Reservoir, North Carolina);

- reconstruction of the model to remedy deficiencies (addition of deoxygenation sinks in both the water column and sediment);

- sensitivity analysis of the reconstructed model to determine priorities in refining the precision of input data and model parameter estimates;

- assembly of input data for the Wreck Cove system, and simplifications of the model where detailed input data was not necessary for the questions being addressed;

- initial application to Wreck Cove using existing data;

- further model modifications (density-temperature and vertical mixing relationships) together with laboratory and field studies (sediment oxygen demand) to improve predictive capabilities; and

- evaluation of possible operating policies.

6.4.3 Model Successes and Limitations

The model was successful in achieving the intended objectives. As a result of the modelling, different operating policies were evaluated, and changes made in the proposed development (W.J. Snodgrass, pers. comm.; Ruggles 1985). In general, predictions on oxygen levels have been confirmed (Ruggles 1985).

The chief limitation of this model application was the lack of field data for calibration. Though some temperature and oxygen data were available for the reservoirs, they were not collected frequently enough to accurately calibrate the model for the zone and time period of greatest potential impact (i.e., deep water during periods of vertical stratification). In this instance, the limitation of the model was not telling, since the uncertainties were not considered large enough to affect the rank ordering of the alternative project configurations. Also, fisheries in the area generally are of low productivity due to oligotrophic, acidic conditions and therefore oxygen was not considered to be the most limiting factor to fisheries production (W.J. Snodgrass, pers. comm.).

The inadequate calibration of the model could have been overcome with more intensive sampling after the construction of the project, with the potential benefits of improving the effectiveness of mitigation strategies at Wreck Cove and perhaps in similar projects elsewhere. Post-operational data collection, however, involved only monthly samples, which would have been insufficient for calibration. The modeller on the project felt that a good opportunity was being lost, and attempted (without success) to get funding from other sources to properly calibrate the model (W.J. Snodgrass, pers. comm.). It is not clear, however, whether the inadequacy of post-operational data collection was due to unwillingness on behalf of provincial and federal government agencies to fund detailed data collection, or due to a lack of clarity in the consultant's final report. Though the need for better model calibration was stressed in the modelling section of the report, the summary conclusions (Beak Consultants Ltd. 1977a) recommended that only monthly samples be collected for the first two years, with less frequent sampling thereafter.

A follow-up study on the Wreck Cove project (Ruggles 1985) pointed out substantial errors in the EIA predictions relating to color, pH, nutrients, and primary production, due to an underestimate of the increases in primary nutrients and organic acids from flooded soils. It is impossible to say whether these predictions would have been any better had these water quality components also been modelled. It is conceivable that errors in fundamental assumptions would merely have been incorporated into the model.

6.4.4 Implementation

The major lesson from the Wreck Cove study is that successful application of models requires a careful examination of model behavior by experienced scientists who understand how the real system behaves. This allows the modeller/scientist to distinguish potentially significant impacts from quirks created by the model structure and parameter values. In this case, application of existing models without careful analysis of their uncertainties and simplifying assumptions could have led to erroneous conclusions concerning both the preferred project configuration and the level of confidence in model predictions.

The second lesson from this study is that models can be useful for qualitative comparisons even in the absence of sufficient data for complete calibration. Basic data on field conditions, though incomplete for proper calibration, provided guidelines for evaluating whether the model predictions were realistic. Sensitivity analyses indicated which processes most strongly influenced model predictions, which led to laboratory and _in situ_ measurements of sediment oxygen demand. These intensive studies of important processes helped to give confidence to the model predictions, even in the absence of data for proper calibration.

Finally, the Wreck Cove case illustrates the need for post-operational monitoring studies to consider the temporal and spatial resolution of data required to calibrate and validate models. Without such data, improvements in modelling are likely to proceed very slowly.

6.5 Biophysical Impact Assessment: Ecological

The Hudson River Controversy

This case study concerns a controversy over the impact of electric power generation on fish populations near the mouth of the Hudson River. Simulation models played a central role in this controversy, and their utility and limitations are very well-documented. Three papers are particularly valuable for examining the role of modelling, including the interaction of models with ecological theory (Hall 1977); field sampling personal biases (Christensen et al. 1981); and courtrooms (Barnthouse et al. 1984). Details on the models themselves can be found in references cited in these publications. The discussion below is drawn largely from the papers by Christensen et al. (1981) and Barnthouse et al. (1984), and from a conversation with S.W. Christensen (Oak Ridge National Laboratories).

The controversy lasted 17 years, and involved five electrical utilities, four federal agencies, the states of New York and Massachusetts, and a number of local and national organizations and citizens' groups. At the core of the controversy were two projects proposed by Consolidated Edison Company of New York, Inc. (Con Ed):

1) the Cornwall Project, a large, pumped-storage facility falling under the regulatory jurisdiction of Federal Power Commission (FPC); and

2) the Indian Point Unit 2, a nuclear power plant 25 km downriver from the Cornwall Project, and falling under the regulatory jurisdiction of the Atomic Energy Commission (AEC) and the Atomic Safety and Licensing Board (ASLB).

6.5.1 Integration with the Environmental Assessment Process

The evolution of the conflict and the models used to address it are best described in the form of a chronology.

By 1965, the Cornwall facility had been proposed and strong opposition arose around the concern that entrainment (removal of eggs, larvae and young juveniles with the pumped water) would significantly reduce the abundance of striped bass, a popular sports fish. The Hudson River Policy Committee (HRPC) was established to assess this problem.

In 1968, the HRPC issued a report which computed impacts on striped bass populations based on the proportion of average daily tidal flow of the Hudson River that would be withdrawn by the Cornwall facility. No significant adverse effects were anticipated. A method used to estimate impact, however, was shown to systematically underestimate mortality.

In 1971, AEC began hearings on environmental impacts of the Indian Point Unit 2 facility. The issue of impingement (trapping of older, larger fish on the screens used to remove debris from the pumped water) was raised, in addition to entrainment.

The Atomic Safety and Licensing Board held hearings on Indian Point Unit 2 during 1972 through 1973. At these hearings, Con Ed presented their consultant's model (the "QLM model") which assumed that entrainable striped bass life stages were uniformly distributed in the water column, and computed entrainment mortality based on the proportion of estuary volume withdrawn. Effects on adult fish population size were projected from mortality estimates of one year's plant operation. Only negligible effects on fish populations were anticipated. AEC (supported by experts from Oak Ridge National Laboratories) disputed the Con Ed QLM model and produced their own model, which cycled young striped bass downstream in an upper, freshwater layer and then back upstream in a lower saltwater layer. Much higher mortalities were anticipated (i.e., 30 - 50% of each year class). The AEC model assumptions were attacked by Con Ed and vice versa. A new model (QLM 1-D), developed by Con Ed, used one-dimensional hydrodynamic equations, "migration factors" to model movement of juveniles, "w-factors" to account for nonuniform spatial distributions of organisms in the vicinity of intake, and "f-factors" to account for less than 100% mortality of entrained organisms. A biological compensation component was included (i.e., entrainment mortality offset by a decrease in the natural mortality rate of nonentrained fish).

In 1973, ASLB, after applying conservative assumptions to uncertain parameter values in the models, ordered Con Ed to use a closed-cycle cooling system (i.e., cooling towers instead of water withdrawals). Con Ed appealed the decision and won. The Licensing Board granted a delay in their order while the models were reexamined.

Between 1973 and 1977, the FPC held hearings on the Cornwall Project, and the U.S. Nuclear Regulatory Commission (NRC, the successor to the AEC) held additional hearings on Indian Point Unit 2. During this time, a whole series of new hydrodynamic models was developed by the utilities and Oak Ridge National Laboratories. At the same time, a large amount of field work was completed, measuring the distribution and abundance of young striped bass for model calibration. The positions of each group remained the same, however, and neither commission could draw conclusions.

Between 1977 and 1980, hearings were conducted under the aegis of EPA. During this time both parties abandoned hydrodynamic simulation models for empirical "bookkeeping" systems (e.g., the Empirical Transport Model (ETM), Boreman et al. 1981) which used measurements of fish distribution directly, rather than trying to predict them from hydrodynamic equations. Progress was made in reducing the number of arbitrary assumptions, in explaining models to lawyers and judges, and in shrinking the gap between opposing parties. In 1980, negotiations were held to develop methods of reducing water withdrawals and entrainment mortality (e.g., seasonal flow reductions, scheduled shutdowns, "cross-plant outage credits"), using empirical models to evaluate alternative actions. A settlement agreement was ultimately reached.

6.5.2 Implementation

This epic saga of environmental conflict is filled with many lessons for decision makers, EIA practitioners, and modellers:

- The hearing process, though very expensive and time-consuming, did eventually lead to changes in methods, and substantial convergence of opinions on at least some issues (Christensen et al. 1981).

- The laws of hydrodynamics, while perhaps valid for eggs, do not explain the movements of yolk-sac larvae, post yolk-sac larvae, or juvenile fish. Extensive data collection to calibrate hydrodynamic-based predictions of these distributions led to the abandonment of hydrodynamic models and use of the data directly in empirical bookkeeping systems (Christensen et al. 1981). Interestingly, "these empirical models are so simple they don't really need to be tested; if you acquired more data you would be best off just to add it to the model and reduce-sampling uncertainty" (Christensen, pers. comm.).

- "Objective" science, in this case, appeared to be very much a function of scientists' personal convictions pertaining to their attitudes towards development and acceptable levels of environmental impact (Hall 1977).

- It proved impossible to obtain reliable estimates of the magnitude of biological compensation, so that long-term population projections were highly dependent on arbitrary assumptions. Models cannot provide short-cuts where there is insufficient understanding of fundamental processes (Barnthouse et al., 1984).

- Problems involving comparisons of relative impacts or methods of mitigation are more easily solved than questions of long-term population change, and are best approached using simple empirical models designed to fit available data (Barnthouse et al. 1984).

- Decisions regarding long-term effects will have to be made under uncertainty, rather than being deferred indefinitely in the hope that scientists can produce definitive and defensible answers. The length of EIAs can be substantially reduced by asking answerable questions relating to methods of mitigation, rather than focusing on unanswerable long-term questions (Barnthouse et al. 1984). Nevertheless, models are necessary to define the potential importance of impacts, and provide the motivation to pursue methods of mitigation. The key issue seems to be getting the parties to agree to examine methods of mitigation once the possibility of significant impacts has been generally recognized, rather than waiting until the likelihood and magnitude of such impacts is proven quantitatively.

These conclusions are particularly relevant to the acid rain problem, where a number of complex models have been developed to address questions concerning the long-term response of watersheds (e.g., the Integrated Lake-Watershed Acidification Study (ILWAS) model, Chen et al. 1983).

6.6 Toxic Chemicals

Field Testing of EXAMS on a Detergent Chemical

The EXAMS model (Exposure Analysis Modelling System) developed by EPA (Burns 1985) is typical of current models used for toxic chemical evaluation, and has been selected for this case study because of its widespread use. As of 1980, over 500 copies of the model had been distributed (L.A. Burns, EPA, pers. comm.). EXAMS is used by at least three different offices within EPA: the Office of Pesticides to assess suggested pesticide application rates, the Office of Toxic Substances to compute the chemical exposures associated with effluent and unintended spills from manufacturing processes, and the Office of Water Regulations and Standards for waste-load allocation analyses (Slimak and Delos 1982; L.A. Burns, pers. comm.). EXAMS is also used by various industries to evaluate the fate of chemicals either currently or potentially discharged into aquatic systems.

The EXAMS model, like other models of its type, is attractive to use because:

- it is a generalized aquatic system model, and as such, can be relatively easily set up for a stream, lake, or ocean environment;
- it assembles equations based on the input parameters for the chemical of interest, and produces both steady-state and time varying output;
- it conducts sensitivity analyses of results based on an input range of parameter uncertainty; and
- its generality allows it to be used on a wide variety of chemicals, facilitating comparisons.

Notwithstanding these advantages, one user (in the case study described below) found EXAMS "somewhat cumbersome" for his particular application (W. Bishop, Procter and Gamble, pers. comm.). This appears to be virtually inevitable for generalized models, since large parts of them will not apply in specific instances.

6.6.1 Relationship to the Environmental Assessment Process

It was surprising to find that neither the creator of EXAMS (L. Burns, pers. comm.), nor several other experts in the field (D.M. DiToro, Hydroqual Inc.: T. Fontaine, NOAA; and D. Mackay, University of Toronto; all pers. comm.), were aware of any applications of toxic chemical models to environmental assessments. This appears to be due primarily (at least in the United States) to the existence of regulations which require assessment of potentially toxic chemicals at a fairly early stage in project formulation, long before a proponent publically presents a specific proposal to build a plant that will discharge potentially toxic chemicals. This type of assessment is similar to those performed for air pollutants (see Biophysical Impact Assessment: Air - Dispersion).

The case study discussed here was recommended by the author of EXAMS as an interesting application. It concerns a private company's field test of the ability of EXAMS to simulate observed concentrations of a detergent chemical. The field test is described in detail in Games (1982), and is summarized below. Though this use of a model did not take place in the context of a formal EIA, there were some lessons learned in terms of the potential success of EXAMS (or similar models) in EIA applications.

The chemical tested is known as LAS, an anionic surfactant widely used commercially in detergents. Procter and Gamble decided to test EXAMS on Rapid Creek, South Dakota, where a sewage treatment plant releases substantial quantities of LAS. Several factors made this test application easier: relatively few processes need to be considered in modelling LAS; the effluent consisted almost entirely of domestic sewage; so that interactions with other industrial chemicals were not a concern; and the sewage treatment plant represented the only significant source of LAS to the creek.

6.6.2 Model Structure and Validation

Details of the manner in which EXAMS was set up to model LAS are found in Games (1982). A few points are mentioned here as necessary background. The creek was divided into five reaches spanning a distance of 87 km downstream from the outfall. The important physical characteristics for LAS (solubility, adsorption to sediment and bacteria) were measured in the laboratory, while field measurements produced estimates of the biodegradation rate. Other processes, such as volatilization or photochemical transformations, were judged to be unnecessary for LAS. Within EXAMS, all mixing processes at the sediment/water interface are summed and expressed within a single dispersion coefficient. Unfortunately, there was no method or rationale for assigning a value to this coefficient, and the single value chosen for all reaches was simply the one giving the best fit to observations.

The model produced agreement with measured concentrations in water and sediment, in that existing concentrations fell within the confidence bounds on model predictions. This agreement, however, was only possible by the arbitrary choice of a dispersion coefficient. Sensitivity analyses confirmed that model predictions were most sensitive to the dispersion coefficient and even more sensitive to the biodegradation rate. These two parameters are unfortunately the least understood and most difficult to measure.

6.6.3 Implementation

EXAMS was useful in quantifying the level of uncertainty in exposure predictions, but one can ask the question, "useful to whom?". Quantification of uncertainties is of value to researchers, since it indicates the need for more field experiments to better understand biodegradation and mixing in the sediments. This is a common area of uncertainty for many organic chemicals (Everitt _et al._ 1985). Nevertheless, from the point of view of the industry which applied the model, "given the wide confidence intervals associated with predictions, it seems we were doing just as good a job with simpler dilution type models" (W. Bishop, pers. comm.). It seems likely that if this model application had taken place in the context of an EIA, the level of uncertainty would have been too great to aid in decision making. Though very wide confidence intervals are not found in all applications of models to toxic chemicals, they are a common problem.

A second lesson emerging partially from this case study and partially from the literature is that credible model predictions of toxic chemical exposures require a sustained investment in model development, calibration, and validation. This may be difficult within the private sector. In the case of Procter and Gamble, work on EXAMS, and toxic chemical modelling in general, declined after 1980, largely because the person most involved in modelling was transferred elsewhere (W. Bishop, pers. comm). Now that a new staff person with interest and experience in modelling is available, further modelling applications are being considered. Though such discontinuities are common within both the public and private sectors, modelling of new organic chemicals probably progresses somewhat more slowly because of confidentiality concerns of the manufacturers, which limit sharing of information on chemical characteristics and behavior.

A third issue raised by this study concerns the kinds of models required for EIAs related to toxic chemicals. Generic models like EXAMS were designed to provide exposure assessments for a large number of chemicals, not precise fits between predicted and observed concentrations at a particular site. Although with further field work on Rapids Creek, the width of confidence intervals could be narrowed, the more calibration that is required for successful field validation, the less applicable the model will be in a general, evaluative sense for other sites.

What does all of the above imply for toxic chemical models and EIA? If this application had taken place in the context of an EIA, say with a valuable fish species downstream of the point source with known sensitivities to LAS, the modelling would probably not have helped resolve the issue of potential impacts due to the large uncertainty in predictions. To make matters worse, the uncertainty is likely to be considerably greater for complex mixtures of effluents, or for chemicals toxic at low concentrations that are difficult to measure accurately. In EIAs with a highly contentious environmental issue, it seems that direct empirical evidence of potential impacts (e.g., field experimentation in test streams) is the only route likely to provide the basis for a consensus. Such experimentation is considerably more expensive than modelling, but may at some point become more cost-effective.

6.7 Technical Risk Analysis

Beaufort Sea Oil Spill Risk Analysis

The Beaufort Hydrocarbon Development involves the production and transportation of Beaufort Sea oil and gas to southern markets. The oil spill risk issue associated with the development can be succinctly stated:

> "The risk of a large oil spill was the major environmental concern expressed by many northern residents and intervenors. At the public sessions of the Panel, each community had its particular concern. Communities in the Mackenzie Valley expressed concern about a rupture in a pipeline crossing the Mackenzie River, the Great Bear

> River, and smaller rivers. Residents of the Beaufort Sea spoke of spills into the Beaufort Sea. Communities along the proposed tanker route expressed fears about a potential tanker spill. Communities along the Labrador coast expressed the fear that an oil spill north of 60 degrees north latitude, the area covered by the present review, might be carried south onto the Labrador Coast." (Beaufort Sea Environmental Assessment Panel 1984: 31).

Because risk analysis demands quantification, some would argue that it can objectify some aspects of environmental assessment. Somewhat paradoxically, the increased quantification demanded by technical risk analysis often lays bare the judgement and value side of assessment. It is as if the need to be explicit about assumptions makes it impossible for assessors to gloss over the uncertainty inherent in all environmental assessment. The case of the Beaufort Sea was no exception. The Panel saw fit to emphasize in its report that

> "...the Panel is well aware that judgement must be used in the interpretation and analyses of oil spill risks." (Beaufort Sea Environmental Assessment Panel 1984: 31).

6.7.1 Integration into the Environmental Assessment Process

An Environmental Assessment Panel was created under the auspices of the Federal Environmental Assessment Review Office (FEARO) to make recommendations to federal Cabinet ministers. For the most part, the risk analysis with respect to oil spills was done to help the Beaufort Panel make its recommendations.

A technical risk analysis was performed to identify and priorize the risks. This analysis used fault trees to provide a numerical estimate of the risk of an oil spill associated with each component of any proposed production and transportation system (Beaufort Sea Environmental Assessment Panel 1984). As such, it appears the risk analysis did not directly assess the effects of oil spills but focused on the likelihood of occurrence of accidental spills; the fault tree models focused on the quantification of risk, not the prediction of effects.

6.7.2 Model Structure and Validation

The risk analysis was based on a number of logic network or fault tree models constructed to assess the risk for the different components of the production and transportation system. Existing statistical and mathematical techniques were used for quantification of the trees. Extensive analyses of historical databases from analogous situations in other parts of the world yielded base estimates of probabilities. These probabilities had to be modified to take account of the technologies being proposed and the unique aspects of the Arctic environment. Because of the nature of the technology and the lack of experience with the region, it was not possible to make a systematic calibration of the models for the Beaufort. In addition, many circumstances in other areas were different from the Beaufort, both in scale and type of development as well as the unique problems of the Arctic environment; therefore, the data had to be modified to fit the Beaufort situation (Beaufort Sea Environmental Assessment Panel 1984).

6.7.3 Model Limitations and Uncertainties

The analysis was criticized by experts in government departments and by the Panel's technical experts. The models' credibility was called into question because of the new technology involved. This is the essence of the case study. Because the practitioners were keenly aware of the uncertainties, the models were continually and critically examined. It was soon recognized that the uncertainty would be the focus of the public hearings. A committee of the proponent, the proponent's consultant, government intervenors, and membe'rs from the Panel Secretariat was formed to sort out the conflicting views on the risks.

The major limitation of the analysis was the lack of an empirical database to base probabilistic estimates needed for the models. In their report, the Beaufort Panel carefully noted there was considerable discussion (disagreement) about methodological issues, such as the merit of various statistical techniques and *databases. The risk analysis could not provide definitive answers because of the inherent uncertainty. While the methodology was ultimately shown to be sound, and extensive analyses were done of worldwide historical data, the uncertainty persisted. In spite of their limitations, however, the models contributed to a greater understanding of the issue.

6.7.4 Implementation

The events surrounding the use of a technical risk analysis of the oil spills associated with Beaufort Sea hydrocarbon can be viewed from two different perspectives:

- the technical disagreements among experts illustrate the fallibility of using models and other quantitative techniques in environmental assessment; or

- the technical disagreements among experts increased understanding and lead to the focusing of an issue fraught with scientific uncertainty and complex value judgements.

The risk analysis was successful in achieving each of its intended objectives of identifying and priorizing the risks. It also served as a vehicle for presenting and communicating the analysis of a complex issue. The technical risk analysis helped resolve the issue of oil spill risk. The issue began as a disaster scenario and gradually a more realistic view emerged. The fault tree models presented the issue in a logical and systematic fashion.

In spite of, or perhaps because of, the conflicting views presented in a number of official documents and submissions to the Panel, the Panel requested the preparation of a short summary of the issues that had been resolved and remaining disagreements. This summary was prepared at a meeting with the Panel's technical specialist, the proponent, the proponent's consultant, and Environment Canada that occurred during the time of the public hearings. After referring to the usefulness of previous reports and documents, the summary concluded (Lemberg 1983):

> ". . . However, the participants [in the special meeting] feel that this report represents a rough approximation of the most important data and that further precision may not be useful."

There are two interlinked lessons:

- o Discussing technical disagreements within the analytical structure of risk assessment models allowed for an examination of basic assumptions and quality of data, thus improving the understanding of a complex issue.

- o To be relevant to the decision making process (in this case, the deliberations of the Assessment Panel), the technical disagreements and agreements needed to be presented in a simplified and summary form.

6.8 Health Risk Assessment

Assessment of the Radiological Impact of Uranium Mining

Environment Canada and the Atomic Energy Control Board commissioned an assessment of the radiological impact of uranium mining in Saskatchewan (IEC Beak Consultants Ltd., 1986). An environmental pathways model, comprising a set of mathematical models, was used as the basis for a method for determining the cumulative radiological impact of uranium mining and milling. This study is of interest for three reasons: it is an example of the use of modelling as a method for performing cumulative impact assessment; it illustrates the value of environmental pathways models in estimating doses to human individuals; and it demonstrates how a number of models can be linked together to take account of the transfer of radionuclides through atmospheric, aquatic, and, terrestrial pathways to estimate doses to humans.

Models were used for calculating source terms for the operation phase, modelling dispersion and deposition of radionuclides, examining the environmental pathways by which radionuclides move from sources through to humans, and estimating the doses received by individuals. Doses to terrestrial and aquatic biota were estimated separately from those to humans.

6.8.1 Integration into the Environmental Assessment Process

Each company wishing to begin uranium mining operations in Northern Saskatchewan is required to submit an Environmental Impact Assessment to the Saskatchewan Department of Environment. In the environmental assessment, the effects of released radionuclides and other toxic chemicals are to be predicted. In addition, uranium mining companies must meet standards for emissions and effluents. These standards are set out in the Metal Mining Liquid Effluent Regulations and well as AECB licenses. The environmental impact assessment and compliance with the regulations relates solely to an individual mine and mill complex. Because of an anticipated increase in the amount of uranium mining activity in Northern Saskatchewan, however, there was a concern for the regional (cumulative) radiological impact of a number of mine and mill complex all being in compliance with the standards. Mathematical models were used as a major part of the study to assess the cumulative radiological impact.

6.8.2 Model Structure and Validation

The overall model was basically an environmental pathways model. Environmental pathways are the physical, chemical, and biological mechanisms by which releases of radionuclides reach humans. Environmental pathways models are mathematical models developed to predict doses to humans. The structure of the major components of the environmental pathways model used in the study were:

- Atmospheric dispersion- relied on Gaussian plume model in MILDOS.
- Transfer of radionuclides in terrestrial pathways - published transfer factors were used.
- Aquatic dispersion - chain lake river model was developed based on hydrological data supplied by Inland Waters Directorate and planimetry from topographic maps.
- Transfer of radionuclides to aquatic biota- published bioaccumulation factors.
- Dosimetry calculation were based on models and parameters recommended by the International Committee and Radiation Protection (ICRP 1977)

The MILDOS model was based on the UDAD (Uranium Dispersion and Dosimetry) model developed by Argonne National Laboratory (Momeni et al. 1979). It is assumed that UDAD was previously tested. MILDOS was not designed to consider food webs in Northern Canada and contamination levels in terrestrial biota were calculated outside of the model. A separate model had to be developed for the **air-lichen-**caribou-man food chain.

Site specific data were used where possible; however it is unclear that a rigorous attempt was made to calibrate the model to the site. In addition, the model model was not validated, nor were sensitivity analyses performed.

6.8.3 Model Limitations and Uncertainties

The model only considered operational facilities and neglected abandoned tailings and waste rock areas. These areas may significantly add to the regional impact and will likely have to be included for a more credible cumulative impact assessment. The model only makes regional estimates and does not make claims to estimate impacts at or near the existing facilities. This means that the local impacts are not considered.

The model requires a considerable amount of site specific data. At present much of this data is not available and would likely be difficult and costly to obtain. The following improvements to the models are required: refine estimates of atmospheric and aquatic source terms through **site-**specific measurements; improve aquatic dispersion modelling by including more detailed physical data (dimensions of lakes and rivers, flow rates); and estimate site-specific, environmental transfer coefficients for radionuclides to biota and humans.

As no sensitivity or uncertainty analyses were carried out it is difficult to suggest which of the needed improvements to the model would lead to the greatest reduction in uncertainty.

6.8.4 Implementation

The environmental pathways model used here was successfully integrated into a method for assessment of regional radiological impact. While the study results showed that doses were far below the acceptable limits, it does not appear that the assessment resolved the issue at hand. Since the assessment only included operational releases of radionuclides, the results do not imply that uranium mining will or will not have significant long term radiological impact on Northern Saskatchewan (IEC Beak Consultants Ltd. 1986).

The model was not used as part of a formal approval process. The study may be useful, however, should uranium mining activity increase in the future. The model can then be used again to assess regional (cumulative) radiological impacts. The study demonstrated that models can be used to assess the cumulative impacts at a regional scale of a number of uranium mines and mills. It also showed that in this application the model contained a great deal of uncertainty. Hence, there is a great deal of uncertainty about the cumulative impact. This leads to the conjecture that cumulative impact assessments may have greater amount of uncertainty associated with them than project assessments.

The model was concerned with assessing regional impacts; therefore, the results are not applicable to local conditions at or near any specific mine and mill complex. The spatial representation of impacts only at a regional scale indicates that impacts of each uranium mining and milling complex were not simply combined, although an environmental pathways model could have been used to make such estimates at or near the uranium operations. The fact that this was not done seems to be a failing of the analysis.

In terms of the general health risk assessment model outlined in the previous section, this case study only conducted hazard identification (step 1) and exposure assessment (step 3). Then an extensive dose assessment was undertaken. The results of the dose assessment were then compared against minimum acceptable doses and found to well below the standards. No attempt **was** made to integrate exposure assessment with dose response curves.

7.0 RECOMMENDATIONS

Improving the state-of-the-art in EIA demands the formulation of questions that will direct researchers. The task is 'akin to developing a scientifically testable hypothesis. Specifically, with the use of mathematical models, this means going beyond questions that apply generally to the use of information in EIA. For improvements to occur, we have to begin to examine what is special or unique about quantitative models compared to other techniques and tools.

The recommendations proposed herein are organized into three major groups: those concerned with consolidation existing best practice; those of a scientific and technical nature; and those of an institutional nature. The recommendation with respect to consolidating existing best practice are directed towards developing a knowledge base that allows EIA practitioners to make informed decisions on model use. Ideally, EIA practitioners should have the necessary information to decide which models (if any) to use, and when and how they should be applied. The scientific and technical recommendations are directed towards difficult problems regarding the inputs, outputs, structure, and integration of models. The institutional recommendations deal with the use of models as tools for communication, negotiation, and coordination and also address problems of model misuse and barriers to their successful application.

7.1 Consolidating Existing Best Practice

Workshop participants (cf. Appendix 1) had a strong feeling that much common knowledge and experience existed but was not documented. Therefore, they had a strong desire to have this knowledge codified in such a manner as to increase the awareness and use of quantitative models in EIA. This section makes three interlinked recommendations directed towards these ends. The first recommendation is to develop a comprehensive framework for classifying applications. The second proposes that a study be done to reveal the knowledge about how modelling strategies are used to coordinate an EIA. The third recommendation urges the development of an expert system as a vehicle by which information in the framework, and knowledge about modelling strategies, can be transferred to the practitioners of EIA.

7.1.1 The Need for a Comprehensive Framework

RECOMMENDATION 1: A comprehensive framework should be developed for classifying past and potential applications of models and modelling as to model type, the area of application, and phase of EIA process to which the model applies.

Many types of quantitative models have and are being applied in various ways to a range of problems. Clearly, a comprehensive framework is needed to integrate existing information about the use of models in EIA. After developing an initial typology of models, the categories should be classified according to the application area (e.g., socio-economic, biophysical, risk assessment, etc.) and the phase(s) of the EIA process in which the model could be applied, the implication being that an agreed upon framework for characterizing the EIA process exists. An example of one element in such a classification scheme would be an economic-demographic model used at the scoping phase in the socio-economic impact assessment of a nuclear plant.

This work could build upon the typology already developed by de Broissia (1984), and extended in the supporting research for these recommendations. As well as providing guidance for researchers in EIA, the framework would help potential model users and practitioners understand the place of models and modelling in EIA.

7.1.2 Modelling Strategy

RECOMMENDATION 2: A study of modelling strategies, incorporating the following tasks, should be undertaken:

1) review case histories where a modelling strategy has been used to coordinate a large environmental assessment or research project;

2) identify where such strategies fail to meet expectations;

3) develop a preferred modelling strategy, outlining all steps involved;

4) outline the necessary conditions that will ensure the success of the strategy; and

5) conduct an analysis of the costs and, if possible, the cost savings of such a strategy.

Although most formal environmental assessments and large environmental research projects use a suite of models, only some use models as part of an overall strategy to coordinate research and analysis. Such strategies determine how different kinds of models can be linked or how the results of one model can be used by another. For example, the strategy may define a hierarchy of models. More commonly, however, the assessment or planning process utilizes a more adaptive strategy; that is, learning from earlier modelling efforts and taking advantage of opportunities.

In developing the preferred strategy (task 3 above), it will be necessary to consider the appropriate balance of theoretical versus empirical models as well as validation and sensitivity analysis procedures.

Theoretical Models Versus Empirical Models

Any good model should have both theoretical (mathematical descriptions of basic processes) and empirical (based on the fitting of data) features. In general, the more complex theoretical models are designed to represent causal explanations for the behaviour of systems. Empirical models, while they should be firmly grounded in theory, simply represent an association between environmental components. The basic parameters of theoretical process models should be verifiable by data collection or experimentation. Similarly, more empirically based statistical models usually gain credibility if they are built on theoretical understanding. Parameters of theoretical models have biophysical meaning (e.g., rates of nutrient uptake): while in empirical models (e.g., regression models) the parameters usually have no biophysical meaning.

Empirical models are relatively easy to apply, and often are more readily accepted in environmental assessment than theoretical models because of their relative simplicity. The statistical basis of the models ensures that estimates of the error associated with predictions are readily available. Theoretical models are best used when it is important to evaluate alternate hypotheses or causality. In general, it is accepted that while theoretical models are often poor predictors, they are a necessary step in any analysis.

A modelling strategy should include a plan to use the strengths of both theoretical and empirical models. In the development of this plan, the following questions should be considered:

- In which types of model applications to EIA are empirical models more effective than process models and vice versa?

With respect to models of toxic contaminants, for example, generalized process models may be better suited to comparative analyses of several sites or several contaminants, while more empirical models may be better suited to precise assessments of specific contaminants at particular sites.

- Can individuals or groups applying models recognize, at an early stage, the appropriate balance of theory and empiricism for the issue of concern, or is convergence by trial and error the only route?

Model Outputs, Validation, and Sensitivity Analysis

Model outputs, validation, and sensitivity analysis raise a number of scientific and technical questions. There are also a number of questions, however, about their role in a modelling strategy. A modelling strategy should clearly specify how outputs will be decided, whether validation is to be done, and how sensitivity analyses will be conducted. The following points should also be incorporated:

- The design of a set of modelling procedures should ensure the model output meets the needs of the institutional actors in the EIA process, recognizing that the output is dependent upon the definition of the problem and the needs of the assessment.

- Because validation and sensitivity analysis are extremely important parts of modelling, recognized formal procedures for these activities should be incorporated in the overall design of a modelling strategy.

7.1.3 Strategy Development using Expert Systems

RECOMMENDATION 3: An expert system should be developed for prescribing the details of a modelling strategy for environmental impact assessment.

An expert system is computer software that emulates the problem-solving process of humans because the knowledge of experts is built into the decision-making system of the software. The time is right to develop an expert system for this application because there is both sufficient knowledge and appropriate (microcomputer) technology available to create a powerful management tool. Given information about the problem and the stage of the EIA process, the expert system would make recommendations about which types of models might be used. The system would be built around the expert knowledge that goes into the implementation of a modelling strategy (Recommendation 2, task 3), and would require the framework for classifying applications (Recommendation 1).

Developing an expert system requires specifying the rules used by experts in deciding which aspects of an environmental assessment are amenable to modelling and which types of models are most applicable. For example, one rule might be if there is ample data, then use an empirical model as a tool for making predictions; if there is little data, then use a theoretical model to guide data collection programs. We recommended developing an expert system based on such rules to provide a complete strategy for how models can be used, with suggestions on the type of models to be used.

The development of an expert system should be guided by the following questions:

- Within each application area of EIA, for what kinds of questions are existing models most appropriate? What is the role of each type of model' at the various stages of the EIA process?

- o What set of criteria (e.g., model features, performance statistics) should be considered in selecting a model for a given application?

- o For the models evaluated in each application area, what field data is needed to adequately calibrate the model to represent current conditions in the area under study, and give satisfactory answers to the questions the model was designed to address?

- o Based on the criteria developed in the second question, what are the best models in each application area for each stage of the environmental assessment process?

Answers to these questions would be valuable in their own right but when combined together in the logical framework demanded by the expert system they would be part of a powerful management tool.

RECOMMENDATION 4: CEARC should sponsor programs to develop other expert systems, which incorporate mathematical models, for use in EIA.

In general, expert systems could be used for many aspects of environmental assessment. For example, expert systems could be applied in the design of research and monitoring systems, the development of impact hypotheses, and the coordination of emergency responses.

7.2 Scientific and Technical Questions

As a general rule, scientific questions must be formulated in the context of a given subject area. Exceptions to this rule are questions concerned with the integration of models, which span all subject areas. This section discusses questions of model integration, but first deals with questions relating to the inputs, outputs, and structure of models.

7.2.1 Model Inputs

RECOMMENDATION 5: A study should be conducted to demonstrate how the input data needs of a model could be used to direct the data needs for the environmental assessment.

Model inputs are of three kinds:

- data characterizing the set of activities being assessed (e.g., emissions, effluents, land requirements, etc.);
- data characterizing the biophysical and socio-economic environment (e.g., winds, currents, rainfall, baseline population levels); and
- parameters for the model's relationships (e.g., dispersion coefficients, lethal toxicities, accident probabilities, growth rates, and employment multipliers).

Each kind of input introduces uncertainty into model predictions; a poorly specified development scenario may vary greatly from what development actually occurs; variation due to sampling error and deviations inherent in historical data often make it impossible to detect impacts; and errors in the estimation of model parameters may also lead to erroneous predictions.

Modellers deal with uncertainty by presenting a range of development scenarios and biophysical conditions in their analyses. This, combined with sensitivity analyses of model predictions, has given a fairer picture of the range of possible futures. This is only a more sophisticated form of modelling, however, and is not an improvement in the model's input.

Improvements in model inputs will come through greater commitment to data quality. Data quality, however, is not an unique issue to models; data quality. affects all forms of analyses in an EIA. Improvements in model inputs will also come through greater coordination of data collection and modelling activities. This coordination could be achieved by first developing the model early in the environmental assessment process. Then the field collection programs could be designed for collecting input data for the model. In practice, the results of field programs would likely lead to increased scientific understanding and this in turn would lead to a better model.

Note this recommendation is complementary to Recommendation 13 which deals with the use of models in integrating EIA.

7.2.2 Model Outputs

RECOMMENDATION 6: A study should be conducted to establish a set of validation standards for commonly used models in EIA.

The validation process is not without pitfalls. Comparisons of model results with historical data are often based on the implicit assumption that future events will mimic past events. If major structural changes occur in the system under study, then the historical data pattern may be an inappropriate yardstick against which to compare model results. Thus, the degree of credibility that is attached to a validated model, and the amount of effort that should be expended in model validation, is highly context- or problem-dependent. Presently, in the air pollution modelling field, considerable effort is being expended with formal validation processes to determine the best predictive models. In other fields, like economic-demographic modelling, while validation on historical data sets is often done, it is of limited value. Although it offers a test of the ability to reproduce past changes, shifts in the structure of the reference system or major changes in the values of key systems variables can adversely affect the model's future performance (Leistritz and Murdock 1981).

More specific questions relating to the technical and scientific side of the validation of model predictions are:

- What are the technical criteria for accepting the results of a model as valid?
- Does the absence of a formal validation of a model reduce its utility in EIA?
- What steps can be taken during the application of a model to ensure that model outputs are valid in the context of EIA?
- In some fields, most notably air quality, competitions are held to determine which models possess the best predictive abilities. These competitions have at least two major effects: improvements in the state-of-the-art and increased awareness of models and modelling. Are there other fields in which competition of this sort might lead to improvements?

7.2.3 Model Structure

RECOMMENDATION 7: CEARC should encourage research programs directly related to improving the scientific understanding underlying each of the scientific disciplines that support EIA. Special encouragement should be given to researchers who are applying models as part of their research.

Model structure refers to the relationships and parameters that make up a model. The structure of any model is related to the degree of scientific understanding about the system available at the time the model is constructed; thus, improvements in model structure come with improvements in our understanding of the systems being modelled. It is generally believed that the degree of understanding contained in models decreases as we move from the physical to the biological to the social sciences.

Because scientific understanding varies greatly across the many scientific disciplines that contribute to EIA, it is not possible to generalize about all application areas. Before meaningful research questions can be developed, there is a need to characterize the dominant modelling paradigms in each application area. Clearly, some areas, like air quality modelling, have generally accepted paradigms for model structure, whereas other application areas (e.g., socio-cultural impact assessment) have none.

Next, an analysis of the required theoretical development should be undertaken. In many areas there is considerable need for improving our conceptual understanding, particularly for models designed to address biological and social impacts. For other areas, no new research on the theoretical aspects of models may be required and work can concentrate on amassing empirical evidence for the relationships. This appears to be the case for many of the atmospheric dispersion models. If both the theory and empirical evidence are at an advanced state, there seems little practical value in further improvements for the purposes of EIA. Of course, this depends on the degree of certainty expected from the predictions of models.

7.2.4 Integration of Models

RECOMMENDATION 8: A study should be done to investigate the technical feasibility of constructing integrated interdisciplinary models for EIA.

Such a study would likely go through the following steps:

- develop a conceptual model of the system under study. A central question here is how many components to include in the model;
- in the conceptual model, identify the major components and their linkages for which there is insufficient knowledge to construct a quantitative model; and
- describe why these linkages or submodels cannot be constructed and suggest how these problems might be overcome.

The above approach is, of necessity, application and area-specific. If such an approach was adopted it should be possible to identify priority areas where improvements in integrated models are most needed.

Perhaps the greatest unrealized potential for using models in EIA is that of integrating the various parts of the assessment. EIA is a truly interdisciplinary endeavor. To address most environmental problems we must consider physical, biological, and social processes. In many environmental assessments, the impacts or effects are not adequately addressed because of either a failure to link models across disciplines or a failure to link analysis and information. Our conceptual models have begun to make these linkages but there are few good examples of truly integrative quantitative models. For example, we need models that can reliably predict:

- the fate and biological effects of oil spills;
- the fate, biological effects, and health effects of releases of toxic chemicals; and
- the exposure to and health effects associated with air pollution and/or radiation.

These are only a few examples of where our conceptual understanding is sufficiently well-advanced, and where the use of quantitative models could make a significant contribution. While this is the one research area where there is the greatest need for technical improvement, there is very little directed or even opportunistic research being done.

RECOMMENDATION 9: Analysis of a case where integrated set models have been used in environmental assessment should be conducted. Two potential case studies are: oil spill fishery interactions on Georges Bank, and the Grand River Basin Water Management Study.

Spaudling et al. (1983) described an oil-spill fishery impact assessment model which was applied to the Georges Bank - Gulf of Maine region to address probable impacts of oil-spills on several key fisheries. The main model comprises sub-models dealing with the following processes: oil-spill fate; shelf hydrodynamics; ichthyoplankton transport and fate; and fishery populations.

The Grand River Basin Water Management Study (Fortin and McBean 1985; Grand River Implementation Committee 1982) was a multiple-objective planning study of water resource use in the Grand River Basin of Ontario, Canada. Within the basin there were short and long term problems with flooding, water quality impairment, and water supply shortfalls. Through a series of engineering and scientific studies, a number of potential water management actvities were identified and described. A number of models, including simulation and linear programming models, played a prominent role in these studies.

7.3 Institutional Questions

Institutions can be rules or entities for guiding human behaviour. Under this general definition, the basic components of an institutional framework for environmental impact assessment and management are:

- o the entities that establish rules or laws about how resources may be developed and managed - usually legislative bodies and regulatory agencies;
- o the rules or laws governing the development and management of resources;
- o the entities that participate in deciding which resources will be developed and managed; and
- o the entities that implement the development and management of approved programs.

In an institutional context it is useful to think about models as an information source and modelling as a tool to facilitate decision making. In this framework, models, modelling, and modellers have influenced and have the potential to influence institutional actors, who include decision makers, the public, judges, environmental hearing boards, and regulatory agencies.

RECOMMENDATION 10: An institutional analysis should be carried to ascertain:

- o how current formal environmental assessment institutions (e.g., FEARO, NEPA) affect the quality and potential application of models; and

- how institutions are affected by the use of models.

More specific institutional questions can be grouped under five headings: communication between modellers and the institutional actors; misuse of quantitative results; the role of models in negotiations; modelling to coordinate and integrate assessments; and barriers to application.

7.3.1 Communication

There are two main challenges under this topic: developing more effective tools for communication and developing models and modelling strategies that respond to an ever changing institutional environment. Perhaps there are special problems inherent in communicating model results as opposed to communicating other kinds of information. Attempts to have institutional actors understand the details of models usually fail. Thus, to be relevant to the decision making and approval processes, the results of models must be presented in a simplified and summary fashion.

RECOMMENDATION 11: Institutional analyses should be undertaken to better understand how models can be merged into the institutional environment. It is expected that these analyses would include:

- A review of the effect of modelling on decisions in past applications. This would be a continuation of the case study analysis done in this report.

- An interview-based study on the awareness of decision makers and proponents/opponents with regard to the capability and utility of models and modelling.

- o An interview-based study on modellers' awareness of the information needs of decision makers and proponents. This would involve a review of the use of models at various stages of an EIA process.

- o Recommendations on ways in which models can have greater influence on the institutional entities responsible for EIA.

- o An assessment of existing or potential methods and techniques (e.g., interactive gaming via computer graphics, audio-visual presentations to explain model assumptions and results) that have proven successful in communicating model results to different audiences (e.g., decision makers, the public, judges, or environmental hearing boards).

7.3.2 Misuse of Quantitative Results

RECOMMENDATION 12: A study should be conducted to determine the extent and seriousness of misuse and misinterpretation of model results in the context of environmental assessment. The study should answer the following questions:

- o How can misuse of the quantitative results of models be avoided?

- o Is the problem of misuse serious enough to avoid using models where the potential for misuse is great?

- Does an overemphasis on quantitative modelling demean qualitative analyses?

Results can be misused in one of two ways: out of ignorance and out of self-interest. Misuse out of ignorance assumes that decision makers are desperately looking for something to base their decision or position on, and seize upon a number. The mystique of the computer may contribute to an unjustified belief in the certainty of the predictions (i.e., the quality of the information). Misuse out of self-interest implies overstatement or misrepresentation of the model's results.

7.3.3 The Role of Models in Negotiation

RECOMMENDATION 13: A study should be conducted to investigate how models and modelling can productively bring substantive information to bear in resolving environmental conflict. The study should be guided by the following questions:

- Is the "hired gun" phenomena that often arises in environmental conflicts exacerbated or diminished by the use of models?

- Given two or more contending positions, how can the modelling process foster cooperation, negotiation, and agreement?

- For which types of environmental mediation problems are models most useful?

- Under what conditions will the participants in environmental mediation accept modelling and model results?

If one views EIA as essentially a bargaining or negotiating process, then models have a potential role to play in the negotiations. The best known example of such an application is the use of the MIT Cost Model of Ocean Mining and Associated Regulatory Issues in the Law of the Sea Negotiations (Sebenius 1981). This example demonstrates the use of the model in helping the participating institutions determine the rules and regulations governing seabed mining. Four of the case histories in this report (i.e., Beaufort Risk Analysis, NEDAM in Fort Union Coal, and the air quality case studies) are examples of a slightly different application. The models were used for conflict resolution rather than negotiation.

Much of the negotiation process is concerned with form; it appears that models could provide some of the substance for negotiations. It should be noted, however, that models have traditionally been used to deal with scientific and technical issues. In some instances competing models or competing experts have focused an issue through rigorous critique of assumptions and methods. This focusing, however, costs considerable time and money, and the role of the models seems primarily to define where the experts agree to disagree.

7.3.4 Modelling to Coordinate and Integrate Assessments

RECOMMENDATION 14: A study should be conducted to evaluate the utility of existing procedures for coordinating and integrating environmental impact assessments. This study should address the following questions:

- In the context of EIA, is the process of building models more important than the predictive capability of models?

- Does interaction between the various actors lead to more appropriate model definition and forms of predictions?

- How do current formal environmental assessment procedures (e.g., NEPA, EARP) facilitate or frustrate this kind of interaction with modelling? (This question is a subset of the first question in Recommendation 10 above.)

- Which existing approaches and techniques to modelling have a proven track record in coordinating and integrating large environmental programs?

In Chapter 2 of this report, several benefits of modelling were presented. Among them, the process of building models has great potential for increasing understanding and cooperation amongst the institutional actors. Many of the successful applications of models have involved interaction among modellers, proponents, regulators, and in some cases, the public.

Comparing the benefits with the institutional and technical questions outlined above, it appears that if modelling were widely accepted and done well, many of the current problems and research questions might be resolved. The argument here is that modelling forces interdisciplinary and cross-interest cooperation and provides rigor to the assessment. Models and modelling, however, are not widely accepted as tools in integrating assessments, nor in environmental mediation.

7.3.5 Barriers to Application

RECOMMENDATION 15: An assessment should be conducted of Canadian capability to undertake modelling in EIA, as well the costs and benefits of increasing the use of models in EIA. This study should consider the following questions:

- What skills and experience are required for an individual or group to apply models in EIA?
- Can private companies or government agencies who act as proponents in EIAs develop the skills and experience for applying models in-house, or should they rely primarily on outside experts?
- How many centres of excellence in modelling can Canada maintain within each region and application area?
- What are the costs and benefits of formal regulations that require the use of quantitative tools in EIA?

There are a number of potential problems that may serve as limitations to more widespread applications of models in EIA:

- Occasionally an inappropriate use of a quantitative model occurs because of inexperience either with the model or with EIA.
- It may be inadvisable to institute formal requirements to use models in EIA, because this may

penalize existing EIA practitioners who do not have modelling capabilities.

Many client agencies do not have sufficient expertise in-house to build or modify models. This may restrict clients to only use models for evaluating alternatives.

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APPENDIX 1

APPENDIX 1

List of Participants Attending a Workshop in Toronto, March 12 - 13, 1986.

NAME	AFFILIATION	TELEPHONE
Beanlands, Gordon E.	CEARC Halifax, N.S.	902-424-7044
Burnett, R.A.	Health & Welfare Canada Ottawa, Ont.	613-990-8896
Conover, Shirley	Maritime Testing Ltd. Dartmouth, N.S.	902-463-2486
Everitt, Robert R.	ESSA Ltd. Vancouver, B.C.	604-689-2912
Fortin, Mike	Ecologistics Ltd. Waterloo, Ont.	519-886-0520
Griffin, Brian J.	F. Bercha & Associates Calgary, Alta.	403-270-2221
Leistritz, Larry F.	Univ. of North Dakota Fargo, ND	701-237-7441
Maher, John	Ontario Hydro Toronto, Ont.	416-592-5163
Marmorek, David R.	ESSA Ltd. Vancouver, B.C.	604-689-2912
Neil, Elizabeth	Reid Crowther & Partners North Vancouver, B.C.	604-986-6181
Portelli, R.V.	Concord Scientific Downsview, Ont.	416-630-6331
Rapaport, Robert	Procter and Gamble Cincinnati, OH	513-423-1539
Wolf, Charles P.	Social Impact Assessment Center New York, NY	212-966-2708

APPENDIX 2

APPENDIX 2

List of Interviews

NAME	AFFILIATION
Angle, Randy	Ministry of Environment Edmonton, Alberta
Bennett, Richard	Ministry of Environment Victoria, B.C.
Bishop, Bill	Procter and Gamble Cincinnati, Ohio
Burnett, Rick	Health and Welfare Ottawa, Ontario
Burns, Larry	EPA Athens, Georgia
Cabe, Loren	BLM Billings, Montana
Chalmers, Jim	Mountain West Arizona
Chandler, John	Concord Scientific Toronto, Ontario
Christensen, Sigurd	Oak Ridge Nat. Lab. Oak Ridge, Tennessee
Churcher, Archie	Dome Petroleum Calgary, Alberta
Cohen, Phil	DOE Ottawa, Ontario
Conover, Shirley	Maritime Testing Halifax, Nova Scotia
Coupal, Bernard	Andre Marsan and Assoc. Montreal, Quebec
Davis, Rod	Ministry of Environment Victoria, B.C.
DiToro, Dominic	Hydroqual Inc. Mahwah, New Jersey
Erickson, Diane	Consultant Victoria, B.C.
Flynn, Jim	Mountain West, Seattle, Washington
Fontaine, Tom	NOAA Ann Arbor, Michigan
Fortin, Mike	Ecologistics Waterloo, Ontario

Griffin, Brian	Frank Bercha and Assoc. Calgary, Alberta
Hickman, Fred	Tetratech, San Bernadino, California
Leistritz, Larry	University of North Dakota Fargo, North Dakota
MacKay, Don	University of Toronto Toronto, Ontario
Maher, John	Ontario Hydro Toronto, Ontario
Marshall, Dave	FEAR0 Vancouver, B.C.
Millan, John	EPS, DOE West Vancouver, B.C.
Neil, Elizabeth	Reid Crowther North Vancouver, B.C.
Portelli, Ron	Concord Scientific Toronto, Ontario
Reuber, Barbara	University of Toronto Toronto, Ontario
Rapaport, Rob	Procter and Gamble Cincinatti, Ohio
Sector, John	Ministry of Environment Victoria, B.C.
Sherwood, Bob	EPS, DOE West Vancouver, B.C.
Snodgrass, Bill	Beak Consulants Ltd. Toronto, Ontario
Walters, Carl	University of British Columbia Vancouver, B.C.
Weibe, John	DOE Vancouver, B.C.
Wilson, Rick	Ministry of Environment Victoria, B.C.
Winter, Richard	Argonne Labs Argonne, Illinois
Wolf, Charlie	Social Impact Assessment Center New York, New York
Wolfe, Larry	Consultant North Vancouver, B.C.

APPENDIX 3

APPENDIX 3

Case Histories

1.0 SOCIO-ECONOMIC

1.1 RED-l and REAP Economic Demographic Model 1

Project Where Used

North Dakota Regional Environmental Assessment Program (REAP), a state-funded planning and information program directed at both the local and state levels. During 1977-1979, the model was applied by over 50 government agencies and private firms. Evaluated fiscal impacts from large scale coal and oil shale developments in rural areas.

Authors

A social science team from both the University of North Dakota and North Dakota State University, in combination with consultant Arthur D. Little, Inc.

Output from Model

Baseline and single or multiple project impact projections at regional, county, and local levels. Output: employment by type; population by cohort; school enrollments (by age); housing type requirements; public sector costs and revenues; and fiscal impact projection of public service costs and revenues.

Role of Model

To assist in the development of state taxation policies, through evaluation of various scenarios, guide administration of a rural-based impact assistance program, and aid local government in planning local facilities to accommodate sudden increases in populations. Use of the model had a substantial influence on the development and implementation of the taxation/finance program.

Was the Model Validated? How?

Not stated.

Other Comments

Results from the model were used to justify opposing points of view by legislators. Consequently, the tasks of the modellers was made more difficult by the divergence in users' goals. Successful use of the models was due to: early and continued-involvement of users in design and development of models, timely provision of model results to the decision process, effective organization and management of the inter-disciplinary model team, and continuity of technical support; i.e., updated databases and professional support, appropriate application of the model and interpretation of results.

Reference

Leistritz, F.L., S.H. Murdock, N.E. Toman, and D.M. Senechal. 1982. Local fiscal impacts of energy resource development: applications of an assessment model in policy making. North Central Journal of Agricultural Economics 4(1): 47-57.

1.2 SEAM and EIAM (Social and Economic Assessment Model)

Project Where Used

EIAM was applied in the southern U.S. (Alabama, Kentucky, Georgia, Florida, Tennessee) to assess impacts of construction and operation of waterway (early 1980s) at a county level. SEAM was applied in the midwest U.S. to evaluate the national energy plan to develop coal resources (mid 1970s).

Authors

SEAM: Argonne National Laboratory

EIAM: Argonne & U.S. Corps of Engineers (USCE)

Output from Model

SEAM: Population projections, economic (export base) data, public service and fiscal impacts.

EIAM: In addition to the above, a revenue expenditure model (linear regression driven by population growth rates) was used.

Role of Model

SEAM: Used for prediction of impacts of new policy direction – Carter's Energy Plan. This plan had to evaluated quickly so there was little interaction between the modellers and decision makers.

EIAM: Used more as a planning tool (economic redevelopment) than as a tool for impact assessment. This interactive model was used by county governments to create various development scenarios. By comparing the benefits of these scenarios, the county can select the optimum strategy for taking advantage of the newly constructed waterways.

Was the Model Validated? How?

SEAM: Not scientifically validated but the users and decision makers felt the results were useful.

Other Comments

The EIAM model is introduced to county governments through an innovative concept in mobile training facilities. A truck-trailer unit, complete with computers linked to a central facility and database, is moved from county to county. In this training unit, county planning staff can access both the EIAM model and a computerized mapping program. If the model is seen as being useful to the planning process, a county can make a contract with the USCE for computer services.

Reference

Richard Winter; Argonne Labs, Argonne, Illinois, pers. comm.

1.3 AFSEM (Air Force System Evaluation Model)

Project Where Used

To evaluate the impact of constructing MX missile sites in the midwest (early 1980s).

Authors

URS-Berger, consultants to Air Force; Tetratech Consultants later amended the model.

Output from Model

Includes 6 components: economic (input-output), demographic, economic-demographic interface, residential allocation, public service, and fiscal impacts.

Role of Model

1) To predict impacts on the regional economy, and 2) to determine if public service resources are adequate to meet demand.

Was the Model Validated? How?

Results from each component of the model were compared to historical data and to changes that were monitored; 10% variance within an 8 year period.

Other Comments

When this type of model is used, the researcher is still faced with making many assumptions about the data (i.e., expected family size of workers). Therefore, the person running the model has to be experienced, making it more difficult to transfer the model to various projects.

Reference

Fred Hickman; Tetratech, San Bernadino, California, pers. comm.

1.4 SEARS (Socio-economic Analysis of Repository Siting)

Project Where Used

Evaluating sites for a high level nuclear waste repository in the southern U.S. (1983-present).

Authors

SEARS is based on RED 1, RED 2 (see above) and TAMS (Texas Assessment Modelling System).

Output from Model

Business activity; personal income; employment by type; population changes; population cohorts; housing demand; school enrollments; requirements for public, medical and justice services; public sector costs and revenues; and net fiscal balances. The model can also assess the impacts from multiple projects. SEARS comprises 6 submodels; the economic model is an input-output model.

Role of Model

For prediction of economic, demographic, public service and fiscal impacts at local and regional levels.

Was the Model Validated? How?

Validation is underway.

Other Comments

The user can specify the reporting format or modify the assumptions. The model was also designed to be transferrable to different geographic areas. In addition, the model is well-documented so someone not familiar with the development of the model can still use it.

Reference

Hamm, R., S.H. Murdock, F.L. Leistritz, and R.A. Chase, 1984. A socio-economic impact model for assessing the effects of a high level nuclear waste repository site. Impact Assessment Bulletin 3: 6-19.

2.0 BIOPHYSICAL - AIR QUALITY

2.1 PTDIS, PTMAX, PTPLU (Point of Maximum Concentration)

Project Where Used

Various industrial sites in B.C.

Authors

From EPA UNAMAP series; Gaussian dispersion models.

Output from Model

Temporal and spatial concentrations of specified pollutants.

Role of Model

The provincial government uses the model for pre-permit evaluation of projects. If, through modelling, it appears that concentrations will be above the regulatory limit, the environmental controls for the industrial facility are redesigned.

Was the Model Validated? How?

Yes, always validated with on-site measurements.

Other Comments

Does not account for terrain variation; it is a simplistic model.

Reference

Rod Davis; Environmental Services, B.C. Ministry of Environment, pers. comm.

2.2 MPTER: Multiple Sources With Terrain Adjustment.

Project Where Used

Prince George (1985-ongoing) - simulation of airshed quality.

Authors

EPA UNAMAP series.

Output from Model

Maximum peak concentrations of sulphides either hourly, daily or annually. Valid for area up to 50 km radius from sources.

Role of Model

To evaluate alternate control scenarios for reducing the overall concentrations of sulphides in the regional airshed.

Was the Model Validated? How?

Validated with actual measurements.

Other Comments

A committee with representatives from industry (3 pulp mills and a refinery) and the provincial government are reviewing the results of the analysis: the committee's purpose is to define a regional air quality management program.

Reference

Rod Davis; Environmental Services, B.C. Ministry of Environment, pers. comm.

2.3 Gaussian Dispersion Model

Project Where Used

Proposed Dow Chemical plant, San Francisco Bay, California (1974).

Authors

Bay Area Air Pollution Control District.

Output from Model

Provided an estimate of the impact from the proposed plant on the ambient air quality for primary pollutants. This analysis was based on 11 point sources and one area source.

Role of Model

Used for pre-project evaluation. The results indicated there would be a significant impact so the project was disallowed.

Was the Model Validated? How?

Not discussed.

Other Comments

Dow Chemicals challenged the assumptions of the analysis, the confidence limits of the model, and the sensitivity of the model to background concentrations. "These and other questions indicate that mathematical models should be used only as an aid to decision making and should never be allowed to make the actual decision." (Neely 1980).

Reference

Neely, W.B. 1980. Chemicals in the Environment: Distribution, Transportation, Fate, Analysis. New York: Marcel Dekker.

2.4 Utility Simulation Model of Sulphur Dioxide Concentrations

Project Where Used

In the Ohio River Basin Energy Study (ORBES), completed in the late 1970s, the model was used to evaluate the impacts of additional electrical utility operations in the years 1976-2000.

Authors

Developed by Teknekron Research Incorporated, Waltham, Massachusetts.

Output from Model

Model takes account of projected power demands, pollution control costs, electricity prices, and regulatory constraints (increasingly restrictive). sulphur dioxide emission projections were translated into regional air quality impacts for short and long concentration averaging times.

Role of Model

To evaluate changes in air quality with variations in electrical demand, regulatory constraints and power plant retirement schedules, and start-up of new coal-fired power plants. The results showed that there would be a reduction in sulphur dioxide emissions if regulations were complied with. The short term concentrations would, however, exceed standards at times. For these areas and times, other models (i.e., puff trajectory) could be used to gain a better understanding of the influence of background concentrations.

Was the Model Validated? How?

Compared results of model with measured air quality values in 1974 - "relatively good agreement".

Other Comments

Noted inability of Gaussian dispersion models to simulate pollution transport in high emission density areas. Other models are more reliable.

Reference

Mills, M.T., E.Y. Young, A. Hirata, and A. Van Horn, with L. Smith. 1981. Air quality projections for the Ohio River Basin. In Air Pollution Modelling and its Application. (C.D. Wispelaene, ed.). New York: Plenum Press.

3.0 BIOPHYSICAL - WATER RESOURCES

3.1 Linear Programming Screening Model

Project Where Used

Grand River Basin Water Management Study (19784982).

Authors

Fortin and McBean. Ecologistics and University of Waterloo, respectively.

Output from Model

A conceptual model was used to select, from a range of management actions, the optimum strategy to reach stated objectives.

Role of Model

To identify a range of feasible and effective plans that would satisfy objectives of controlling flooding and maintaining the water quality and supply.

Was the Model Validated? How?

This was the first time the model was applied so it is now undergoing validation through post-project analysis.

Other Comments

In the process of developing and running this model, the data deficiencies in the project were highlighted. Later, further analyses were guided by the initial results from the model. The process of modelling also forced analysts to adopt a system-wide approach to planning.

Reference

Fortin, M. and E.A. McBean. 1985. A linear programming screening model for the Grand River Basin. Canadian Journal of Civil Engineering 12: 301-306.

3.2 Linear Programming Model

Project Where Used

At Carnegie Lake in Mercer County, New Jersey the model was used to to assess the cost-effectiveness of appropriate point and non-point source phosphorus control measures. The eutrophic state of the lake was seriously affected by non-point source nutrient loading (started in 1977).

Authors

R.B. Paterson, M.Sc. Thesis, Rutgers University, plus authors of reference given below, who work for the New Jersey Department of Environmental Protection.

Output from Model

The design of the model is based on in-stream loading from various sources of phosphorous. The transport of phosphorous is modelled, giving total phosphorous concentration within the ith reach of the watershed, which can be related to the concentrations at the beginning of the reach. Combining these results with four Lake Eutrophication Models, the Linear Programming Model can be used to identify where inputs from various sources can be reduced in order to achieve target phosphorous loadings at minimum cost.

Role of Model

Discovered that it was difficult to find a solution without reducing standards (increasing acceptable levels of phosphorous) or that K levels could only be reduced at a significant cost for point source treatment.

Was the Model Validated? How?

Yes, results of the model were compared with data collected at a gauging station.

Reference

Jenq, T.R., C.G. Uchrin, M.L. Granstrom, S.F. Hsueh. 1983. A phosphorous management model for Lake Carnegie (NJ.). In Analysis of Ecological Systems: State-of-the-Art in Ecological Modelling. (W.K. Lauenroth, G.V. Skogerboe, and M. Flug, eds.). New York: Elsevier Scientific Publishing Co.

3.3 Water Quality (SQUAL)

Project Where Used

O'Shaughnessy Dam on Scioto River, Columbus, Ohio to comply with regulations (19784979) of the Federal Energy Regulatory Commission (FERC) during construction of power generating facility on an existing reservoir.

Authors

Burgess and Niple Limited, Engineers and Architects.

Output from Model

This water quality model, characterized as a one dimensional, non-dispersive model for BOD, DO, N, NH3-N, NO2, and N03, quantified the differences in the dissolved oxygen content downstream of the dam, with and without hydro generating facilities. The results indicated the location of the recovery zone and identified times at which problems would occur.

Role of Model

To identify the magnitude of the dissolved oxygen problem, based on modelling under various scenarios. The proponents suggested mitigation measures based on these results. The authors noted that the methodology was acceptable to both federal and state agencies. In the final stages, the government agencies required that there be DO monitoring of the hydroelectric intake and discharge.

Was the Model Validated? How?

Calibrated based on research and field observations from same area.

Other Comments

Initially, the effects of the dam on fisheries resources and water quality was of concern. The options were either to do direct experimentation, which was too expensive and time-consuming, or modelling. Although a dynamic model would have been more applicable, the proponents chose a steady-state model because of its simplicity, the need for a smaller database, and because the assumptions were explicitly stated.

Reference

Walkenshaw, B.G., G.B. Jones, and J.R. Kerr. 1983. A practical water quality model for assessing low head hydroelectric projects. In Analysis of Ecological systems: State-of-the-Art in Ecological Modelling. (W.K. Lauenroth, G.V. Skogerboe, and M. Flug, eds.). New York: Elsevier Scientific Publishing Co.

4.0 BIOPHYSICAL - ECOLOGICAL

4.1 Ecological-Economic Analysis (input-output analysis)

Project Where Used

Mississippi Deltaic Plain Region, Northern U.S. Gulf Coast (circa 1980-1982); underway when reported.

Authors

Coastal Ecology Laboratory, Center for Wetland Resources, Louisiana State University. Funding by U.S. Department of Interior, Bureau of Land Management, Fish and Wildlife Service, National Coastal Ecosystems Team.

Output from Model

Identifies commodity flow, by process, through an input-output table. The model is basically an accounting system for keeping track of production and consumption of various commodities, such as ecological goods and services. After the table is constructed, it undergoes mathematical manipulations to determine shadow prices (in terms of taxes and subsidies) for ecological commodities. Then the table can be converted to units of dollar value or embodied energy in order to calculate equivalence between commodities. This model can also: calculate direct and indirect impact-multipliers; quantify impacts, and therefore estimate direct and indirect impacts of small perturbations about the average conditions; and create a preliminary database for more sophisticated simulation modelling.

Role of Model

The information produced is useful to environmental managers as a description of the functional interdependence of systems. Calculations can be seen as the "value" of ecosystems and their components. The model is a useful conceptual and analytical tool.

Was the Model Validated? How?

No, because it is conceptual and output cannot be measured in the field. Validated in terms of personal knowledge and experience.

Other Comments

The structure of this model attempts to deal with the issue of establishing social costs for environmental changes versus the usual route of government regulation of anticipated impacts (problem of joint product calculation - these are ecological costs). Long term or dynamic effects are better described by simulation modelling. Although the model is not very precise in terms of economics, it does attempt to integrate economics with ecology. Also, through the process of collecting and inputting data into the model, the researchers were able to catalogue a large volume of data from diverse sources.

Reference

Costanza, R., L.M. Bahr, C. Neill, S.G. Leibowitz, and J. Fruci. 1983. The Mississippi Deltaic Plain Region (MDPR) study: An application of ecological models to the analysis and management of a complex coastal region. In Analysis of Ecological Systems: State-of-the-Art in Ecological Modelling. (W.K. Lauenroth, G.V. Skogerboe, and M. Flug, eds.). New York: Elsevier Scientific Publishing Co.

4.2 Western Spruce Budworm/Forestry Interactions

Project Where Used

Developed for Canada/United States Spruce Budworm Program (1977-1983) by authors, one of several study teams assigned to project.

Authors

Colbert: USDA Forest Service, Portland; Sheehan: University of Idaho, working at Pacific Northwest Forest and Range Experiment Station, Portland; and Crookston: University of Idaho, Forestry Sciences Lab, Moscow, Idaho.

Output from Model

For this project several interrelated models were used: population dynamics, stand growth, and yield. Western Spruce **Budworm** (population dynamics) - 2 components: BWFLY is adult dispersal and egg laying; BWMOD is life cycle of egg hatch to adult emergence. STAND-PROGNOSIS model simulates the growth of trees in a distance independence manner (used by USDA Forest Service, BLM, state forestry departments in Washington and Idaho, B.C. Forest Service, and private forest companies in both countries). The combined results are yield tables, indicating the impact of **budworm** defoliation on forest productivity. Tables can be used with other models for forest resources planning and harvest schedules.

Role of Model

Previous versions helped to identify areas for further research. Sensitivity analysis was also used to direct further research. The models were used to explain the integration of various studies to resource managers who can then see how specific research results can answer their questions. The models are based on data that is currently being collected or already exists: in other words, the use of these models does not require new field observations. The models can also be used in a gaming sense to see the effects of decisions on both forest productivity and the effectiveness in controlling spruce **budworm.** In addition, this model can be integrated with economic assessments of suppressive actions: i.e., compare the cost of spraying to the costs from potential losses of productivity.

Was the Model Validated? How?

The validation process of this model is ongoing. It is part of a series of models being developed and coordinated overall by a specially chosen research group. Annual meetings are held between resource managers and researchers to promote exchange of information and review of proposed research and model development.

Reference

Colbert, J.J., K. Sheehan, and N.L. Crookston. 1983. supporting decisions on Western Spruce Budworm in forest management using simulation models. In Analysis of Ecological Systems: State-of-the-Art in Ecological Modelling. (W.K. Lauenroth, G.V. Skogerboe, and M. Flug, eds.). New York: Elsevier Scientific Publishing Co.

4.3

Oil Spill Trajectory Analysis Model and Population Recovery Model

Project Where Used

Northern Gulf of Alaska, Proposed Outer Continental Shelf Lease #55.

Authors

U.S. Geological Survey.

Output from Model

Probability estimates of oil spills, simulation of probable movement of oil spill, and assessment of damage and recovery to those seabird populations affected by a spill.

Role of Model

To determine the probability of significant reductions in specific bird populations due to oil spills. The Monte Carlo simulations provided estimates of likely risks to seabird populations over time. These risk calculations are then evaluated by decision makers.

Was the Model Validated? How?

Field data and historical data were used as inputs to both models, but they have not been validated.

Reference

Samuels, W.B. and K.J. Lanfear. 1.982. Simulations of seabird damage and recovery from oil spills in the Northern Gulf of Alaska. Journal of Environmental Management 15: 169-182.

5.0 TECHNICAL RISK ASSESSMENT

5.1 Ranking Environmental Risk from Oil Spills

Project Where Used

West Coast Offshore Exploration Environmental Assessment Review - presented to panel conducting hearings (October, 1985).

Authors

Dr. Phil Cohen and J. Slater, Environment Canada, prepared for Environment Canada.

Output from Model

Using a 18 km x 18 km grid over the Queen Charlotte Islands and west coast of B.C. the authors identified and evaluated the sensitivity of the environment to oil spills. The model distinguishes between 7 resources and activities occurring in the area and evaluates the impact on each of them. The final product is an aggregate impact index for each grid which can be categorized from extreme through 3 categories to low. This output allows the reader to gain a conceptual/intuitive feel for the magnitude of impacts. Can alter assumptions for resource weightings to change impact scenarios.

Role of Model

The results of the model were used to support Environment Canada's policy stance at the hearings. The use of the model also simplified the data, thereby reducing the gap between statisticians and laymen.

Was the Model Validated? How?

No, the documentation does not give the research context for the development of this methodology so comparisons with other studies is lacking.

Other Comments

Cohen said the model was not well received at hearings - it was too technical for the audience and they did not see the implications of applying it to this problem. The model would work better as an interactive model that decision makers could use to develop scenarios. (Note that the format of this model follows from one of the recommendations of the Beaufort Sea Environmental Board; that is, proponents should identify areas where and when renewable resources could be adversely affected, p. 36.)

References

Cohen, P. and Slater, J. 1985. Environmental Sensitivity to Oil Spills of the Queen Charlotte Islands Area. Report Number 6. Pacific and Yukon Region, Environment Canada, Vancouver, B.C.

Phil Cohen; Environment Canada, Ottawa, pers. comm.

Beaufort Sea Environmental Assessment Panel. 1984. Beaufort Sea Hydrocarbon Production and Transportation Proposal. Federal Environmental Assessment, Review Office, Hull, Quebec.

5.2 Public Risk - LNG Plant Siting

Project Where Used

La Salle Terminal, Texas.

Authors

Woodward-Clyde Consultants for El Paso LNG company. Submitted report to Federal Power Commission.

Output from Model

The model has three components: development of accident scenarios and associated probabilities; quantification of public risks; and evaluation of public risk. The actual output includes the probability, extent, location of spills, the probability of the vapor cloud igniting, location and size of vapor cloud at ignition, and probabilities of fatalities under various conditions and accidents (computes annual estimates of fatalities per year and risk levels).

Role of Model

To integrate scientific knowledge and assumptions from several disciplines into a framework; to use sensitivity analysis to test the significance of assumptions in the overall operation of the facility; to systematically go through the estimates of public risk, identify what they are, and when and where they occur; and develop strategies to reduce risks.

Was the Model Validated? How?

Validation was not discussed.

Reference

Keeney, R. 1980. *Siting Energy Facilities*. New York: Academic Press.

5.3 Slick Trajectory Model

Project Where Used

Beaufort Sea Environmental Impact Statement (1982).

Authors

Arctic Sciences Ltd. for Dome Petroleum Ltd.,- ESSO Resources Canada Ltd., and Gulf Canada.

Output from Model

The output of the model graphically describes the movement of a slick within a gridded area. Movement of the oil is traced by lines through the grid. At discrete points in time, the output gives the oil composition, the degree to which the slick dispersed, and the location of the slick.

Role of Model

To predict the movement of oil spills so that countermeasures to clean up oil spills and mitigate impacts can be developed. Because the results are imprecise, they are not seen as predictive but rather as a basis for discussions of possible impacts. Archie Churcher of Dome Petroleum said that the process of risk assessment helps identify those parts of an industrial process which are poorly designed, or in other words, are the weakest link in a chain.

Was the Model Validated? How?

The documentation did not discuss validation of the model but it is based on results from other research done in the area. The Beaufort Sea Environmental Assessment Board recommended that the proponents and federal government departments cooperate to improve and validate this model.

Other Comments

The interaction of oil and ice was not taken into account in this model because it was not completely understood.

References

Beaufort Sea Environmental Assessment Panel. 1984. Beaufort Sea Hydrocarbon Production and Transportation Proposal. Federal Environmental Assessment Review Office, Hull, Quebec.

Dome Petroleum Limited, Esso Resources Canada Limited, and Gulf Canada Limited. 1982. Beaufort Sea - Mackenzie Delta Region Environmental Impact Statement. Volume 6: Accidental Spills. Dome Petroleum, Calgary, Alberta.

Archie Churcher; Dome Petroleum, Calgary, Alberta, pers. comm.

6.0 HEALTH RISK ASSESSMENT

6.1 Dose Response of Laboratory Animals

Project Where Used

Laboratory tests to determine exposure levels of vinyl chloride monomer (VCM) that lead to the growth of tumors.

Authors

Various; authors bring together many pieces of research. Several researchers used the same statistical model in analyzing results.

Output from Model

This study compared three types of dose-response calculations: probit, logit and weibull. The purpose of the studies that were summarized is to take maximum exposure levels, determined through lab experiments (where number of tumors found is below predetermined acceptable levels), and extrapolate those figures to human exposure levels. (Output expressed as concentrations to give a lifetime risk factor of 10^{-6}.)

Role of Model

This type of model is not used directly in EIA. The role of this model in health risk assessment is to help establish maximum human exposure levels. If these levels are acceptable to decision makers, they become government regulatory standards.

Was the Model Validated? How?

Model validation was not discussed because this type of analysis comes from a long, rigorously developed history of statistical methodologies.

Other Comments

Values derived in this study were dependent on the model used, assumptions made, and experimental data extrapolated from.

Reference

Purchase, I.F.H., J. Stafford, and G.M. Paddle. 1985. Vinyl chloride - a cancer case study. In Toxicological Risk Assessment. Vol. 1. Biological and statistical criteria. (D.B. Clayson, D. Krewski, and I.C. Munro, eds.). Boca Raton: CRC Press.