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RESEARCH MEMORANDUM

MODELLING AND SIMULATION FOR ENVIRONMENTAL IMPACT ANALYSIS

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Modelling and Simulation for Environmental Impact Analysis

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I. Introduction

This paper has been written to appeal to a scientific audience. It is intended to provide guidelines for the individual directly responsible for designing an environmental impact assessment. He may be a project administrator in government or industry, or he may be the head of a committee charged with developing an independent assessment. In any case, he has a specific and well-defined role in the full decision process and must interact with the other role players. He is presumed to have a technical staff, and it is assumed that he is himself directly involved in the strategic evaluation and that his staff will be involved in the technical evaluation.

The paper begins by describing the essential characteristics of a model and then goes on to identify the criteria which will establish the need for a model in environmental impact assessment. Then, assuming that the use of a model is appropriate and worthwhile, the paper gives advice on how to start, on what the decision maker will need to do, and on what he will need to ask his staff to do. After a brief description

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of a simple policy analysis which will determine whether or not it is worth continuing with the development of the model, the processes of modelling and validation are outlined so that our administrator will know what the technical experts concerned with these stages are doing. The use of models in complex policy analysis and possible forms of presentations of the results of the analysis are then described. Finally, a very brief description is given of possible developments in modelling techniques relevant to environmental impact assessment.

II. What is a Model?

The simplest illustration of the concept is to regard a model as a caricature of reality. We can never produce a perfect copy of reality, but, if we can mimic that most important features, then the caricature will be recognizable and useful. Physical models can often be constructed, as in hydraulic models of estuaries, but these, although sometimes helpful, cannot usually include ecological or social effects. To include these effects, the most practicable model is usually a mathematical representation, in which the physical connections are replaced by logical relationships. The apparent loss in reality is compensated by the ability of the mathematics to handle large numbers of elements and the complicated linkages between those elements. Most important, however, the simulation provides greater flexibility particularly if the mathematical modelling is combined with the use of a computer. It is possible to investigate the consequences of many options and in this possibility lies the particular advantage of computer models for environmental assessment.

There are, however, constraints. Are the data good enough? Do we know all the important links? If not, the output from the model may be misleading--a good caricature, but of the wrong person! In the next section, we shall try to define the criteria required for a useful model, stressing both the value and the limitations of such a model for environmental impact assessment.

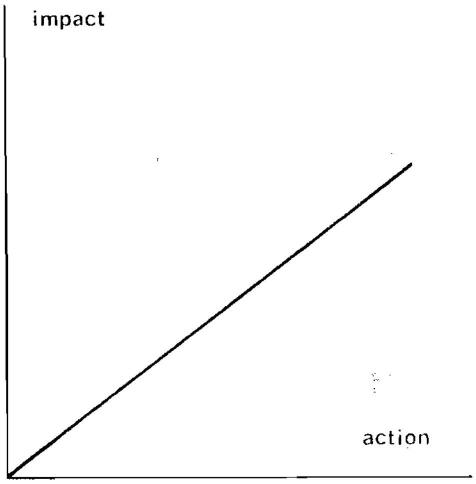
III. Should I Use a Model?

The essential feature of environmental impact assessment is the choice between a range of alternatives. Any choice will effect several heterogeneous "elements"--physical, ecological, and social. Further, these elements are usually interrelated in complicated ways and there is a mass of information. The mass may be small, it may have obvious, and not so obvious, gaps in it, and it is likely to appear, initially, in a thoroughly indigestible form. We have described elsewhere methods for ordering this information, for displaying the links between elements and for evaluating the alternatives. When will it be valuable, or even essential, to go beyond these techniques and set up a "model"?

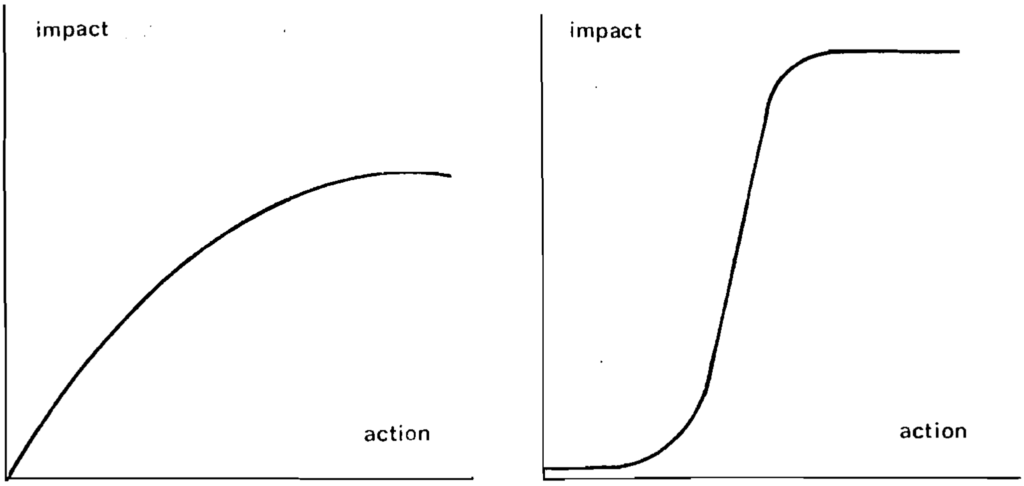
The best known feature of computers is their ability to use large amounts of data. Typically, such data belong to a few simple categories--e.g. hours worked and pay scales--and the calculations performed are, individually, straightforward--e.g. wages paid. It is the volume and speed of the calculations which are impressive.

Criterion 1. If your assessment will require the handling of large quantities of data, or large amounts of simple calculations, a computer-based mathematical model will generally be desirable.

The interconnected nature of the elements in the environment poses special problems for impact assessment because the linkages between these elements are often far from simple. If we have two related elements, representing an action and an impact, the simplest assumption to make is that, when we alter one element slightly, the other element will change slightly and proportionately (Figure 1.1). The technical term for such relationships is "linear." Very often, in natural or social systems, the assumption of linear relationships is false. An action may produce significant change, but increasing the action may not cause significantly more change in the impact (Figure 1.2). Alternatively, a gradually increasing action may produce negligible change until a point is reached at which dramatic alterations in impact occur (Figure 1.3). Both of these relationships are



(1)linear relationship



(2) non-linear relationship

(3) complex non-linear relationship

Figure 1. Typical forms of relationships between action and impact.

technically described as "non-linear." In the former, we may overestimate the probable impact of increased action by assuming linearity; in the latter we may not foresee a potential catastrophe. Further, these responses may be displaced by the system and appear as impacts at points structurally or geographically distant from the action.

In the descriptive methods that are now used to develop impact statements, we assume either explicitly or implicitly that the links between action and impact are of the simple linear type, although we may wonder what would happen if they were not. Also, there is a limit to the number of links which we can comprehend at any one time, particularly when some of these links are direct and some are indirect. Exploration of the possible influences of non-linearities and of indirect links is frequently possible by the use of mathematical models, and where there are many such links these models can best be explored by the use of computers.

<u>Criterion 2</u>. If there are many complex links between the elements of your environmental impact assessment, the use of a computer-based model will be necessary.

Many environmental impact assessments concern not only the scale of the changes to be imposed, but also the rate at which these changes will be introduced. For example, the impact may be less if we proceed slowly, or alternatively, changes may continue to occur even after the project has been completed. If, for each of the links, the relationships with time can be defined, particularly the delays or time lags, then the sequences in the overall alteration can be determined. In mathematical terms, the analysis would then be dynamic and not static.

Criterion 3. If it is essential to determine the changes of the environment with time as a result of the proposed actions, a computer-based mathematical model will usually be helpful.

One apparent disadvantage is that every element and every link in the assessment has to be defined explicitly. It is not enough to say "wildlife will decrease through lack of food." It is necessary to define the species of deer, to estimate the size of the present population, what they eat, the rate of migration, the present death rate, and so on. In fact, this apparent disadvantage is actually a major advantage. The nature of the modelling process forces into the open hidden assumptions which may have too little basis in fact. It reveals areas where information seems inadequate, and, especially, it makes the participants in the assessment, who may have very different backgrounds, aware of each others' problems.

Criterion 4. If increased definition of assumptions and elements will be valuable in drawing together the many disciplines involved in the assessment, a model may be helpful.

When these elements and links have been defined, it is likely that very few will have the exactness of simple elements like "hours worked" or "wage rates." Many will have wide limits to their probable values, either through our lack of knowledge or because they do really vary in space and time, and some may even have to be guessed. If the average value of each element is used as basis for the simulation, then the computer will produce a single, apparently exact, result of the consequences of an environmental change. Even when several alternatives are included, the succession of exact results is still an illusion. The quality of the results produced can be no better than that of the elements that formed the input to the simulation.

Again, however, the variability of the input variables may be used by the model to provide indications of the probable range of effects. Technically, this is termed probabilistic or stochastic modelling. If, for example, we are examining the impact on a deer population of building a dam, preliminary examination of the model may suggest only slight decreases in the size of the population, and no further information on this effect needs to be sought. Similarly, if the effect is shown to be large, then clearly it must be evaluated, but, again, no further information needs to be collected. Where, however, the effect is shown to be highly variable and dependent upon the input assumptions, then considerable further information may be required about the reality of the assumptions concerning the relationship between dam construction and deer populations.

Criterion 5. If some or all of the relationships between the elements of the assessment can only be defined in terms of statistical probabilities, a model will be essential.

The above example illustrates the circular nature of the modelling process and the value of starting a simulation early. It also illustrates some of the limitations of the process. How important is the deer population? This value judgment is a critical part of the assessment. It can define what must go into the model and in how much detail it needs to be described. But it is not part of the model itself. The assessors of environmental impact must determine regional, political, and social factors to be taken into account. Can these factors be fitted within the constraints imposed by the nature of simulation modelling? If the assessors consider that some factor is so important that it must be included, but is too ill-defined that even main features of its interactions with other aspects cannot, or should not, be expressed quantitatively, then modelling may not be an appropriate technique.

Criterion 6. If there is no possibility of defining the essential elements of the assessment and the relationships between the elements, there is no point in attempting to use a model.

It is important also to stress that there are constraints on the technical experts. They must ensure that the inadequacies in the data or the assumptions are not conveniently lost within the computer. Facts and values must not become confused. It is the role of the assessor to relate them. Because answers are usually required quickly, it is no help to start a long-term research program (although a first attempt at simulation can reveal critical gaps in existing data). Finally, in contrast to scientific research, no experimental test of the model is normally possible in environmental impact studies.

In the best of all possible worlds, therefore, it would seem that computers and models are admirably suited to cope with the complexity of impacted environmental systems. A perfect tool, surely, for impact assessment? Unfortunately, many of the products of the past fifteen years of active research have fallen far short of the promise. It is not that the potential was not a reality. It is rather that the understandably enthusiastic relief of at last being able to grapple with complex problems led to uncritical and grandiose dreams. These dreams did generate "caricatures of reality," but better caricatures are found in fairy tales and science fiction. But that swell of enthusiastic effort was necessary and useful. A very small subset of models and modelling approaches has now emerged that has directly contributed to assessing impacts of large-scale developments by identifying unanticipated benefits and dangers that have subsequently become fact, by forcing modification of the assessment procedure, and by illuminating critical areas of weakness in data and policy.

Generally, the useful and useable techniques developed to data have emerged from very small groups of scientists, who have had a well-defined and rather narrow focus and have made great efforts to link the modelling effort, from the start, with policy questions and with vigorous data validation. If we forget about the early "over-selling" of the technique, some useful progress has been made.

Criterion 7. In general, be cautious of applying any integrated set of modelling techniques and procedures unless they have been designed, from the start, with policy questions as the first consideration.

Finally: how much will it cost? With costs varying from country to country, the best we can do is describe the minimum requirements in terms of personnel and facilities. A barely adequate assessment is feasible with three scientists having, between them, experience in several resource areas and in modelling, one computer programmer, and a secretary. In addition, there must be access to a small computer, to data, and to resource specialists.

In the Appendix, an example is discussed of a simple but useful preliminary assessment of part of a major hydroelectric development in Canada. This assessment took three weeks with a staff similar in size to that described above and cost approximately Canadian $8,000 in staff and computer time. An essential ingredient, however, was a five day workshop involving twenty policy and resource specialists from the contracting agency. The costs of their travel and salaries are not included.

Criterion 8. Construction of a model for environmental impact assessment will require a minimum of three professional staff, two support staff, and access to a small computer and to the necessary data and specialists.

IV. How Do I Start?

The basic criteria described above suggest that, whatever the apparent complexity of the problem, we can at least attempt to use a model in an environmental impact assessment. There is no magic formula for finding the entrance to the problem, but there is one undeniable fact. We will always be in a position to obtain the most satisfying solution if we set up a clear strategy from the beginning. From the moment we begin to work on the problem, we have to use all our resources and expertise to impose our goals on the solution, instead of allowing the problem to impose on us a solution which is unsatisfactory. How do we attain this desirable position?

The strategy to be employed will depend upon an evaluation of the problem, an evaluation which can only be performed after we have adequately delimited the problem itself in terms of the questions to be posed and the scale and complexity of the problem.

The major practical limitation is usually time, because the assessment will be required by a certain date. A second limitation is usually one of facilities. Do you have the necessary computing facilities, and people with the necessary expertise to prepare the programs? These purely administrative constraints may decide not merely whether or not it is practical to use a mathematical model but also the limits of the scale and complexity of the model. Leaving the latter aside, we will focus our attention on the technical problems.

V. What Do I Do?

A. Delimitation of the Problem

Clearly, problems of environmental impact assessment will be interdisciplinary, impinging on almost every facet of human interest. However, our strategy will start by imposing some specific limits to the real universe surrounding the problem. Answers to the following four types of questions will help us to reduce the problem to the principal dimensions of interest to our strategy:

1. What classes of output will we need to make decisions?

From the whole host of variables involved in the problem, only a fraction of them (or a certain combination of them) will be relevant to the final decision. We see here a first step in a weighting process which will also be performed at other levels. Only the group of people involved in the decision making process will be in a position to select the variables relevant to the decision; the consequences of this selection have wide repercussions on the operational aspects of the environmental impact assessment.

2. What are the geographical limits to the problems?

Although human technology has proved to be capable of producing effects at the global scale, with few exceptions we will be able to place geographical limits on the size of the problem. Again, this is an arbitrary limitation which usually reflects the interests involved, and helps to indicate the desired strategy. In consideration of the effect of environmental changes on the fishing industry, for example, global effects such as international price increases of cheap protein due to fish stock depletion could be included in the analysis if desired; or these international aspects could be ignored and the problem reduced to a regional or national geographical scale.

By restricting the problem to too small an area, important factors may be ignored; by trying to take in everything, the problem may become unmanageable. The preliminary analysis may indicate, however, that certain aspects can be omitted. The failure of the anchovy fishery in Peru was caused by a combination of abnormal water movements and very heavy fishing. The abnormal environmental conditions off Peru appear to be part of general changes in the circulation of water in the Pacific, which themselves depend on fluctuations in very large-scale atmospheric distributions. Is it necessary to include all these factors in an environmental impact assessment model? The answer is "no." The model requires information only on how often this adverse condition is likely to occur and what effect it has on survival of young fish spawned by the adults in the stock.

It is important to distinguish between an environmental impact assessment model and the model that would be required for a general research program. In the long run, an understanding of the environmental changes off the Peruvian coast can improve not only our knowledge of the basic factors controlling the fish population, but also indicate how certain types of environmental fluctuations would affect other stocks, as yet unexploited, in quite different parts of the world. Excluding these types of study from an impact assessment model is not denying the long-term need for research on these factors.

3. What are the time horizons of the impact?

The assessment of a given environmental impact has to be performed in relation to a given period of time. Once more, there is no simple way to define this dimension, and the decision will depend on the many specific factors surrounding a given problem. Nevertheless, at least a word of caution is desirable. Frequently, the events involved in environmental impacts are characterized by non-linear processes, or by lags and delays between cause and effect, so that consequences which are negligible in one period of time may become important if that period is extended.

4. What are the subsystems affected by the model?

The previous sections have shown some of the problems of setting boundaries of time and space to the model. The result, in technical terms, will be a listing of elements and of the links between them, either as a table or a flow chart. The number of elements may be relatively small or very large. The links may also be large in number and each link of a relatively simple kind, or there may be complex interactions at many points. The next stage in the delimitation of the problem is to see if this mass of elements and links needs to be, or can be, considered as a group of subsystems.

How can subsystems be identified? Are there, in the table or flow chart representation of the problem, smaller areas which, although highly interconnected internally, have relatively few links with other parts of the system? If so, we may regard such areas as valid subsystems. They may be geographical or structural, representing groups of people, organisms, or activities. This decomposition of the problem into subsystems is useful, not only for the strategic analysis of the problem, but also for the management of the assessment, as it will partially separate those involved into groups mainly concerned with particular aspects of the problem.

B. Strategic Evaluation of the Problem

For any major development, there is always a set of possible alternatives. The initial generation of these alternatives is a crucial step, because it provides the frame of reference which will largely determine the kind of information you will need, as well as the type and usefulness of the model to be constructed, and the universe of more detailed alternative options which will need to be assessed. The development may not even be feasible as originally proposed, but may be feasible or more useful when considered in some alternative form.

The initial generation of alternatives may be greatly helped by some rules for providing a systematic frame of reference. While it would be impossible, and often of no value, to present a complete list of alternatives for many projects, a few guidelines may help the search for alternatives.

Usually, the most obvious proposal for a development in a particular region is the one which is expected to produce the maximum benefit (economic, social, etc.) assuming nothing goes wrong. However, it is important to look for alternatives which will imply a minimal cost if things do go wrong. In addition, one may look for alternatives with a high probability of being successful (low probability of failure), even if the potential benefits are not very high.

We may sometimes suppose that all of these considerations have been taken into account in the original proposal but it is advisable to separate them explicitly. For instance, in a water resources development for a particular region, the first proposal may be to build a large dam across the river, taking advantage of the efficiency of centralization and of the benefits of economy of scale. This is the "maximum benefit" approach. However, the consequences of a failure of the assumptions in the construction of the dam, or in the environmental impact assessment, might well be disastrous. We might, therefore, as an alternative, consider the construction of a series of small dams across the water courses, so that the overspill of a few dams will not affect the whole region, and some of the dams could even be modified if unsuspected environmental consequences become evident. The alternative may well be less efficient, from a traditional point of view, but safer than building a big dam, and might be regarded as the "minimal cost of failure" approach. Finally, we might propose the construction of medium-sized dams in a planned sequence, modifying the project whenever unexpected effects are detected. This would be the "maximum probability of success" approach, and, while it may be less efficient than the first alternative, will entail less risk.

The above three viewpoints (i.e. the maximum benefit, the minimum cost of failure, and the maximum probability of success), can be distinguished at each major step of a development, and the feasible compounded alternatives listed as the chains in a branching process.

VI. What Do I Ask My Staff to Do?

Now that you have constructed a strategic bounding and evaluation of the problem, the first and obvious essential is to gather together all the available information and to identify the people who can contribute to the model--usually specialists of various kinds, including systems analysts and computer programmers. Some of these people will be consultants, brought in to help your own staff, and some of them must have a broad policy view of the problem. What do you ask them to do? There are several specific guidelines which may be useful.

A. Initial Variable Identification and Organization

Having carefully identified the problem, within the strategic framework developed above, and listed the essential variables, the following steps will be necessary.

1. Organize these variables into classes identified by their common effect or source.
2. Specify hypotheses concerning the response of each class of variable and demonstrate these responses graphically. Some thought should be given to the form of the independent and dependent variables in order to facilitate interfacing with the rest of the model.

3. Identify, for each response, all reasonable alternative hypotheses and make rough estimates of the maxima, minima, and thresholds. Preserve these alternative hypotheses for subsequent sensitivity tests in simulation.

B. Assigning Degrees of Precision

When a problem can be divided into subsystems, it is important to have approximately the same degree of precision recognized between subsystems. The best way to do this is to make an initial statement of the precision required for each subsystem, identifying inputs, model detail, and outputs. The choice of the appropriate level of precision should be a joint effort by you and your staff and be based on the kind of questions you want answered, the time available for the study, and quality of the data.

C. Construction of A Flow Diagram

There is a wide choice of the conventions to be used in drawing flow diagrams, drawn from control system theory, cybernetics, and information theory. The best conventions seem to be the simplest, in which one symbol designates an input or output, another an intervention, and a third, a process. These standard symbols are used throughout in describing both the model and its constituent submodels.

D. Interaction Table

If separate subsystems are analyzed independently by subgroups of your staff, one of the most difficult tasks is to ensure effective interfacing between the submodels. The device that seems to work best is an interaction matrix or table, designed to be used after each subgroup has developed a fairly clear understanding of the general form of their submodel, the inputs they expect to receive, and the outputs they expect to generate. The matrix identifies the inputs each subsystem expects to receive, and after the table has been drawn up, each group is then asked to see if the output expected of them as input to another subsystem is the kind of output they intend to produce. Very often it is not, and resolution proceeds in a series of steps until a consistent table of interactions between variables is available.

By this time, all the necessary steps have been taken to permit the start of the actual modelling. Your staff has largely been responsible for generating the interaction table which shows exactly which variables are affected by possible changes in each of the variables. Moreover, it should be possible to suggest the direction of the influence. For example, if nutrients in a reservoir increase, they will have a stimulating effect on some variables and a possible inhibiting effect on others. A further level of qualitative information might indicate different ranges over which the effect might be zero, plus, or minus. Finally, enough insight might have been gained by this time to weight, subjectively, the intensity, of the cross-variable effects.

The above sequence of steps can be developed very quickly. For example, once the data for the James Bay study described in the Appendix were collated, the group of twenty workshop participants completed all the above steps in two days. Moreover, the interaction table provides, in a concentrated form, an immense amount of qualitative information which itself could form the basis for a preliminary assessment. Alternatively, if the resources, time, and information are not available for an extensive assessment and evaluation, the same table could be the basis for a formal evaluation. But, if this is the case, the process should now move out of the control of your staff into your hands, with staff assistance. The trick now is to develop a simple procedure for policy analysis, aimed at producing a rough qualitative picture of the impact of each of the alternative development proposals.

VII. How Do I Make A Simple Policy Analysis?

Three sets of information are necessary for the first step in the analysis. Your staff will have provided one of these sets as the systems information in the interaction table. The two remaining sets are obtained as follows:

1. You must identify and organize the key impact indicators in relation to the overall goals of the project.

2. You must specify the specific policy or management actions which together define any one plan.

A. Developing Impact Indicators

The strategic evaluation should have identified the major impact categories in relation to the original goal of the project. Together they represent the possible social, economic, physical, and ecological consequences of the project. But these classes are very broad and they must be disaggregated into variables which are measurable and relevant to the project. For example, social indicators must be made specific in terms of jobs, leisure time, or similar variables. Having developed a list of indicator variables, it is then often necessary to express them in the forms most relevant to the decision. For example, it might be more useful to express "jobs" not in absolute terms, but as a rate of change, or as "jobs per capita," or as "diversity of job opportunity."

By this time, the list is defined as the impact indicators--measurable variables which have policy relevance. But you are still uncertain, because of the large areas of unknowns, as to whether you can rely on this set. There are uncertainties and unknowns in all the steps described so far. Some of the more critical uncertainties can be illuminated, as described later, if you proceed to the modelling stage. But, even then, a hedge against uncertainty can be provided by adding another dimension to the existing impact indicators--a dimension which is designed to keep one laert to the possible foreclosing of future options after the project is implemented.

As an example, consider the list of impact indicators previously described. One way to design proposals that maintain options and that allow for the plan itself to absorb the unexpected is to include a capacity for considering the resilient aspects of each alternative project in the model. Resilience, in this sense, determines the degree of persistence of the relationships within a system in relation to the frequency and intensity of disturbance. A review of resilience and stability of ecological systems is found in Holling [2].

B. Developing Policy and Management Actions

In any one development, there are several internal options for action during the construction and post-construction phases. Some relate directly to the project itself and some are indirect actions. In the James Bay example (see Appendix), there were three sets of actions: those directly concerning power production (e.g. schedule of dam construction, character of water diversion and water flow controls), those concerning environmental quality (e.g. silt control, tree clearance in reservoirs, sewage treatment), and those affecting demand (e.g. recreational controls, job allocation between insiders and outsiders, road access). The essential feature is that classes of policy and management action must be decomposed into specific, definable actions.

This process is identical to the effort your staff made to decompose the environmental system into the system variables, and it is identical to the effort you performed to decompose project goals into impact indicators.

C. Putting the Pieces Together

You now have the three elements necessary to develop the first rough assessment: the system variable interaction table, the list of impact indicators, and the list of policy actions. Your goal is to develop a table of action vs. impact variables and it is the table showing the interaction between system variables which allows you to perform this trick.

Briefly, the first step is to develop two intermediate tables. The first is designed to show how each action is likely to affect each system variable (Box II, Fig. 2). The second shows how each system variable is related to each impact variable (Box III, Fig. 2). These two tables, combined with the interaction table (Box I, Fig. 2) then allow you to form an action vs. impact table (Box IV, Fig. 2).

With tables of this kind for each of the alternative plans, it should then be feasible to reject the most extreme and leave a smaller set for final discussion and decision by other links in the decision process. It is an understandable desire and ultimate necessity to have a single number which can be used to evaluate alternative projects, but this is part of the decision process at higher levels. To do it now is to subvert the political process to a technique with spurious vigor.

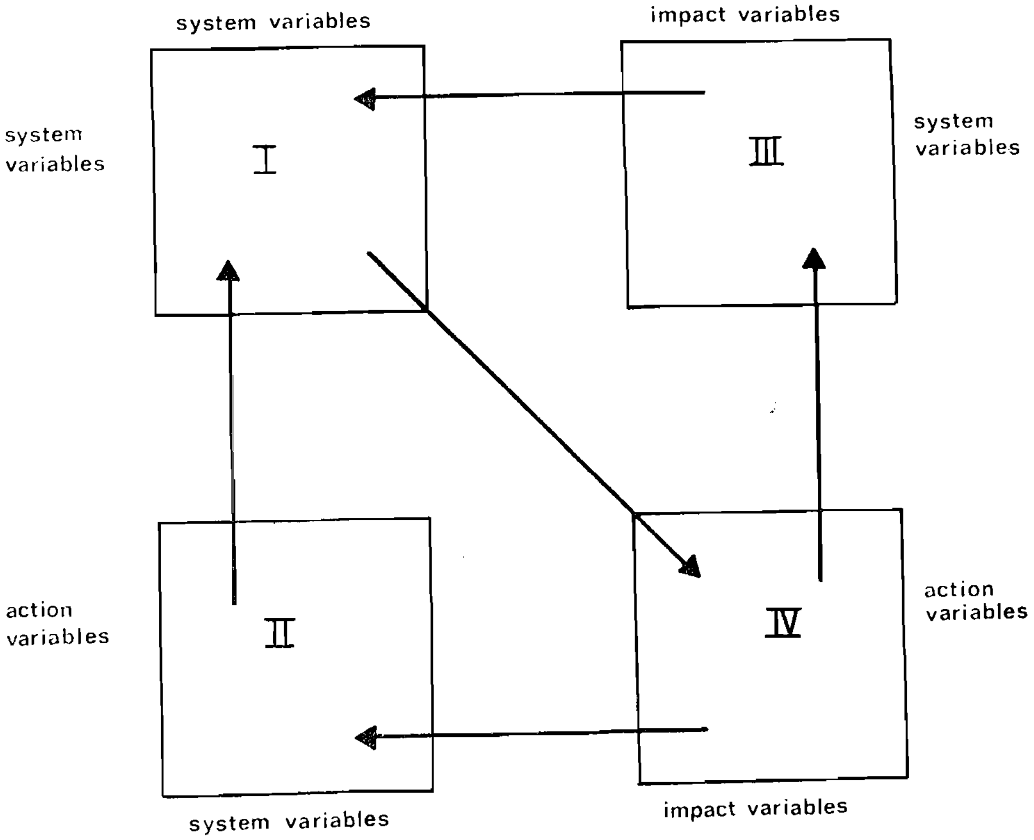


Figure 2. Relationships between tables of system, action, and impact variables.

VIII. What Happens in the Modelling Process?

Now that the problem has been defined in terms of its boundaries, its subsystems, its possible variables, and their couplings, we are ready to begin the modelling process itself, assuming that we have decided to proceed beyond the stage of the simple policy analysis. It is at this point that the expertise of the mathematician, already used as a consultant in the strategic and tactical definition of the problem, becomes paramount, and some understanding of his role is necessary if you are to retain the necessary control of the impact assessment.

The mathematician's expertise will first be exercised in the choice of the kind of model to be used. In this, he will be guided by the size of the problem, the nature of the various classes of variables, and by the degrees of uncertainty present in the relationships between them. His choice will be influenced by his knowledge of the various "families" of models which already exist and which have previously been applied to similar problems, in much the same way that a field naturalist is guided by his knowledge of the natural families of plants in his identification of an unfamiliar flower.

Broadly, his choice will lie between the following classes of models:

a) Deterministic and probabilistic models. In the former, all the relationships are assumed to be defined by mathematical functions. In the latter, some, or all, of the relationships can only be defined in terms of statistical probabilities.

b) *Linear and non-linear models*. Although it may be convenient to assume that relationships between variables are linear, most practical problems require the more complex assumption of non-linearity.

c) *Static and dynamic models*. Static models do not include time as a variable, while dynamic models have time, with its characteristic property of only being able to change in one direction, as a major variable.

d) *Predictive and decision making models*. Predictive models enable the consequence of particular decisions to be explored, while decision making models indicate the decisions which are optimum in some defined way.

Impact assessment models will frequently belong to the most difficult class of dynamic, non-linear, probabilistic, decision making models.

The construction of the mathematical model is made possible by the use of the computer, and, particularly by the need to program such computers in a completely unambiguous way. The resulting "algorithm" defines the model so that its essential features can be communicated to other experts, and so that it can be tested to ensure that all the component parts of the model operate correctly. Once the mathematician has a version of the model which begins to simulate the real-world system, he will experiment with the model in an attempt to find particular sets of conditions for which it gives obviously unrealistic results. By refining the model at this point and subjecting the refined model to further analysis, he can hope to make successive improvements within the limitations of the boundaries of the time/space constraints of the impact assessment.

In the process of the continuous analysis and refinement of the model, the mathematician will seek two essential criteria. First, he will look for information on the degree of change produced in the output from the model by changes in the basic parameters or assumptions about the relationships between variables. He will be constantly aware of a possible lack of precision or of a bias in the estimation of parameters and relationships; knowledge of the effects of these possible inadequacies will help to define where further work must be undertaken if the model is to be improved. This testing of the "sensitivity" of the model to input assumptions is known technically as a "sensitivity analysis."

Second, the mathematician will seek the maximum simplification of the model which is consistent with its value in a predictive or decision making process. Frequently, it is possible to show that parts of the model which have been developed to satisfy theoretically important considerations have relatively little effect on the final outcome of the modelling process. In such cases, simplification of the model is both desirable and readily achievable.

IX. How Is the Model Validated?

In theory, the repeated stages of analysis and refinement can continue indefinitely, but, in environmental impact assessment, they will usually be brought to a halt by the need to provide results within a severely limited period. Indeed, there may be too little time for the development of the model which would be desirable in a research investigation. At some stage, therefore, an attempt at validation of the model will usually be necessary.

We should admit, however, that validation (the matching of our model with reality) in environmental impact assessment is not easy. Sometimes, the only apparent validation which can be achieved is the matching of future performance of the environmental system with the expectation from the model--a test which hardly meets the criteria of good science. Nevertheless, some confirmation of the appropriateness of our model can be obtained.

First, the analysis which was necessary in the refinement of the model will have given us some confidence that the behavior of the modelled system is consistent with our expectations. Where it has been possible to divide the total system into subsystems, the behavior of these subsystems, singly and aggregate, will have reinforced our knowledge of the dynamics of the system. If, as is likely, the behavior of an aggregated system runs counter to our intuitive expectations, we will have been forced to reconsider the basis of our "common sense" expectation. In this way, confidence in the value of our model, as at least a working approximation, will have been increased.

Second, experimentation with model systems may indicate critical experiments which would enable a valid test of the model to be carried out as a direct appeal to nature consistent with the logic of the scientific method. Such a test may seem relatively unlikely in environmental impact assessment, where the time scale for the assessment is limited, but experimental evidence may already exist which can be matched against predictions from the model system.

Third, where it has been possible to undertake surveys to obtain the necessary data for the construction and parameterization of mathematical models, it may be desirable to hold back a certain proportion of the data collected so that they may be used in an independent test of the hypothetical model derived from the main data set. In this way, the logical fallacy of formulating and testing an hypothesis on the same set of data can be avoided. Whatever method is used in an attempt to validate the model system, one of the paramount advantages of mathematical models dominates the argument at this point. In contrast to all other forms of reasoning, the mathematical model is explicit in its statement of the relationships between the variables and of the assumptions underlying the model. If anyone disagrees with these assumptions or relationships, he has only to replace them by some equally explicit set to verify that the changes make corresponding changes in the expectations of the environmental impact assessment.

X. How Do I Use the Output from the Model in a Complex Policy Analysis?

Once a model has been satisfactorily validated, a set of possible alternative policies or actions will have been generated. The problem is now: "Which of the alternatives do I choose?" This choice is a complicated process, influenced by factors taken into account in the model, by elements not considered in the model, by value judgments, etc. However, it seems possible to help the search for a "best" choice by some evaluation of the elements needed for the choice and by explicitly indicating the main differences between the kinds of choice available for a particular set of alternatives.

Suppose you are confronted with a set (say, A,B,C,D,E,F,) of alternative policies of action, generated by some kind of model. For each of the alternatives, an estimate is feasible of the probability of being right or wrong, on some objective basis. That is, according to the uncertainties involved in the construction of the model, the likelihood of a critical hypothesis being wrong, etc., you may allocate (or be given) the degree of confidence to be placed on the success or failure of the policy. For each of the alternatives, you may also have an appreciation of the benefit of succeeding or the cost (economical, social, political, etc.) of failing, and this appreciation can be given a numerical value, or at least a ranked order.

Given the necessary information, there are different ways of choosing, which can be best illustrated by a hypothetical example. Suppose you have six alternative policies or actions, and their associated probabilities and the consequences of being right or wrong are:

	Probability of		Consequences of	
	Failure	Success	Failure	Success
A	.2	.8	-80	10
B	.8	.2	-40	100
C	.5	.5	-15	10
D	.1	.9	-90	50
E	.1	.9	-20	60
F	.1	.9	-500	80

From these two sets of values, it is possible to estimate, for each alternative:

1. The probable loss (the probability of failing times the cost of failing);
2. The probable benefit (the feasibility of succeeding times the benefit of succeeding);
3. The most likely benefit/cost (the probable benefit minus the probable cost).

The total information might be presented as follows:

Table 1

	Probability of failure	Probability of success	Loss if fails	Gain if succeeds	Probable loss	Probable benefit	Most likely net benefit
A	.2	.8	- 80	10	-16	8	- 8
B	.8	.2	- 40	100	-32	20	-12
C	.5	.5	- 15	10	- 7.5	5	- 2.5
D	.1	.9	- 90	50	- 9	45	+36
E	.1	.9	- 20	30	- 2	27	+25
F	.1	.9	-500	80	-50	72	+22

Now, by using this table, it becomes possible to identify possible criteria for the choice of alternatives.

The first criterion is trivial, and consists of choosing the alternative which has the greatest probability of success (lowest of failure) without considering the size of the benefits or costs associated with success or failure. Using this criterion, either alternatives D, E, or F would be chosen.

A second criterion consists of choosing the alternative which would provide the highest gain, if successful (alternative B, with a possible benefit taken as 100 in the example). This criterion has been widely used, either explicitly or implicitly, sometimes with disastrous consequences. No account is taken of the consequences of the action being wrong, of the probability of the action being right.

A third criterion is to choose the alternative which could produce the lowest cost in case of failure, which is in a sense, the safest choice. Using this criterion, alternative C (with a loss of 15 if the alternative is wrong) will be selected.

A fourth criterion is to use the alternative which would provide the highest probable gain, which takes into account both the magnitude of the possible benefit and the probability of succeeding. In this case, alternative F (probable gain of 72) is chosen. A fifth criterion is to pick alternative E, which has the lowest probable loss. Finally, the sixth criterion, selecting the alternative with highest most likely net benefit, takes into account both the probable gain and the probable loss, which, in the case under consideration, is alternative D. Alternative A is not chosen under any of the above criteria.

The above simple example is intended to make the following points:

1. There are many different criteria for choosing alternatives; that is, there are many ways of deciding what "best" or "worst" mean in a given context.
2. Some evaluation of the likelihood of failure or success and of their respective costs and benefits is necessary for the alternatives themselves to be evaluated.
3. The six different criteria for choice defined above can be essentially grouped into two classes: aiming at maximizing the gain or at minimizing the loss, i.e. the ambitious and the cautious. Our ignorance about the behavior of complex systems, particularly environmental systems, is so vast that it is often foolish to adopt anything but a cautious view of the outcome. Failure to do so, and attempts to increase the highest possible benefit without proper consideration of the risk involved, have already transformed golden dreams into black nightmares in many parts of the world.

XI. How Can the Results Be Presented?

Perhaps the greatest potential Achilles heel for the decision maker who includes model-generated information in environmental impact assessments lies in communicating the results. Two problems will assume unusual importance. First, the decision maker may become the recipient of an unsettling if not alarming mass of information that he must bring into rational and simple focus before communicating the results to other decision makers. Second, the credibility of the model-generated information may be viewed with cautious optimism at best and skeptic hostility at worst. The potential seriousness of both foregoing problems may oddly enough increase in proportion to the model's capacity to help analyze complex problems.

Thus, the decision maker's first absolute requirement should be consciously designed information to fit the interpretative capabilities of whatever other decision maker(s) he must communicate with. A safe rule of thumb is to consider the final information inappropriate if it exists in one form only (such as tables). The decision maker's second absolute requirement should be the capability to state clearly the relevant steps through which raw data were converted to finished information. A safe rule of thumb for this requirement is to consider the information's credibility in jeopardy if the information ever passes through a "black box," as interpreted by the decision maker.

Regardless of whether the model has been adopted for use on a computer, it is at this stage of assessment that computer-aided communication forms (actually communication models) can be of immeasurable value. With a common set of data, a computer system can simultaneously produce a wide variety of specialized displays, including flow charts, tables, matrices, graphs, response surfaces, maps, and reports in traditional prose form. With such a graduated series of displays which trade off depth of explanation (credibility) for simplification (ease of interpretation) almost any decision maker can locate a display form which suits his interpretative abilities and through which he can build an understanding and belief in more or less complex forms of assessment (see Figure 3). In this manner two or more decision makers, each with widely divergent interpretative abilities, have a common communication package from which they may achieve an understanding of the lower or higher decision maker's viewpoint.

XII. What Development of These Ideas Can I Expect in the Near Future?

The descriptions and evaluations of modelling concepts relevant to environmental impact assessments given above are based on our present incomplete knowledge of the behavior and mathematics of complex systems. This knowledge is rapidly growing, and while it is impossible to predict where the major advances and achievements will lie, some generally promising directions can be identified.

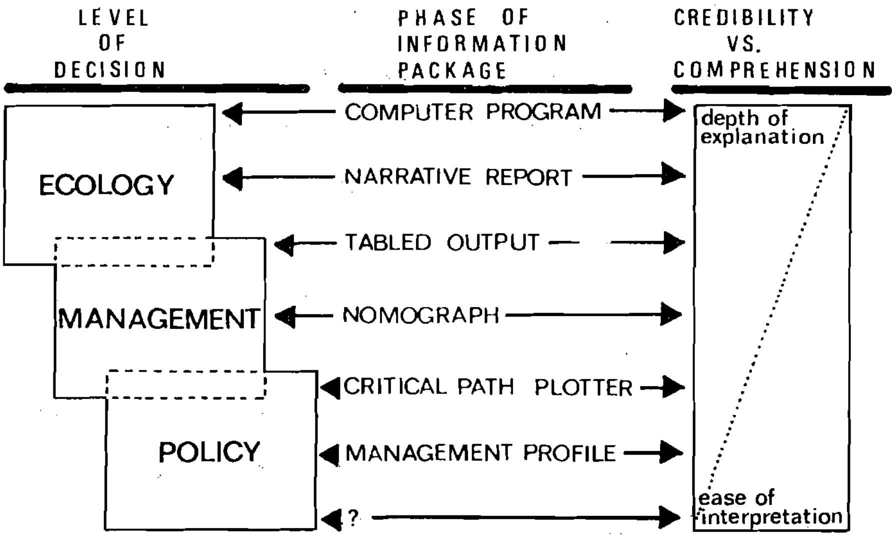


Figure 3. Relationships among levels of decision making, form of displaying information in the information package, and comparative depth of explanation vs. ease of interpretation of each form (from Gross et al. [1]).

It is likely that the present trend towards more precise and complex models for specific situations will continue. Some major advances to be expected in this direction are the development of better procedures for the analysis of the role of spatial characteristics of systems, the development of a theory of self-organizing systems, improvement of the techniques of search for optimum sets of conditions, and the establishment of techniques for conflict reconciliation in complex systems. Of particular relevance to environmental problems would be the development of procedures of efficient search for optimality in hierarchical systems, where the optimization at each subsystem level must be reconciled with optimality of the highest level of the system.

In addition, a trend towards generalization of environmental model structures is beginning to emerge. We can expect the development of flexible, easy to use, computer languages for environmental simulation, allowing the user to concentrate on the conceptual problems, without having to worry about how to communicate with the computer. Closely related is the possibility of developing functional packages, or modules, for essential and invariant ecological processes. These could be combined in different ways for each particular problem, in much the same way as physical laws currently are introduced in the construction of meteorological and hydrological models.

Finally, a trend towards model simplification may be expected, better adapted to cope with uncertainty and with the important qualitative aspects of environmental and ecological problems. Such models, by using semiquantitative or even non-numerical, mathematics, should be cheaper in terms of the data and resource requirements than most current types of model and still provide rigorous answers to the basic questions posed. This approach may be expected to help in solving the current dilemma for developing countries between, on the one hand, the urgent need to understand their ecosystems in order to provide adequate management, and, on the other, the severe restrictions on the money available and on the number of specialized scientists who can be deployed.

However, no consideration of future possibilities should be allowed to conceal the more important fact that techniques already exist to take environmental impact assessment far beyond the subjective and speculative stage at which it is frequently left at present, and that there is an urgent need for wider and rational use of existing methodologies.

XII. Recommendations

We do not believe that this is the place to present recommendations concerning future research on methodology. But it is the place to present recommendations for important ways to facilitate application of present methodology. We have three recommendations and each touches on the issue of training.

1. A Training Program on Techniques of Environmental Impact Assessment. Sufficient techniques and procedures for assessing the impact of major developments can now be organized into a coherent package. But few people and few countries are familiar with their use. Since effective application requires a minimum team of individuals, training of separate individuals would be less effective than training of small teams which have worked together and would continue to do so on their return to their home country or agency.

One member of the team should have managerial and policy experience and the remaining should be his technical staff. Such a team should spend one year as a cohesive unit in one of an identified set of centers experienced in assessment procedures. A key requirement is for the home country or agency to assure that the team remain together and apply their experience on their return. Otherwise, the experience would become fragmented and diluted.

If the team has interest in modelling approaches, the technical staff should jointly have knowledge of several resource systems and some modelling experience. One member should be a programmer.

2. A Handbook of Resource and Environmental Modelling could now be prepared to present a detailed guidebook for the

staff of an environmental impact assessment team. Its best use would be in conjunction with the training program described above.

3. <u>Existing Communication Soft Ware Packages</u> similarly could be consolidated into a set which on one hand would help the staff concentrate on conceptual, rather than computer problems, and on the other, would help the assessor understand and manipulate the data and analyses generated by his staff.

APPENDIX

An Example of the Use of Models in Preliminary Assessment

We have chosen the following example (summarized from Walters [4]) to show one way in which modelling techniques and procedures can be used for a very rapid preliminary assessment of a specific large scale regional project. Its purpose was to identify missing gaps in knowledge, and to alert the assessors to some of the critically significant questions that should be answered.

The development project concerned a large hydroelectric development in the James Bay Territory in Quebec, Canada, covering 133,377 square miles, an area twice the size of England. The project will provide minimum power of more than eight million kilowatts and involves the construction of four power houses, four main dams, twelve spillways, six control structures, eighty miles of dikes, and three ancillary reservoirs. Four major river systems will be affected and the complex will be built over a twelve-year period.

The purpose of this preliminary assessment was to involve a group of twenty people--high level policy makers, specialists in different resource sciences, and the developers themselves--in an integrated view of the impact of the development and of the long range management of the area. An immediate goal was to see if the assessment agency should modify its existing plans for impact studies. The group was supported by a staff of five professionals with experience in related resource systems, simulation modelling, and programming. An initial three week period was spent by the staff collating available information and this was followed by an intensive five-day workshop involving all participants. The problem was defined, the model developed, and its behavior explored during this five-day period. The modelling and evaluation techniques used incorporated many of the features described in this paper, and a fuller description of both the techniques and of the workshop procedures can be found in Walters [4] and Holling and Chambers [3].

At the outset, the spatial focus for this impact study was part of the terms of reference. Potentially, there are a nested series of spatial impacts within Canada, within the Province of Quebec, within the James Bay Territory, and within the watersheds directly affected. But, in order to make this first step of assessment feasible, the group concentrated on the scale of the watersheds, leaving open the analysis of impacts at larger scales for future steps.

The James Bay exercise began with the identification of a basic set of specific predictions which the model had to handle; this was a tactic for helping to identify the key problems and questions of interest. First, it was decided that the model must represent the time course of broad impact on land area, water coverage, and shoreline of the hydroelectric dams and diversions. This is essentially a data summary and bookkeeping problem. Second, it was necessary to show the overall biotic response over time to these gross changes; it was expected that the development will destroy habitat for some organisms, but improve conditions for others. Third, it was expected that hydroelectric development will alter the temporal stability of aquatic and shoreline environments by reducing variation in water flows. The model was expected to represent effects of this stabilization on vegetation, fish, and wildlife. Fourth, construction and maintenance activities are likely to generate various water pollutants, especially silt. The model was expected to represent the spatial and temporal distribution and dispersal of these materials, and give some prediction of biotic impacts for at least extreme conditions. Finally, development will dramatically alter accessibility of the area, which may result in greatly increased human activity. The model was to represent the general impact of increased exploitation on animal populations of the area.

The identification of these problem areas led to the subsystem breakdown and information transfer scheme shown in Table 1. System components missing from this table include the marine environment and the atmosphere. Hydroelectric development is expected to alter marine conditions, especially winter ice patterns, and there is also the possibility of climatic changes. Meaningful predictions concerning these

Table 1. Information transfers in the James Bay (LeGrande Basin) model.

	USING SUBMODEL				
SUPPLYING SUBMODEL	Hydrology and Hydroelectric development	Vegetation and Shoreline Environment	Wildlife Populations	Water Quality and Fisheries	Demand for Wildlife and Fisheries
Hydrology and Hydroelectric development	Water flow regulation, land area changes, construction patterns	1. Area inundated, shoreline mile changes 2. Reservoir depths, area covered & uncovered each year 3. Seasonal water flows	1. Location of active construction sites 2. Seasonal water flows and lake levels	1. Silt, nutrient, and coliform inputs due to construction operations 2. Seasonal water flows lake levels	1. Construction and operating schedule 2. Road access pattern 3. Jobs available to indians
Vegetation and shoreline environments	1. Silt inputs along stream & reservoir banks 2. Nutrient input to reservoirs after flooding	Successional dynamics of vegetation, shorelines	1. Acreages in different vegetation types 2. Mudflat area and stream bank successional states	1. Stream bank vegetation condition (present or absent)	1. Width of mudflats along reservoirs. 2. General index of vegetation quality
Wildlife Populations			Population dynamics in response to habitat and hunting		1. Kills and kills per effort for eac species in each land area
Water Quality and Fisheries			1. Silt concentrations in rivers	Pollutant concentrations and population dynamics	1. Catches and catches per effort by species and area
Demand for Wildlife and Fisheries		1. Land used for campsites	2. Hunting effort for each species in each area, indian and recreational	1. Coliform and nutrient inputs due to campers 2. Fishing effort by species and area	Demand by indians and whites as a function of quality and past returns

questions would require the development of very specialized and complex spatial models, which were beyond the scope of the workshop session. Along with the information table, it was necessary to decide on a system for representing spatial patterns. It was decided to divide the area into a series of irregular land units, with each unit containing no more than one component of the hydroelectric development (e.g. one dam) and small enough to be considered homogeneous with respect to transportation access and general productivity for wildlife and fish.

The submodels indicated in Table 1 were then developed, following the procedures outlined in this paper, by subgroups, each comprised of policy makers, resource specialists, and one staff person. The emphasis was on disaggregating the submodels, choosing appropriate levels of precision and concentrating on conceptualizing relations between variables. The programming and mathematics was kept in the background as a technical problem of translation, so that the group could concentrate on the key issues of conceptualization.

As the submodels (details in Walters [4]) were being programmed, the participants were reformed from their submodel groups into policy analysis groups, each representing a major interest focus of the James Bay controversy. Each group was then asked to do three things: (1) develop a list of impact variables that best indicated those aspects which are of concern to the interest group; (2) develop a set of _a priori_ intuitive predictions about the effect of each intervention on each output indicator variable; and (3) formulate several overall management scenarios, each expressed as a combination of policy actions, which the group felt would represent different management goals. After some discussion, three of these groups were formed reflecting three broad categories of impact: resource development, environment, and Indian welfare.

The impact of each action on each impact variable was simply shown as 0, +, or -, first during the construction phase, and then after the construction. A section of this table is shown in Table 2 for the post-construction phase with the predictions of the model included for comparison. The key result of this exercise was that the basic impacts (positive or negative) predicted by the model were exactly opposite from what had been expected for over 70% of the action-impact combination. In every case, a simple explanation for the difference was clear after brief examination of the model structure, and the participants generally agreed that there had been obvious flaws in their intuitive reasoning.

An example of some detailed predictions of two management scenarios is shown in Figure 1. The model made three major predictions which were counter to any expectations expressed either by the workshop group or in published impact statements related to the James Bay area. First, by

Table 2. Qualitative summary of management interventions, and their simulated impacts according to the James Bay model as opposed to intuitive predictions of workshop participants. Sign before each slash is intuitive expectation of impact (+ for beneficial); sign after slash is the model prediction.

IMPACT	AREA OF IMPACT															
	RESOURCES				ENVIRONMENT								INDIANS			
POLICY ACTION	Power generated	Indian harvests	Non-consumer recreation	Employment	Quality	Char	Trout	Pike	Whitefish	Caribou	Beaver	Geese	Harvest jobs	Welfare load	Salary jobs	Abundance of game
Power																
Slower dam construction	-/-	+/-	+/+	+/0	+/-	+/-	+/-	+/-	+/-	0/0	+/-	-/+	+/-	-/0	+/+	+/-
No water diversion	-/-	+/-	+/-	0/-	-/+	+/-	0/0	+/-	+/+	0/0	+/-	+/-	+/-	-/+	-/-	+/-
Control minimum water flows	-/-	+/0	+/+	0/0	+/+	+/+	+/0	+/0	+/+	0/0	+/0	+/-	+/0	-/0	-/0	+/0
Quality																
Clear trees in reservoir pool	0/0	+/0	+/+	+/+	+/+	+/0	+/-	+/-	0/0	0/0	0/0	+/0	0/-	0/0	0/+	+/0
Control silt input	0/0	+/+	+/+	+/0	+/+	+/+	+/0	+/0	+/+	0/0	+/0	+/0	+/+	-/-	+/-	+/0
Demand																
Indian job interest	0/0	+/-	0/0	+/+	0/0	0/+	0/+	0/+	0/+	0/+	0/+	0/+	-/-	-/-	+/+	0/+
Jobs allocated to indians	0/0	-/-	0/+	0/0	0/+	0/+	0/+	0/+	+/+	0/+	+/+	+/+	-/-	-/-	+/+	+/+
Access controlled to reduce recreation	0/0	+/+	-/-	-/-	+/+	+/+	+/+	+/+	+/+	+/-	+/0	+/+	+/0	-/+	+/-	+/+

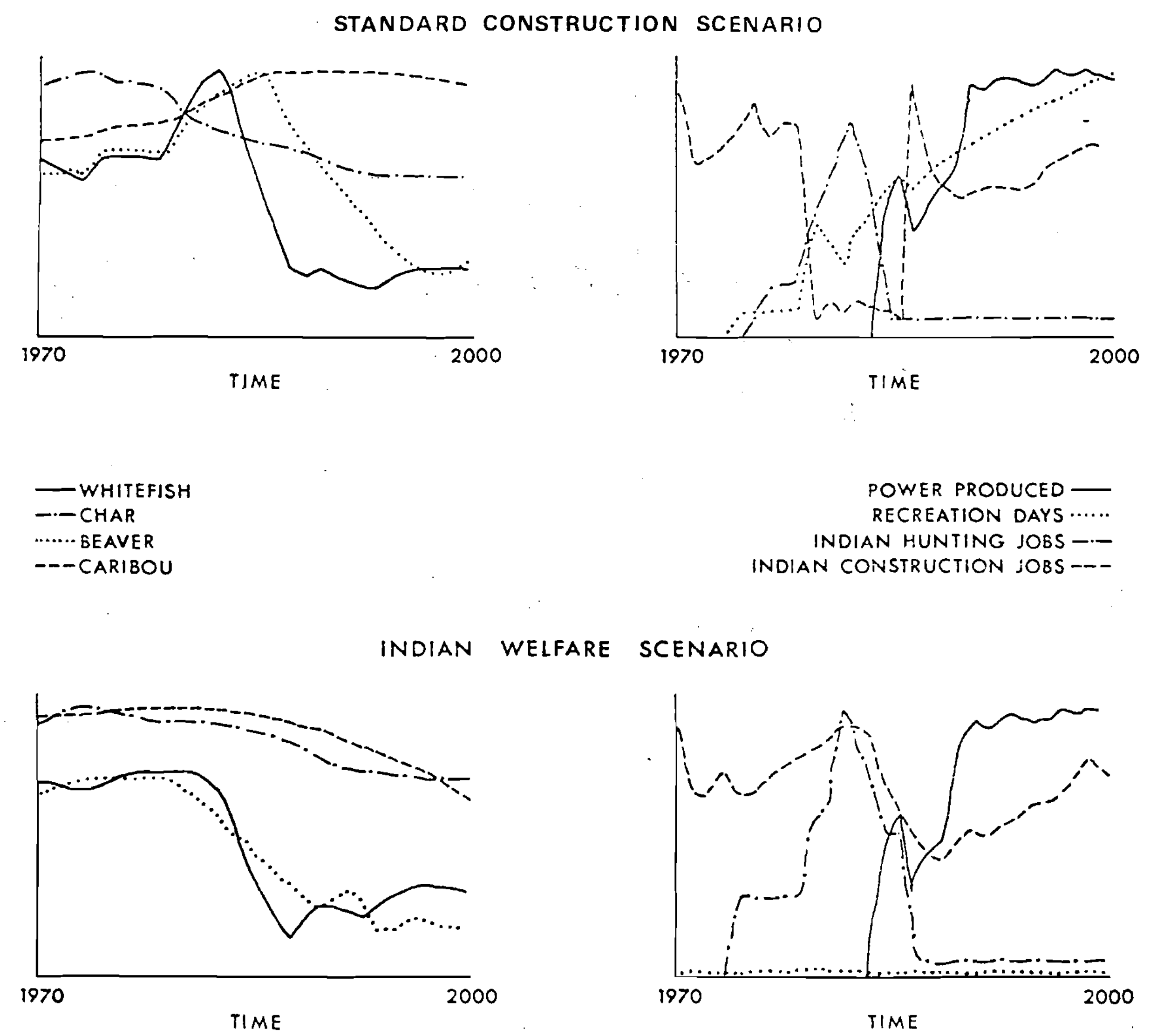


Figure 1. Sample predictions from the James Bay Model for three alternative management scenarios. All predicted values are on relative scale.

providing an overall bookkeeping assessment of the land and water areas involved in hydroelectric development, the model pointed out that the direct impacts of dam construction are not likely to be significant; only a small percentage of the land will actually be inundated. Second, by far the largest impact on fish and wildlife resources is likely to come from the increase in recreational demand; in retrospect it is obvious that even small recreational fisheries can seriously deplete northern lakes and streams that can support only a few fish per acre, turning over only once every several years. Finally, it is not simply the case that more intensive hydroelectric development in the area would result in worse environmental problems. Even without the dams, serious future environmental consequences were predicted. In addition, the model was tested with the standard LeGrande Complex construction plan, then compared to an even more elaborate dam and diversion plan which has been contemplated (The Complex du Nord). The hydrology submodel predicts that the LeGrande Complex would not result in much regulation of water flows and levels, so reservoirs would be surrounded much of the time by large mudflat areas which would not be attractive for recreation (geese might prosper, however, in these areas). On the other hand, the complex diversion scheme in the Complex du Nord should result in much stabilized flows and levels , making river banks and reservoirs more attractive for recreation (but some waterfowl habitat would be lost).

Considering these predictions, it is not surprising that the workshop suggested several possible changes in their impact assessment studies. In particular, it appears that much more emphasis should be placed on monitoring of lands and waters which are not directly involved in the development, but which will be made accessible for recreational use. Also, the impacts of the construction workers should be carefully monitored. The model predictions were critically sensitive to the hypotheses concerning Indian values and resource utilization. While this had always been recognized, there had been no clear focus for the data collection until the model had been developed.

Throughout the workshop, participants were asked to compare information requirements of the model to the data gathering plans which have already been formulated for the LeGrande area. In general, the plans as then formulated for intensive surveys and environmental monitoring would contribute very little to future management design, even though data gathering for eventual systems analysis is considered to be a central goal in the James Bay area. It is hard to imagine how effective management decisions can be made without answers to some of the questions which arose during the development of the model described above, and it is clear that those questions would not have been answered by the impact studies originally planned.

Obviously, many of the parameter estimates used in the model were pure guesses; in many cases better estimates simply do not exist, especially those related to recreational demand. Simulation models in resource management are often open to this criticism, and typically, the conclusion is drawn that modelling is premature. The James Bay exercise points out very nicely the fallacy of this conclusion; given current direction of research and monitoring effort, the appropriate data would <u>never</u> be collected. We tend to forget that all data collection is guided by some model of nature; workshops and other exercises only try to bring this model out into the open so that its basic assumptions can be examined objectively.

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