SELECTED MATHEMATICAL MODELS IN ENVIRONMENTAL IMPACT ASSESSMENT IN CANADA

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FOREWORD

The Canadian Environmental Assessment Research Council (CEARC) was established on January 30, 1984 by the federal Minister of the Environment to advise government, industry and universities on ways to improve the scientific, technical and procedural basis for environmental impact assessment (EIA) in Canada.

CEARC is currently in the process of establishing research programmes related to improving the practice of environmental assessment. The Council has identified the use of mathematical and simulation modelling in EIA as an area of research interest and plans to pursue this topic over the longer term.

The purpose of commissioning this paper, and indeed of all the other CEARC-sponsored background documents, is to provide relevant information and to stimulate discussion on the topics of interest to the EIA community. The opinions expressed, however, are strictly the authors' own and do not necessarily reflect the views of the members of the Council or its Secretariat.

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PREFACE

The mandate of this study was to review mathematical models used in the evaluation and prediction of environmental impacts due to new projects. The review includes a description of current models, the nature of their utilization and the existence of validation (and/or) verification steps.

The information contained in this report is the result of two months of visits and inquiries. Due to this limited amount of time and budgetary constraints, most of the information relates to activities taking place in central Canada.

A literature survey was conducted on the following data bases:

- BIOSIS,
- AQUALINE,
- ENVIROLINE,
- ENVIRONMENT (Environment Canada)
- ENVIRODOC (Environment Quebec)

The literature is voluminous on the subject and we have kept only certain references which are cited in the text.

We tried to meet, as far as possible, people writing impact assessment reports (consulting firms) and people working on more sophisticated models (research agencies). Appendix A gives a list of people met. Only a few visits were made to university researchers, due to time constraints.

The utilization of mathematical models is well spread for environmental applications, and their classification is not obvious. We shall present these models in the following order:

- air dispersion,
- hydrology and hydrodynamics,
- water quality,
- ground water quality,
- erosion and sedimentation,
- oil slick and liquefied natural gas (LNG) spill,
- risk and pathways analysis, and
- biotic models.

It should be noted that some models incorporate more than one of these classifications.

We describe the utilization of models by consulting firms involved in environmental impact assessments in each of these fields.

Frequency of citation of particular consulting groups is not intended to be any form of endorsement. Rather, it is a reflection of the amount of information provided to us. In the same vein, omission of a particular group does not imply lack of expertise. We did, however, manage to meet most of the major consulting groups in Ontario and Quebec who regularly apply computer models.

We wish to express our gratitude to the numerous people who provided us with information, including project proponents who kindly sent us copies of impact statements. Some of these people went quite far out of their way to aid us, and without their help this report would not have been possible.

1. MATHEMATICAL MODELS

Many problems arise in the evaluation of environmental impacts due to new projects; for instance:

- the determination of the pertinent variables,
- the choice of methodology to follow,
- the need to inform the project proponent and regulatory agencies at every step of the evaluation process, and to present the best assessments possible for a variety of alternatives,
- the necessity to provide understandable information to the public.

These problems are emphasised by the presence of many specialists of different disciplines who have to find a common language to integrate their experiences towards the same aim: the prediction of the impacts of a new project. Mathematical modelling presents a unified way to meet these requirements.

The study was divided into two parts: abiotic and biotic models. Abiotic models include water quality and water management modelling. Biotic models take into account the biological aspects which have been used for impact assessments.

The work is based primarily on visits to groups that are active in using modelling (or creating models) and simulation for impact assessment, and on literature surveys.

The usefulness of mathematical models in impact assessment is supported by the number of recent studies on the subject (Beanlands and Duinker 1983; Frenkiel and Goodall 1978; Munn 1977; Holling 1978; ESSA 1982; ERL 1984). Mathematical models provide the possibility to simulate the behavior of systems for different strategies.

Karplus (1983) states:

> *All decision making involves an implicit (if not explicit) use of models, since the decision maker invariably has a causal relationship in mind when he makes a decision. Mathematical modelling can therefore be regarded as a formalization of decision-making processes.*

As stressed by Forrester (1971), mathematical models make it possible to extend the "mental" models which are built continuously in a natural way. In a few occurrences, the mathematical model can even yield answers which are in contradiction with current "mental" models (counter-intuition effect).

Usually environmental management encompasses the following steps:

- perception of needs,
- problem definition and monitoring program,
- problem analysis and modelling,
- simulation to test alternative strategies,
- evaluation of alternatives,
- selection by decision makers,
- implementation and monitoring program.

In this context, modelling plays an important role in the decision-making process. However, the results are are uncertain because:

- the conceptual analysis (summation of "mental" evaluations and physical concepts) is incomplete,
- the mathematical relations used are representative of present knowledge,
- some uncontrollable or unpredictable even (e.g., natural catastrophe) can occur.

This uncertainty has led modellers towards an incremental approach (Holling 1978). Table 1 (reproduced from Holling (1978)) presents a list of positive and negative aspects of mathematical modelling.

Table 1:
Advantages and Disadvantages of Simulation Modelling

Disadvantages	Advantages
Requires computer facilities (*)	Promotes communication between disciplines
Requires expertise and a fair amount of time	User forced to clarify assumptions anc causal mechanisms
Results may be too easily believed by decision makers	Any form of relationship can be handled — linear or nonlinear
Results are usually complex (if there are many variables) and are therefore difficult to communicate to decision makers	Helps to identify key variables or relationships that need to be investigated or are sensitive
Relations between variables usually assumed constant through time	Can include uncertainties of various types
	Can easily compare alternative management schemes
	Can use detailed information concerning processes in the natural system
	Graphics output a good way of communicating impact
	Can utilize information about known processes that have not been investigated for the particular system of study but that have some generality (e.g., predation, population growth)

(*) Holling's book was written in 1978 just before the explosion in computer accessibility.

FROM BLACK BOX TO WHITE BOX

Mathematical models are based on the fundamental concepts of physical systems. A physical system is described by a few measurable variables and well-defined boundaries. Modelling the environment requires finding analytical relationships between variables knowing some responses of the system under various stimuli. This is known as an inverse problem (Karplus 1983) because it can be solved by a variety of mathematical relations. A simple algebraic mode, known as a black box, can represent the response of a system for very specific applications. If the model is to be used in a wide spectrum of different situations, it has to rely as much as possible on principles of physical systems (conservation principles of mass, energy and momentum). Most of the time (Taft 1965), due to numerous factors (computatiorial limits, unknown parameters, complexity of the formulation,...), mathematical models are simplified, taking into account only some of the fundamental equations. So, in air pollution, even in the case of wind field modelling, the principle of mass conservation alone is taken into account. In water modelling, equations of mass and momentum are currently used, simplifying assumptions being made either on spatial representation (e.g., omitting one or two dimensions) or on the transient nature of the system. With this perspective, it appears that the robustness of a model will depend upon the assumptions which have been made. Figure 1, taken from Karplus (1983), presents this situation, It appears, that air pollution and ecological modelling are still at the boundaries between clean mechanistic models (white box models) and models with incompletely known factors (black box models).

This uncertainty in the models must be considered carefully. As stated by Karpius (1983):

It is important to recognize, in evaluating and in using mathematical models, that each shade of gray in the spectrum carries with it a built-in "validity factor". The ultimate use of a model must conform to the expected validity of the mode/.

As the mathematical models are intended to help the decision maker, it is of paramount importance to analyse their limits.

SCOPE, VERIFICATION, CALIBRATION AND VALIDATION OF MODELS

The precision required of a mathematical model depends upon the output expected from that model. The studies conducted in EIA can be schematized in two parts.

The first is evaluation of different strategies: In such situations, we wish to rank several scenarios which have been previously established. This is the case when several options are in balance. In response to the question, "Is it better to develop coal or nuclear plants?", the decision maker does not ask for an evaluation of his energy policy. He is looking for the optimum way to apply his policy.

In that perspective, models do not need to precisely predict future impacts. Rather, they have to rank the different strategies that the proponent is looking at.

The model has to be as simple as possible with some comparison or sensitivity analysis to establish its credibility.

The second is prediction of non-compliance with standards: Legislation has established certain environmental standards, necessitating assessment of new projects or proposed

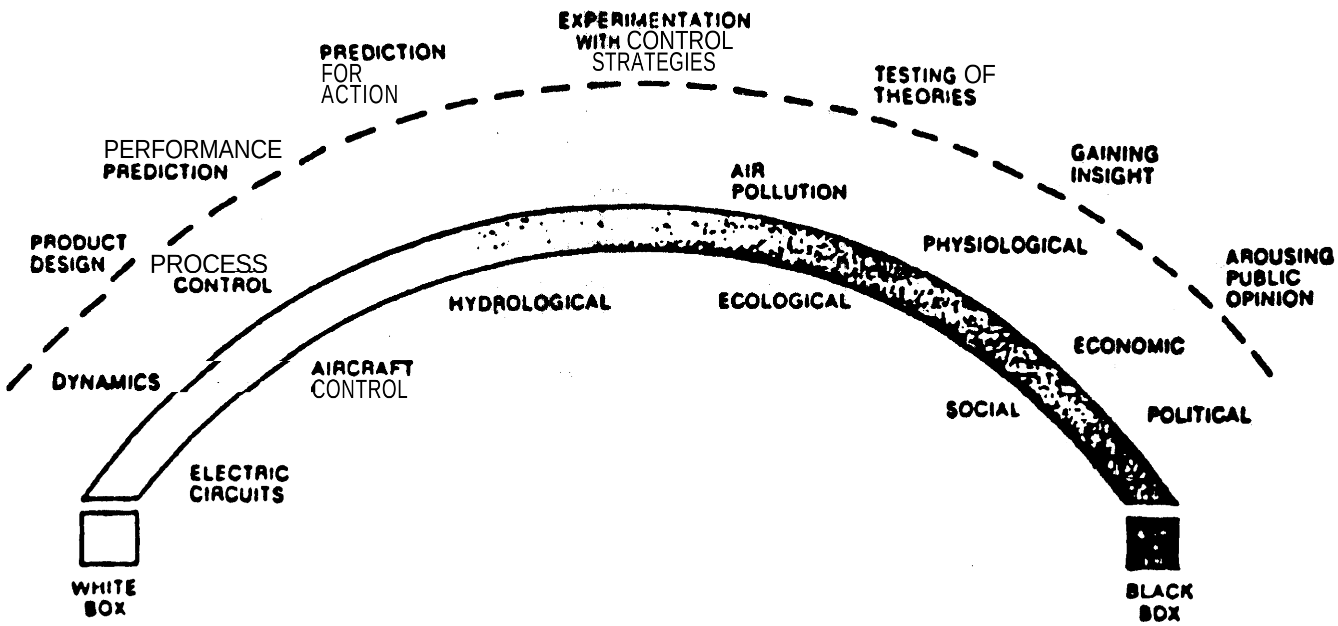

Figure 1. Spectrum of Mathematical Models

modifications of existing plants. In these cases, the models are used to evaluate impacts considering technical data given by the proponents. Modelling can directly affect equipment design (stack height, water treatment unit, etc.), therefore precise prediction is expected by the proponent. Unfortunately, the nature of systems under study and state of the art in modelling usually preclude accurate predictions. Introduction of a high security factor (e.g., as is usually the case in structure design) can make a project unfeasible.

Usually, establishing prediction as precise and reliable as possible necessitates the utilization of models of growing complexity, yielding successively less conservative evaluations. If at any level of complexity the project respects the standards, then the modelling effort is ended. Figure 2, adapted from Fabrick et *al.* (1977), shows this process.

To establish credibility of models, we need some concept to measure model accuracy. As seen previously, the model might be more reliable if it rests upon physical laws, rather then transfer functions for which the parameters have been found in a very specific situation. The degree of confidence will depend also upon its verification, calibration, and validation (McLeod 1982; Park 1982).

By verification, we mean that the fundamental equations with the implied basic assumptions and the computer code have been checked, and are error-free. It is difficult to get error-free codes, and techniques of good programming (structured programming with independently checked procedures) might be used. The verification of fundamental equations and basic assumptions might involve the proponent and, ideally, independent experts. The robustness of the model can be checked with a sensitivity analysis of its parameters and some modifications may follow.

By **calibration, we** mean that the parameters of the model are chosen. The range of these parameters may be found in the literature. Calibration is done when the parameters of the model, while respecting some defined ranges, are adjusted to give the best fit of model results to some field or laboratory measurements.

By **validation, we** mean that the model with its previously defined parameters is applied in a new situation and its results are compared with field or laboratory experiments. This validation step gives to some extent the degree of confidence of the model. This confidence is limited to similar applications. If the natural system is to be perturbed far from its present state, the model may only yield at best the general trends of the perturbed system.

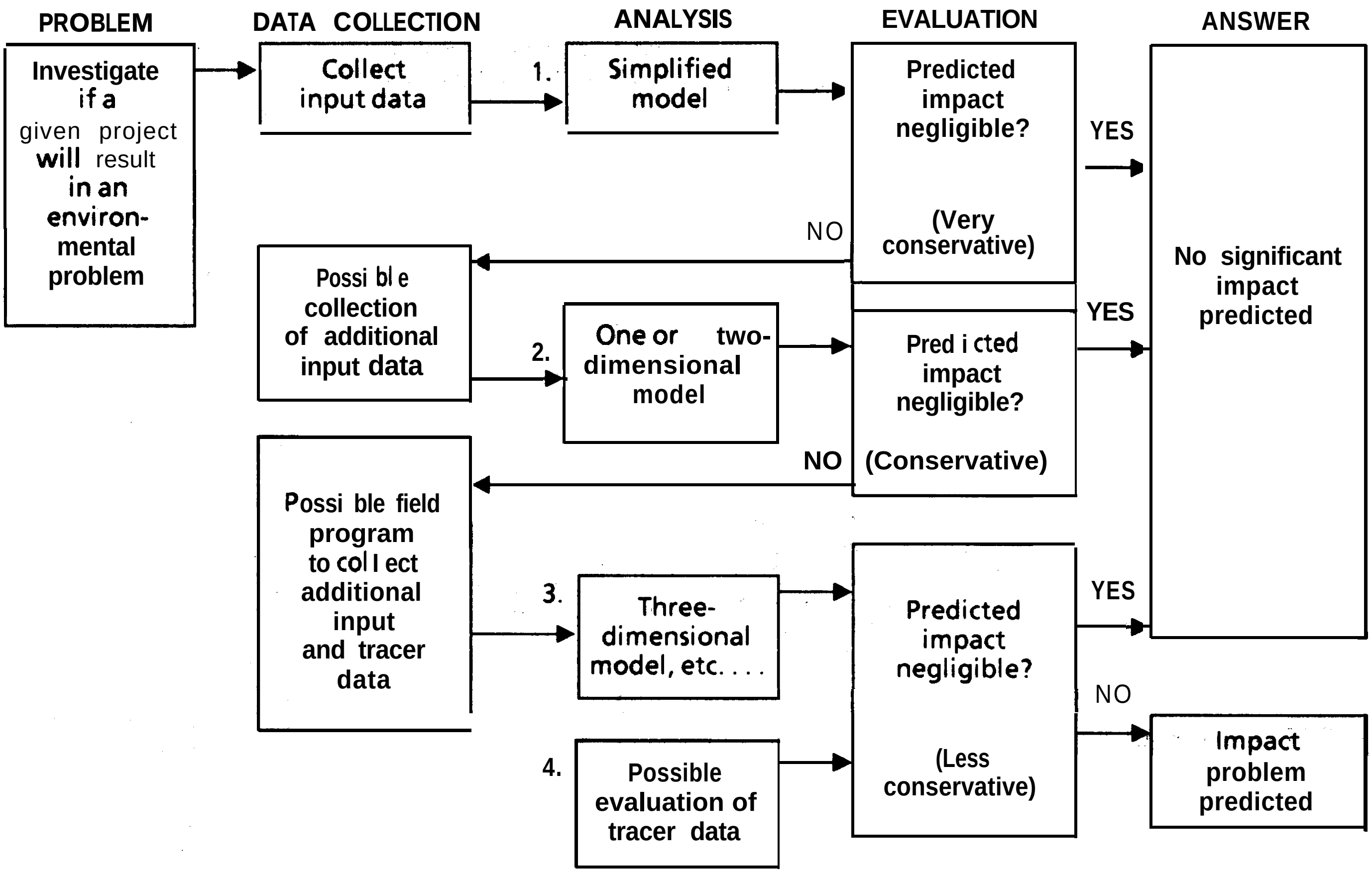

Figure 2. Hierarchical Analysis of Impact Assessment to Meet Standards

2. AIR DISPERSION MODELS

Air dispersion modelling is, by far, the main mathematical tool used by consulting firms in the environmental area. This is understandable because air is, with water, one of the chief dilution and transport media. This is also due to the fact that several mathematical models are available (mainly from U.S. EPA), and are easy to use. Many companies or government agencies in Canada have developed their own models, and information about these models ranges from excellent to very poor. Some calibration and validation have been done, but the results are not always easy to interpret.

Table 2 gives a classification of the models currently used. A more detailed description can be found in Hanna et *al.* (1982).

Table 2:
Different Types of Air Dispersion Models

Short- to Medium-Range: — Gaussian distribution Steady state, continuous release, puff model, instantaneous release, variable wind field — Statistical Non-uniform distribution Monte-Carlo simulation (Lagrangian) — Box model — Eulerian model (diffusion-advection equation)
Long-range: — Lagrangian — Gaussian — Box model — Eulerian

Short-range (up to about 10 km) to medium-range (up to about 30 km) models are applied close to the source. Long-range models examine the fate of pollutants which travel hundreds or thousands of kilometres, and must generally consider the physical processes of dry and wet pollutant deposition and chemical change.

Short-range models are used mainly for hazard determination during emergencies, or for assessing impacts of new sources and their compliance with air quality standards. Long-range models are used for assessing the impacts of distant sources, often in other countries. The impact at any given instant is usually weak, while the cumulative effects may be severe.

SHORT- AND MEDIUM-RANGE MODELS

Gaussian Models

Air dispersion modelling is largely dominated by the Gaussian model established some twenty years ago (Pasquill-Gifford equations). This model assumes normal distributions of pollutants along the vertical and horizontal, perpendicular to the direction of wind. It permits assessments of continuous or instantaneous release of pollutants, with or without a linear reaction rate or decay.

Further developments have consisted of the inclusion of special features which were not part of the original model:

- pollutant reflection at the ground and at the inversion lid,
- introduction of a variety of different sources (point sources, line sources, area sources, volumic sources, fugitive sources),
- linear reaction or decay rate, washout by rain, settling of particles, uptake by vegetation or water,
- topographic effects,
- lake or sea breeze,
- temporal and spatial variation of meteorological conditions.

Table 3 presents a list of models currently used and easily available. It is noted whether these models have been modified or validated. Table 4 gives a list of models developed by (or for) Canadian groups in the whole spectrum of short to medium-range models (Gaussian or statistical) with their main features.

Among Table 3 models, the UNAMAP programs developed in the United States for the EPA became, a few years ago, the standard in air pollution modelling and are still extensively used. There are many different models adapted to most situations (UNAMAP-4 itself is composed of twenty-one different models). Several of these programs have been validated in Canada e.g., CDM and VALLEY (Chambers et *al.* 1983), BLP (Andre Marsan and Associates 1982; MacLaren Plansearch 1984), and CDM (Intera 1980). Ontario Regulation 308 and STACKS are models imposed by provincial governments treating simple but common situations. If the problem under study necessitates a more elaborate treatment, other models are used.

GEM/GEMGAR is a standard Gaussian model developed in the United States. UDAD, also from the United States, provides, in addition, estimates of potential radiation exposure in the vicinity of a uranium processing facility.

As mentioned earlier, Table 4 indicates models set up in Canada or for Canadian groups. Acres, Beak, Monserco and SENES groups have developed puff models. Acres was considering a blast in an open pit mine. Monserco devised a computer code, GASPROB, which includes special effects such as terrain elevation, lake breeze, vertical jets and flares, building wake effects and a dense gas option. They wrote a specific model treating accidental release of tritium oxide from a fusion test facility or a tritium removal plant. SENES made a model to assess accidental releases of heavy gas and spills of

Table 3:
Current Short- or Medium-Range Models

COMPANY	UNAMAP-4 (EPA) (used more frequently)	Other models
Acres	MKPTR, PAL (M)	Ontario Regulation 308 (**)
BC Hydro		IMPACT
Beak	CDM	
EAG	PTMAX, CDM (M)	Ontario Regulations 308
ESL	CDM (*), PAL	STACKS (*) (***)
Hydro-Quebec		IMPACT (modified and named MAGIC for gas turbines applications) GEM/GEMGAR (modified)
Intera	CDM (*)	
McLaren	ISC, PAL, RAM	UDAD
Marsan	BLP (*), VALLEY (M)	
ORF	ISC (*), CDM, PAL	
SENES	CDM, VALLEY (*)	Ontario Regulation 308 STACKS IMPACT (*)

Legend :

- (*) comparison or validation has been conducted
- (**) Regulation 308 of the Ontario Environmental Protection Act
- (***) Alberta Environmental Protection Services
- (M) some modifications have been introduced in the original codes

aviation gasoline. They proposed a simplified approach (Hopper and Chambers 1983) to puff modelling.

Environment Canada's Atmospheric Environment Service (AES) has developed a group of programs (AQPAC) to be used for emergency situations. It contains two short-term models for continuous or instantaneous releases, and a medium-range surface trajectory model. These programs are installed on several mini-computers (HP1000) at AES regional weather centres, and utilize real-time meteorological data from the nearest meteorological station. These data are updated continuously on an hourly basis.

AES has developed a second group of programs (AIMS) which provide the opportunity to assess potential pollution for several situations on a short-term basis. The AIMS library is not yet complete. It gives access to a few dispersion models installed at Dataline Systems Ltd. in Toronto by AES. Dedicated telephone lines allow inexpensive access to the models from most regions. AES intends to include UNAMAP programs in this library in the near future, but no time schedule has yet been fixed. It is interesting to note that the majority of consulting firms are not aware of (or interested in) this service.

Hydro-Quebec contracted the development of a specialized Gaussian model, based on GEM/GEMCAR (Fabrick et *al.* 1977), to assess gas turbine operation including several conversion options from NO, to No, No_2 and O_3. They also obtained a mathematical model for real-time control of a fuel-burning peak power plant to change fuels depending on atmospheric conditions. Some comparisons were conducted with field data.

Marsan has developed a program to evaluate long-term gaseous fluoride concentrations. This model takes into account uptake by vegetation and bodies of water. Marsan contributed to some modifications of the BLP program (part of UNAMAP-4) with the originator, Environmental Research and Technology (ERT) of Concord, Massachusetts.

SENES devised a model to forecast the accumulation of ice on train tracks due to the proximity of an air cooling tower.

MEP created a multi-source Gaussian segmented-plume model for short to medium range. This model is a full three-dimensional model, as wind field and meteorological data are modified with time and location. Wind field can be externally generated or interpolated from sparse data. A plume rise model takes into account stratification of the atmosphere and wind variation with height. This model (named MUST) is extended for real time control (SCS) and complex sources (WES). A special code (CPT) predicts the behavior of moist plumes emanating from natural or mechanical draft cooling towers. Plume rise takes into account the presence of water vapour, including condensation and evaporation.

The Ontario Ministry of the Environment has developed an air quality model which is an adaption of the regional model originally designed for Connecticut (Hilst et a/. 1967). Strong sources are treated by the Gaussian plume method, while distributed sources of low intensity are treated backward from the receptor to the source. The model allows wind to vary in time and space and the Gaussian model is developed along the trajectory. This model has been applied to assess different strategies to reduce SO_2 levels in the Toronto and Sarnia areas (Shenfeld et *al.* 1977). The validity of the model has been established with several field measurements.

Too little information was obtained from Concord and Intera groups to present models that they have developed. It is felt to be a regrettable omission.

Statistical Models

Gaussian models cannot constitute the only answer in air modelling. It was shown by Misra (1982 a,b) and Venkatram (1982) that Gaussian assumptions of normal distributions are

Table 4:
Short- and Medium-Range Air Dispersion
(Specific models written for or by users)

Authors	Description	Type	Wind	Passive or Active Pollutant	Sources	EM	RE	Range Scale SR-MR
Acres	puff model	G	UWF	PA-SE	VS	IR	ST	SR
AES	AQPAC	G	UWF	RC-WO-SE	PS-AS-VS	IR-CR	ST	SR
	(applied for emergency)	S	VWF	RC-WO-SE	PS	CR	ST	MR
Beak	puff model	G	UWF	PA-SE	VS	IR	ST	SR
ESL	radon release	B	UWF	RC	AS	CR	ST	SR
Hydro-Quebec	real-time	G	UWF	CO	PS	CR	ST	SR
	gas turbines	G	VWF	RC	PS	CR	ST	SR
Marsan	stat. model	S	UWF	PA	LS	IR	ST	SR
	FLUOR	G	UWF	SE	LS-PS	CR	LT	SR
MEP	MUST	G	VWF	PA	PS	CR	ST	SR-MR
	SCS	G	VWF	CO	PS	CR	ST	SR-MR
	WES	G	VWF	PA	CS	CR	ST	SR-MR
	complex valley	G	VWF	PA	CS	CR	ST	SR
	CPT	G	UWF	MP	CS	CR	ST	SR
MOE	fumigation	S	UWF	PA	PS	CR	ST	SR-MR
	Air Quality	G	VWF	RC	PS-AS-VS	IR-CR	ST	SR-MR
Monserco	GASPROB	G	UWF	DE	PS	IR	ST	SR
	tritium release	G	VWF	RC	PS	IR	ST	SR
SENES	puff model	G	UWF	DE	PS	IR	ST	SR
	radon release	B,G	UWF	RC	AS-PS	CR	LT	SR-MR

Legend:

B = Box model; G = Gaussian model
S = statistical model
AS = area source
CO = real-time control
CR = continuous release
CS = complex sources (building wakes)
DE = densegases
EM = emission types
IR = puff release
LS = line sources
LT = long-term concentration
MP = moist plume, ice formation
MR = medium range
MS = multiple sources
PA = passive pollutant
PS = point sources
RC = chemical reaction or decay
RE = receptor type
SE = settling
SR = short range
ST = short-term concentration
UP = vegetation or water uptake
VS = volume sources
WO = washout
VWF = variable wind field
UWF = uniform wind field

not sufficient to represent a convective boundary layer. In that situation, downdraft and updraft plumes are composed of statistically independent distributions which present distinct behaviors. A normal distribution is kept to model horizontal spreading perpendicular to the wind direction. The product of the distribution functions gives an expression for the concentration which is similar to the Gaussian formulation. Validations of this kind of model have been conducted on two different locations (Nanticoke generating station (Misra 1982b) and the Inco stack (Venkatram 1982) in Sudbury.

On a completely different basis, it is possible to build statistical models from Monte Carlo particle trajectories. Reid (1979b) from AES applied this technique to estimate vertical dispersion from a ground-level source. Marsan built a model to evaluate the dispersion and impingement on foliage of insecticide droplets sprayed from a plane, based on work done at the University of New Brunswick by Picot. The results of this short-range Lagrangian model were compared with site measurements.

Box Models

This kind of model assumes constant concentration in a control volume, and has been used to predict average concentrations in cities where the heat-island effect is non-negligible (Summers 1967).

A box model has been used in a different context by ESL to simulate release of radon gas in an open pit mine. This model is built with several adjacent boxes and yields average concentrations with time. It has been tested and validated by comparison with a wind tunnel model.

Eulerian Models

These models are based upon the conservation equation, using a co-ordinate system fixed in space. First-order closure models treat turbulence as diffusion term, and are known as gradient transport or K models (higher-order closure is not yet used in impact assessment studies). The use of gradient transport models is still rare, but they provide some extra possibilities as compared with Gaussian models. Wind field may vary with space, diffusion parameters may vary with height, and pollutant kinetics can be as complex as necessary. This method also presents several disadvantages. Diffusion parameters are not well known, wind field must be computed or partially observed at the site, and computations are complex and lead to numerical problems. IMPACT (Table 3) is the best-known code (Fabrick et *a/*. 1977) associated with gradient transport models. It contains a submodel (named WEST) which computes the wind field to be non-divergent, with some perturbations to take into account atmospheric stability, while requiring a limited number of meteorological stations to measure wind (typically one or two).

BC Hydro, SENES and Hydro-Quebec (using MAGIC, a modified version of IMPACT) are the only groups or governmental agencies among those visited who have used such a model. Senes has applied it in a valley with two open pit mines. The model was validated for wind fields by measurements made from a helicopter and released balloons, but not for pollutant transport. BC Hydro conducted tracer experiments to validate IMPACT and obtained fair agreement. Concentrations were computed in 0.5 km^2 by 50 m boxes.

LONG-RANGE MODELS

Lagrangian Models

These are based on computation of trajectories between sources and receptors. These models are useful to evaluate different strategies of reduction of long-term and long-range pollution (e.g., acid rain).

TGDPA is a Lagrangian model developed by collaboration of MENVIQ (ministere de l'environnement du Quebec) and INRS-Eau (Institut national de la recherche scientifique) which is based on the gradient transport model. Turbulent diffusion is considered uniform along the vertical. It is also a statistical model because it uses time average rather than meteorological data, except for wind field. This model takes into account four different forms of sulphur (dry and wet SO_2, dry and wet SO_4). Pollutants undergo chemical reactions and are submitted to wet and dry deposition as well as vertical diffusion. Wind field is updated every six hours and the numerical integration is performed with a time-step of three hours. Precipitation is simulated by way of a Markov chain. The cumulative effects of deposition are computed over a season or a year.

The MOE (Ontario Ministry of the Environment) model follows the same concepts. Trajectories are evaluated every three to six hours. Bookkeeping of deposited pollutant is done on receptors based on a grid size of 127 km by 127 km.

AES and Monserco have developed codes on the same basis; insufficient information has been obtained to describe them.

Gaussian Model

The only model found in this field is MEP model (MEPTRANS code). It follows the same concepts as described for short- to medium-range modelling (MUST code). It is a segmented Gaussian model (Gaussian dispersion around a trajectory with four atmospheric layers and mixing depth variations with seasons. It takes into account SO_2, SO, wet and dry chemistry and NO,. Wind field is generated by three-hour surface pressure, and pollutants are tracked for five days. Some validation was made for 1978.

Box Model

This approach has been used by McMahon et a/. (1976) in association with Acres. Assumptions of uniform concentration are made along the vertical and along a circular arc drawn from the source over an angle representing the angular variation of the plume trajectory. Concentration is lowered with distance as the plume disperses within the widening box. Time-step is one day and meteorogical data are averaged over that time period. Output can be on a monthly, seasonal, or annual basis. The pollutant trajectory is assumed bounded by the sides of the wedge-shaped box. Wind data are taken at the station nearest to the receptor considered.

Acres applied this model to follow the chemistry of SO_2, SO., (wet and dry), NO, and No, for the Nova Scotia Power Corporation and for Ontario Hydro. Projected sulphate loadings on the Great Lakes in the year 2000 were also conducted (Reid 1979a). Some validation of this model has been made.

SENESLRT, on the same basis, developed a code to give monthly concentrations of carbon 14 (as $^{14}CO_2$) released from a continuous point source into the air. The meteorological data is given on a monthly basis. The model takes into account the uptake of $^{14}CO_2$ by various plant crops, the release of $^{14}CO_2$ flux in water. This model is followed by a pathway study and shows that for man, the dose from inhalation is much smaller than the dose by ingestion.

Eulerian Models

MOE is contracting MEP and ERT to build a gradient transport model for long-range studies. MEP is designing the meteorological model including a detailed profile of the boundary layer. ERT is developing the gradient transport model. The chemistry taken into account is complex and non-linear. At the beginning, the model was looking at 114 different chemical reactions. The number of chemical reactions has been reduced to 35 after some sensitivity analyses. The model requires twenty-four hours of computer time on a Cray computer for a ten-day simulation, and is still in development.

VALIDATION STUDIES

As mentioned earlier in the text, to be accepted, a mathematical model has to be verified, calibrated and validated.

Verification is relatively easy. It can be done comparing output of different models used in the same relatively simple situation. For instance, an Eulerian model can be checked against a Gaussian model.

Calibration is usually not done. Plume rise and vertical or horizontal standard deviations are computed making a choice between well-known available formulae. However, it is interesting to note that this choice is not always well adapted to Canadian conditions (Reid 1979a). Moreover, measurements conducted on different sites by MOE or Hydro-Quebec have shown that the "BRIGGS 1975" plume rise formula leads to over-prediction of plume heights. Thus at the Nanticoke generating station (Misra 1982b), factor "1.6" had to be changed to "I", reducing plume rise by 37 percent. BC Hydro found large discrepancies between plume rise generated by Briggs's formula and measurements made by helicopter. As cited in the text and in Table 2, several validation studies have been conducted. It is difficult to draw general conclusions from these studies for several reasons:

- As mentioned by Fabrick et *al.* (1977), the application field of air pollution is so wide that any validation study as limited to specific conditions which can't be generalized easily. Validation of a model in a precise situation doesn't ensure its validation for different situations.

- The validation problem cannot be dissociated from the measurement problem which is complex in air due to turbulent fluctuations and precision of the sensors (Intera 1980).

- Statistical tests may lead to bad interpretations. Fabrick et *al.* (1977) showed that an error of 2° in the wind direction gave a correlation coefficient of 0.01, while a model with an error of a factor of two in horizontal dispersion standard deviation produced a correlation coefficient of 0.85.

- Sector averaging (8 *vs* 16 directions) may lead to significant differences in predicted concentrations (Intera 1980).

For short to medium-range modelling, several UNAMAP models have been validated in several situations. Usually, these models yield conservative estimates of ground level concentration (Andre Marsan and Associates 1982; MacLaren Plansearch 1984; Intera 1980) inside a factor of two to three.

Intera did an extensive validation study for the Alberta Oil Sands Environmental Research Program (Intera 1980). They compared their own model and the CDM model with measured data. As mentioned previously, the comparison with the observed values was very poor. They found a better correlation coefficient with their own model, but the details of their model were not presented. They used CDM results from another study, conducted by another consultant, using a different meteorological data base.

Marsan pointed out the poor results obtained with stable atmosphere and low wind velocities. Most of the codes permit computing the concentration 10 km from the source with a wind speed of 1 m/s (3.6 km/h) on an hourly basis. These situations give very poor estimates, even on a long-term basis.

SENES validated CDM and VALLEY (modified to get long-term concentrations) to evaluate levels of uranium in total suspended particulates (Chambers et *al.* 1983) in the summer of 1981. CDM predictions were found to correspond well near the emission plant, and VALLEY predictions were found to correspond better far from the plant.

The Ontario Research Foundation just ended a study on SO_2, NO, and total suspended particulates, using the ISC model from UNAMAP-4. They looked at mean annual concentrations within several 30 km radius areas with several hundred sources. They reported excellent validation for SO_2, good validation for NO, and results difficult to interpret (due to background) for total suspended particulates (TSP). Unhappily, this work, which was done for provincial Crown corporation, is not yet public.

MEP, with their segmented Gaussian model, told us that they found comparisons much better than a factor of two on an hourly basis.

Good predictions have been obtained for specific meteorological conditions at Nanticoke and Noranda (Misra 1982b; Venkatram 1982) with new models to represent the convective boundary layer. The Ontario Air Quality Model, used to assess pollutant dispersion in urban areas, is reported to perform well (Shenfeld et *al.* 1977).

Long-range transport models are under validation. Acres found good approximations with a rather simple model. MEP reports good results for the year 1978 with a segmented Gaussian model. The more recent models from MOE or MENVIQ have been verified. They might permit comparisons of different scenarios for the treatment of gaseous effluents in North America.

DISCUSSION

It is generally well accepted that air dispersion models are very useful to "provide guidance rather than prediction required for emission control" (Venkatram 1982). If the model is designed for real-time control, it must be fitted by adjustment of plume-rise and dispersion coefficients with data collected on-site. However, air dispersion models permit evaluation of different strategies, while the prediction of non-compliance with standards (see Section 1 “Scope, Verification, Calibration and Validation of Models”) remains a difficult task. They are well-fitted to make site selection which is part of a strategic choice. The good results obtained by Misra (1982b) under fumigation conditions give some hope for improvements under specific conditions.

Special efforts have to be made to increase the confidence in these models. These efforts might bear on three different aspects: data collection, enhancement of models, and the establishment of standard statistical tests to help in validation studies.

Data collection is a tremendous problem. Measurements are frequently done at the limit of precision of the detection unit used, and wind field is often taken at a distant airport. However, automatic stations for pollutant sampling and meteorological data recording are improving steadily. It must be noted that the choice of the receptors is problematic.

The models provided by the U.S. EPA cover a wide spectrum of distinct situations. They are easy to use. However, it would be worthwhile to apply new concepts for specific situations (convective boundary layer or complex terrain). Now that computing time and cost are no longer limiting factors, it appears worthwhile to develop the use of gradient transport models, especially for complex terrain. Difficulty remains for the choice of turbulent diffusion parameters with time and height, for different stability conditions.

The Briggs formula for plume rise might be assessed for typical plants. This verification is simplified by new technologies such as LIDAR.

The difficulty of developing good statistical tests has been mentioned previously. The validation study conducted by Intera in Alberta (Intera 1980) presents several tests (linear correlation, rank correlation, Pearson Chi-square test, Kolmogorov-Smirnov test). A contingency table could also be used if the number of observations is sufficient.

It would be of great value to develop a certain number of case studies representing different climatological conditions with different types of emissions and topographies. Precise measurements might be made on site and would help any private companies or government agencies to validate a model.

Validation is an important step. It must be noted, however, that mathematical models give the opportunity to assess situations for which data are not available, while getting good insight into what could happen. As an example, we can cite the work done by Munn (1983) to assess atmospheric dispersion from buried nuclear wastes over a a period of one million years and encompassing several ice ages.

3. HYDROLOGY AND HYDRODYNAMICS

A good knowledge of water flow field is a prerequisite to any water quality modelling. Direct measurement is seldom sufficient to provide good insight into water motion. Many factors influence the behavior of a body of water: seasonal conditions, rain, snow or ice melting, topography of the bottom, characteristics of the bottom surface, thermal motion, wind at the surface, tidal effects, Coriolis forces, etc. A mathematical or a physical model must be used to obtain the flow conditions.

A summary of the state of the art in hydrology and hydrodynamics can be found in the proceedings of a seminar held in Montreal in March 1982 (Schneeberger et *al.* 1982; Marché and Gaudette 1982; Bilodeau 1982; Cochet et a/. 1982; Morin 1982).

HYDROLOGICAL MODELLING

Many mathematical models are available to calculate flow rates in rivers over time, requiring only a few meteorological factors. CEQUEAU model from INRS-Eau is a good example of such a model. This model was first used to find the dimensions of the structures of the La Grande River reservoirs (instead of stochastic models which were common at this time). Presently, this model is the basis for water quality studies (Ste-Anne River) and water quality management (Yamaska River). The basin is divided into square parcels of equal surface. Certain physiographic characteristics are obtained for each parcel: a representative elevation and the percentages of forest, lakes and marches. Each parcel is subdivided along the line of drainage, and the direction of water flux is indicated. The only meteorological data used are liquid or solid precipitation and minimum and maximum temperatures on a daily basis. The model is calibrated to take into account:

- snow build-up and melting,
- evaporation and evapotranspiration,
- underground accumulation and flow,
- propagation of water from one parcel to the other.

Several applications in Quebec have shown the validity of this approach.

Many other models are used for hydrological modelling. HSP-F is the well-known U.S. EPA program which is extensively used in Canada (for example, by Acres, Beak, and Maclaren). It is a versatile code for simulating water quantity and water quality on land surfaces and in river reaches or in reservoirs. Snow accumulation and melting are taken into account. CREAMS (developed by the U.S. Department of Agriculture and used by Maclaren) is oriented toward sediment transport and erosion. Canada Centre for Inland Waters (CCIW) developed its own model for small basins (for surface flow with or without groundwater flow). Société d'énergie de la Baie-James (SEBJ) contracted development of a hydrological model for subarctic areas including frozen ground (Bertrand et a/. 1981; Leconte et *al.* 1984). Hydro-Quebec developed a FEM surface flow model (Marché and Gaudette 1982).

HYDRODYNAMIC MODELLING OF HORIZONTAL FLOW

The mathematical equations used to represent general flow with a free surface are special applications of Navier-Stokes equations. These equations involve three momentum equations (velocities in three directions) and one continuity equation (usually written in terms of water depth). The resolution of this three-dimensional problem is still intractable most of the time, and simplification is necessary. For this reason, the flow is generally solved in one dimension (along the flow) for narrow rivers and in two dimensions for large bodies of water (to give the so-called "shallow water equations"). For two-dimensional problems, it is assumed that velocity is the same throughout the water column. For one-dimensional problems, it is assumed that the velocity is the same at any point of a section perpendicular to the flow. In most cases, some pseudo-viscosity must be added to dissipate local turbulence which cannot be represented properly with the inherent approximations that must be made for the numerical process. These equations are solved numerically either via finite difference techniques or via finite element methods (FEM). Several codes exist for the solution of such equations:

- Laval University's MEFLU (Cochet et *al.* 1982) is a finite element solution that can be used for steady-state or transient conditions. A simplified approach to treat three-dimensional problems is under investigation (by way of multiple layers). The model has been tested in many different situations.
- Sydor (1982), of Environment Canada, uses a finite difference technique for integration, following Leenderste discretization. This model has been used and validated extensively in the St. Lawrence River and in Lake St-Louis.
- Simons (1982) of CCIW developed a simplified circulation model for lakes and reservoirs. The shallow water equations are linearized and give a good approximation to circulation flow for a modest computing time. This model has been used extensively to evaluate the transport of pollutants, and has been validated.

OTHER HYDRODYNAMIC MODELS OF COMPLEX FLOW

In some circumstances, it is preferable to evaluate the flow field along a vertical plane. This is the case for flow in an estuary where the tide is affecting the general pattern of flow field. The equations are integrated, assuming uniform velocity along the direction perpendicular to the flow. Hydro-Quebec has developed and validated the code ESTUAR to treat this situation. In the case of a stratified estuary with a complex geometry, it would be necessary to integrate the full three-dimensional model.

CCIW wrote several models to treat different situations. The Lake Erie model (Lam et *al.* 1983) is a compartmented model (three, six or nine boxes) in which the thermocline is used to define separation between upper and lower layers when using six or nine boxes. They also developed a vertical two-dimensional model and a three-dimensional model. All these models have been validated for Lake Erie. A turbulent model (K model) has been written to describe mixing under an ice cover (Lau and Krishnappen 198 1 b).

The LARM model is frequently used for thermal analysis of an elongated reservoir with non-horizontal thermoclines. Maclaren used this model for reservoirs in Alberta and Saskatchewan, and for estuary studies in New Brunswick.

Acres used the RMA-2 and RMA-3 models for the Keating Channel study, with an assumed vertical velocity distribution and both horizontal velocity components calculated over the area examined.

MEP is designing a two-layer two-dimensional model to simulate oceanographic currents. It will be applied to oil slick displacement.

CONCLUSIONS

For most of the problems it is possible to define the flow field with good precision and to extend these models to predict new situations.

It is interesting to note that most of the time consulting firms do not want to model flow circulation and ask the proponent or specialized agencies to furnish velocities. These models are time-consuming, their utilisation is not easy for inexperienced people, and they generally need some adjustments for each new case.

4. WATER QUALITY MODELLING

As stated previously, water quality modelling is closely related to flow field. One equation is used to express conservation of mass and, if necessary, another one to express conservation of energy. The structures of these equations are quite similar. In rivers, the equations are integrated along the direction of flow (one-dimensional) assuming constant properties in a cross-section. In lakes and reservoirs, concentration of a pollutant is frequently considered as constant along the depth, leading to two-dimensional models, and temperature is considered constant along a horizontal plane, leading to one-dimensional models.

In several situations, the flow field is ignored, assuming a uniform state in the body of water. This is often the case when a quick evaluation is needed.

Table 5 summarizes the different aspects of water quality modelling.

ONE-DIMENSIONAL MODELS

Along the Vertical

In a lake or a reservoir, it is frequently assumed that temperature is uniform along a horizontal plane and varying with depth. This assumption is well corroborated in many lakes and reservoirs. Most of the models used are derived from the work of Ryan and Harleman in 1971. This approach is based on an energy budget between air and water including short-wave and long-wave radiation, precipitation, evaporation and convection. Water entering the lake or reservoir is introduced at the depth corresponding to the same temperature level. The work of Ryan and Harleman is currently extended to include ice cover with time and the height of a varying mixed zone due to wind shear stress. These models have given good approximations when tested in several lakes and reservoirs.

The prediction of dissolved oxygen in lakes and reservoirs is a direct consequence of a temperature profile. The equation is quite similar to the temperature equation. It is necessary to include a re-aeration rate at the surface. The difficulty is to define the oxygen uptake by sediments, and this factor is frequently ignored.

Such models are currently used by Beak (Wreck Cove project), CCIW, EAG (Environmental Applications Group, Toronto) (RESMOD model), Hydro-Quebec (Marcotte et a/. 1977), Ontario Hydro (Harris 1982) and SEBJ (Baldasano et *al*. 198 1 a, b; De Broissia et *al.* 1981).

Along the Flow

Different models assume homogeneity of parameters over a cross-section perpendicular to the flow. These models include several factors.

Beak applied this kind of model for pulp and paper industries in New Brunswick, Ontario and Quebec. It resulted in the development of waste treatment alternatives and operational policies. In another field, winter oxygen depletion in a river in Alberta due to decay of algae and macrophytes was computed; the effects of a series of weirs was carried out to evaluate their re-aeration rate.

CENTREAU modelled the change of salinity profile following the flow rate reduction in the Eastmain (Dupuis and Ouellet 198 1) and Koksoak (Ouellet and Ropars 1979, 1980) rivers as

Table 5:
Modelling Water Quality

MODELS	VARIATIONS	COMPONENTS OR REMARKS
One-dimensional	along the vertical	temperature in lakes and reservoirs; dissolved oxygen
	along the flow	passive or active contaminant(s); temperature in rivers
Two-dimensional	along a vertical plane	temperature in lakes and reservoirs; salinity
	along a horizontal plane	passive or active contaminant(s)
Three-dimensional	variations in any direction	no restrictions but difficult to incorporate boundary conditions and true velocity field
Well-mixed	homogeneous in a definite box	used for quick approximations or for complex multicomponent equilibria
Hydrological	over a basin	utilize a combination of 1-D or well-mixed models
Water sediment exchange	along the vertical	heavy metals and radioactive components

a result of the La Grande hydroelectric project. The model was validated after the flow diversion in the Koksoak River (Ouellet and Robert 1980).

Hydro-Quebec devised an elaborate model for winter regime (temperature and ice formation and displacement on rivers, formation of frazil) (Marcotte and Duong 1973; Marcotte et al. 1977; Marcotte 198 1 a, b).

Norecol used QUAL II (U.S. EPA model for rivers: temperature, BOD, DO, ammonia, nitrate, coliform, phosphate and algae) for four different coal projects.

TWO-DIMENSIONAL MODELS

Along a Vertical Plane

Several kinds of problems belong to this category where lateral homogencity is a reasonable assumption. In long lakes or reservoirs, the model LARM assumes variation of temperature vertically and along the flow. MacLaren used it for thermal pluming in the Battle River Reservoir, and for evaporation studies in the Rafferty Reservoir.

CCIW combined a two-dimensional model along a vertical plane for temperature and dissolved oxygen with a two-dimensional model along a horizontal plane in Lake Erie (Lam et *a/.* 1983). Lam et *al.* (1981) conducted research to evaluate the turbulent diffusion parameters from observations.

As seen previously, diversion of rivers for production of hydroelectricity strongly modifies saline intrusion in some estuaries. The model ESTUAR has been developed by Hydro-Quebec to compute iso-salinity in modified estuaries. They are taking into account tidally induced motion, wind at the surface and ice cover.

Marsan developed a two-dimensional FEM code to compute the vertical plume of suspended solids from dredging (Ottawa River). The model permits the evaluation of deposition and re-entrainment of sediments on the river bed.

Along a Horizontal Plane

These models are used frequently for large bodies of water (lakes, reservoirs, estuaries, etc.). They assume homogeneous concentrations on the vertical axis for active or passive contaminants. Transport is the result of flow convection and turbulent diffusion.

Acres compared temperature profiles obtained with a computer code (Koh-Fan model) with those obtained from a physical mode. The mathematical model didn't give good results and it was modified. This modified model was applied at the Cayuga Lake nuclear generating station in the United States.

Acres used the RMA-3 model to predict source-receptor relationships for sediment-related contaminants in the vicinity of Toronto harbour. This model has been widely used in the United States.

CCIW has set up a model for tranverse mixing in natural streams where velocity and depth are not uniform and the channel is not straight (Lau and Krishnappen 1981a). A transient thermal plume model has been built and calibrated at Pickering, on Lake Ontario. Another model considered total phosphorus transport in Lake Erie, taking into account phosphorus resuspended by wind-induced turbulence. A tritium spill model treats accidental release of tritium mixed with heated effluents from a generating power station. This model is valid except during the winter (i.e., sinking of the plume).

CENTREAU wrote a model to assess the location of the thermal effluent of a generating station for transient or steady-state conditions.

Hydro-Quebec models are looking at temperature, dissolved oxygen (assumed uniform over depth), BOD_5 and saline intrusion in estuaries under a modified regime. MEFLU combined with an equation for temperature has been used to evaluate the thermal plume at the Gentilly Ill site (Cochet et *a/.* 1982). Some sensitivity analyses were conducted.

Marsan developed a finite element method to estimate the consequence of a methanol spill at Kitimat Arm, British Columbia. This model is taking into account tidal motion. Another FEM model estimates the spreading of an oil slick after an accidental release.

Roche simulated the release of waste water from a diffuser. The model was calibrated with tracers.

THREE-DIMENSIONAL MODELS

The three-dimensional convection-diffusion model can be solved analytically in simple situations where flow field can be considered uniform. The treatment of boundary conditions, using the image method, is tedious. This model can provide rough estimates of concentration with time and position. (Marsan has used it at Kitimat Arm.)

CCIW developed a multi-layer two-dimensional model for chloride distribution for lake epilimnion and hypolimnion. This model was applied to Lake Erie and gave a good match with observations (Lam et *al.* 1983). The same model was validated for Lake Superior (Lam 1978).

Beak is presently working on a three-dimensional model for the dispersion of pulp and paper effluents (Lake Superior outfall).

WELL-MIXED MODELS

In several circumstances, a well-mixed model gives very quick estimates of variation of concentration in a body of water with time. This method is useful to look at mean content of chemical species. Very often, the body of water can be split into several boxes, with some kind of information about fluxes between boxes.

Acres did a study of a system of reservoirs and intercommunicating channels in the Rideau and Cataraqui River basin.

CCIW applied three, six and nine interconnected boxes for simulating distribution of dissolved oxygen, soluble reactive phosphorus and total phosphorus in Lake Erie. The model was verified (Lam et a/. 1983), and subsequently validated for Lake Ontario (Simons and Lam 1980).

Marsan studied several strategies (De Broissia et *al.* 1981) for the NBR (Nottaway-Broadback-Rupert) hydro-electric complex in Quebec. Some reservoirs of the complex were split into smaller parts, to take into account the dimensions and different inputs into a reservoir of great size. The retained variables were total dissolved solids (TDS), total phosphorus, nitrates, ammoniacal nitrogen and organic nitrogen. In another study, the use of a natural lake as a water reservoir was assessed in Saint-Bruno, Quebec. Maximum chlorine concentrations and effects on biota were evaluated, considering the hydraulic regime of this controlled lake.

SEBJ used a well-mixed model to evaluate water quality effects of four different operating scenarios for the LG-2 (La Grande 2) reservoir. The reservoir was divided into zones, and each zone was further divided into epilimnion and hypolimnion.

SENES used such a tool for modelling the underwater disposal of uranium mine tailings in Elliot Lake (Halbert et *a/.* 1982). The lake was split into two compartments (one for epilimnion and the other for hypolimnion). The effect of nine management scenarios on four different quality variables (pH, NH_3, TDS, radium-226) was observed.

HYDROLOGICAL MODELS

So far, water quality modelling has been applied to rivers, lakes or reservoirs. Numerous models have been developed with a more integrated point of view. They are based upon hydrological modelling, including river, lake and reservoir modelling.

Acres applied HSP-F (U.S. EPA program). This code is flexible and can be used for simple or complex situations. It can examine BOD, plankton, pH, phosphorus and nitrate simulation. Applied to the Humber River, it was found to be reliable and flexible.

Beak examined the management of radioactive tailings. Numerous policies were tested (Elliot Lake watershed) and transport modelled through the surface waters to the Atlantic.

INRS-Eau has developed several water quality models based upon the CEQUEAU hydrological model: TDS, temperature and suspended solids (Morin et *al.* 1983a, b,c). A water management study is in progress on the Yamaska river, considering total phosphorus, BOD and suspended solids. Different strategies of water treatment plants are evaluated with different cost functions (maximizing water quality, minimizing effluents, minimizing costs). They stress the necessity to create a good data base (Couillard and Cluis 1980a) to obtain good management of water resource (Couillard and Cluis 1980b; Cluis and Durocher 1976).

MacLaren issues HSP-F for general purposes and CREAMS for sediment transport and erosion of agricultural management systems.

Norecol used HSP-F for the Quinsam Coal Project.

SENES has developed SERPENT for studying the water quality of the Serpent basin (Halbert et al. 1980). This model was used to evaluate a range of situations, from improved effluent treatment to expansion of mining facilities. Retained water components were TDS, radium-226, ammonia and pH. The model has been verified and calibrated under current operations.

WATER-SEDIMENT EXCHANGES

Heavy metals and radioisotopes accumulate in sediments due to industrial activities (the partitioning of these chemical wastes will be discussed later in “Risk and Pathways Analysis”). These compounds are released from sediments into water with time, and act as distributed sources.

Acres simulated the quantity of heavy metals that could be released from tailings dumped at the bottom of a lake. The analyses took into account oxygen supply limitations, diffusion in the sediments, thermodynamic equilibria and the hydrology of the area. The solubility of potential toxic materials such as lead, zinc and arsenic were evaluated under a range of pH and oxidation states. Applied to an inland lake on Baffin Island, it was shown that metal releases in the receiving sound would have no significant impact on the concentrations.

Beak developed a model (Holloran 1982) to assess the absorption and release of heavy metals and radioisotopes. Results of the modelling suggested that the sediments have a small effect on instream concentrations during the active phases of mining and milling. The sediments were predicted to act as a distributed instream source after completion of milling activities. The significance of this post-operational source is a function of the initial effluent loading, elapsed time and site-specific river characteristics.

Bukata and Bobba from CCIW use a one-dimensional equation of mass transport to general ^{210}Pb concentration profiles with depth in sediment (Bukata and Bobba 1984). In comparison with measured concentrations, an iterative least-squares optimization technique gives the “best” diffusion coefficients associated with the transport of ^{210}Pb in sediments.

Tessier and Campbell from INRS-Eau studied interaction of trace metals between sediments, water and organisms (Tessier et al. 1980; 1983). They modelled the water-sediment interface, making analogies with electrochemical reactions. They examined speciation of heavy metals (five different fractions) and applied their analyses to several rivers and lakes in Quebec.

SENES assessed the effects on water quality of underwater tailings-disposal at the bottom of a lake in the Serpent River watershed (Halbert et *al.* 1982). Field and laboratory experiments were conducted to evaluate rates of pyrite and ammonia oxidation, and pH-alkalinity relationships. A one-dimensional steady-state equation describes the oxygen concentration with depth into the tailings.

MISCELLANEOUS MODELS

Acres developed a model of water consumption for energy-related development. It allows forecasting of water demand, evaluates the impact of low flows and simplifies, for example, the choice between the air or water cooling for thermal power plants. The code is implemented on an IBM-PC and has been applied in several situations (Cold Lake and oil sands areas, and the South Saskatchewan River).

CCIW studied the dispersion of dredged spoil when dumped as a slug in deep water (Krishnappan 1983). Based on the theory of dimensions, it takes into account bulk fluid motion. This model can be used to predict the vertical height and the horizontal size distribution of the heap formed due to the deposition of the dredged spoil at the bottom of deep water.

CONCLUSIONS

Many models exist in the field of water quality. Transport mechanisms of passive contaminants are well understood in bodies of water where turbulent mechanisms are moderate.

Models of growing complexity may be applied (Lam *et al.* 1983; Ouellet 1983). As complexity is increased (e.g., one-dimensional to three-dimensional), the boundary conditions can be fixed from previous and simpler simulations. Thus, three-dimensional models can be applied for a small area, while boundary conditions are given by two-dimensional models applied on a larger scale (Ouellet 1983).

Modelling contaminants in sediments is still a difficult task as reaction mechanisms are complex and not yet precisely known.

Availability of observed data is, most of the time, a key factor to calibrate or validate water quality models.

5. GROUNDWATER QUALITY MODELS

Infiltration of liquid pollutants into the ground is becoming a main concern in environmental studies. Pollutants can be soluble in water and partially adsorbed and reacted. Liquid (usually contaminated water) percolates through porous materials and flows along fractured rock to reach the water table.

Acres developed two two-dimensional finite element models to simulate groundwater transport through porous materials and fractured rock. One model is integrated in a vertical plane to represent vertical flow and lateral diffusion. The other model is horizontal to simulate transport into the water table. These models have been applied to leaching from radioactive and chemical waste disposal areas.

Beak modelled the transport of radionuclides and associated heavy metals through a regional groundwater system for Canada Wide Mines, and developed a model for Esso Minerals to assess infiltration of contaminants through the pit walls associated with deep pit tailings-disposal\ of radioactive materials. In La Tuque, Quebec, Beak computed groundwater transport and resurfacing of “black liquor” for CIP.

Hydro-Quebec, with the Geos Company, designed a one-dimensional transient model to assess the underground transport of radionuclides (GEOSPR). This model takes into account water dissolution and adsorption of contaminant.

In another one-dimensional model, infiltration of hydrocarbons into dry ground is evaluated after an accidental spill at the surface. Hydraulic conductivity has been calibrated on a physical model.

SENES used several two-dimensional groundwater flow and contaminant transport models developed in the United States, including FEMWATER, FEMWASTE, and AT123D. They have also developed SGWT, a microcomputer version of a TVA model.

Groundwater quality modelling is a sector in development. It might play an important role as data collection is costly and may cause side effects. Indeed, extensive drilling is needed to obtain a good evaluation of contaminated soil and this can result in increased contamination of the water table.

6. EROSION AND SEDIMENTATION

IN RIVERS

The cross-section geometry of a river may be altered if its hydrograph or sediment supply is modified by changes in land use or by river developments such as dams.

Acres uses HEC-2 and HEC-6, well-known models from the U.S. Army Corps of Engineers. They applied these models at Keating Channel instead of MOBED (Mobile Boundary Flow Model), after some comparative evaluations.

CCIW developed MOBED (Krishnappan 1984a; 198 1). This model estimated the changes which would occur in the bed of a river if its hydrograph or sediment supply are altered. It can also be used for short-term events including flood waves and tidal boundaries. HEC-6, based upon quasi-steady-state assumptions, cannot evaluate rapid perturbations. MOBED differs from HEC-6 in that it does not require any calibration and is an actual transient model. However HEC-6 can consider many size fractions for sediments while MOBED utilizes two sizes of sediments to represent the whole spectrum. MOBED and HEC-6 have been compared by Krishnappan (1984b) and validated for South Saskatchewan River. Comparisons after a ten-year period were very good.

CENTREAU treated sediment transport in Rivière-à-Mars, Quebec. It was intended, with the help of control works, to reduce deposition of sediments, thus reducing the need for dredging and the subsequent release of accumulated pollutants from sediments.

Hydro-Quebec modified the CAFE model (Marché and Gaudette 1982) to evaluate suspended solids in rivers. It was applied to the Aux Outardes estuary to assess a change in the flow regime. This model is used with different granulometries and computes bottom modification of the estuary with time.

Marsan developed a two-dimensional finite element model to evaluate the sedimentation and re-entrainment of suspended solids. The model computes the concentration distribution with time and depth along the flow. It was applied to the Lachine Canal and to predict suspended solids distribution while dredging the Ottawa River.

IN LAKES OR RESERVOIRS

Shorelines of newly created reservoirs and natural lakes used as reservoirs erode over time. This process can be very long (i.e., decades) and is a function of water management policies. Severe erosion of shoreline exposed to wind occurs when wind velocity and water level are high. The problem is even more complex when the shoreline is constituted of such materials as till.

Acres modelled shoreline erosion as a function of wave energy with considerations of soil characteristics, bank slope and vegetation. This model was applied to the Arnprior reservoir at twenty different sites.

Marsan developed a model to compute shoreline erosion of reservoirs with time. Hourly winds and fetches were used to compute wave climate and the resulting energy reaching the shoreline. Erosion was considered as a function of longitudinal and normal components of energy, bank slopes and type of eroded materials. The model was applied to Lake St-Jean in Quebec to assess different water management policies. It was calibrated on a physical model and back-validated over a period of seventeen years. (The shoreline was restored from its actual state by applying storms backward, and the shoreline was compared with aerial photographs taken seventeen years earlier.)

7. OIL SLICK AND LIQUEFIED NATURAL GAS SPILL

OIL SLICK MODELLING

As stated by Huang (1983), the fate and behaviour of spilled oil is affected by several mechanisms: advection, spreading, evaporation, dissolution, emulsification, dispersion, auto-oxidation, biodegradation and sedimentation. Many models currently used treat the first mechanism, while neglecting the other aspects which are important to assess the impact on the system under study. These different mechanisms are largely influenced by physico-chemical properties of the spilled oil, and MacKay et al. (1980) developed some equations to represent these properties. Mackay (1984) distinguishes four kinds of mathematical models in that field:

- "real-time trajectory" models for emergency situations.
- "environmental assessment" models to evaluate the impact of eventual accidents.
- "war-games" models to train people in charge of emergency situations.
- "regional ecosystem impact" models to assess long-term oil development impacts on fisheries, for example.

AES developed two kinds of models. The first (Venkatesh et *al.* 1981) is used for an emergency situation and is implemented on mini-computers available in six regional centres in Canada. The response-time is of the order of a few minutes, and wind forecast for the next fourty-eight hours is available at any time. This model takes into account the advection of the oil slick by wind-driven and other residual water currents, plus the spreading of the slick according to the Fay algorithm. The model has been tested for actual spills.

The second model (Hirt et *al.* 1982), developed in collaboration with MEP, takes into account the same mechanisms plus weathering effects such as evaporation, emulsification and dissolution in a more elaborate analysis. For instance, the slick is composed of several parcels to represent break-up from with a more realistic point of view. An interactive data base gives wind field. Surface currents are derived from Madsen's formulae. Operational tests gave good predictions on the location of the spill after twenty-four hours.

Beak used the UOT (University of Toronto) model (see further) on the Mackenzie River.

EAG added some spatially variable winds to the simple AES model.

Marsan wrote a trajectory model with wind persistency as a special input for environmental assessment. Probability patterns are derived. This model has been applied in several locations (Hibernia, Nova Scotia, Lancaster Sound and the Ottawa River). The advection law between wind and residual water currents have been verified with drifter experiments on the Ottawa River.

MEP developed the SOS model with AES. Oceanographic current modelling is under development, taking into account surface currents and deeper ocean currents. This model is based upon research conducted at the Bedford Institute in Nova Scotia. For impact assessment, worst possible cases are considered.

Roche designed a model to evaluate the contamination resulting from an oil slick into the mud flats at Ile d'Orleans, Quebec. A trajectory model was used for Pointe Noire Harbour near Sept-Iles, Quebec.

The UOT model was created by MacKay et al. (1980j. This model takes into account many of the physico-chemical mechanisms described at the beginning of this section. The slick is separated in two parts (thin and thick slick) to obtain a better representation of spreading, evaporation and dispersion. A simple formulation is proposed for emulsification.

Many methods allow predictions of probable displacement of a given slick, and real-time trajectory models are becoming easier to use, with wind forecast incorporated automatically as input data for several hours ahead. However, the fate of the oil in the aquatic system is more difficult to evaluate. A few models have been proposed for evaporation, emulsification and dispersion processes, but they still contain a high degree of empiricism (Huang 1983). Mechanisms such as auto-oxidation, biodegradation and sedimentation are not well understood yet.

Mackay (1984) proposes some guidelines to simulate oil slicks and to present modelling results which will permit a better comprehension for decision making.

LNG SPILL MODELLING

The modelling of an liquefied natural gas (LNG) spill over a body of water may be divided in three phases:

- growth of the LNG slick, controlling the evaporation rate;
- spreading of a heavy gas cloud;
- gas and air turbulent mixing, advection of the cloud.

Usually, simple assumptions are made for phase one. SIGMET is a three-dimensional model (Havens 1979; England et *al.* 1978) which describes phases two and three. We obtained no information about its utilization in Canada. Acres and Marsan worked on risk analysis related to LNG transport by sea. Marsan made some simple evaluations of the motion and spreading of a methane cloud at Gros-Cacouna, Quebec.

8. RISK AND PATHWAYS ANALYSIS

Modelling work failing within this category is fundamentally different from the other types of modelling. It is not dynamic modelling, although input from dynamic models (e.g., water quality) may be used. Among the consulting groups interviewed, the following have used these techniques: Acres, Beak, ESL, Maclaren, Marsan, and SENES. Hydro-Quebec and the Ontario Ministry of the Environment have also used them.

PATHWAYS MODELS

Pathways modelling is used to examine the distribution or accumulation of persistent contaminants in the environment, usually with accumulation in humans as the desired outcome. The accumulation within an organism may then be compared with dose-effect data to evaluate the health risk to an individual. Critical pathways models examine dosages to the most exposed members of the population. Most frequently, pathways models are applied to radionuclides, but they are also applied to heavy metals and toxic organic compounds.

The pathways for the transmission of the contaminant through the environment are identified, and uptake coefficients are used to quantify transfers from each stage of a pathway to the next. The underlying system (e.g., food chain) is usually considered as being in steady state. A notable exception is the fugacity approach (Mackay and Patterson 1982), where the system need not be in steady state and where fluxes of the contaminant are controlled by fugacities (or partial pressures). The concentrations throughout the system tend toward thermodynamic equilibria. This approach, developed by Mackay et *al.* (1983a), permits determination of the chemical distribution and persistence of pollutants in the environment (air, water, soil, sediments, and biota). Mathematical models have been derived for lakes (Mackay et al. 1983) and rivers (Mackay et *al.* 1983b).

Since the initial concentration of contaminant must be known before distribution through the pathways, these models are frequently coupled to, or use, output from air dispersion and/or water quality and/or groundwater quality models. SENESLRT is an example for the coupling of a pathways model with air dispersion and CO,-cycling models. Beak and SENES have both used pathways models coupled with water quality models, and Beak has also coupled pathways with groundwater quality models. Maclaren's CHINTEX system model has been used to examine all three situations.

By itself, pathways analysis is a very simple technique to apply since it is essentially linear algebra. One consultant uses a spreadsheet program to make these calculations on a microcomputer.

EPIDEMIOLOGICAL RISK ANALYSIS

Epidemiological risk analysis is essentially based on actuarial calculations. Changes in life expectancy as the result of exposure to some sort of environmental change are usually examined. For example, if one wishes to know the increased risk to the population of the proposed installation of a certain type of industry, one could examine differences in life expectancy around similar plants already existing elsewhere, as compared with the life expectancy of the population as a whole.

Such studies have been applied to plant workers and uranium miners in the United States and Canada, but we did not encounter any publicized studies for impact assessment.

ACCIDENT RISK ANALYSIS

Accident risk analysis is also based on actuarial calculations.. Using directly applicable historical data, or extrapolated from indirectly applicable historical data, probabilities of certain occurrences are calculated. These probabilities are then multiplied and/or summed, to arrive at an overall probability that a certain series of events will occur.

An example of such a series of calculations is Marsan's risk evaluation for the installation of a LNG terminal at Gros-Cacouna, Quebec. Here, probabilities of tanker collisions were calculated for the different segments of the tanker routes. For each collision scenario, the chances of a fire versus formation of a vapour cloud were calculated. The risks to the population for each combination of the above-mentioned events were then calculated, based on population densities within certain distances of the possible accident sites.

While simple algebraically, such calculations can be very detailed and tedious. Even though the best information available is used, there is frequently great uncertainty in the estimation of some of the probabilities, especially since some of the events so investigated may never yet have occured.

As with pathways analysis, results from other models may serve as inputs. In the afore-mentioned example, the risks posed to members of the population were based on a model of dispersion of a spill and on a model of heat generation due to a fire of the spilled liquid natural gas. If risk is being calculated for an accidental release of an air-borne substance, air dispersion models are used.

9. BIOTIC MODELS

Far and away the vast majority of biotic models have been used for research purposes only, and their use in impact assessment has been rare. This is because:

- many models cannot be applied generally,
- some models have prohibitive input requirements,
- we lack adequate quantitative knowledge to model reliably certain processes, especially fluxes of material or energy between trophic levels,
- many models are tautological in nature,
- there is a lack of confidence in biological models,
- most biological models have not been validated,
- there is a lack of personnel with expertise in both biology and modelling, and
- quantitative impact predictions for biological components are not always required by regulating agencies

Even in the academic community there is controversy about the usefulness of biological models. Confronted with these factors, few consultants are willing to devote the time and expense necessary for the development and/or implementation of a model. In pre-project impact assessments reviewed, the only explicit dynamic biological models found were for the spruce budworm in terrestrial systems or for bacteria in aquatic systems.

implicit modelling is more frequent. For instance, when a water quality model examines BOD_5, there is implicit model of the organisms consuming the oxygen. Carbon and phosphorus cycling are other examples of implicit biological modelling. Implicit modelling was used for almost all processes in SEBJ's model of water quality changes as a result of decomposition of vegetation and soil in the LG-2 reservoir. Somewhat farther removed are models that consider habitat “accounting”, where changes in the amount of available habitat are calculated based on man-induced changes such as water level or land use. Pathways models can also be seen as implicit biological models, since biota are parts (or the endpoints) of the pathways but they themselves are not necessarily modelled. Since these types of models have been covered elsewhere, this discussion is limited to explicit models.

Explicit models of biota are usually compartmental and treat the various components under examination in terms of biomass, energy, or numbers of individuals. Biomass and energy are in fact equivalent, since biomass can be seen as representing stored potential energy, respiration and natural mortality as entropy, predation and grazing as energy transfers, etc. For these two approaches, populations are considered homogeneous. An example of a biomass model is SEBJ's phytoplankton model for the LG-2 reservoir.

When numbers of individuals are used, there is usually also an age structure in the population (e.g., immature vs. mature). in addition to population size, age distribution is also followed over time. An example of this type is spruce budworm modelling as done for New Brunswick (Task Force 1976) and, by Marsan, for Quebec.

MODELLING APPROACHES

Biotic models can be grouped roughly into two categories according to their output: quantitative and quasi-quantitative. Quantitative models are intended to give precise predictions. Quasi-quantitative models are instead intended to give relative predictions, and sometimes the predictions are not the actual purpose of such models. The dividing line between the two types is not clear-cut, because some quasi-quantitative models can give fairly precise results.

Quantitative Models

The use of quantitative models has been far less frequent for biological impact prediction than for other aspects of the environment. The work that has been done has for the most part examined aquatic systems, linked with or part of water quality models. Typical biotic state variables are bacteria (usually coiiforms), primary productivity or chlorophyll-a or phytoplankton, zooplankton, and fish. Most of these models have been research-oriented, but they have been applied by CCIW, SEBJ and Beak.

Quasi-Quantitative Models

These models have been applied to a certain extent in impact assessment, particularly by Environmental and Social Systems Analysts Ltd. (ESSA) and associates at the University of British Columbia in what is called adaptive environmental assessment. Examples of use of these models include management of the British Columbia salmon fisheries, pre-study planning for the Mackenzie Delta (Liard River development), and spruce budworm management in New Brunswick. Marsan has applied the latter model to Quebec. These models are used to give relative evaluations of the impacts of policy alternatives, or in some cases, the applications are heuristic to suggest possible types of impacts and focus subsequent research directions.

The philosophy of such models is that the information and detail required to make precise predictions are frequently either unobtainable or impractical to obtain, but that by using available quantitative, functional, and empirical information, part of the general behaviour of the system can be mimicked. If and when additional information and data become available, they are incorporated into the model, and sensitivity analyses can direct the efforts of information collection.

COMMUNITY TYPES

Aquatic Models

A large number of aquatic food-chain models have been developed at research institutes and universities, but rarely have they been applied to impact assessment in Canada. Applications of such models have been done for the Great Lakes (CCIW) and the LG-2 reservoir (SEBJ). Norecol has used the MINI-CLEANER model. Such models are usually linked with water quality and transport models, or at least require flow rates and water quality parameters (e.g., temperature, oxygen, phosphorus, nitrogen, etc.) as inputs. All such models are similar in structure, and a general examination of these can be found in Jorgensen (1980) and Platt et *al.* (1981).

Dynamic fish models have been used to compare different scenarios for management and exploitation of pelagic stocks, especially in British Columbia (Holling 1978). These models are usually based on numbers of individuals, with an explicit age structure in the population. Degree of exploitation and hatchery management are the major perturbations compared, and factors external to the questions of prime interest are considered to be constant. Fish models differ in spatial representations from other aquatic models, due to the high degree of non-passive mobility of fish.

Terrestrial Models

These models may examine from one to several species, and infrequently group various species together into a smaller number of compartments. The model of the spruce budworm (Holling 1978; Marsan and Coupal 1981) is an example of a terrestrial model. Budworm population dynamics and forest growth are modelled together, including cross effects. Forest management and insecticide-spraying scenarios are superimposed to evaluate changes in the system. Other examples are ESSA's model for evaluating exploitation rates for fur-bearers and ungulates. A model written by the U.S. Fish and Game service evaluates the effects on summer pest bird densities in the northern United States and Canada resulting from control measures carried out at the wintering grounds in the southern United States.

DATA PROBLEMS

Data problems have plagued quantitative modelling of aquatic systems. Plankton tend to have patchy distributions, reducing the reliability of density estimates. Patchiness is taken to the extreme in benthic communities, and even research models have tended to ignore them. Above-sediment macrophyte production is relatively easy to sample, but root biomass is more difficult. Bacteria, frequently representing negligible biomass but the largest gross turnover of material, are usually neglected, except, for example, in Beak's studies evaluating wastewater treatment. Commercially important fish species are the best-known elements of aquatic systems, due to large data-collection efforts for management purposes.

Terrestrial models have had greater data problems than aquatic models. A major reason for this is that aquatic (freshwater) systems have fixed boundaries, and immigration-emigration across these boundaries is limited and quantificiable (e.g. plankton densities in water entering a lake). In contrast, terrestrial study areas seldom have rigid boundaries. Terrestrial animals, especially birds, have a high degree of mobility across these boundaries, and such movement can be difficult to quantify. (The same is of course true of ocean movements of pelagic fish). As spatial scale increases, this difficulty is reduced but accurate population estimation can become more difficult. Naturally such problems do not exist for forest models.

MODEL VALIDATION

General validation of biological models has been weak to date. Many models simply cannot be validated in the strictest sense because the output is in too general a form to be compared with specific data. Quite often these models are not meant to be validated anyway. Some other models operate over such a long time-scale that validation may not be possible until a decade or more after the simulation predictions have been made.

Even in some studies where validation has been attempted, the results have been inconclusive. A case in point is a study using a variant of the model CLEANER (Collins 1980). In this study, a very complicated model of plankton dynamics was calibrated to data collected over a one-year period at a lake, and was subsequently applied (again over a one-year period) at another lake. Since the model predictions did not diverge much from observations in the second lake, the model and associated parameters were considered to be validated. However, there are two problems with this procedure. One year of data collection may not be adequate to find good parameter estimates (Simons and Lam 1980). In addition, even where parameters have been estimated using a relatively long time-series of data, application of the same model and data to another location for only a one-year period may not show divergence from observations, while over a longer period divergence becomes significant (Morrison et *al.* 1985).

Even if a model has undergone rigorous validation, there may still be problems. A model that is valid for a system undergoing limited or no perturbations may not be suitable for a system undergoing radical modifications.

The validation problem is serious, because confidence in model results is directly related to model validity. There are Only a few projects where post-project monitoring has had the time scale necessary for model validation. This situation may not improve until project proponents are required to undertake long-scale post-project monitoring. The monitoring problem is not unique to biological models.

CONCLUSIONS

The application of quantitative biotic models is not increasing. Consultants indicated that rather then going through the exercises of data collection and model set-up, they were more likely either to use an empirical model (e.g., the fish production model of Ryder), or to present physical and chemical predictions to biologists for qualitative predictions on impact to biota. This is not something peculiar to Canada, having been noted as a general phenomenon by ERL (1984). They concluded:

> *The current state of our knowledge of how activities affect plants and animals, and the large resources required by the few models that do exist, means that for most environmental assessments, ma **thema tical** models for predicting effects on plans and animals are either not available or not feasible to use.*

In contrast, it seems that the use of quasi-quantitative models is increasing. They are used not for impact prediction *per se,* but rather to aid in policy formulation and/or planning. Such models can assume a quantitative nature, as successively better information and data are incorporated.

10. CONCLUSIONS

A description of mathematical models has been done following a logical framework. When conducting an impact assessment, models of differing natures are put together. Appendix B contains a list of fourteen different studies where models have played an essential role. However, it must be recognized that several problems are related to the utilization of these tools. The following points have been stressed by model users during our visits.

It is current practice among consulting firms to think of mathematical models when doing an environmental impact assessment. However, sophisticated models are not always a necessity. Frequently, the simpler the approach, the better.

Model outputs are a function of assumptions made when writing the fundamental equations. In many models, there is some degree of uncertainty in the formulation of physico-chemical mechanisms involved. Thus, mathematical modelling of La Grande reservoirs allowed evaluation of the dynamic response of plankton or fish after impoundment. However, nobody thought that mercury levels in newly created reservoirs could be a major problem. Thus, mercury was not incorporated at the beginning of the study as a parameter of the system. In the end it was a major concern.

Model outputs are a function of available data, but data collection can encounter difficulties. Sometimes the detection level of equipment is too low. Nevertheless, the previous example demonstrates the need for continuous monitoring of a maximum number of parameters. Automatic remote stations and teledetection could play a valuable role. Mathematical models may help to reduce the number of stations and to analyse the collected data. Redundancies and poor location of stations sometimes result from surveys done by different levels of government or public agencies. Good data bases could be established if measurements were integrated.

Very few attempts have been made to validate mathematical models. Proponents are usually not interested in this exercise. However, many environmental impact assessments result in compulsory monitoring programs for the proponents. Data are collected and not always used.

Compatibility exists between physical and mathematical models. Thus, a mathematical model calibrated with a physical model can be directly validated on-site without any “tuning” of parameters.

Compatibility exists between mathematical models. INRS-Eau presented a good example of this point. A hydrological model was used, which had been validated for several years with the same set of parameters. As a new question was introduced to describe water quality, it was found necessary to modify the calibration which previously was thought correct.

Biological models are not as developed as water quality models. Biological systems are more difficult to simulate due to their complex nature. Moreover, it was frequently stated during our visits that mathematical content is not sufficient in biology curricula at universities.

In conclusion, some important features should be emphasized:

- Most of the time, the modeller might follow the approach proposed in Figure 2. A study can include several applications of models of increasing complexity. Each intermediate model gives indications which can be used to verify the next more sophisticated model. As seen previously, a simpler model can help to define boundary conditions for a more complex one.

- Models must be made more credible. Public perception is not always related to the actual hazard. It is well-known that the risk associated with nuclear power stations is feared much more than the risk associated with cigarette smoking or road casualties. To obtain that confidence, several actions can be undertaken:

  - validation of impacts predicted by past studies and follow-up of the projects with monitoring efforts;
  - organization of comparisons between physical and mathematical models;
  - organization of comparisons of various mathematical models in the same field — the World Meteorological Organization is conducting a comparison of ten different hydrological models in seven different countries, and the results of this comparison will be published at the end of the year with detailed descriptions of each model;
  - consulting firms could be asked to publish complete documentation when using a mathematical model in an impact assessment study; external experts and other consulting firms might then be in a position to evaluate the work done; and
  - universities could increase the amount of mathematics tauaht to bioloaists.

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APPENDIX A

INTERVIEWS

GROUPS	PEOPLE MET	DATE OF INTERVIEW	NATURE OF THE TOPICS DISCUSSED
AES (Toronto)	A.K. Lo	84/04/05	air quality
	S. M. Daggupaty	84/04/05	air quality
	M. Philipps	84/04/05	air quality
	I.D. Rutherford	84/04/05	oil spill motion
	S. Venkatesh	84/04/05	oil spill motion
Acres (Niagara Falls)	David Judge	84/04/30	hydrology and water quality
	I.K. Hill	84/04/30	general information
	Tom Lavender	84/04/30	general information
	Ed Skiba	84/04/30	hydrodynamics and
	Gary Struggins	84/04/30	groundwater quality
	John Walker	84/04/30	air quality
BC Hydro (Vancouver)	A. Brotherston	May 84(*)	air quality
Beak (Toronto)	Michael Holloran	84/04/06	general information
CCIW (Burlington)	D.C.L. Lam	84/04/30	hydrodynamics and water quality
	Y.L. Lau	84/04/30	erosion, sedimentation
Centreau (Quebec City)	Yvan Ouellet	84/04/17	hydrodynamics and water quality
CONCORD SCIENTIFIC (Toronto)	J. Hunt	84/05/01	air quality
ENVIRCON (Vancouver)	B. Jenkins	May 84(*)	general information
Environmental Applications Group (EAG) (Toronto)	R. Kolomeychuk	84/05/01	air and water quality
Environmental Sciences Ltd (ESL) (Vancouver)	T. Jandali	May 84(*)	air quality
ESSA (Vancouver)	R.R. Everitt	May 84(*)	ecological modelling
Hydro-Quebec (Montreal)	J.C. Tessier	84/04/26	general information
	M. Quach	84/04/26	general information
	L. Varfalvy	84/05/14	air quality

GROUPS	PEOPLE MET	DATE OF INTERVIEW	NATURE OF THE TOPICS DISCUSSED
INRS-Eau (Quebec City)	Andre Tessier	84/04/24	trace metals and biological organisms
	Daniel Cluis	84/04/24	water quality
	M. Morin	84/04/24	hydrology
	M. Couillard	84/04/24	water quality
	M. Lachance	84/04/24	air dispersion (long range)
	C. Auclair	84/04/24	biology
	J. P. Villeneuve	84/04/24	water quality
	J. P. Fortin	84/04/24	air dispersion (long range)
Intera (Calgary)	D.S. Davison	May 84(*)	general information
Maclaren (Toronto)	Douglas B. Hodgins	84/04/06	general information
	Alex Buchnea	84/04/06	general information
Marsan (Montreal)	Andre Marsan	84/04/26	general information
	Bernard Coupal	84/04/26	general information
MENVIQ (Quebec City)	Claude Lelièvre	84/04/17	air dispersion (long range)
	Robert Boudrault	84/04/17	impact assessment analysis
MEP (Toronto)	T. Scholtz	84/05/01	air quality, oil slicks and hydrodynamics
MOE Ontario (Toronto)	B. Hodgins	84/05/02	impact assessment analysis
	P.K. Misra	84/05/15	air quality
	D. Yap	84/05/15	air quality
Monserco (Toronto)	R.P. Bell	by phone	air quality
Norecol (Vancouver)	R. A. Hawes	May 84(*)	water quality
Ontario Hydro (Toronto)	B.J. McCormick	84/04/06	general information
	Reed C. Harris	84/04/06	general information
Ontario Research Foundation (Toronto)	Monika Dobson	84/05/02	air quality
Roche (Quebec City)	Donald Labrie	84/04/17	general information
	Claude Vezinat	84/04/17	general information
	Marc Delagrave	84/04/17	general information
SEBJ (Montreal)	Danielle Messier	84/04/26	water quality
SENES (Toronto)	David W. Hopper	84/04/05	general information
	Brett G. Ibbotson	84/04/05	general information
University of Toronto	D. Mackay	84/05/15	oil slicks and pollutant,
	S. Patterson	84/05/15	distribution and persistence
	R.E. Munn	84/05/15	air quality

(●) People met by a third party upon our request

APPENDIX B

CASE STUDIES

We have selected fourteen examples of studies in which models have been used. For each case study the proponent and the nature of the project are presented, modelling activities are highlighted, and the usage of model results are noted. We have reported only on modelling aspects, but for most of these studies modelling was only a part of the assessment. For studies lasting over several years we have noted the date of the final report.

This examination is by no means exhaustive, even of the reports reviewed for this project. It is meant only to provide an indication of some of the different types of projects to which modelling has been applied.

PROJECT	PROPONENT	NATURE OF PROJECT	MODELLING	NOTES
1. Sulphate Loadings on the Great Lakes	Canada Center for inland Waters, 1975	Evaluation of atmospheric loading of sulphate to the Great Lakes	Long-range transport of SO, from many different sources into the Great Lakes	Comparison of different scenarios for increased **coal** use and different pollution control programs on SO, loading
2. Wreck Cove Hydro-electric Project	Nova Scotia Power Corporation, 1977	Construction and management of a multi-reservoir hydro-electric complex	Temperature and oxygen modelling in each reservoir Hydrologic modelling of riparian flows	Comparison of impacts on oxygen and temperature of different reservoir configurations Calculation of necessary water release to maintain fish habitat
3. Elliot Lake Uranium Mines Expansion	Rio Algom Ltd. and Denison Mines Ltd., 1979	Expansion of uranium mining activities	Hydrology of the surrounding basin Water quality impacts of effluent discharge Air dispersion of radionuclides Radiation pathways analysis	Comparison of impacts resulting from different scenarios for development, waste disposal, and waste reduction.
4. Gros Cacouna Liquified Natural Gas Terminal	Arctic Pilot Project and Trans-Canada Pipelines Ltd., 1980	Construction and operation of a liquefied natural gas tanker terminal	Dispersion of a spill of LNG Radiant heat transfer due to a fire resulting from a spill Accident risk analysis	Calculation of size of danger zone due to a spill and possible fire Calculation of risks to the local population due to accidents
5. Eastmain River	James Bay Energy Corp. (SEBJ), 1981	Diversion of 90 % of the flow from the Eastmain River	Water transport model (hydrodynamics)	Evaluation of tidal effects on currents and salinity intrusion into the mouth of the river
6. Midwest Project	Canada-Wide Mines Ltd., 1981	Development of a new uranium mine	Air emissions dispersion from mining operations Stream contamination from mine tailings, etc. Groundwater flow and contamination Terrestrial and aquatic pathways of radionuclides	General calculations of contaminant distribution Comparison of pit vs. underground mining for dewatering Comparison of scenarios for wastewater disposal
7. Liard River Hydro-electric Development	B.C. Hydro, 1982	Creation of a hydro-electric complex	One model incorporating submodels of hydrology, vegetation, wildlife, aquatic biology, and socio-economics	Limited to downstream effects at the Mackenzie Delta Quasi-quantitative model; not for prediction Allowed identification of probable types of impacts in order to focus subsequent field studies
8. 1200 MW Thermal Generating Station	Saskatchewan Power Corp., 1982	Site selection for a new thermal generating plant	Water quality and thermal pluming Air dispersion from stacks Groundwater impacts due to ash disposal	Comparison of impacts of 3 different sites Comparisons of operating scenarios at each site

PROJECT	PROPONENT	NATURE OF PROJECT	MODELLING	NOTES
9. Little Jackfish River Mile 12.5 Reservoir	Ontario Hydro, 1982	Creation of a hydro-electric reservoir	Water quality	Prediction of dissolved oxygen and phosphorus concentrations and temperature profiles over one year using different meteorological scenarios
10. Regional Transport and Environmental Cycling of Carbon- 14	Ontario Hydro. 1982	Assess carbon- 14 dispersion and human uptake due to its release from CANDU nuclear reactors	Sector-box long-range transport of CO_2 CO_2 cycling Pathways analysis of ^{14}C doses to humans	Estimation of typical doses to humans of ^{14}C due to one CANDU reactor
11. Keating Channel	Metropolitan Toronto and Region Conservation Authority, 1983	Dredging of a channel and diking of a river to maintain navigation and reduce flood risk	Hydrology of the Don River Erosion, sediment transport and sedimentation in the river and adjacent channel Hydrodynamics of the harbour and near-shore Lake Ontario to estimate distribution of contaminants	Different scenarios for dredging and river maintenance were compared for effectiveness of flood control and impact on water quality and navigation
12. Lac St-Jean	Alcan Ltd., 1983	Erosion control for the shores of Lac St-Jean	Wave generation due to wind speed and direction, and length of fetch Erosion of the shoreline due to wave size, water level and shoreline structure	Comparison of future shoreline erosion under different water-level regimes
13. La Grande 2 Reservoir	James Bay Energy Corp. (SEBJ), 1983	Creation and management of a large hydro-electric reservoir	Hydrology of a drainage basin Velocity field in a reservoir Water quality changes due to decomposition of flooded vegetation and soils Plankton dynamics Fish redistribution	Comparisons of different operating scenarios on water quality Interpretation of changes in fish catches and plankton densities at various sampling stations in the reservoir
14. Control of the Spruce Budworm in Quebec	Quebec Ministry of Energy and Resources, 1984	Annual spraying of various insecticides	Aerial dispersion of sprayed insecticides Pathways analysis of insecticides Dynamics of the budworm-forest system	Ground-level concentrations of insecticides allowed worst-case evaluations of risks to humans and other animals Scenarios of treatment vs. lack of treatment compared on the basis of budworm populations and wood production

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